

Engineering Fronts 2022

Project Group of Global Engineering Fronts
of Chinese Academy of Engineering



中国工程院战略咨询中心
Center for Strategic Studies, CAE

 Clarivate™

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Foreword

Engineering science and technology is an important force to change the world, and engineering fronts represent important directions for the future innovation of engineering science and technology. Currently, changes of the world, of our times and of history are unfolding in ways like never before. The new round of scientific and technological revolution and industrial transformation continue to deepen. Human society is facing unprecedented challenges. It has become the common choice of all countries to keep abreast of the trends in world science and technology, accurately identify changes, respond to them scientifically, and proactively seek changes.

In order to track the development trend of engineering science and technology, the Chinese Academy of Engineering (CAE), the most honorable consulting academic institution in China, has been organizing a project known as “Global Engineering Fronts” every year since 2017. The research identifies and releases nearly two hundreds of engineering research fronts and engineering development fronts every year to guide academic development and promote the innovation of engineering science and technology.

The 2022 Global Engineering Fronts research rely on nine academic divisions and academic journals of the CAE to identify 95 engineering research fronts and 93 engineering development fronts, collaborating with Clarivate. This is done by paying equal attention to the engineering research and development fronts, integrating quantitative analysis and qualitative research, and combining data mining and expert argumentation. Among these, 29 key engineering research fronts and 29 key engineering development fronts are selected for detailed interpretations.

In 2022, we explored and formulated a technical system at the initial stage of the project to define the technology boundary and structure of the nine fields and sort out the correlation among the branches of technology. In the process of key engineering fronts interpretation, a development roadmap tool is introduced to study the development directions of key engineering fronts in the next 5–10 years.

This report presents the results of the 2022 project and comprises two parts. Part A explains the data and methodology. Part B presents the technology reports focusing on nine fields: (i) mechanical and vehicle engineering; (ii) information and electronic engineering; (iii) chemical, metallurgical, and materials engineering; (iv) energy and mining engineering; (v) civil, hydraulic, and architectural engineering; (vi) environmental and light textile engineering; (vii) agriculture; (viii) medicine and health; and (ix) engineering management. Each report describes and analyzes the engineering research and development fronts in these fields and explains the key fronts in detail.

Identifying engineering fronts is a complex and challenging task. For six years, the research team have been focusing on the development hotspots and challenges of the global engineering science and technology and gradually explored a unique research path, that is, the research, forums, and journals were closely integrated to promote each other. The project was supported by nearly a thousand of academicians and experts from various fields and institutions. We are grateful to all of them!

Part A Methodology

Engineering is the practical activity in which human beings transform the world with the help of science and technology. An engineering front refers to the key direction that is forward looking, leading, and exploratory. It has a major influence and plays a leading role in the future development of engineering science and technology and serves as an important guide for cultivating the capabilities for innovation in the field of engineering science and technology. According to the innovation stage of the front, Engineering fronts are categorized into engineering research fronts which focuses on the theoretical exploration and engineering development fronts which focuses on the practical application of engineering science and technology.

Underpinned by experts' evaluation and data, the Global Engineering Fronts 2022 project has adopted multi-round interactions between experts and data for iterative research and analysis, realizing a deep integration of judgments of experts and data analyses. In 2022, 95 global engineering research fronts and 93 global engineering development fronts are selected, with 29 engineering research fronts and 29 engineering development fronts being listed as the key focus of interpretation. The distribution of engineering research and engineering development fronts among the nine fields is shown in Table 1.1.

The research of fronts consists of three stages: data preparation, data analysis, and expert review. In the data preparation

stage, the domain, library, and information experts formulate the literature and patent search strategy according to the technological systems to define the scope of data mining. In the data analysis stage, the co-citation clustering method is used to obtain clustered literature topics and the co-word clustering method to obtain the Theme Scape patent maps. In the expert review stage, the fronts are gradually selected and determined through front topic section, front name revision, expert panel discussions, and other methods. To address the problem of lacking of novelty due to algorithm limitations or lags in data mining, experts from different fields were encouraged to check the results of the data analysis to revise, combine, and expand the engineering fronts. A flowchart of the operation procedure of the Global Engineering Fronts project is illustrated in Figure 1.1, in which the green, purple, and red boxes indicate the data analysis, expert research, and multi-round iterative interactions between experts and data, respectively.

1 Identification of engineering research fronts

The identification of the engineering research fronts is performed in two steps. The first step involves determining the clustered literature topics through the co-citation clustering method according to the SCI journal papers and

Table 1.1 Distribution of engineering research and engineering development fronts among the nine fields

Field	Number of engineering research fronts	Number of engineering development fronts
Mechanical and Vehicle Engineering	10	10
Information and Electronic Engineering	10	10
Chemical, Metallurgical, and Materials Engineering	12	10
Energy and Mining Engineering	12	12
Civil, Hydraulic, and Architectural Engineering	10	10
Environmental and Light Textile Engineering	10	10
Agriculture	11	11
Medicine and Health	10	10
Engineering Management	10	10
Total	95	93

data of conference proceedings collected from the Web of Science Core Collection. The second step is calling for the engineering research themes through expert nomination. Candidate engineering research fronts that were identified through expert argumentation and refinement went through questionnaire surveys and multiple rounds of expert discussions, yielding 95 engineering research fronts in the nine fields.

1.1 Acquisition and preprocessing of paper data

Firstly, the mapping relationship between the technology systems of nine academic departments of the CAE and Web of Science disciplines was constructed, and the lists of academic journals and academic conferences corresponding to each field were obtained. After the correction and supplementation by domain experts, the sources for data analysis in the nine fields were determined to be 12 709 journals and 48 260 conferences. In addition, for articles from 79 multidisciplinary sciences journals, the field of each article was reassigned to the most relevant subject area according to the subjects cited in its references.

Accordingly, the articles and conference papers published between 2016 and 2021 were retrieved (the cut-off date of the citations was January 2022). For each field, the differences between journals and conferences, the publication year,

and so on were comprehensively considered. By processing journals and conference proceedings separately, papers with high impact that are ranked among the top 10% of the citations were selected as the original dataset for the analysis of the research fronts, referring to the highly cited papers in Web of Science, as shown in Table 1.1.1.

1.2 Mining of clustered literature topics

Through the co-citation clustering analysis of the top 10% highly cited papers in the aforementioned nine data datasets, all the clustered literature topics in the nine fields were obtained. The topics of the journal and conference papers published during 2016–2019 were selected according to the number of core papers, total number of citations, mean publication year, and the proportion of consistently cited papers. Consequently, 35 diverse literature topics were extracted. The topics of the journal and conference papers published during 2020–2021 were selected according to the number of core papers, total number of citations, and proportion of consistently cited papers. Thereafter, 25 different literature topics were obtained. Overlapping topics were replaced by topics that did not intersect with other fields. In addition, subjects that were not covered by clustering topics were extracted separately by keywords. Finally, 772 clustered literature topics in the nine fields were obtained (Table 1.2.1).

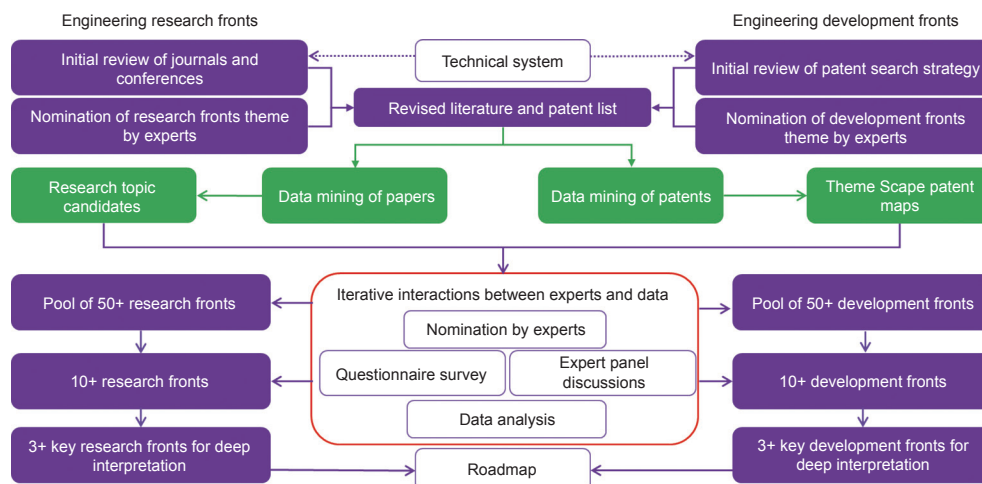


Figure 1.1 Operation procedure of the Global Engineering Fronts project

Table 1.1.1 Number of journals, conferences, and top 10% highly cited papers in each field

No.	Field	Number of journals	Number of conferences	Number of top 10% highly cited papers
1	Mechanical and Vehicle Engineering	533	3 026	96 918
2	Information and Electronic Engineering	999	21 306	220 667
3	Chemical, Metallurgical, and Materials Engineering	1 209	4 259	292 796
4	Energy and Mining Engineering	938	2 682	149 334
5	Civil, Hydraulic, and Architectural Engineering	650	1 284	71 484
6	Environmental and Light Textile Engineering	1 362	1 376	225 197
7	Agriculture	1 363	934	165 566
8	Medicine and Health	4 835	12 072	499 690
9	Engineering Management	820	1 321	55 778

Table 1.2.1 Statistics of co-citation clustering results in each field

No.	Field	Number of Clustered topics	Number of core papers	Number of candidate engineering research hotspots
1	Mechanical and Vehicle Engineering	10 734	43 833	103
2	Information and Electronic Engineering	22 342	96 506	71
3	Chemical, Metallurgical, and Materials Engineering	29 447	119 038	61
4	Energy and Mining Engineering	16 204	68 338	96
5	Civil, Hydraulic, and Architectural Engineering	7 893	34 302	126
6	Environmental and Light Textile Engineering	24 309	98 407	93
7	Agriculture	17 736	69 902	78
8	Medicine and Health	50 805	214 345	65
9	Engineering Management	5 662	22 140	79

1.3 Determination and interpretation of research fronts

While processing and mining the paper data, domain experts put forward research front issues via a comprehensive analysis of data pertaining to science and technology news and policies, and integrated them into each stage of front determination.

In the data preparation stage, the library and information experts transform the front research issues raised by domain experts into search strategies, which are an important part of the initial data source. In the data analysis stage, for

subjects that are not covered by clustered literature topics, domain experts provide keywords, representative papers, or representative journals for customized search and mining. In the expert review stage, domain experts will check for omissions based on the clustered literature results and conduct the second round of nomination for fronts that do not exist in the data mining results but are considered important. Library and information experts provide data support. Finally, the domain experts merge, revise, and refine the engineering research front topics obtained through data mining and expert nomination. Subsequent to questionnaire surveys and multiple rounds of conference discussions, approximately 10 engineering research fronts were selected for each field.

In each field, three or four key research fronts were selected according to the development prospects and the significance. Authoritative experts in the front direction were invited to interpret the fronts in detail from the perspectives of national and institutional layout, cooperation networks, development trends, and R&D priorities.

2 Identification of engineering development fronts

The identification of the engineering development fronts is primarily performed using two methods. First, based on the Derwent Innovation patent database, the top 10 000 patent families of 53 subjects in the nine fields with highest citations were clustered, and 53 Theme Scape maps were obtained. The domain experts interpreted the candidate engineering development fronts from these maps. The second approach involves nomination by experts. The candidate development fronts obtained through these two methods went through multiple rounds of expert discussion and questionnaire surveys. Consequently, approximately 10 engineering development fronts were identified in each field.

2.1 Acquisition and preparation of patent data

In the data preparation stage, based on the Derwent Innovation patent database, the initial patent data retrieval scope and search strategies for the 53 disciplines of the nine fields were determined using the Derwent World Patents Index (DWPI) Manual Codes, International Patent Classification numbers, United States Patent Classification numbers, and other patent classification numbers and specific technical keywords. Domain experts deleted, supplemented, and improved the patent search strategies to determine the patent retrieval criteria and nominated candidate front topics, which were then transformed into patent search strategies by library and information experts. The above two parts of the search strategies were integrated to determine the patent search strategies of the 53 disciplines, searched in the “enhanced patent data—DWPI and Derwent Patent Citation Index (DPCI)” collection, and obtained the patent literature of the corresponding

disciplines. The retrieved patents were published between 2016 and 2021; the cut-off date of the citations was January 2022. To further concentrate patent literature, the millions of patent documents were screened according to the annual average number of citations and technical coverage width indicators, thereby obtaining the top 10 000 patent families in each discipline.

2.2 Mining of patent topics

Semantic similarity analysis of patent texts were conducted for the top 10 000 highly cited patents on 53 disciplines in the nine fields. Based on literature topic clustering using DWPI titles and abstracts, 53 Theme Scape patent maps were obtained, which effectively display the distribution of the engineering development techniques and show the overall technical information of the collected patents in the form of keywords.

Experts from various fields, with the assistance of library and information experts, selected the engineering development fronts from Theme Scape maps, merged similar fronts, and determined the final development fronts. Finally, they selected the candidate engineering development fronts of each specialty group. To avoid missing emerging fronts, domain experts interpreted the data from patents with few citations and poor correlation in the Theme Scape maps.

2.3 Determination and interpretation of development fronts

While processing and mining the patent data, domain experts identified issues on development fronts based on a comprehensive analysis of other data, such as science and technology news and policies, and integrated them into each stage of front determination.

In the data preparation stage, the library and information experts transformed the key front issues raised by domain experts into patent search strategies as an important part of the basic dataset. In the data analysis stage, domain experts conducted the second round of front nomination to supplement the emerging technology points that are significant but have been submerged in data mining with few

patents. In the expert review stage, domain experts studied highly cited patents, and library and information experts assisted them in interpreting patent maps from multiple perspectives, such as “peaks” “blue oceans” and “islands”. Finally, domain experts merged, revised, and refined the interpreted results of the patent maps and fronts nominated by experts to obtain candidate engineering development fronts, and then selected approximately 10 engineering development fronts in each field through questionnaire surveys or multiple rounds of seminars.

In each field, three or four key development fronts were selected according to the development prospects and the significance. Authoritative experts in the front direction were invited to interpret the fronts in detail from the perspectives of national and institutional layout, cooperation networks, development trends, and R&D priorities.

3 Development roadmap

Technology roadmaps are an important tool to depict the development trend of technologies. To strengthen the academic leading role of the engineering fronts, the Global Engineering Fronts 2022 project conducted detailed analysis on the development focuses and trends of three key engineering research fronts and three key engineering development fronts for each field, and drew a development roadmap in a visual way for each front in the next five to ten years.

4 Terminologies

Publications/Papers: This includes peer-reviewed and published journal articles, reviews, and conference papers retrieved from Web of Science.

High-impact papers: Papers that are in the top 10% in terms of citation frequency are considered to be of high impact, taking into account the year of publication and journal subject category.

Clustered literature topic: A combination of topics and keywords obtained through a co-citation clustering analysis of high-impact papers.

Core papers: Depending on how the research front is obtained, core papers have two meanings. If it originates from a front that is obtained from data mining and revised by experts, the core paper is considered as a high-impact paper. If it comes from a front nominated by domain experts, the core paper is included in the top 10% of papers in terms of citation frequency obtained using the corresponding search strategy.

Percentage of core papers: The proportion of core papers in which a country or institution participates among the total number of core papers produced by all countries or institutions.

Citing papers: Collection of papers that have cited core papers.

Citation number: The number of times the paper has been cited by the Web of Science Core Collection.

Mean publication year: Average publication years for all papers among the clustered literature topics.

Consistently cited papers: Papers included in the top 10% in terms of citation velocity.

Citation velocity: An indicator used to measure the growth rate of the cumulative number of citations for a certain period. In this study, the citation velocity of each paper begins with the month of publication, and the cumulative number of citations per month was recorded.

Highly cited patents: The around top 10 000 DWPI families ranked by the average annual DPCI citations.

Core patents: According to the different ways of obtaining a development front, core patents have two meanings. If they come from the fronts of the patent map, core patents refer to highly cited patents. If they are from the fronts nominated by domain experts, core patents refer to all patents obtained by topic search.

Percentage of published patents: The proportion of core patents in which a country (priority country) or institution participates among the total number of core patents produced by all countries or institutions.

Theme Scape map: A themed landscape representing the overall outlook of a specific industry or technical field. It is a visual presentation in the form of a map obtained by analyzing the semantic similarity of value added DWPI information of patents to gather the patents of related technologies.

Technical coverage width: It is measured by the number of DWPI Classes to which each DWPI patent family covers. This indicator can reflect the breadth of the technology coverage of each patent.

Specialty division criteria system of the academic divisions of the CAE: This is specified in the Specialty Division Criteria of the Academic Divisions of the Chinese Academy of Engineering for Member Election (Trial). It refers

to 53 specialized disciplines covered by the nine academic divisions of engineering science and technology, including Mechanical and Vehicle Engineering; Information and Electronic Engineering; Chemical, Metallurgical, and Materials Engineering; Energy and Mining Engineering; Civil, Hydraulic, and Architectural Engineering; Environmental and Light Textile Engineering; Agriculture; Medicine and Health; and Engineering Management.

Part B Reports in Different Fields

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The ten most-researched engineering fronts in the field of mechanical and vehicle engineering include: mechanical, transportation, ship and marine engineering; weapon science and technology; aeronautical and astronautical science and technology; and power and electrical equipment engineering and technology (as listed in Table 1.1.1). Among these, “human–robot contactless collaboration”, “underwater navigation and positioning technology”, “cooperative unmanned driving and operation optimization technologies”, “active/passive control technologies for turbulent flow around high-speed trains”, “variable stiffness technologies for robots”, and “mini and micro unmanned aerial vehicle (UAV) detection” are extensively studied traditional topics. “Autonomous ship deck landing technology for aircraft”, “triboelectric nanogenerator”, “theory and method of continuous multidimensional variable configuration flight control”, and “microrobot active drug delivery technology”

are considered as emerging topics.

The annual publication of papers during the years 2016–2021 is listed in Table 1.1.2.

(1) Autonomous ship deck landing technology for aircraft

Aircraft autonomous ship deck landing refers to the processing information obtained from airborne equipment during the landing phase to obtain landing information with sufficient precision so that the aircraft can complete the autonomous landing process. It involves the cross-integration of the ship and marine engineering, aircraft design, satellite navigation, radar tracking, computer vision, artificial intelligence, and other disciplines. The technology of aircraft autonomous ship deck landing has experienced four stages, namely, full manual mode, manual-assisted semi-automatic mode, automatic mode, and unmanned aerial vehicles full autonomous mode. The related research is mainly divided into two aspects: one is the research of autonomous landing guidance technology, which is mainly used to determine the relative position of the aircraft and ship, generate the reference glide trajectory, and calculate or measure the trajectory tracking error. The second is the research of autonomous landing control technology,

Table 1.1.1 Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Autonomous ship deck landing technology for aircraft	8	191	23.88	2018.0
2	Human–robot contactless collaboration	3	161	53.67	2019.7
3	Triboelectric nanogenerator	21	1 157	55.10	2019.5
4	Underwater navigation and positioning technology	85	2 836	33.36	2017.6
5	Cooperative unmanned driving and operation optimization technologies	10	226	22.60	2018.0
6	Theory and method of continuous multidimensional variable configuration flight control	15	232	15.47	2017.7
7	Microrobot active drug delivery technology	41	2 564	62.54	2019.0
8	Active/passive control technologies for turbulent flow around high-speed trains	20	866	43.30	2017.7
9	Variable stiffness technologies for robots	6	344	57.33	2017.2
10	Mini and micro unmanned aerial vehicle (UAV) detection	6	175	29.17	2017.0

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Autonomous ship deck landing technology for aircraft	1	2	2	2	1	0
2	Human-robot contactless collaboration	0	0	1	0	1	1
3	Triboelectric nanogenerator	0	0	5	6	4	6
4	Underwater navigation and positioning technology	26	16	20	13	9	1
5	Cooperative unmanned driving and operation optimization technologies	2	3	2	0	2	1
6	Theory and method of continuous multidimensional variable configuration flight control	4	2	3	6	0	0
7	Microrobot active drug delivery technology	1	5	10	9	9	7
8	Active/passive control technologies for turbulent flow around high-speed trains	3	6	7	3	1	0
9	Variable stiffness technologies for robots	1	3	2	0	0	0
10	Mini and micro unmanned aerial vehicle (UAV) detection	2	3	0	1	0	0

which explores the landing control strategy and method with robustness to achieve the fast-tracking of the ideal glide trajectory in a complex environment and can maintain the stability of the aircraft attitude. To date, the research on aircraft autonomous ship deck landing has been developed in the direction of multi-information, all-round, and autonomy. Meanwhile, with the continuous development of satellite navigation, precision radar, visual navigation, artificial intelligence, advanced control, and other related technologies, the reliability of ship deck landing for aircraft will increase and eventually realize autonomous and intelligent landing.

(2) Human-robot contactless collaboration

Human-robot contactless collaboration means that a robot maintains a sufficiently safe distance from a human worker in the same physical space while assisting the human to complete specific tasks and reduce human labor work. Collaborative robots are featured with safety, adaptability, and comfort in the process of human-robot cooperation; specifically, the robot should not harm humans, the robot can understand the human intents accurately and adapt to human movements actively, and the robot action conforms to the cognitive habits of humans so that people can understand the action intention of the robot. The related research can be mainly categorized into three aspects, namely, the studies of prevention of collision events, prediction of human motion intention, and generation of robot anthropomorphic motions.

① To prevent collision events, exploring new sensing technologies for multi-modal information, including object

distances, contact forces, and joint torques, is worthy to study the motion principles and deformation mechanism of coupled rigid-flexible-soft robots and develop collaborative robots with collision avoidance ability. ② With regard to the prediction of human motion intention, key research topics include object identification in unstructured environment, adaptive control with motion intent prediction and hand-eye coordination, and virtual reality of human-robot interaction. ③ To generate robot anthropomorphic motions, there are critical challenges to reveal the mechanisms of human-limb natural motions, identify biomechanical characteristics of human musculoskeletal systems, establish the bionic design theory, develop the generation method of robot anthropomorphic motions, and implement feedback control method that conforms to human cognitive habits. With the development of soft material science, intelligent sensing technology, ergonomics, and related disciplines, collaborative robots are expected to make breakthroughs in key technologies, such as multi-modal perception, intention recognition, environmental modeling, anthropomorphic motion, and decision optimization, and enhance the interactive experience and operation efficiency of human-robot contactless collaboration.

(3) Triboelectric nanogenerator

Triboelectric nanogenerator (TENG) is an emerging ambient energy harvesting technology used to convert mechanical energy created by the periodic contact/separation motion of two different materials (i.e., triboelectric pair) into electrical

power. Based on the coupling of triboelectrification effect and electrostatic induction, the positive and the negative charges are generated at the interfaces of triboelectric pair, and then the induced charges are driven to flow in the loop to form the current that resulted from the periodic alternating of potential difference between the triboelectric pair. In general, the development of TENG has experienced three stages, namely, fundamental study and operation models, hybrid mechanisms and circuit design for integration, and self-powered smart microsystems. The related research activities can be summarized into three categories. First, the working principle of triboelectric nanogenerators, including triboelectric effect investigation, materials selection, and structural design, is studied further to enhance the electrical performance. Second, the hybrid mechanisms by the combination of triboelectric effect with other effects, including piezoelectric, electromagnetic, photovoltaic, and thermoelectric effects, are explored to design high-efficient energy generators together with power management circuit and storage devices. Third, the triboelectric nanogenerators are integrated with other functional components, especially multi-functional sensors, to construct the self-powered smart microsystems. With the advantages of high efficiency, sensitivity, and integration, the triboelectric nanogenerators show attractive potentials to address the power challenges of low-power consumption devices and microsystems, which represent the development tendency of smart self-powered electronics.

(4) Underwater navigation and positioning technology

Underwater navigation and positioning focuses on obtaining vehicle state information. This includes position, velocity, orientation, and other information concerning its motion. Traditionally, such methods rely on inertial measurements, underwater acoustics, or marine geophysics. As the demand for better navigation and positioning accuracy intensifies, techniques that rely on a single type of information fall out of favor. Moreover, subject to extended mission duration, underwater navigation and positioning technique is developing toward primary inertial guidance facilitated by underwater acoustics and marine geophysical feature matching. Currently, high accuracy instrumentation remains to be a critical topic in the area, with multiple types of information, including inertial measurement, ocean magnetic and gravitational field sensors, underwater acoustics propagation, seabed mapping, hydrologic environment, global positioning system, surface buoy, and underwater

beacon. Other crucial topics focus on time synchronization, feature fusion and matching, and the state estimation problem. Meanwhile, navigation and positioning-for autonomous underwater vehicles using star tracker and highly coordinating swarm is being actively researched.

(5) Cooperative unmanned driving and operation optimization technologies

Road and waterway transportation systems have lagged behind air and railway transportation in terms of unmanned due to their inherent complexity and variety. However, recently, the above two transportation systems have received substantial achievements in unmanned, flexible manned, and monomer intelligence technologies. Moreover, self-driving has been applied at scale in specific scenarios in road transportation systems, such as ports, logistics parks, and open pit mines. Similar application cases for inter-island navigation and intelligent navigation of ships in ferries and closed waters emerge in waterway transportation. However, technique bottlenecks remain in unmanned vehicles in arterial transportation and urban transportation on road, and intelligent navigation of long-distance inland waterways, open seas, and ocean-going ships. Great improvements in the reliability of unmanned driving and efficient operation of transportation system can be achieved with the theoretical and methodological breakthroughs on cooperative unmanned driving and operation optimization key technologies of road and waterway transportation. The self-driving and driving optimization for a vehicle mainly concentrate on the intelligent decision making and control of a multiagent system. The key research includes multidimensional perception of a vehicle swarm, and the mechanism of vehicle dynamics under the affection of vehicle states, road conditions, and traffic environment. In addition, the decision-making optimization for multiple vehicles under strict constraints, such as time, space, and task in a specific region, and the control for a heterogeneous vehicle platooning with the time-varying communication topology are novel hotspots in this field. Ship intelligent navigation and transportation optimization mainly focus on ship collaborative remote-control technology. The main research directions include ship dynamic modeling under complex sea conditions and environments; environmental situational awareness and autonomous navigation for a single ship; cooperative motion control theory and methods for multiple ships; multi-ship formation structure; and path planning methods. Future development will focus on the

transformation from single dynamics to group dynamics, individual perception to collaborative perception, and single autonomous decision making to group interactive decision making, which reflects the technology upgrade from single action planning optimization to a group level.

(6) Theory and method of continuous multidimensional variable configuration flight control

As an emerging new and high-technology weapon and equipment, continuous multi-dimensional variable configuration aircraft has become a key development direction of major military powers in the world. Given its ability to change the aerodynamic configuration on a large scale and realize multi-mission flight within a large flight envelope, this aircraft will surely play an important role in the future battlefield and is of great significance to safeguarding our country's security and development interests. The main research directions of continuous multi-dimensional variable configuration flight control include: aircraft model analysis under uncertainty and nonlinear dynamics caused by continuous deformation; flight dynamics coupling control mechanism under strong uncertainty environment; dynamic characteristics of rigid, flexible, and hydraulic coupling and control system modeling theory; smooth switching control theory under agile maneuvering at large angles of attack; integrated intelligent control method for variable configuration and aircraft; and cross-domain seamless autonomous navigation and online autonomous planning decision-making for environment-task self-matching. In the future, the control of continuous multi-dimensional variable configuration aircraft will achieve breakthroughs in the following directions: aircraft deformation control based on adaptive reinforcement learning methods; network communication characteristics of distributed deformation structures and coordinated control between distributed drives; flight control theory for nonlinear and uncertain large-scale variant aircraft with time-varying characteristics; coordinated control of a large number of actuators with communication constraints; coordinated control of large-scale distributed systems with shared channels; adaptive mechanics and control under continuous multidimensional large deformation intelligent decision making, autonomous control and trajectory planning methods under strong uncertain conditions, such as weak models, strong coupling of multiphysics, tasks and environments.

(7) Microrobot active drug delivery technology

Microrobots have a good development prospect in biomedical fields, such as active drug delivery and precision therapy, because of their small size, autonomous movement, and precise control. Compared with the traditional drug particles that passively rely on the human circulatory system, the microrobot active drug delivery technology can make microrobots accurately reach the predetermined tissue through self-driving or external environment driving to achieve accurate drug delivery. At present, the main driving modes include chemical/biochemical driving, field driving, and biological driving. The microrobot active drug delivery technology designs the drug loading, driving, and drug release modes of microrobots according to the pathological conditions to realize accurate drug delivery, improve drug efficiency, and reduce the side effects of drugs. In the future, microrobot active drug delivery technology still faces many challenges in terms of biological/human safety, driving, and navigation.

(8) Active/passive control technologies for turbulent flow around high-speed trains

The aerodynamic drag exerted on the trains increases sharply with the continuous increase in the speed of high-speed trains. Moreover, the aerodynamic drag accounts for an increasing proportion of total drag. The aerodynamic noise surpasses traction noise and wheel-rail noise as the main noise source. The above phenomena lead to considerable energy consumption and noise pollution problems. The aerodynamic drag and noise generated by the train traveling at high speed are closely related to the turbulent flow field around the train. Therefore, the active and passive control of the turbulent flow around the trains has become an increasingly prominent and urgent problem that must be solved to ensure the safe operation of the trains and meet the requirements of "energy saving, environmental friendliness, and comfortable riding". In recent years, the continuous development of active and passive flow control technologies and theories has allowed the control of the turbulent flow of high-speed trains. The research on the control of turbulent flow around high-speed trains aims to reduce drag by controlling large-scale turbulent vortex structures or near-wall turbulence characteristics. The specific research directions include drag and noise reduction based on train aerodynamic shape optimization, aerodynamic drag reduction of the high-speed trains based on bionic

structure spoiler, passive drag reduction based on dimples mounted on the surfaces of aerodynamic bodies, drag reduction based on jet flow, and wall turbulent drag reduction based on plasma actuators. Future research directions include the development of new active flow control technologies with high reliability and robustness that can adapt to the harsh operating environment of trains and solve the bottleneck of current control technologies. The development of the closed-loop turbulent flow control scheme and theory based on machine learning is also included.

(9) Variable stiffness technologies for robots

The stiffness of a robot is a measure of how well it interacts with the external environment. Variable stiffness technology not only combines some of the advantages seen in compliant robots with the performance of traditional rigid robots, but it also provides physical intelligence to robots, thus it is well-recognized as enabling technology in many branches of robotics. With robots shifting from spatially isolated automatic production lines into human working and living environments, by actively changing the stiffness in real time in response to dynamic events in the interaction process, emerging applications, for example, human-robot collaboration, rehabilitation assistance, multi-fingered fine manipulation, legged bionic mobility, soft robots, can provide higher task robustness, cooperative safety, motion flexibility, operational dexterity, and energy efficiency than less sophisticated systems. Traditional variable stiffness technology passively changes the stiffness of branch chains, adding series/parallel elastic elements to the rigid structure of the robot, and offline adjusting robot elastic elements by morphing or changing the robot size, resulting in large structure size, overweight, low stiffness ratio, slow response, and difficulties in transitioning between “softness” and “rigidity”. Therefore, this kind of technology cannot meet the requirements of those emerging applications to which large stiffness ratio, high bandwidth, and fast response are critical. A current trend and hot spot in robotics is the integration of structure-actuation-transmission-perception-control by integrating materials, structure, and control of robots to achieve the active variable stiffness of robots. The main research directions of robot variable stiffness control technology include: ① integrate design and control of intelligent material-intelligent structure to achieve the unity of large deformation motion and large stiffness ratio and easily obtain a smooth transition between “softness” and

“rigidity”; ② make a breakthrough in the high-power-density (quasi) direct drive technology and the integration of drive, transmission, sensing and control, to reduce the structural inertia, and to improve the speed of variable stiffness control; ③ drill into robot whole-body optimization control method to reduce the complexity of high-dimensional complex variable stiffness control and improve the real-time performance and accuracy of variable stiffness; ④ adopt machine learning to construct and enrich the stiffness profile library for typical human-robot-environment interaction application scenario to enhance the intelligent decision level of robots guided by the specific application scenario.

(10) Mini and micro unmanned aerial vehicle (UAV) detection

In recent years, mini and micro unmanned aerial vehicles (UAVs) have been misused because of their portability, simple operation, and multiple access channels. The possibility of using UAVs to create a disturbance has increased considerably. Thus, using UAVs has become a growing security threat. However, mini and micro UAVs are characterized by low flying altitude, slow speed, and small size (“low, slow, and small targets”). Thus, detecting mini and micro UAVs involves many challenges. At present, detection means mainly include radar detection, radio detection, acoustic detection, and photoelectric detection. Radar detection suffers from the interference of low-altitude complex background and clutter. At present, relevant research focuses on clutter and interference suppression technology and refined signal processing technology of echo signals. Radio detection equipment can only passively detect radio signals from airborne targets. In terms of acoustic detection, mini and micro UAVs cannot be detected easily because of the electric-motor-driven mode, which exhibits low disturbance, low noise, and slow speed. Photoelectric detection equipment can use different bands to obtain the target UAV image. However, the detection range of a visible camera is relatively limited, and the field of view and visual details are hard to reconcile. The resolution of infrared detection is limited. Distinguishing drone pixels from noise points is difficult when the UAVs are too far. The image information processing technology based on artificial intelligence has gradually attracted intensive attention. Integrating two or more sensors for joint detection based on multisource information fusion technology has become a trend to meet the requirements of mini and micro UAV detection in the actual complex environment.

1.2 Interpretations for three key engineering research fronts

1.2.1 Autonomous ship deck landing technology for aircraft

The technology of aircraft autonomous ship deck landing is an important index used to measure the safe flight of carrier-based aircraft. According to relevant statistics, aviation accidents caused by human factors during the take-off and landing phases are up to 50%. Therefore, providing a systematic guided landing solution with a high degree of automation and reliable navigation and positioning accuracy for the aircraft will help promote its application scenario and reduce the burden of personnel operation further. In this case, studying the aircraft deck landing technology is imperative and relevant. Compared with landing on a fixed platform, the successful landing on a moving ship requires overcoming more challenges, mainly the narrow landing area and the simultaneous translational and rotational movements during the landing. In addition, the landing phase will inevitably face severe external disturbances, such as atmospheric turbulence, wind over deck, and ship wake. These conditions will be further complicated when the weather and sea conditions are harsh.

With the development and application of science and technology, autonomous control of aircraft has become a research hotspot in the fields of aerospace science and technology, control science and engineering, and information and communication engineering. Thus, the aircraft autonomous ship deck landing technology is an important development trend of carrier-based aircraft autonomous landing and aircraft autonomous control. This technology has experienced four stages: full manual mode, manual-assisted semi-automatic mode, automatic mode, and unmanned aerial vehicles full autonomous mode. Due to the complex landing environment, precise guidance and control technology has become the most important tasks for the safe landing of carrier-based aircraft. The research on aircraft autonomous ship deck landing technology in China began relatively late but has been developing rapidly in recent years. The relevant research is mainly divided into two aspects, namely, studies on autonomous landing guidance and autonomous landing control. In terms of autonomous landing guidance, multi-modal information fusion landing guidance technology is explored, high-reliability wireless data links are designed,

efficient real-time image processing technology is developed, and high-precision autonomous navigation and positioning are achieved. In autonomous landing control, flight control technology with strong robustness is developed, artificial intelligence methods are used to improve the estimation accuracy of the ship deck motion state, the interference of the ship wake, deck motion, air gusts and other factors are suppressed. In addition, multi-system integrated autonomous landing control technology is explored to fast-track the ideal glide trajectory in complex environments, and the stability of the aircraft attitude is maintained. The aircraft autonomous ship deck landing technology is inseparable from the development of control engineering, sensor technology, computer, artificial intelligence, and other information technologies. It has essential theoretical research value in navigation, guidance and control, instrument science, aircraft design, and other disciplines. Overall, autonomous ship deck landing technology is of great practical significance for China to achieve a strong naval force and move toward a maritime power.

The top three countries with the greatest output of core papers on “autonomous ship deck landing technology for aircraft” are China and Singapore; and the top three countries with the greatest output of citations per paper are Australia, Canada, and Tunisia, as seen in Table 1.2.1. Among the Top 6 countries with the greatest output of core papers, China has more cooperation with Singapore, and Canada has more cooperation with Tunisia, as shown in Figure 1.2.1. The top three institutions with the greatest output of core papers are Nanyang Technological University, Beihang University, and Nanjing University of Aeronautics and Astronautics. The top four institutions in the number of citations per paper are the University of New South Wales, Carthage College, University of Sfax, and University of Quebec, as shown in Table 1.2.2. As shown in Figure 1.2.2, Carthage College, University of Sfax, and University of Quebec have a lot of cooperation. Nanyang Technological University, DSO National Laboratories of Singapore, and National University of Singapore have a lot of cooperation. And Nanyang Technological University also has cooperation with Beihang University. The country with the greatest output of citing papers is China, as shown in Table 1.2.3. The main output institutions of citing papers are Beihang University and Nanjing University of Aeronautics and Astronautics, as shown in Table 1.2.4. Figure 1.2.3 shows the roadmap of this front.

Table 1.2.1 Countries with the greatest output of core papers on “autonomous ship deck landing technology for aircraft”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	4	50.00	84	21.00	2018.5
2	Singapore	2	25.00	46	23.00	2017.5
3	Australia	1	12.50	42	42.00	2017.0
4	Canada	1	12.50	33	33.00	2017.0
5	Tunisia	1	12.50	33	33.00	2017.0
6	South Korea	1	12.50	13	13.00	2020.0

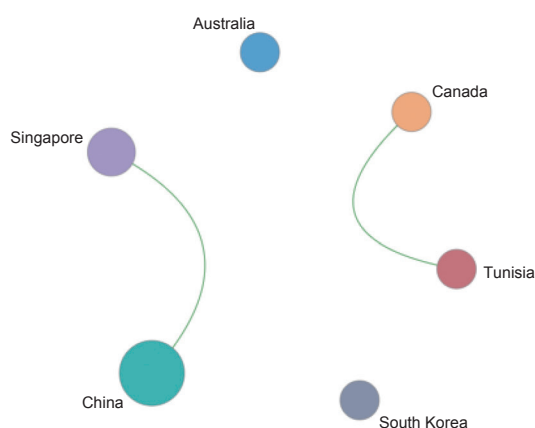


Figure 1.2.1 Collaboration network among major countries in the engineering research front of “autonomous ship deck landing technology for aircraft”

Table 1.2.2 Institutions with the greatest output of core papers on “autonomous ship deck landing technology for aircraft”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Nanyang Technological University	2	25.00	46	23.00	2017.5
2	Beihang University	2	25.00	44	22.00	2019.0
3	Nanjing University of Aeronautics and Astronautics	2	25.00	40	20.00	2018.0
4	The University of New South Wales	1	12.50	42	42.00	2017.0
5	Carthage College	1	12.50	33	33.00	2017.0
6	University of Sfax	1	12.50	33	33.00	2017.0
7	University of Quebec	1	12.50	33	33.00	2017.0
8	DSO National Laboratories of Singapore	1	12.50	19	19.00	2016.0
9	National University of Singapore	1	12.50	19	19.00	2016.0
10	Ulsan National Institute of Science and Technology	1	12.50	13	13.00	2020.0

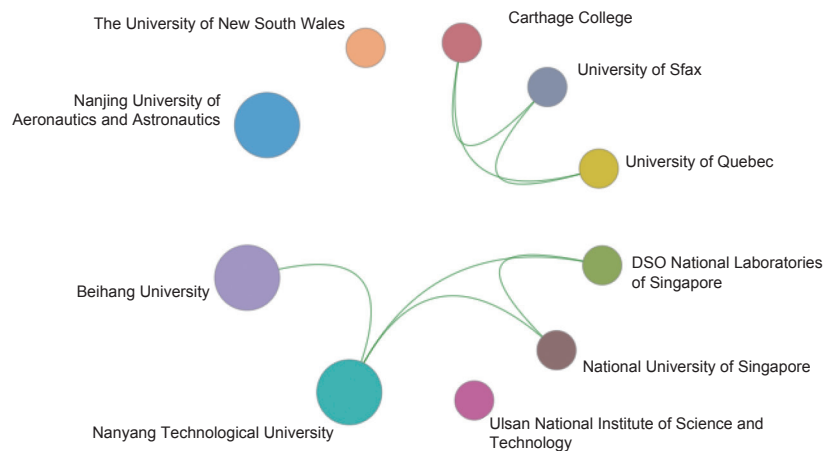


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “autonomous ship deck landing technology for aircraft”

Table 1.2.3 Countries with the greatest output of citing papers on “autonomous ship deck landing technology for aircraft”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	105	63.64	2020.0
2	USA	13	7.88	2019.1
3	South Korea	12	7.27	2019.6
4	Italy	7	4.24	2019.4
5	Singapore	6	3.64	2020.0
6	UK	5	3.03	2019.6
7	Canada	5	3.03	2020.2
8	Australia	4	2.42	2020.2
9	Romania	3	1.82	2020.3
10	India	3	1.82	2020.7

Table 1.2.4 Institutions with the greatest output of citing papers on “autonomous ship deck landing technology for aircraft”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Beihang University	18	21.95	2019.9
2	Nanjing University of Aeronautics and Astronautics	15	18.29	2020.3
3	Beijing Institute of Technology	9	10.98	2019.7
4	Tongji University	7	8.54	2019.7
5	Harbin Engineering University	7	8.54	2020.0
6	University of Science and Technology Beijing	6	7.32	2019.7
7	Nanyang Technological University	5	6.10	2020.0
8	Northwestern Polytechnical University	4	4.88	2020.0
9	Hubei University of Economics	4	4.88	2020.2
10	Chongqing University	4	4.88	2020.2

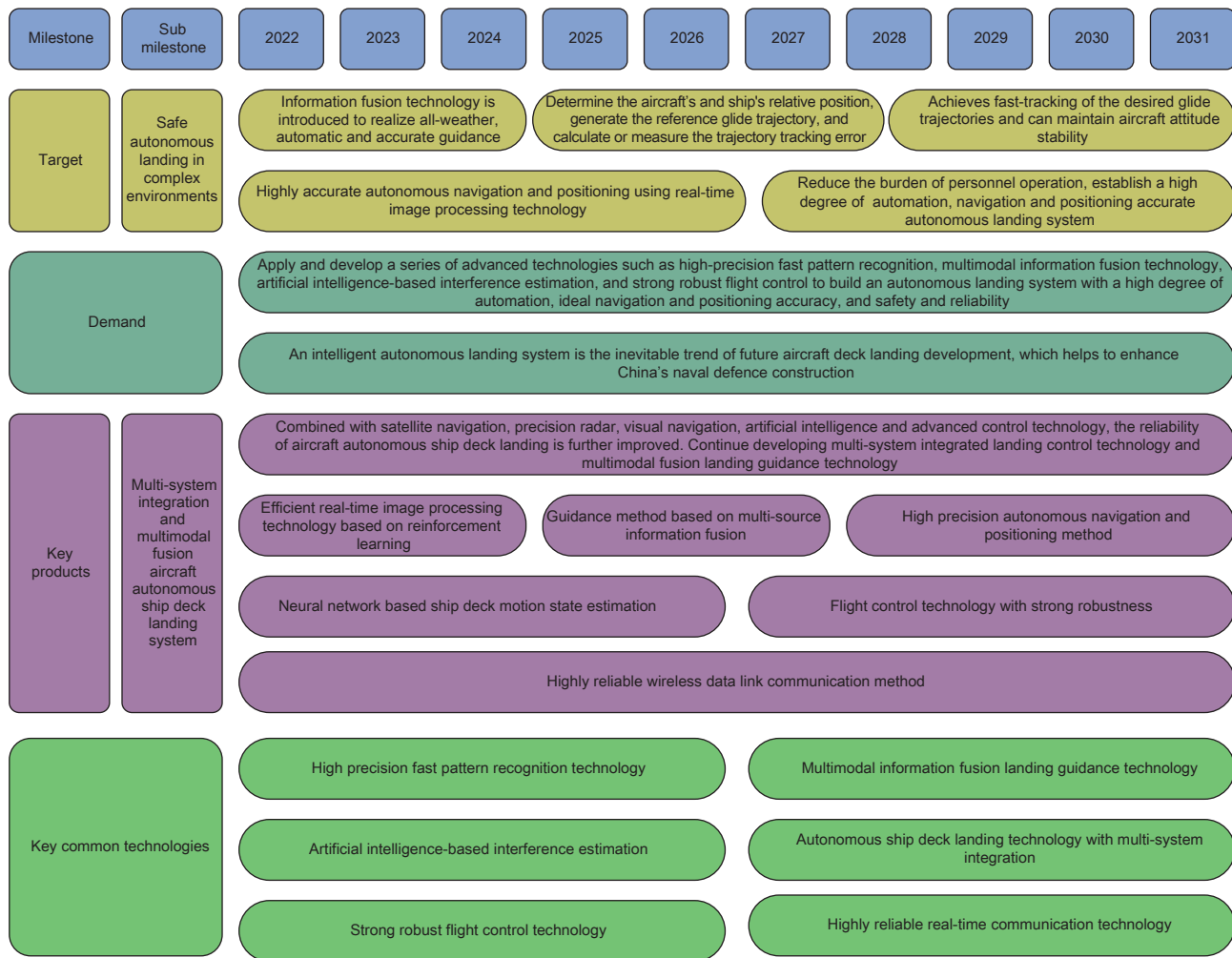


Figure 1.2.3 Roadmap of the engineering research front of "autonomous ship deck landing technology for aircraft"

1.2.2 Human-robot contactless collaboration

With the increasingly strong demand for advanced manufacturing, such as green manufacturing, intelligent manufacturing, and personalized customization, robots materialize the wisdom and experience of human experts in manufacturing activities, so that the manufacturing system can carry out intelligent activities, such as independent perception, reasoning, learning, and decision-making, share human physical labor through cooperation with people in manufacturing, expand, extend, and partially replace the mental labor of experts, and improve the flexibility adaptability and autonomy. Close cooperation between humans and robots is developing toward the direction of human-machine integration, which is the essential feature of the new-generation of robot systems. Because of the high

rigidity, fast response, and large torque, traditional industrial robots can only work in the physical environment isolated from people to ensure personnel safety. As an important part of intelligent manufacturing process, collaborative robots have been widely used in electronic processing, parts grinding, paint spraying, cargo sorting, or component assembly because of their compact size, high flexibility, and master-slave teaching. Since General Motors attempted to develop a robot that worked with human workers in 1995, cooperative robots, such as UR5 of Universal Robots, LBR iiwa of KUKA, YuMi of ABB, and CR-35iA of FANUC have appeared in succession. In 2016, the International Organization for Standardization issued the latest industrial standard ISO/TS 15066 for collaborative robots.

Collaborative robots are featured with safety, adaptability, and

comfort in human–robot cooperation. Specifically speaking, human–robot contactless collaboration should avoid human injury. The robot can understand the human intents accurately and adapt to human movements actively. Moreover, the robot action conforms to the cognitive habits of humans, so that people can understand the action intention of the robot. The related research can be mainly categorized into three aspects, namely, the studies of prevention of collision events, prediction of human motion intention, and generation of robot anthropomorphic motions. ① To prevent collision events, new sensing technologies for multi-modal information, including object distances, contact forces, and joint torques, are worth exploring to study the motion principles and deformation mechanism of coupled rigid-flexible-soft robots and develop collaborative robots with collision avoidance ability. ② With regard to the prediction of human motion intention, key research topics include object identification in unstructured environment, adaptive control with motion intent prediction and hand–eye coordination, and virtual reality of human–robot interaction. ③ To generate robot anthropomorphic motions, there are critical challenges to reveal the mechanisms of human-limb natural motions, identify the biomechanical characteristics of human musculoskeletal systems, establishes the bionic design theory, develop the generation method of robot anthropomorphic motions, and implement feedback control method that conforms to human cognitive habits. With the development of soft material science, intelligent sensing technology, ergonomics, and related disciplines, collaborative robots are expected to make breakthroughs in key technologies, such as multi-modal perception, intention recognition,

environmental modeling, anthropomorphic motion, and decision optimization, and enhance the interactive experience and operation efficiency of human–robot contactless collaboration.

The country with the greatest output of core papers on “human–robot contactless collaboration” is Italy, as shown in Table 1.2.5. Institutions with the maximum number of core papers and the highest citations per paper are University of Modena and Reggio Emilia and Sapienza University of Rome, as shown in Table 1.2.6. Cooperation can be observed between these two Institutions (Figure 1.2.4). The top three countries with the greatest output of citing papers are Italy, China, and the USA, as shown in Table 1.2.7. The main output institutions of citing core papers are University of Modena and Reggio Emilia, Chinese Academy of Sciences, and Wuhan University of Technology, as shown in Table 1.2.8. Figure 1.2.5 shows the roadmap of this front.

1.2.3 Triboelectric nanogenerator

Prolific research toward the development of microelectronics technologies is greatly beneficial to human life since 2000s. Meanwhile, the power supply of mass number timely devices became a huge issue though it is low-power consumption. Traditional bulky and rigid battery packs could not meet its application and development demands well. As an alternative, triboelectric nanogenerators (TENGs), which convert the mechanical energy created by motion into electrical energy, offer a highly attractive energy harvesting strategy to power electronics, such as e-skin, implantable electronics, flexible

Table 1.2.5 Countries with the greatest output of core papers on “human–robot contactless collaboration”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Italy	3	100.00	161	53.67	2019.7

Table 1.2.6 Institutions with the greatest output of core papers on “human–robot contactless collaboration”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Modena and Reggio Emilia	2	66.67	158	79.00	2019.0
2	Sapienza University of Rome	2	66.67	22	11.00	2020.5

University of Modena and Reggio Emilia • Sapienza University of Rome

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “human–robot contactless collaboration”

Table 1.2.7 Countries with the greatest output of citing papers on “human–robot contactless collaboration”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	Italy	47	23.74	2020.5
2	China	43	21.72	2020.3
3	USA	23	11.62	2020.6
4	UK	18	9.09	2020.7
5	Germany	14	7.07	2020.3
6	Sweden	13	6.57	2020.2
7	Spain	9	4.55	2020.2
8	France	8	4.04	2020.2
9	Finland	8	4.04	2020.5
10	Portugal	8	4.04	2020.8

Table 1.2.8 Institutions with the greatest output of citing papers on “human–robot contactless collaboration”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	University of Modena and Reggio Emilia	11	17.19	2020.5
2	Chinese Academy of Sciences	9	14.06	2020.2
3	Wuhan University of Technology	7	10.94	2020.4
4	Polytechnic Institute of Turin	5	7.81	2020.4
5	Italian Institute of Technology	5	7.81	2020.4
6	Italy National Research Council	5	7.81	2020.8
7	Malardalen University	5	7.81	2020.0
8	University of Minho	5	7.81	2020.8
9	Polytechnic University of Milan	4	6.25	2020.2
10	University of Birmingham	4	6.25	2020.0

devices, and systems. Meanwhile, TENG is a robust energy source that can be applied in many fields, such as healthcare monitoring, biosensing, environmental detection, and artificial intelligence.

In the past 10 years, intensive research has been attempted and conducted in the field of triboelectric nanogenerator. The related research can be summarized into three directions, namely, fundamental study and operation models, hybrid mechanisms and circuit design for integration, and self-powered smart microsystems. First, the mechanism of triboelectric nanogenerators has been analyzed. Scientists investigated the triboelectric effect comprehensively by electromagnetic theory and physical models. Four operation

models, including contact-separation (CS) mode, relative-sliding (RS) mode, single-electrode (SE) mode, and free-standing (FS) mode, were developed to build-up the theoretical domain of TENGs. In addition, the research activities on triboelectric pair selection and configuration design were carried out to strengthen the output performance of TENGs. Second, the researchers paid much attention on hybrid working principle that combined triboelectric effect with other effects, including piezoelectric effect, electromagnetic effect, photovoltaic effect, and thermoelectric effect. Furthermore, the proposed devices were integrated with suitable power management circuits and energy storage devices to form high-efficiency and stable power units. Third, the integration of triboelectric nanogenerators with sensors

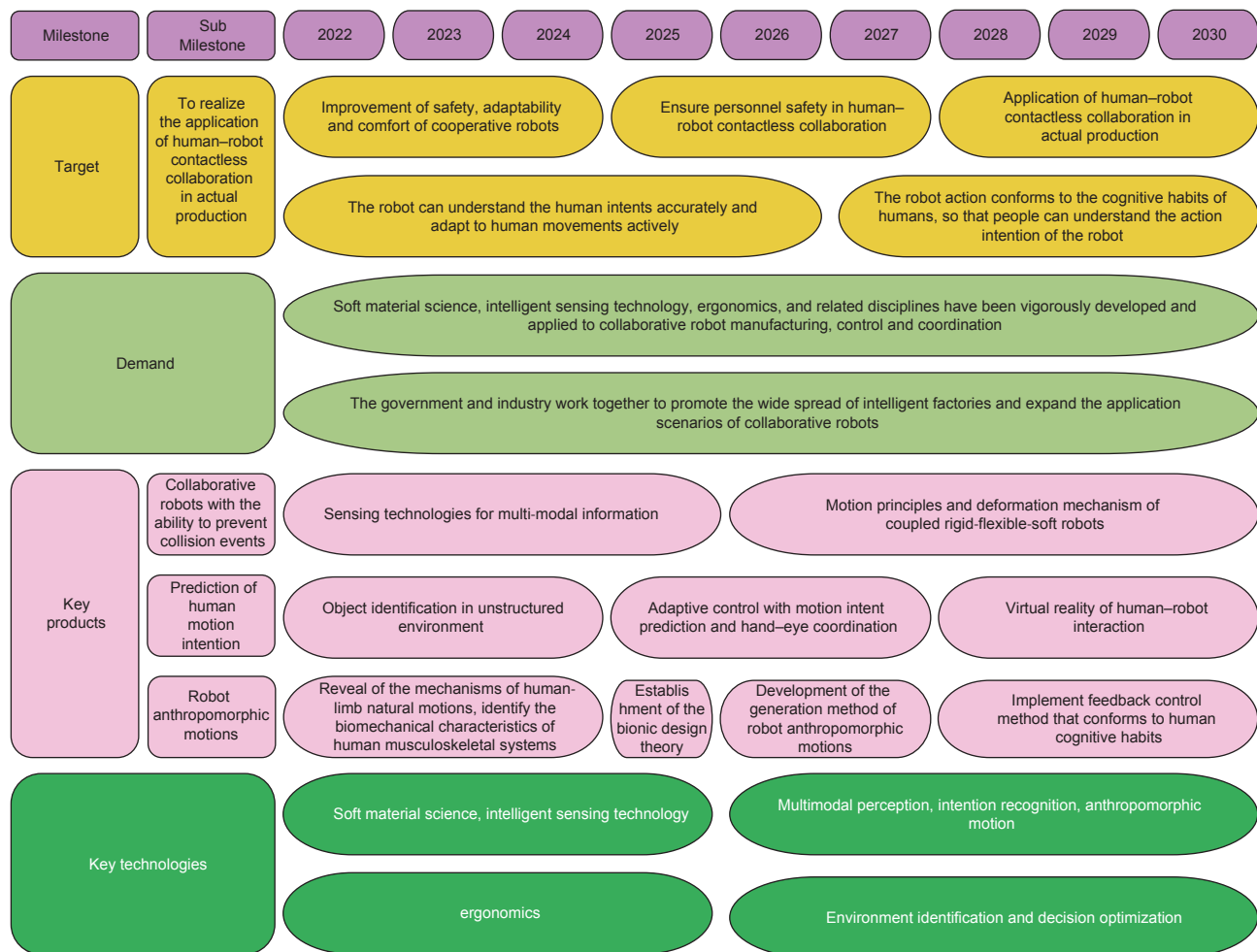


Figure 1.2.5 Roadmap of the engineering research front of “human-robot contactless collaboration”

was studied well to verify the feasibility of self-powered smart microsystems, in which TENGs serve as either a power source to supply the microsystem or an active sensor by figuring out the relation between output electric signals and external stimuli.

As the next challenging and technical acme in the field of sustainable energy, triboelectric nanogenerators offer a significant technical support to realize smart microsystems. The associated merits provide essential tools and technical approaches for exploring massive applications of electronics devices. The development of triboelectric nanogenerator can improve our country’s independent technical levels in the field of sustainable energy, promote the popularization and application of microelectronics, and achieve the leading position in the international high-end smart system research

and development.

The top two countries with the largest number of core papers published on “triboelectric nanogenerator” and the highest citations per paper are China and the USA, as shown in Table 1.2.9. Among the top four countries with the most published papers, more cooperation has been observed among China and the USA, as shown in Figure 1.2.6. Among the top ten institutions with the largest number of publications, institutions with the maximum number of core papers are University of California, Los Angeles and University of Electronic Science and Technology of China. The institutions with the highest citations per paper are Stanford University, Chongqing Normal University, and Chongqing University, as shown in Table 1.2.10. More cooperation can be observed between Chongqing Normal University, Chongqing University,

Chinese Academy of Sciences and Stanford University, as shown in Figure 1.2.7. The top three countries with the greatest output of citing papers are China, the USA and South Korea as shown in Table 1.2.11; the top three institutions with

the greatest output of citing papers are Chinese Academy of Sciences, Georgia Institute of Technology, and University of California, Los Angeles, as shown in Table 1.2.12. Figure 1.2.8 shows the roadmap of this front.

Table 1.2.9 Countries with the greatest output of core papers on “triboelectric nanogenerator”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	18	85.71	1 053	58.50	2019.3
2	USA	13	61.90	711	54.69	2020.2
3	UK	2	9.52	44	22.00	2020.0
4	Canada	1	4.76	30	30.00	2019.0

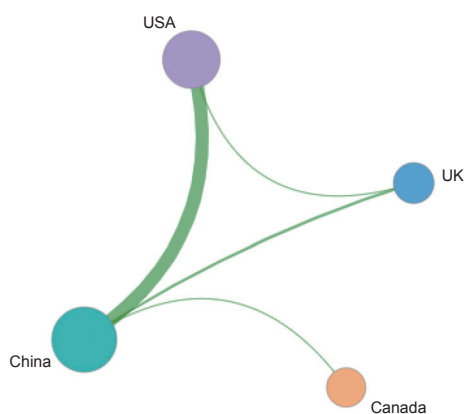


Figure 1.2.6 Collaboration network among major countries in the engineering research front of “triboelectric nanogenerator”

Table 1.2.10 Institutions with the greatest output of core papers on “triboelectric nanogenerator”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of California, Los Angeles	11	52.38	449	40.82	2020.5
2	University of Electronic Science and Technology of China	6	28.57	353	58.83	2019.2
3	Chongqing Normal University	3	14.29	347	115.67	2019.0
4	Chongqing University	3	14.29	347	115.67	2019.0
5	Chinese Academy of Sciences	3	14.29	326	108.67	2018.3
6	Stanford University	2	9.52	262	131.00	2018.5
7	Soochow University	2	9.52	90	45.00	2018.5
8	Southwest Jiaotong University	1	4.76	96	96.00	2020.0
9	Georgia Institute of Technology	1	4.76	95	95.00	2019.0
10	The Pennsylvania State University	1	4.76	71	71.00	2020.0

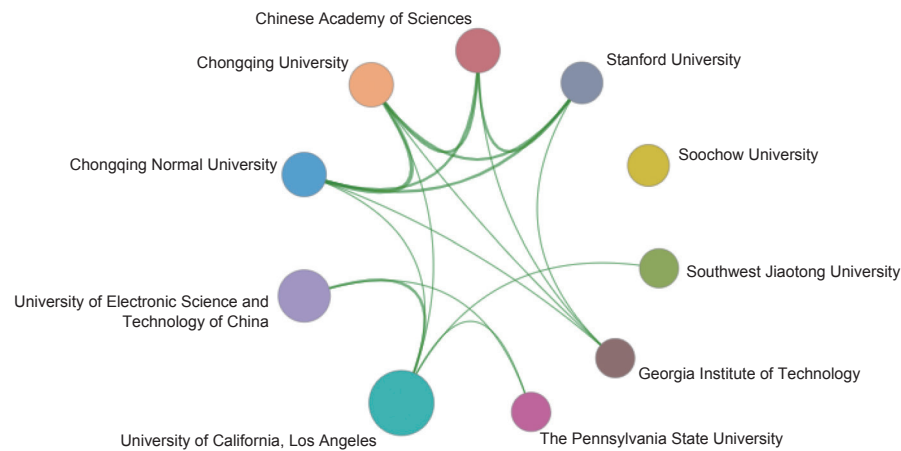


Figure 1.2.7 Collaboration network among major institutions in the engineering research front of “triboelectric nanogenerator”

Table 1.2.11 Countries with the greatest output of citing papers on “triboelectric nanogenerator”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	524	53.58	2020.3
2	USA	180	18.40	2020.3
3	South Korea	86	8.79	2020.1
4	Singapore	47	4.81	2020.3
5	India	38	3.89	2020.4
6	UK	36	3.68	2020.4
7	Australia	24	2.45	2020.6
8	Malaysia	13	1.33	2020.8
9	Iran	11	1.12	2020.7
10	Saudi Arabia	10	1.02	2020.7

Table 1.2.12 Institutions with the greatest output of citing papers on “triboelectric nanogenerator”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	115	25.50	2020.2
2	Georgia Institute of Technology	53	11.75	2019.9
3	University of California, Los Angeles	53	11.75	2020.6
4	University of Electronic Science and Technology of China	40	8.87	2020.0
5	National University of Singapore	39	8.65	2020.3
6	Chongqing University	31	6.87	2020.1
7	Guangxi University	30	6.65	2020.4
8	Soochow University	29	6.43	2019.7
9	Tsinghua University	26	5.76	2020.2
10	Southwest Jiaotong University	18	3.99	2020.3

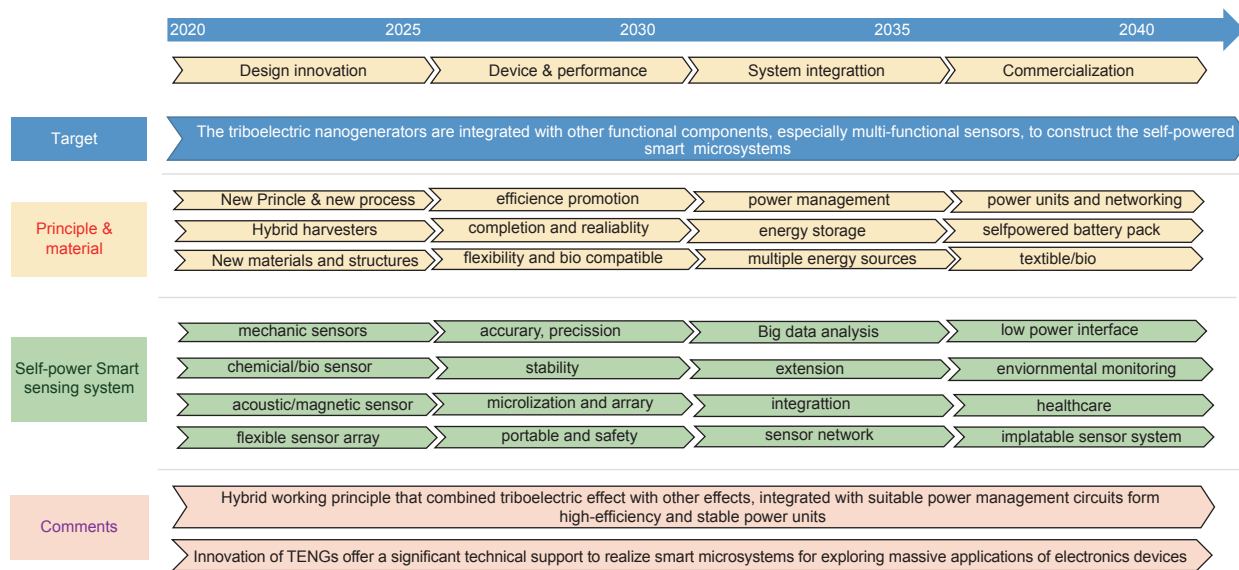


Figure 1.2.8 Roadmap of the engineering research front of “triboelectric nanogenerator”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

Top ten development (as opposed to research) fronts in mechanical and vehicle engineering are listed in Table 2.1.1. Some of these frontiers are characterized by in-depth

traditional research: “multi-sensor data fusion technique of autonomous unmanned systems”, “high bypass-ratio turbofan engine”, “3D printing technology of aviation carbon fiber reinforced composites”, “underwater unmanned vehicle (UUV) based on acoustic-optic detection”, “control and perception system of intelligent mobile robot”, and “high-power-density high-efficiency electrical machine”. There are also other frontiers that are newly emerging: “stealth metamaterials for ships and submarines”, “hydrogen fuel

Table 2.1.1 Top 10 engineering development fronts in mechanical and vehicle engineering

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Stealth metamaterials for ships and submarines	52	496	9.54	2018.7
2	Multi-sensor data fusion technique of autonomous unmanned systems	468	2 117	4.52	2019.5
3	Hydrogen fuel cell vehicle	333	1 335	4.01	2018.1
4	Reusable spacecraft	71	348	4.90	2017.9
5	High bypass-ratio turbofan engine	360	4 094	11.37	2015.8
6	Morphing flexible wing with variable curvature	359	1 965	5.47	2017.5
7	3D printing technology of aviation carbon fiber reinforced composites	67	219	3.27	2019.1
8	Underwater unmanned vehicle (UUV) based on acoustic-optic detection	93	344	3.70	2018.6
9	Control and perception system of intelligent mobile robot	146	2 359	16.16	2018.5
10	High-power-density high-efficiency electrical machine	112	303	2.71	2017.9

cell vehicle”, “reusable spacecraft”, and “morphing flexible wing with variable curvature”. Table 2.1.2 shows the annual number of core patents published from 2016 to 2021.

(1) Stealth metamaterials for ships and submarines

These years, metamaterials, which own extraordinary physical properties in electromagnetic, acoustic, and optic, have been extensively studied. They provide a new pathway for developing superior stealth materials used in ships and submarines. Electromagnetic stealth metamaterials improve their performance by coupling multiple resonant structures and loading high-resistance metasurface. They own stronger absorbing performance but smaller thicknesses compared with the traditional radar absorbing materials, showing significant advantages in competing with radar detection. Furthermore, acoustic stealth metamaterials can achieve super low-frequency sound absorption, vibration reduction, and acoustic strength control due to their low-frequency band gap and supernormal physical characteristics. They have the best effectiveness on submarines to tremendously reduce the threat of acoustic detection. In addition, optical stealth metamaterials remarkably reduce the visual discovery distance of the target. They own good concealability to photoelectric detection but are difficult to resist radar detection. For ship designing, it mainly focuses on stealth

appearances with local application of absorbing materials in the past. Nowadays, it regards stealth appearances and stealth materials as equally important. In the developing process of ships, submarines, and various navy equipment, stealth metamaterials will greatly improve their concealment performance and combat effectiveness.

(2) Multi-sensor data fusion technique of autonomous unmanned systems

The multi-sensor data fusion technique of autonomous unmanned systems refers to achieving the perception of the environment and further accomplish missions, such as understanding complex environments, object tracking, area exploration, and disaster rescue via fusion the information from different individuals and sensors. On the one hand, the unstructured operating environments are heavily obscured with strong electromagnetic interference. Furthermore, the unmanned systems are easily affected by severe weather when operating outdoors, thereby resulting in the poor accuracy and limited detection range of a single sensor. In addition, the objects in the complex environment have the characteristics of multi-type, various scales, diverse morphologies, and insignificant features, which will greatly increase difficulty in object detection and recognition. On the other hand, the multi-sensor fusion could combine the advantages of different kinds of sensors and fuse the information

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in mechanical and vehicle engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Stealth metamaterials for ships and submarines	0	3	12	11	16	6
2	Multi-sensor data fusion technique of autonomous unmanned systems	12	38	56	80	105	169
3	Hydrogen fuel cell vehicle	48	35	45	58	49	65
4	Reusable spacecraft	3	5	10	13	16	11
5	High bypass-ratio turbofan engine	50	37	24	23	18	15
6	Morphing flexible wing with variable curvature	44	44	59	54	58	36
7	3D printing technology of aviation carbon fiber reinforced composites	3	6	8	10	14	22
8	Underwater unmanned vehicle (UUV) based on acoustic-optic detection	9	6	23	11	19	18
9	Control and perception system of intelligent mobile robot	6	21	26	22	26	32
10	High-power-density high-efficiency electrical machine	11	17	20	20	14	15

from each individual, thereby extending the perception scope of unmanned systems effectively and expanding its ability on perception in complex and harsh environment. Therefore, multi-sensor data fusion technique will be an important cornerstone to the automation and intelligence of autonomous unmanned systems. Major research topics include multi-source information preprocessing that aims to overcome the influences from severe weather and complex environment; spatiotemporal registration of heterologous, heterogeneous, and asynchronous information; and the precise association method of large-difference, low-quality, and weakly correlated information.

(3) Hydrogen fuel cell vehicle

Hydrogen fuel cell vehicles (HFCVs) are vehicles powered by electricity generated by fuel cell devices. Hydrogen energy has become an important strategic choice for accelerating the upgrade of energy transformation with the requirement of carbon neutrality. Hydrogen fuel cells offer several advantages over incumbent technologies, such as internal combustion engine and diesel engines, including higher efficiency, reduced emissions, higher torque, and no noise pollution. The core components of the HFCV system include air compressors, hydrogen circulation systems, on-board hydrogen storage systems, and fuel cell stacks. Fuel cell stack accounts for ~60% of the total cost of the vehicle. The core materials in fuel cell stacks include catalysts, proton exchange membranes, gas diffusion layers, and bipolar plates. Particularly, the cost of commercial platinum-based catalysts is still prohibitive (accounts for ~45% of the stack), and their activity/durability also needs to be improved. Therefore, investigating low- or non-platinum catalysts with high performance will be the research focus of fuel cell catalysts in the future. Proton exchange membrane is a type of solid electrolyte, and the current research focuses on the perfluoroalkyl sulfonic acid-based proton-exchange membranes and composite ones. Currently, the stability of membrane needs to be improved, and the preparation process needs to be optimized. The gas diffusion layer plays an important role in collecting current, conducting gas, and discharging reaction product water. However, the conductivity, structural stability, and mass transfer characteristics of gas diffusion layers still need to be improved. The bipolar plate is the “skeleton” of the fuel cell stacks, and the requirements for development are high electron and thermal conductivity, ultra-thin, and ultra-light. At present, the key materials of stacks, such as platinum-

based catalysts and proton exchange membranes, still need to be imported. Moreover, some technologies are monopolized by foreign companies, so the domestic research should be intensively explored.

(4) Reusable spacecraft

As an important direction for future spacecraft development, reusable spacecraft is an advanced spacecraft application mode that can effectively prolong the life, reduce the operation cost, and improve the reliability and convenience of spacecraft. Reusable manned spacecrafts and cargo spacecrafts, space shuttles, and reusable orbital maneuvering vehicles are typical reusable spacecrafts. Given the increasing frequency of human space exploration and development activities, the current single-use spacecraft cannot easily meet the demand because of the high cost and long preparation cycle. Therefore, reusable spacecraft, which can adapt to more convenient and cheaper exploration, development, and utilization of space resources, has emerged as the times require. It has become a frontier hot spot in the current world space technology research field. All major space powers have taken it as the key breakthrough direction for the sustainable development of space technology in the future. The recyclable and reusable requirements of reusable spacecraft pose a major challenge to the traditional design concepts and methods of single-use spacecraft. The key research directions include reusable design theory and method, reusable spacecraft integrated design, reliable and accurate return and landing technology, long-term on-orbit precise orbit/attitude/thermal control and maintenance technology, highly reliable and reusable high-temperature and ablative resistance thermal protection technology, structure life assessment, and health management technology.

(5) High bypass-ratio turbofan engine

A high bypass-ratio turbofan engine usually means that the engine with a bypass ratio larger than 4. High bypass-ratio turbofan engines are widely applied as the engines of civil airliners and military transport aircrafts, owing to advantages of low fuel consumption ratio and noise level. The key techniques and future improvements of high bypass-ratio turbofan engines focus on the following aspects. ① High performance: this factor includes advanced thermo-aerodynamic design and manufacturing of large-scale fan, high-pressure compressor, and low-pressure turbine, such as the aerodynamic design of 3D blades and control of blade

tip. ② Low pollution: NO_x emission is reduced by employing combustion control techniques, such as staged combustion, direct injection of lean oil, and rich-burn, quick-mix, lean-burn combustion. ③ Low noise level: advanced aeroacoustic design and acoustic absorption techniques are employed to reduce the noise level of turbomachines, jet, and combustion. ④ High reliability: the reliability of engine and its components could be improved in various ways, such as designing and manufacturing a long-life and high-power gear reducer.

(6) Morphing flexible wing with variable curvature

The morphing flexible wing with variable curvature can be controlled by the continuous and seamless change of wing camber and thickness through flexible deformation of the wing structure. Compared with the traditional rigid wing, the flexible wing delays the airflow separation, improves the lift-drag ratio, and reduces the aerodynamic noise. Relevant studies often focus on four aspects. The first aspect is the flexible deformable skin. This aspect includes exploring the decoupling design mechanism of in-plane elastic large deformation and out-of-plane flexural bearing capacity, studying the large deformation mechanism and forming process of periodic cellular microstructures, developing the structural technology and deformation compatibility of novel topological cellular microstructures/superelastic matrix composites. Moreover, this aspect aims to make the flexible deformable skin obtain excellent elasticity in the deformation direction and sufficient stiffness in the nondeformation direction. However, the force driving the deformation of the skin is negligible. The second aspect is the deformable support structure. This aspect includes developing a rigid-flexible coupling structure and a fully flexible structure designed by collaborative optimization, investigating the aeroelastic analytical and verification method of the flexible wing, and studying the design method of the deformable support structure with low stress and high life. The third aspect is the lightweight and efficient driving mechanism. This aspect involves developing novel lightweight and flexible driving mechanism, including piezoelectric and artificial muscle actuators with high-efficiency ratios, designing an intelligent control strategy, and obtaining high efficiency, lightweight, and high stability driving system. The fourth aspect is the integration and experiment platform. This aspect includes investigating the integration of novel structures, smart materials, advanced sensing and testing technologies, and efficient miniaturized actuators. It also involves conducting

wind tunnel testing of typical samples and test flight verification of full-size wings. The technology of morphing flexible wings with variable curvature is an important direction of morphing aircraft, which is the development trend of green aviation and aircraft structural design reform in the future.

(7) 3D printing technology of aviation carbon fiber reinforced composites

Three-dimensional (3D) printing of aviation carbon-fiber-reinforced composites is a technology that manufactures aviation carbon fiber composite parts through layer-by-layer accumulation based on 3D model data. The technology can be divided into fused deposition modeling (FDM), stereo lithography apparatus (SLA), selective laser sintering (SLS) modeling, and laminated object manufacturing (LOM) according to different implementation methods. Given its mature manufacturing strategy, low cost, and strong designability, FDM is the most commonly used and widely studied method for the 3D printing of aerospace carbon fiber composite materials, particularly continuous carbon-fiber-reinforced composite materials. At present, considerable research focuses on revealing the influence law of the FDM process parameters, such as printing path, printing temperature, printing layer thickness, printing material, material stacking method, and printing scanning spacing, on the microstructure and on the porosity, interfacial property, and macroscopic mechanical properties of the composites. Therefore, the methods for printing equipment, process parameters, and material pretreatment are improved and optimized. Moreover, the mechanical property test methods and performance evaluation system for the 3D printing of aviation carbon fiber composite materials are established to print strengthened and complex carbon fiber composite structures in aviation.

(8) Underwater unmanned vehicle (UUV) based on acoustic-optic detection

Underwater unmanned vehicle (UUV) based on acousto-optic detection refers to a type of UUV equipped with acoustic and optical detection sensors for performing underwater environmental target detection tasks. At present, typical underwater acoustic and optical detection sensors include sonar, lidar, and visual cameras.

Various sensors have different effects and completeness due to different basic detection principles. The principle of underwater acoustic detection sensors refers to the detection,

tracking, positioning, and identification of underwater acoustic targets within a certain range by accepting the radiated noise or scattered echoes of the target. In wide-area marine environment target detection, the acoustic detection method is the most important and most effective. The detection effect of the underwater optical sensor is easily affected by marine optical environmental conditions. It can achieve high-precision target positioning in shallow water with good visibility and calmness, which is an effective supplement to the acoustic detection method.

At present, the main research highlights in this field include underwater target localization technology based on acousto-optic sensors, underwater target detection and recognition technology based on deep learning, and autonomous detection technology based on feature learning.

Given the advantages of UUV, including good controllability, superior stealth performance, and strong maneuverability, the combined acousto-optic detection technology based on an unmanned mobile platform will be the future development trend in this field. Specifically, it mainly includes environmental background field modeling, marine environmental target feature library construction, multisource sensor information fusion, UUV structure matching optimization, and other research contents. The purpose is to achieve effective detection in high-dimensional, dynamic, complex, and changeable underwater environments.

(9) Control and perception system of intelligent mobile robot

The intelligent mobile robot is a comprehensive system integrating environment perception, dynamic decision and planning, behavior control, and execution. It generally includes land mobile robots, autonomous underwater vehicle, and flying robots represented by unmanned aerial vehicles. Most mobile robots work in unstructured environments. Their performance depends on autonomous perception, autonomous navigation, and motion control. Autonomous perception is the premise for mobile robots to move and complete their work autonomously. It involves multisensor information fusion, external parameter calibration, target detection and recognition, and scenario recognition. Autonomous navigation is the most basic and core technology, involving environment perception, autonomous localization and mapping, and motion planning. The performance of the motor control affects the stability of motion and work.

Representative methods include simultaneous stabilization and tracking control based on kinematics and dynamics, and neural network adaptive control considering the dynamic nonholonomic constraint. Mobile robots have many application fields. To improve autonomous working performance, intelligent navigation systems with high self-adaptability, high real-time, high reliability, and high portability must be developed. Key technologies, such as environmental information acquisition, environmental modeling, environmental cognition, and navigation obstacle avoidance, will become the focus of intelligent mobile robot control and perception research.

(10) High-power-density high-efficiency electrical machine

High-power-density high-efficiency electrical machine is an electromagnetic electro-mechanical energy conversion device with compact structure, high power density, and effective energy conversion. It is the core power unit and key executive component in new energy and power generation, electrified transportation, high-end CNC machine tools and robots, and aerospace equipment, etc. Represented by electrification, a new round of technology revolution in energy and power systems is reshaping the global industries of vehicles, manufacturing, and many others. As the core electromechanical energy conversion equipment of electrification, high-power-density high-efficiency machine has become the technological commanding point worldwide. However, the improvement of machine power density and efficiency has encountered multiple challenges due to the limitations of materials, thermal management, and harsh environmental conditions. Recently, industries and academics have conducted extensive research in the areas of ① new high-torque-density machine topology, ② application and accurate modelling of advanced electrical materials, ③ high-frequency-loss suppression, ④ high-efficiency heat dissipation methods, ⑤ structural integration and weight reduction, and ⑥ multiphysics-based optimization and design. To further improve the power density and efficiency limit of electrical machines and broaden the application of high-power-density high-efficiency electrical machines in the new generation of emerging industries, such as electrified transportation vehicles, intelligent manufacturing, military equipment including electric fighters and tanks, researchers have concentrated efforts on promoting technological breakthrough in the following fields: ① new electromagnetic

principles of flux concentration and flux modulation; ② new electrical material applications, such as supercopper wires and superconductor; ③ new cooling technologies, such as phase-transition heat transfer and direct oil cooling; ④ new intelligent simulation and optimization based on multiphysics modelling of electrical–thermal–mechanical properties.

2.2 Interpretations for three key engineering development fronts

2.2.1 Stealth metamaterials for ships and submarines

Enhancing the performance of stealth to hide from enemy detection is significantly important for ships and submarines, which directly improves their combat effectiveness. In the face of the continuous development of detection methods, traditional absorbing materials gradually expose some problems and shortcomings. In the last two decades, metamaterials have attracted much attention both in the scientific and industry communities, attributing to their extraordinary physical properties in electromagnetic, acoustic, and optic. They provide a new pathway for developing superior stealth materials used in ships and submarines.

The electromagnetic stealth metamaterials improve their performance by coupling multiple resonant structures and loading high-resistance metasurface. They own stronger absorbing performance but smaller thicknesses compared with the traditional radar absorbing materials. The US DDG1000 destroyer and Raytheon's artificial composite skins utilize electromagnetic stealth metamaterials. Furthermore, acoustic stealth metamaterials reveal the low-frequency band gap and supernormal physical characteristics, and show the capabilities of super low-frequency sound absorption, vibration reduction, and acoustic strength control. American researchers have used hexagonal aluminum metamaterials as a coating layer for underwater equipment. Metamaterials are stealth under sonar detection and can be applied to Virginia-class submarines. The three-dimensional broadband underwater acoustic carpet cloak (by Institute of Acoustics, Chinese Academy of Sciences) and omnidirectional acoustic ground cloak (by Duke University, US) are typical acoustic stealth metamaterials. In addition, optical stealth metamaterials remarkably reduce the visual discovery distance of the target, represented by the bioinspired "chameleon metamaterials". By employing electrochromic

glasses, American and Russian researchers have developed metamaterials that can change colors and textures with the environment. They are used in equipment coatings to achieve optical stealth.

Generally, electromagnetic stealth metamaterials show significant advantages in competing with radar detection, which are the most versatile among the above three types of metamaterials. Acoustic stealth metamaterials have the best effectiveness on submarines to tremendously reduce the threat of acoustic detection. Optical stealth metamaterials have good concealability to photoelectric detection, but they are difficult to resist radar detection. For ship designing, it mainly focuses on stealth appearances with local application of absorbing materials in the past. Nowadays, it regards stealth appearances and stealth materials as equally important. In the developing process of ships, submarines, and various navy equipment, stealth metamaterials will greatly improve their concealment performance and combat effectiveness.

Currently, the country with the largest number of core patents published on "stealth metamaterials for ships and submarines" is China, and the top three countries with the highest citations per paper are Canada, the UK, and the USA, as shown in Table 2.2.1. Cooperation can be observed between Canada and the UK, and also between the USA and India, as shown in Figure 2.2.1. The top three institutions with core patent disclosures are Kuang-Chi Cutting Edge Technology Ltd., Aerospace Research Institute of Special Materials and Processing Technology, Luoyang Jianduan Equipment Technology Co., Ltd., as shown in Table 2.2.2. Cooperation has been observed between AVIC Shenyang Aircraft Design and Research Institute and National University of Defense Technology (Figure 2.2.2). Figure 2.2.3 shows the roadmap of this front.

2.2.2 Multi-sensor data fusion technique of autonomous unmanned systems

In recent years, many developed countries and economies all over the world have proposed development roadmaps of unmanned system technology, which aimed at stepping up the layout and seizing the strategic commanding height. As claimed in the 14th Five-Year Plan of China, that it is necessary to strengthen the innovation and application of advanced technology and equipment in the field of major disaster

Table 2.2.1 Countries with the greatest output of core patents on “stealth metamaterials for ships and submarines”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	38	73.08	114	22.98	3.00
2	USA	8	15.38	322	64.92	40.25
3	South Korea	2	3.85	2	0.40	1.00
4	Canada	1	1.92	44	8.87	44.00
5	UK	1	1.92	44	8.87	44.00
6	India	1	1.92	20	4.03	20.00
7	Japan	1	1.92	10	2.02	10.00
8	Netherlands	1	1.92	3	0.60	3.00
9	Spain	1	1.92	1	0.20	1.00

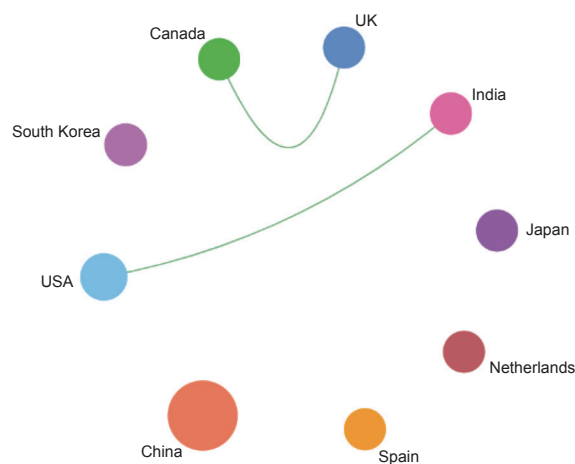


Figure 2.2.1 Collaboration network among major countries in the engineering development front of “stealth metamaterials for ships and submarines”

Table 2.2.2 Institutions with the greatest output of core patents on “stealth metamaterials for ships and submarines”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Kuang-Chi Cutting Edge Technology Ltd.	7	13.46	8	1.61	1.25
2	Aerospace Research Institute of Special Materials and Processing Technology	5	9.62	20	4.03	4.00
3	Luoyang Jianduan Equipment Technology Co., Ltd.	3	5.77	7	1.41	2.33
4	Southeast University	2	3.85	10	2.02	5.00
5	OmniVision Technologies Inc.	1	1.92	285	57.46	285.00
6	Lambda Guard Technologies Ltd.	1	1.92	44	8.87	44.00
7	Invictus Oncology Pvt. Ltd.	1	1.92	20	4.03	20.00
8	AVIC Shenyang Aircraft Design and Research Institute	1	1.92	17	3.43	17.00
9	National University of Defense Technology	1	1.92	17	3.43	17.00
10	China State Shipbuilding Ltd.	1	1.92	13	2.62	13.00

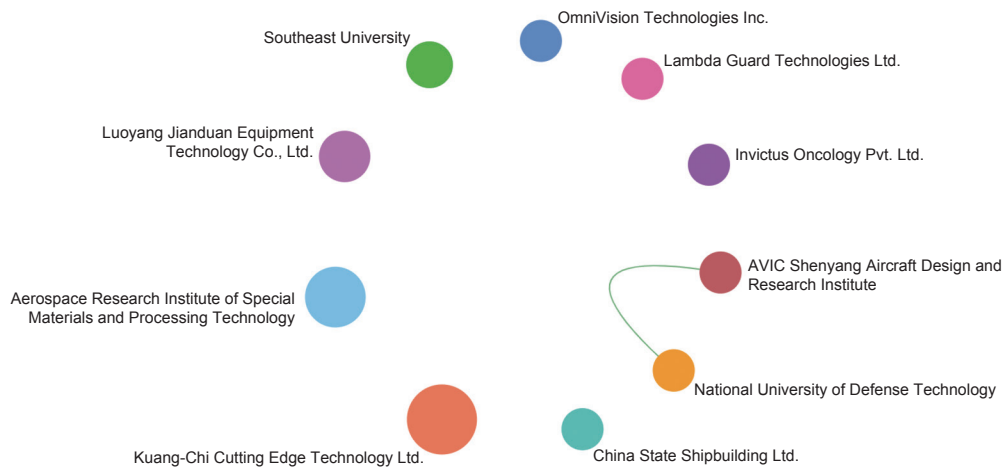


Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “stealth metamaterials for ships and submarines”

prevention and rescue, which puts forward increasingly stringent requirements for the environmental perception of autonomous unmanned systems. Moreover, the China State Council clearly mentioned that “the marine unmanned system needs to cooperate with Beidou navigation, satellite, floating platform, and aircraft remote sensing to form a global service capability” in the national informatization plan, which further emphasizes the importance of multi-source information fusion. Considering the detection precision and scope to ensure that the unmanned systems can detect both clearly and comprehensively has become the focus of the studies. The multi-sensor data fusion technique, which can achieve the collaborative dynamic perception of multi-agents and multi-sensors and improve the accuracy and scope of the perception system concurrently, is essential for the perception in complex environment.

Nowadays, the studies on multi-sensor data fusion technique of autonomous unmanned systems have been conducted in China and overseas. A multi-source information registration system equipped with binocular vision, lidar, navigation radar, millimeter wave radar, side scan sonar, and other sensors and the detection system of heterogeneous unmanned systems equipped with side-scan sonar, magnetometer, and other multi-source sensors have been developed. Some achievements have also been made in the dynamic registration and synchronous transmission of sensor information at air, water surface, and underwater. For example, the School of Artificial Intelligence and Automation of Huazhong

University of Science and Technology has proposed a novel method in the integration of multi-source registration, deep integration and collaborative tracking, which ensures the detection loss rate is less than 0.8%.

However, many major challenges, such as the association of low-quality information, the fusion of deep feature, and synchronous spatiotemporal registration, are still encountered in the multi-sensor data fusion of autonomous unmanned systems. Inconsistent sampling frequencies, different spatial coordinates, and diverse data forms among various sensors cause difficulties in multi-sensor data fusion. Meanwhile, the attitude difference between the agents and the insignificant features of environments further increase the difficulty of spatial registration. In addition, the potholes, muddy ground, forest, and obstacles, etc. will obstruct and attenuate the signal, thereby affecting the reliability of wireless communication and causing the continuity of the information exchange between the agents lack of guarantee, which will generate numerous heterogeneous and incomplete information that is difficult to correlate and complement reciprocally. Therefore, a fusion method designed for heterologous, heterogeneous, and asynchronous sensor information to carry out multi-sensor data fusion of autonomous unmanned systems and build wide-area perception maps that could enable the systems to possess all-weather environmental perception capabilities. The related research includes the fast calibration and registration method that solves the problem of complicated steps and long time

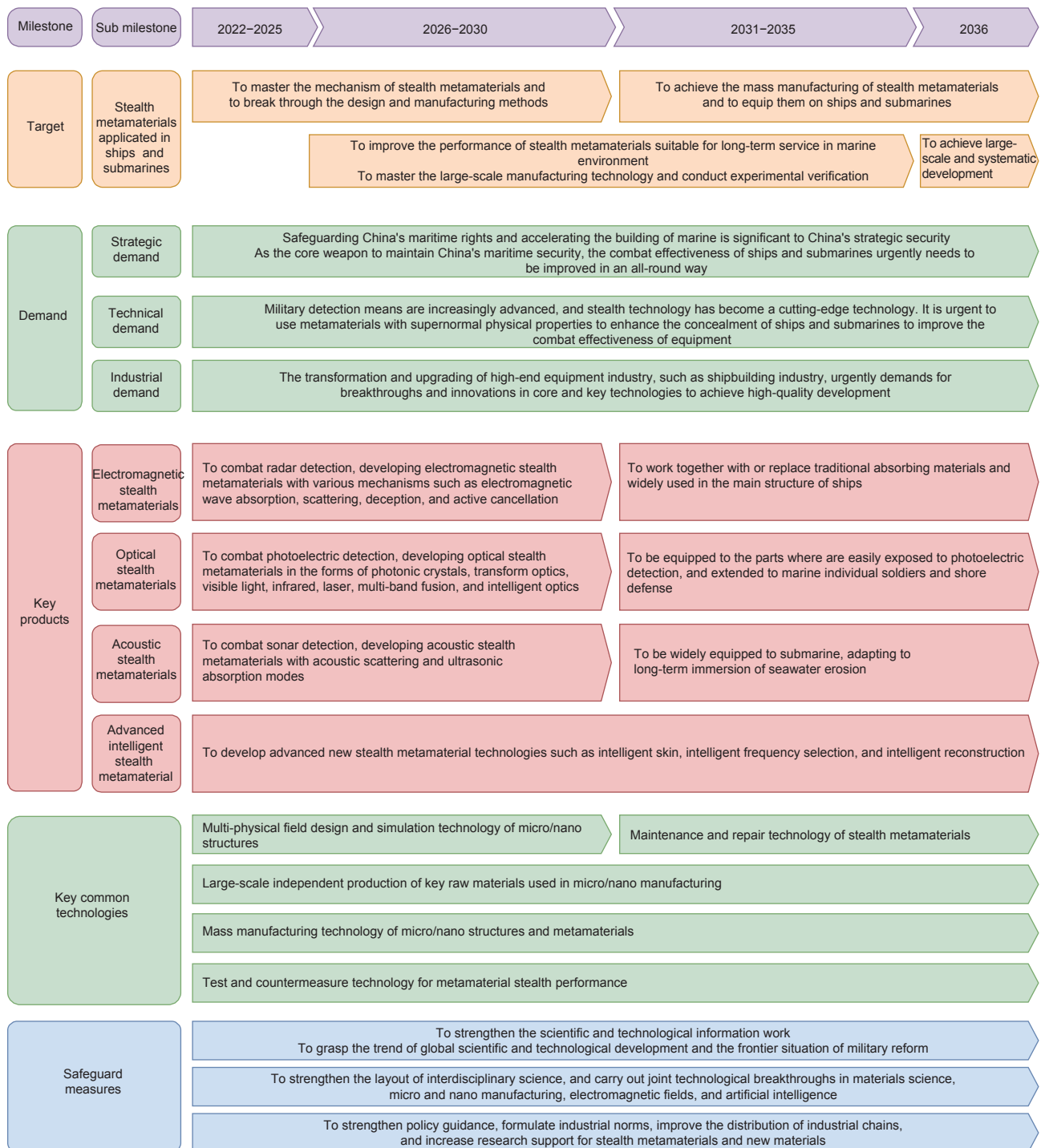


Figure 2.2.3 Roadmap of the engineering development front of "stealth metamaterials for ships and submarines"

consumption in sensor calibration; the spatiotemporal registration method and the law of fusion of the heterologous, heterogeneous, and asynchronous information; the precise association method for large-difference and weakly correlated

sensor information; the method for the building of semantic maps and environment networks based on multi-sensor data fusion; and the method for the mapping of feature spaces that belong to various sensors that can achieve the fusion of

information at the feature layer.

Currently, the country with the largest number of core patents published on “multi-sensor data fusion technique of autonomous unmanned systems” is China, and the top two countries with the greatest citations per paper are the USA and the UK, as shown

in Table 2.2.3. No cooperation can be observed between these countries with core patents. The top three institutions with the largest number of core patents are Nanjing University of Aeronautics and Astronautics, State Grid Corporation of China, and Aerospace Research Institute of Special Materials and Processing Technology, as shown in Table 2.2.4. Cooperation has

Table 2.2.3 Countries with the greatest output of core patents on “multi-sensor data fusion technique of autonomous unmanned systems”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	458	97.86	1 940	91.64	4.24
2	USA	5	1.07	152	7.18	30.40
3	South Korea	2	0.43	1	0.05	0.50
4	Japan	2	0.43	0	0.00	0.00
5	UK	1	0.21	24	1.13	24.00

Table 2.2.4 Institutions with the greatest output of core patents on “multi-sensor data fusion technique of autonomous unmanned systems”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nanjing University of Aeronautics and Astronautics	15	3.21	138	6.52	9.20
2	State Grid Corporation of China	12	2.56	29	1.37	2.42
3	Aerospace Research Institute of Special Materials and Processing Technology	10	2.14	37	1.75	3.70
4	Harbin Engineering University	9	1.92	49	2.31	5.44
5	Beihang University	9	1.92	33	1.56	3.67
6	China Electronics Technology Group Corporation	9	1.92	27	1.28	3.00
7	Shenzhen DJ-Innovations Technology Co., Ltd.	8	1.71	109	5.15	13.62
8	Tsinghua University	8	1.71	71	3.35	8.88
9	National University of Defense Technology	8	1.71	22	1.04	2.75
10	Tianjin University	7	1.50	88	4.16	12.57

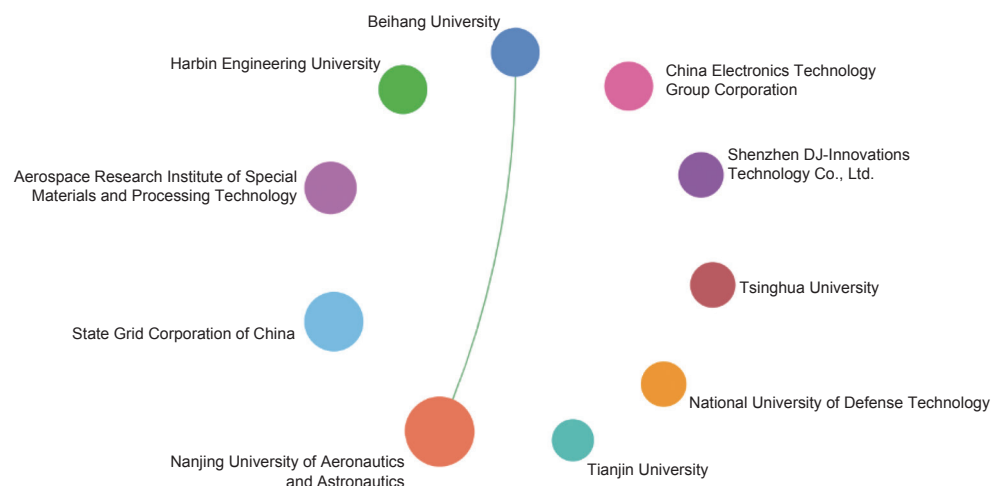


Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “multi-sensor data fusion technique of autonomous unmanned systems”

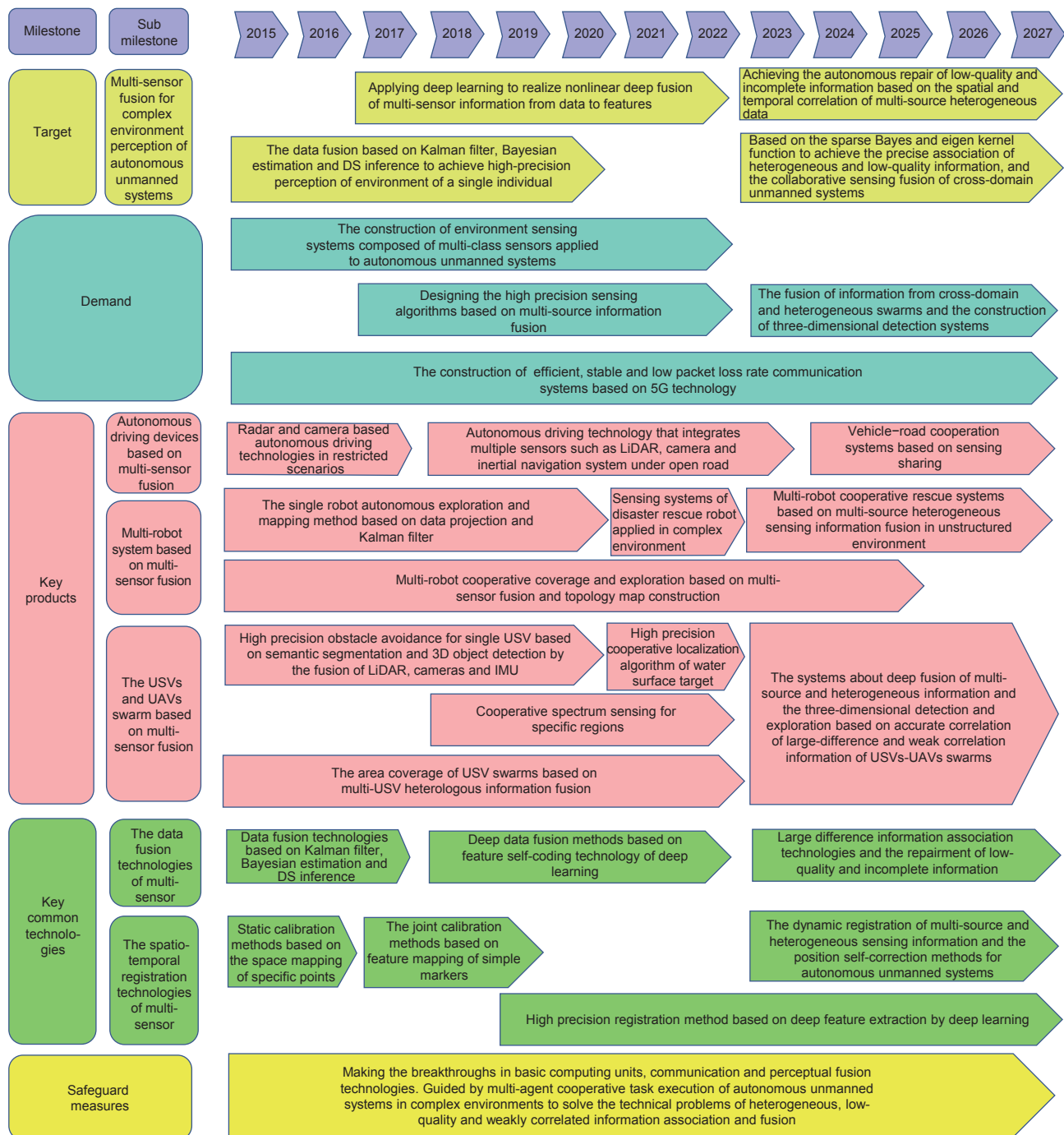


Figure 2.2.5 Roadmap of the engineering development front of “multi-sensor data fusion technique of autonomous unmanned systems”

been observed between Nanjing University of Aeronautics and Astronautics and Beihang University (Figure 2.2.4). Figure 2.2.5 shows the roadmap of this front.

2.2.3 Hydrogen fuel cell vehicle

Hydrogen fuel cells can realize the mobility, lightweight, and

large-scale popularization of hydrogen energy. They can be widely applied in transportation, industry, construction, military, and other fields. In the field of transportation, hydrogen energy is known as the “ultimate form” of vehicle energy due to its advantages of non-pollution, renewable

energy, fast hydrogen refueling, and sufficient life time. The first application of fuel cells was demonstrated in the NASA Gemini spacecraft in the 1960s. With the development of hydrogen energy technology in the 21st century, in December 2014, Toyota Motor Corporation of Japan took the lead in launching the world's first mass-produced hydrogen fuel cell vehicle (HFCV). In addition, the MIRAI-II model, which launched in Japan in 2020, reached a recharge mileage of 850 kilometers. On the basis of the technical characteristics of hydrogen fuel cells, the Ministry of Industry and Information Technology and the Society of Automotive Engineering confirms that the future applications of hydrogen fuel cells will focus on heavy trucks with fixed routes, medium- and long-distance trunk lines, and high load trucks. Fuel cell heavy-duty trucks will be commercialized in the next 5 to 10 years, gradually replacing the traditional fuel vehicle market.

To meet the high requirements of commercialization, the key parts of hydrogen fuel cells, such as catalysts, proton exchange membranes, gas diffusion layers, and bipolar plates, are still being optimized. For the catalyst, the mass activity of the catalyst can be significantly improved, and the amount of platinum can be reduced by platinum particle nanocrystallization and alloying. However, the stability of the catalyst under the acidic and oxidative operating conditions needs to be greatly improved. At the same time, the activity of non-platinum catalysts, such as metal-nitrogen-carbon catalysts, has been comparable to that of commercial Pt/C, whereas the stability needs to be improved under operating conditions. Commercial proton exchange membranes are perfluorinated sulfonate resins, which require material compositing to improve structural strength and reduce costs. The gas diffusion layer is composed of macroscopic porous

substrate and microporous layer, which needs to meet the requirement of high resistivity, stable electrode structure, hydrophilic/hydrophobic balance, and gas transport efficiency. At present, the technology is still monopolized by foreign companies. The mass and volume of the bipolar plate account for more than 80% of the stacks, so reducing the density and thickness of the bipolar plate is an important approach to improve the power density of the stacks. In addition to stacks, in terms of hydrogen storage technology, low-temperature liquid hydrogen storage will become the best solution for long-lasting use in the future. In the management of the entire fuel cell system, the hydrogen supply and circulation system, the air supply system, the water and heat management system, the electronic control system, and the data acquisition system need to be further optimized to ensure that the fuel cell has high energy conversion efficiency and energy output power.

In summary, the development of HFCVs will focus on reducing the cost and improving the critical properties, such as stability under operating conditions, of core materials. At the same time, various technical problems of water electrolysis for hydrogen production and transportation also need to be solved.

The top three countries with the largest number of core patents published on "hydrogen fuel cell vehicle" are China, Japan, and South Korea. The top three countries with the greatest citations per paper are the Saudi Arabia, France, and Belgium, as shown in Table 2.2.5. Japan has been observed to have cooperation with the USA and Austria, and cooperation has also been observed between the USA and South Korea, as shown in Figure 2.2.6. The top three institutions with the greatest citations per paper are Hyundai Motor Company, Toyota Motor Company, and Kia Motor

Table 2.2.5 Countries with the greatest output of core patents in the engineering development front of "hydrogen fuel cell vehicle"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	123	36.94	222	16.63	1.80
2	Japan	94	28.23	484	36.25	5.15
3	South Korea	84	25.23	412	30.86	4.90
4	USA	14	4.20	93	6.97	6.64
5	Germany	14	4.20	37	2.77	2.64
6	Belgium	2	0.60	21	1.57	10.50
7	Saudi Arabia	1	0.30	52	3.90	52.00
8	France	1	0.30	11	0.82	11.00
9	Spain	1	0.30	3	0.22	3.00
10	Austria	1	0.30	0	0.00	0.00

Company, as shown in Table 2.2.6. Cooperation can be observed between Hyundai Motor Company and Kia Motor

Company, as shown in Figure 2.2.7. Figure 2.2.8 shows the roadmap of this front.

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of “hydrogen fuel cell vehicle”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Hyundai Motor Company	79	23.72	408	30.56	5.16
2	Toyota Motor Company	63	18.92	272	20.37	4.32
3	Kia Motor Company	38	11.41	190	14.23	5.00
4	Wuhan Grove Hydrogen Energy Automobile Co., Ltd.	32	9.61	41	3.07	1.28
5	Honda Motor Company	9	2.70	45	3.37	5.00
6	Nissan Motor Company	5	1.50	113	8.46	22.60
7	Audi AG Company	5	1.50	30	2.25	6.00
8	State Grid Corporation of China	5	1.50	3	0.22	0.60
9	Wuhan Geological Resource Environment Industrial Technology Research Institute Co., Ltd.	4	1.20	11	0.82	2.75
10	Mitsubishi Motor Company	4	1.20	5	0.37	1.25

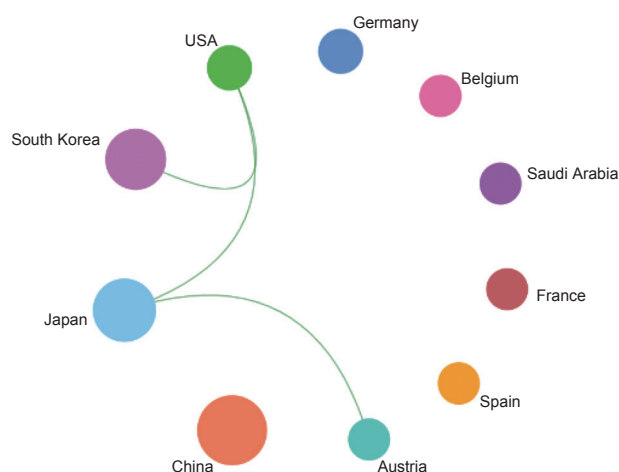


Figure 2.2.6 Collaboration network among major countries in the engineering development front of “hydrogen fuel cell vehicle”

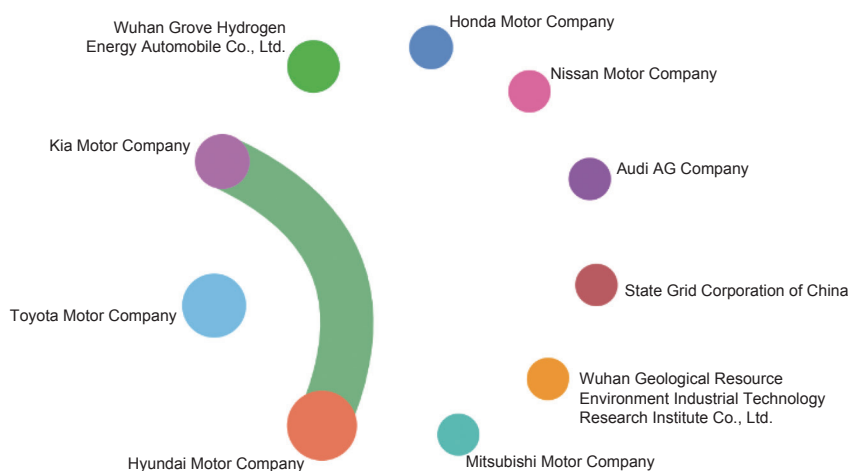


Figure 2.2.7 Collaboration network among major institutions in the engineering development front of “hydrogen fuel cell vehicle”

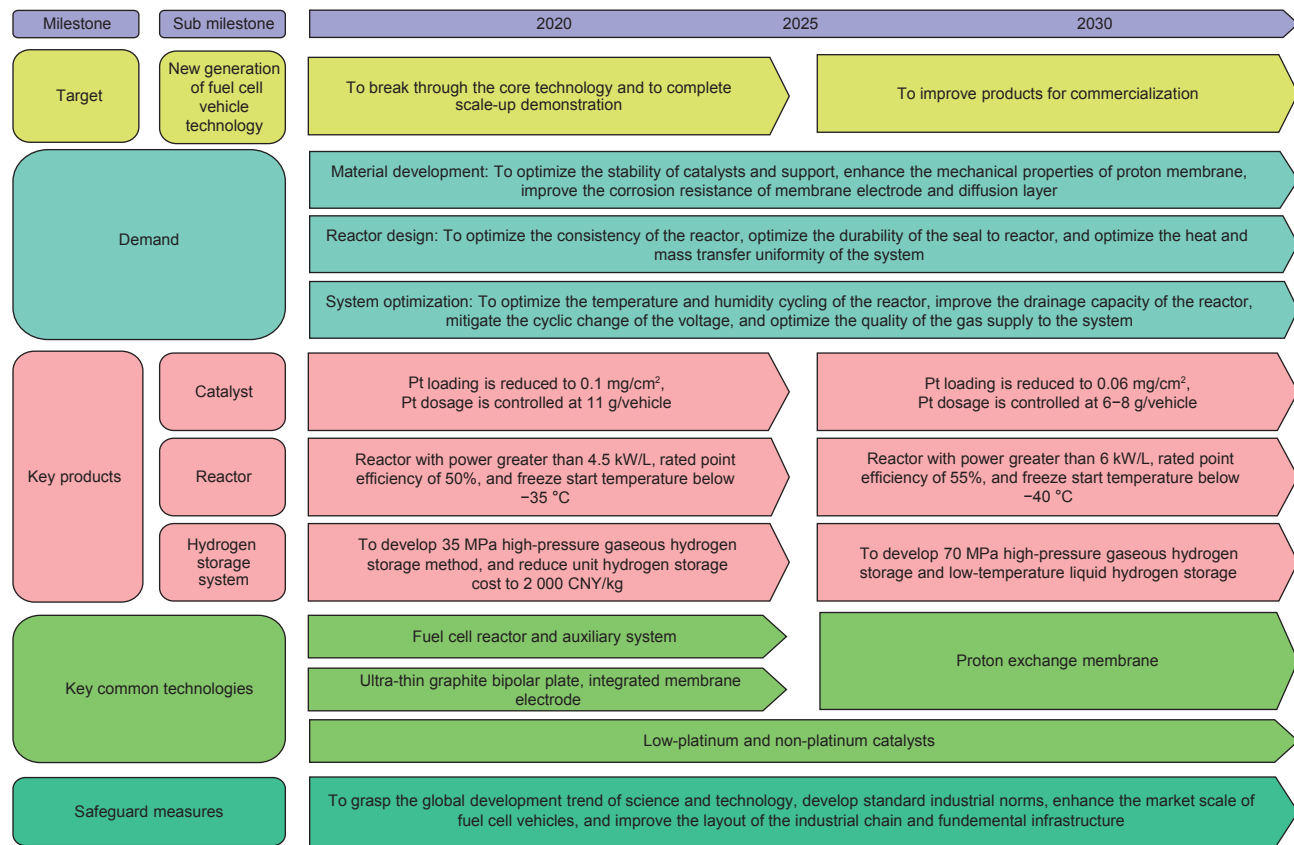


Figure 2.2.8 Roadmap of the engineering development front of “hydrogen fuel cell vehicle”

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II. Information and Electronic Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

Table 1.1.1 summarizes the Top 10 engineering research fronts in the information and electronic engineering field, which encompasses the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. Table 1.1.2 shows the number of core papers published from 2016 to 2021 related to each research front.

(1) Space–air–ground–sea integrated networking theory and technique

The space–air–ground–sea integrated network (SAGSIN) based on the ground network and supplemented and extended by the space, air, and sea networks, can provide ubiquitous, intelligent, collaborative, and efficient information assurance infrastructure for various network services in wide areas. The space network comprises the satellite backbone and access network and supports global coverage, ubiquitous connection, and broadband network access. The

air network consists of the high-altitude platform and the unmanned aerial vehicle self-organized network, which can enhance network coverage, enable edge computing service, and provide a flexible network configuration. The ground network in SAGSIN comprises the ground internet and mobile cellular network, which controls the network service in areas with dense requests. The sea network uses maritime mobile and satellite networks to fulfill the communication requirements in maritime activities. Additionally, based on the deep integration of heterogeneous networks, the SAGSIN can use various network resources effectively and comprehensively to perform intelligent network management and information processing to cope with different network service requirements and realize network integration, network function modularity, and service customization. Therefore, the SAGSIN has shown unprecedented prospects in diverse fields, such as wide-area coverage, the Internet of Things (IoT), intelligent transportation, remote sensing and monitoring, and the military. Specifically, technologies of the low-earth-orbit (LEO) satellite constellation play a core role in establishing an all-coverage, all-connected, and all-knowing SAGSIN. SpaceX’s “Starlink” from the USA currently leads the competition for low-orbit satellite constellations. It intends to launch 42 000 satellites to build a broadband satellite communication network capable of providing global

Table 1.1.1 Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Space–air–ground–sea integrated networking theory and technique	41	3 283	80.07	2019.6
2	Theories and algorithms for trustworthy AI	157	29 067	185.14	2019.5
3	Silicon-based CMOS terahertz imaging technique	122	1 528	12.52	2018.3
4	Silicon-based AI photonic computing chip theory and design	86	2 505	29.13	2019.8
5	High-precision space-based gravitational wave detection technology	220	38 208	173.67	2018.9
6	Manufacture of integrated circuits at the atomic scale	69	5 595	81.09	2018.7
7	Brain–machine interfaces and their clinical applications	219	8 489	38.76	2018.8
8	Humanoid robot behavioral developmental learning and cognitive technology	77	519	6.74	2018.5
9	Quantum circuits and chips	57	7 432	130.39	2019.0
10	Future industrial internet architecture and full-element interconnection	77	5 146	66.83	2019.4

Note: ① AI is short for artificial intelligence; CMOS is short for complementary metal oxide semiconductor;

② For No.3 and No.4, all the detected papers are adopted as the core papers.

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Space–air–ground–sea integrated networking theory and technique	2	2	6	5	10	16
2	Theories and algorithms for trustworthy AI	5	14	22	31	32	53
3	Silicon-based CMOS terahertz imaging technique	22	25	22	17	20	16
4	Silicon-based AI photonic computing chip theory and design	3	6	5	10	25	37
5	High-precision space-based gravitational wave detection technology	25	29	34	35	43	54
6	Manufacture of integrated circuits at the atomic scale	10	10	12	12	12	13
7	Brain–machine interfaces and their clinical applications	25	31	35	39	41	48
8	Humanoid robot behavioral developmental learning and cognitive technology	12	12	14	14	13	12
9	Quantum circuits and chips	7	7	7	8	14	14
10	Future industrial internet architecture and full-element interconnection	4	6	12	14	15	26

coverage. More than 3 000 low-orbit satellites have already been operational in orbit as of August 2022, with more than 500 000 subscribed to broadband access users worldwide. However, several challenges exist in the SAGSIN, as follows: high-dynamic, extra-heterogeneity, ultra-complexity, and multidimensional requirements. The focus of this study includes network architectural design, protocol design, network resource management and scheduling, efficient transmission technology, network security, and privacy preservation, among others.

(2) Theories and algorithms for trustworthy AI

Trustworthy artificial intelligence (AI) enhances the credibility of complex AI systems and algorithms, such as deep neural networks. Specifically, the concept of credibility includes the following four aspects: ① the interpretability and quantifiability of AI systems concerning knowledge representations; ② the interpretability and quantifiability of AI systems regarding representation capacity, which include generalization, robustness, fairness, and privacy protection, among others; ③ the interpretability of AI systems in learning and optimization; ④ the interpretability of the internal mechanism of various AI algorithms.

Therefore, current studies focus on the following to promote the development of trustworthy AI: ① qualitatively or quantitatively interpreting knowledge representations modeled using AI systems, such as visualizing semantic information in intermediate-layer features and quantifying the

importance of input variables to final decisions; ② evaluating, interpreting, and improving AI systems' representation capacity, including generalization, robustness, and fairness, among others; ③ explaining the reasons for the effectiveness of AI system optimization algorithms, and exploring and identifying latent defects in recent empirical optimization algorithms; ④ designing interpretable AI systems to enhance credibility in the system design stage.

Although trustworthy AI has recently received extensive attention, several key bottlenecks are rarely involved and explored, including the following: ① exploring, identifying, and quantifying the essential factors that determine the AI system's representation capacity; ② unifying and interpreting the internal mechanisms of various empirical AI algorithms, thereby uncovering the common nature behind their effectiveness and grasping the essential parts of previous algorithms; ③ the theory-driven design and optimization of AI systems. Particularly, a few international research institutions and teams, such as the Massachusetts Institute of Technology (MIT) and Shanghai Jiao Tong University, have recognized and particularly considered the abovementioned key issues and conducted some forward-thinking explorations on them.

(3) Silicon-based CMOS terahertz imaging technique

The terahertz (THz) imaging technique involves directing continuous or pulsed THz waves onto a target and collecting signals reflected by or transmitted through the object. Fourier transformation algorithm can obtain information of

the intensity and phase of signals from each target point. Subsequently, target imaging can be achieved after spectrum analyses and digital signal processing. The THz frequency band is also located in the electromagnetic spectrum between microwave and infrared waves. It has special characteristics, such as high transmission, low energy, high coherence, and high-transient response. Therefore, imaging techniques at THz frequencies have several incomparable advantages over traditional methods, such as visible light, ultrasonic, and X-ray imaging, and have wide application prospects in national security, safety inspection, biomedicine, and environmental monitoring.

Recently, the THz imaging technique has attracted broad research interest worldwide with the continuous upgrading of silicon-based technology and the great improvement of its radio frequency (RF) performance. The CMOS-assisted technique is characterized by its small size and low power consumption, among others, which can meet the commercial demand for high integration density and low cost. Additionally, the silicon-based CMOS THz imaging technique has achieved several technological breakthroughs in resolution. For example, Cornell University developed a 220 GHz imaging system with a 2 mm lateral resolution and a 2.7 mm range resolution based on the 55 nm bipolar complementary metal oxide semiconductor (BiCMOS) technology. However, overcoming the diffraction limit and further improving the imaging resolution remain an important research focus. Furthermore, the complex parasitic and coupling effects of silicon-based technology, integrated circuit (IC) distribution effects, and source synchronization technology are also the research focus in this field.

(4) Silicon-based AI photonic computing chip theory and design

AI is a strategic technology leading the future, and computing power is a solid foundation to support AI's rapid development. However, as the performance of microprocessors increases slowly, Moore's law is starting to fail, and conventional electronic computing circuits cannot meet the growing demand for AI computing power because of the existence of a "power wall" and "memory wall". Additionally, photons possess inherent advantages, such as low latency, low power consumption, high throughput, and parallelism, over electrons. The silicon-based AI photonic computing chip realizes linear analog calculations using the physical

transmission characteristics of light in the silicon-based waveguide to provide powerful photonic chips for AI applications by leveraging the silicon photonics integration technology.

Considerable efforts have recently been directed to studying silicon-based AI photonic computing chips. Currently, these study areas include limited to image matrix convolution photonic computing chips, integral and differential photonic chips, complex-domain Fourier transform photonic chips, reservoir photonic computing chips, photonic neuromorphic computing (brain-like computing) chips, heuristic algorithm solvers for NP-complete problems, and spiking neural network photonic chips, among others.

Silicon-based photonic computing is envisioned as a potential solution for pushing the limits of electronic computing in the post-Moore era. Interestingly, with the continuous improvement in silicon-based optoelectronic integration, photonic computing chips can greatly accelerate AI algorithms' processing speed and create possibilities for new-processor architectures. Furthermore, combining photonic analog computing and electronic digital logic operation will provide integrated optoelectronic computing with complementary advantages that would change the existing computing system model and build a novel computing basic system with high computing capacity and low power consumption. Therefore, it is an inevitable development trend in the future.

(5) High-precision space-based gravitational wave detection technology

Space-based gravitational wave detection refers to using multiple spacecraft to form a giant laser interferometer in space to detect gravitational waves. Space-based gravitational wave detection mainly focuses on the millihertz frequency band, which contains gravitational wave signals characterized by large magnitude and long duration and also enjoins the rich types, large numbers, and diverse spatial distribution of gravitational wave sources. These factors make the millihertz frequency band the gold mine in gravitational wave detection, with significant implications for astrophysics, cosmology, and fundamental physics research.

Particularly, space-based gravitational wave detection involves two core technologies. The first involves establishing "probe heads" for gravitational wave detection, using a group of objects in nearly ideal inertial motion to provide

reference points in space position for measuring the distance change caused by gravitational waves. The corresponding technology is known as space inertial reference, in which one is faced with the problems of high-precision inertial sensing, micro-Newton-level propulsion, and high-precision drag-free control, among others. The second involves developing a “ruler” for gravitational wave detection, using a laser to measure the distance change between inertial reference points on different satellites. The corresponding technology is known as inter-satellite laser interferometry. Here one faces problems of the ultra-stable optical bench, long life satellite-borne frequency-stabilized laser, and weak light phase locking, among others.

Furthermore, space-based gravitational wave detection necessitates a novel concept of spacecraft development. For example, the thrusters, which originally belonged to the satellite bus, are currently a key element in constructing the gravitational wave “probe heads”. Additionally, the structure and thermal stability of the satellite bus have become key factors that can affect successful gravitational wave detection. Therefore, in designing and developing spacecraft for gravitational wave detection, the boundary between the satellite bus and the payload must be broken down and considered as a whole.

Moreover, any scientific and technological powers that may be capable of space-based gravitational wave detection face a great challenge. After approximately 30 years of planning, the European Space Agency is seeking to launch the first space-based gravitational wave detector in the 1930s, possibly with some minor contribution from the USA. Japan has been relentless in the pursuit of its own space-based gravitational wave detection mission. China is actively studying space-based gravitational wave detection and is striving to play an important role in this field. In 2020, the Chinese Ministry of Science and Technology launched the key R&D plan for “gravitational wave detection”, with the most funds going to support the key genetic technologies of space-based gravitational wave detection.

(6) Manufacture of integrated circuits at the atomic scale

The term “atomic scale” in IC technology generally refers to the thickness of a single atomic layer. This thickness scale depends on the size of atoms and the crystal structure and is typically in the range of 0.1 nm, such as 0.2–0.5 nm. With the development of ICs beyond the 10 nm technology node,

critical physical dimensions, tolerance of deviations in the critical dimensions, and the precision of measurement tools all enter the range of atomic scale. Transistors feature an increasing number of critical layers that are only a few atoms thick or wide. Such critical layers include gate dielectrics, metal gate layers for work function engineering, and fins of the fin field-effect transistor (FinFET), all with a feature size less than 10 atomic layers thick. Interestingly, as the common process for IC manufacture, atomic layer deposition (ALD) produces a film of 0.03–0.07 nm per cycle, far below the atomic scale thickness. Besides the absolute feature size, the mass production of ICs emphasizes the tolerance of thickness or width control, which benefits the yield rate. For example, the work function metal gate layers variation should be less than one atomic layer thick; otherwise, the transistors would suffer from unacceptable deviations in threshold voltage and performance, causing failure of the IC chips integrated with billions of devices. Therefore, the measurement tools applied in IC manufacturing have high-precision of approximately 0.01 nm, which is lower than a single atomic layer, to ensure the precise measurement of the above dimensions. Additionally, two-dimensional (2D) and oxide channel materials have been widely applied in academic research to fabricate transistors and simple circuits, providing a new solution to realizing atomic scale IC manufacture in the future.

(7) Brain-machine interfaces and their clinical applications

The brain-machine interface (BMI) is an intelligent system that establishes a direct and bidirectional communication pathway between the brain and external devices. The BMI either controls the external device using brain signals or modulates the brain state using external devices, aiming to monitor the brain state, treat brain disorders, and enhance brain functions. Since the 1970s, when the concept of “BMI” was first proposed, BMI technology has been continuously advancing, with an explosive development trend in the past decade. The key technologies in BMI are as follows: ① electrode design, fabrication, and minimally invasive implantation technology to obtain large-scale neural signals; ② neural decoding technology to understand the brain activities from complex, large-scale neural signals; ③ electrical, magnetic, and optical technology to stimulate neural populations; ④ closed-loop neural modulation technology based on real-time neural signals; ⑤ high-performance, low power

neurochip technology, which integrates neural signal storage, decoding, stimulation, and modulation.

BMIs have many applications in the diagnosis, treatment, rehabilitation, and other aspects of mental/neurological diseases. For example, first, BMIs will restore motor and sensory functions. Such BMIs use neural signals to decode the brain's movement intentions to drive external devices to complete the intended movements; simultaneously, sensory feedback is provided. Interestingly, these BMIs will provide new approaches to treating motor disabilities, such as paralysis. Recently, this BMI type will be extended to explore the restoration of more precise motor and sensory functions, such as human speech decoding and vision recovery. Second, BMIs will enhance cognitive functions. Such BMIs employ external devices to reconstruct or facilitate the communication between brain regions, aiming to repair or enhance specific cognitive functions. One example is the development of memory prostheses to explore the enhancement of impaired memory functions in patients. Third, BMIs will facilitate the treatment of neurological and neuropsychiatric disorders. Such BMIs use neural signals to guide the external devices in delivering optimal brain stimulation in real-time for a precise intervention. Notably, these BMIs have demonstrated great potential in treating neurological and neuropsychiatric disorders, such as Parkinson's disease, epilepsy, and depression.

Although BMI technology has broad clinical applications, its performance, accuracy, efficiency, and safety still necessitates resolving several major challenges. Some challenges are as follows: ① developing neural recording and stimulation hardware that is stable in the long term, biocompatible with brain tissue, and has high spatial-temporal resolutions; ② developing accurate and stable BMI decoding algorithms to achieve the fine-grained control of various complex external devices; ③ developing precise and robust BMI modulation algorithms to effectively and safely modulate various brain states; ④ studying the ethics and data security of BMI technology.

(8) Humanoid robot behavioral developmental learning and cognitive technology

Humanoid robots should interact with the surrounding physical world in a developmental learning manner to strengthen their behavioral capabilities, enhance their level of human-like cognition, such as movement, manipulation,

understanding, memory, and reasoning, and exhibit more intelligent behavioral actions. The related technology is known as humanoid robot behavioral developmental learning and cognitive technology. The research directions are as follows: ① autonomous behavioral development; ② embodied intelligence (the evolutionary process of ontological structure and intelligence of robots performing various tasks in actual physical environments); ③ affordance learning (potential behaviors between robots and environments and the effects of these potential behaviors); ④ robot learning platforms (simulation software or real physical machines). Therefore, novel algorithms for brain-like constructs with learning and cognitive capabilities, particularly memory and learning, should be developed. The development of behavioral cognitive systems will enable robots to be more human-like and perform active, intrinsically motivated, lifelong learning and development in motor skills and behavioral cognition. Perceptual representations generalizable in different environments and tasks and intertwined with multimodal perceptual joint learning are crucial. Subsequently, AI is considered a physical entity to study, and the changes in robotic bodies in response to natural selection are studied in a simulation environment. This is a completely different paradigm from viewing AI as only an algorithm. Additionally, studying the affordance of robots is necessary to rescue and exploration tasks. Therefore, analyzing the potential behaviors between the robot and the environment and the effects of these potential behaviors can enable the robot to perform better in the unknown environment. Finally, we must upgrade or develop robotic platforms that will enable a better analysis of the functional interaction between robots, humans, and the environment.

(9) Quantum circuits and chips

The quantum circuit model is a universal language for describing quantum algorithms, with each computation process comprising a sequence of quantum gates, measurements, and other possible operations. Most quantum algorithms, including Shor's algorithm, Grover search algorithm, and HHL algorithm, are presented via the quantum circuit model. Additionally, the quantum circuit model is widely used to simulate quantum physical and chemical systems. Currently, quantum computing has entered the era of noisy intermediate-scale quantum systems. Given the current technology and engineering level of physical

hardware, there are inherent limitations on the scale, depth, and qubit number of quantum circuits. Therefore, the degree of simplification of quantum circuits directly affects the scope of quantum computer applications. Designing quantum circuits for various practical computation problems with as few gates as possible, as shallow as possible, and as few qubits as possible is an important research direction in quantum computation. Besides, it is an important research direction to characterize the computation power of quantum circuits under various resource constraints and the separation between quantum and classical circuits.

Quantum chips are compact quantum circuits that are integrated on various physical platforms. The realization of quantum chips is an inevitable path toward the practical commercialization of quantum communication and computation. Additionally, the technical routes of quantum chips can be categorized into the following, based on the dependence of quantum circuits on the different physical platforms: superconducting quantum chips, semiconductor quantum dot (QD) chips, and optical quantum systems. Among these different implementations, superconducting circuits outperform other platforms in the scaling of the qubits that can be integrated; semiconductor QDs have good integrability and scalability, making them strong candidates for realizing solid-state quantum computing; the realization of optical quantum chips benefits from the techniques using traditional photonic ICs and classical optical communication. The major challenges of quantum chip implementations include improving the fidelity of quantum gates, coherence time, and decreasing the crosstalk and measurement error. Fault tolerant circuits/chips will play an important role. For future directions, people are devoted to expanding the scale of integration and improving the coherence time, manipulation accuracy and speed, and scalability.

(10) Future industrial internet architecture and full-element interconnection

The term “industrial internet” was first proposed by General Electric (GE) in 2012. It focuses mainly on predictive maintenance to realize industrial automation and intelligence. After that, European countries, mainly Germany, put forward “Industry 4.0” in 2013. China also announced the “Made in China 2025” plan in 2015, which gave a richer connotation to the “industrial internet” and gradually established the full-element interconnection architecture.

The industrial internet architecture includes the network infrastructure, enabler platform, and security mechanism. The so-called “full-element interconnection” represents connecting people, machines, materials, rules, and the environment through networks and identification systems. The interconnectivity also includes the link between the entire lifecycle management among the value, supply, and industrial chains and R&D, production, and logistics, among others. The related technology expands across four directions as follows: ① network technologies, such as interconnection, deterministic transmission, identifier resolution, and computing and network convergence; ② data-handling operations, such as data collection, cleaning, training, and analyses; ③ intelligent platform and management technologies, such as cyber-physical systems, model and application analyses, supply chain and lifecycle management; ④ security technologies, such as the security of network, data, and physics, among others.

The industrial internet has advanced to the trial and deployment stage from the conceptual consensus. Specific technologies, such as the platform, identifier, and 5G have been applied in the industry. Interestingly, the identifier resolution system has been implemented at the five National Top Nodes in China. The following trends appear on the horizon from the perspective of architecture and technology:

- 1) Toward specific scenarios: Derives architectures for guiding the implementation of various scenarios and expands the deployment to small- and medium-sized enterprises.
- 2) More integrated technologies: IT (Information Technology), OT (Operations Technology), and CT (Communication Technology) are further integrated to solve the ecological interconnection of cloud networks and improve the efficiency and quality of all production and manufacturing links, by combining virtual reality, digital twin, and deterministic lossless connections.
- 3) Trusted and more secure: Privacy-preserving and data-trusted technology will be further adopted to solve the personnel, systems, and equipment security problems.
- 4) Systematic promotion: This improves the overall automation system and leverages new communication technologies. This also enables the generation of a full-element interconnected system, connects the business chain, and creates new industrial models.

1.2 Interpretations for three key engineering research fronts

1.2.1 Space–air–ground–sea integrated networking theory and technique

The SAGSIN comprises the space, air, ground, and sea networks that complement the conventional terrestrial network in coverage, flexibility, and monotonicity and is essential to realize ubiquitous network access and service customization. Because of the non-uniform mechanisms of existing networks, massive variations in resource distribution, complex and dynamic wireless channels, and network security challenge the network operators. The four main research directions of the SAGSIN must cope with the following: network architecture design, protocol design, resource management, and transmission technique. Therefore, we introduce the advances in these aspects as follows:

1) Two main trends exist in network architecture design. The international standardization organization 3GPP promotes the integration of non-terrestrial networks (NTNs), including all NTNs, such as satellite and aerial networks, and terrestrial cellular networks, where the NTNs are vital in the 5G network and future 6G networks to form an interconnected network. However, the other trend is to design an efficient, globally controllable, and low cost virtualized SAGSIN architecture, based on software-defined networking (SDN) and network function virtualization (NFV). Notably, the main research institutions in this direction include the University of Waterloo, Tsinghua University, and Beijing Jiaotong University, among others.

2) For communication protocol design, the Consultative Committee for Space Data Systems (CCSDS) protocol can achieve near-lossless multimedia streaming transmission in the SAGSIN, despite payload limitations through the iterative processing of adjacent frames, which greatly expands the supporting exchange capability of space mission information systems. Digital video broadcasting (DVB) series protocols overcome the limitation of traditional uplink power control on the volume of the RF front-end, which effectively improves the spectrum efficiency of satellite communication links, optimizes the space segment of the network, and significantly reduces the cost of satellite-based internet protocol (IP) services. However, these two protocols were previously proposed, and organizations and institutions, including 3GPP,

are also exploring new communication protocols.

3) Two main trends exist in SAGSIN resource management. One is the AI-driven resource management and scheduling mechanism, which can adapt to the characteristics of several network nodes, large-decision-making space, and heterogeneous resources in SAGSINs, thereby effectively improving the use of network resources. Another trend is the service function chain or network slicing resource scheduling technology, which uses SDN and NFV technologies to abstract and pools the physical network resource to maintain the service isolation between users and the satisfaction of multi-dimensional requirements. The main research institutions in this direction include Tsinghua University, University of Waterloo, Xidian University, and the National University of Defense Technology, among others.

4) Inter-satellite laser communication is a potential technology for efficient transmission technology to realize high-speed inter-satellite links. Compared with RF based inter-satellite communication, it can achieve a much higher data transmission rate through a smaller antenna size. Simultaneously, the laser beam can provide the inter-satellite laser link with a narrower beam and higher directivity, eliminating interference and promoting network security. Currently, microwave communication remains the main inter-satellite link communication method in engineering. Therefore, the preliminary inter-satellite laser communication test and deployment are expected to be performed by the end of 2023. The main research institutions in this direction include Beihang University, Xidian University, Southeast University, Beijing Jiaotong University, and Northeastern University, among others.

The LEO constellation system construction is also a necessary R&D focus for the SAGSIN. The Iridium system is the earliest planned and deployed global coverage satellite network. In 2015, the SpaceX projected “Starlink” LEO satellite network sparked interest in academia and the industry. SpaceX announced that tens of thousands of low-orbit satellites would be launched to provide high-speed network access globally. Until now, “Starlink” has completed its initial deployment, which can reach the highest download speed of 301 Mbps and has provided network access in dozens of European and American countries. Additionally, China has several LEO satellite communication systems that are expected to be built, including “Apocalypse”, “Hongyan”, “StarRides”, and “China

SatNet”, among others. Furthermore, the earliest of them are expected to be deployed by the end of 2023.

Table 1.2.1 presents the countries with the greatest output of core papers on “space–air–ground–sea integrated networking theory and technique”. China has obvious advantages, and the number of core papers is about three times that of second-placed Canada. China’s international cooperation target is mainly Canada; however, it has some collaboration with the UK, the USA, and Japan (Figure 1.2.1). Among the Top 10 institutions with the greatest output of core papers (Table 1.2.2), the University of Waterloo in Canada produces the most papers. Additionally, six of the Top 10 institutions with the greatest output of core papers globally are from China; the rest are distributed in Japan, Norway, and the UK. Regarding institutional cooperation (Figure 1.2.2), five institutions from China collaborate closely with the University of Waterloo and two institutions from China collaborate closely with the University of Surrey, and the Beijing Institute of Technology

and the University of Oslo have some cooperation. Concerning the greatest output of citing papers (Table 1.2.3), China ranks first, accounting for 49.62%, followed by the USA. The rest of the countries are all less than 10%. Among the Top 10 citing paper producers (Table 1.2.4), all are from China, excluding the fifth-ranked University of Waterloo, which reflects China’s considerable attention in this direction.

Currently, the theory and technology of space–air–ground–sea integrated communication networking are at different levels of development in China and abroad. However, they are all in the design and initial deployment stage. Figure 1.2.3 is the roadmap of the engineering research front of “space–air–ground–sea integrated networking theory and technique”. From the perspective of technical indicators, the greatest LEO constellation will contain thousands of satellites by 2025. Additionally, it is expected that the scale of a single constellation will reach tens of thousands by 2030. In the next 5 years, the LEO satellite network test rate can reach 500

Table 1.2.1 Countries with the greatest output of core papers on “space–air–ground–sea integrated networking theory and technique”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	35	85.37	2 958	84.51	2019.6
2	Canada	13	31.71	1 260	96.92	2019.9
3	UK	8	19.51	613	76.62	2019.9
4	Japan	7	17.07	781	111.57	2020.0
5	USA	6	14.63	328	54.67	2020.7
6	Norway	3	7.32	499	166.33	2019.0
7	Saudi Arabia	3	7.32	127	42.33	2021.0
8	Singapore	3	7.32	126	42.00	2020.0
9	Australia	2	4.88	220	110.00	2019.0
10	India	2	4.88	129	64.50	2020.5



Figure 1.2.1 Collaboration network among major countries in the engineering research front of “space–air–ground–sea integrated networking theory and technique”

Table 1.2.2 Institutions with the greatest output of core papers on “space–air–ground–sea integrated networking theory and technique”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Waterloo	8	19.51	978	122.25	2019.6
2	Xidian University	7	17.07	788	112.57	2019.9
3	Southeast University	7	17.07	483	69.00	2020.0
4	Tsinghua University	5	12.20	296	59.20	2019.8
5	Tohoku University	4	9.76	677	169.25	2019.2
6	University of Oslo	3	7.32	499	166.33	2019.0
7	Beijing Institute of Technology	3	7.32	456	152.00	2018.3
8	University of Surrey	3	7.32	362	120.67	2020.3
9	Beijing Jiaotong University	3	7.32	341	113.67	2018.3
10	Purple Mountain Laboratories	3	7.32	285	95.00	2020.7

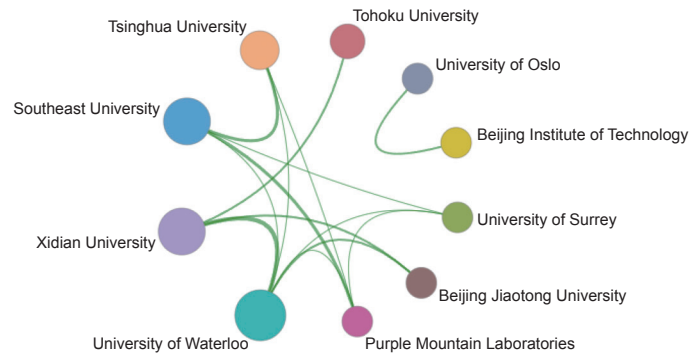


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “space–air–ground–sea integrated networking theory and technique”

Table 1.2.3 Countries with the greatest output of citing papers on “space–air–ground–sea integrated networking theory and technique”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 634	49.62	2020.4
2	USA	340	10.32	2020.4
3	Canada	310	9.41	2020.2
4	UK	219	6.65	2020.5
5	South Korea	147	4.46	2020.6
6	India	141	4.28	2020.5
7	Australia	130	3.95	2020.3
8	Saudi Arabia	119	3.61	2020.6
9	Japan	107	3.25	2020.4
10	Germany	75	2.28	2020.3

Mbps, and the delay can reach 60 ms. Furthermore, the LEO satellite network test rate will reach a minimum of 5 Gbps, with a delay of at least 20 ms from 2027 to 2032. Therefore, the total network throughput of LEO satellite networks is

predicted to reach 97 Tbps, 218 Tbps, and 820 Tbps from 2022 to 2024, 2025 to 2028, and 2032, respectively. From the viewpoint of research direction, the main research directions in current “space–air–ground–sea integrated networking

Table 1.2.4 Institutions with the greatest output of citing papers on “space–air–ground–sea integrated networking theory and technique”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Xidian University	166	15.26	2020.3
2	Beijing University of Posts and Telecommunications	161	14.80	2020.3
3	Southeast University	141	12.96	2020.6
4	Tsinghua University	111	10.20	2020.2
5	University of Waterloo	110	10.11	2019.9
6	Nanjing University of Posts and Telecommunications	76	6.99	2020.6
7	Beihang University	76	6.99	2020.2
8	Beijing Jiaotong University	67	6.16	2020.0
9	Peng Cheng Laboratory	66	6.07	2020.7
10	Nanjing University of Aeronautics and Astronautics	59	5.42	2020.5

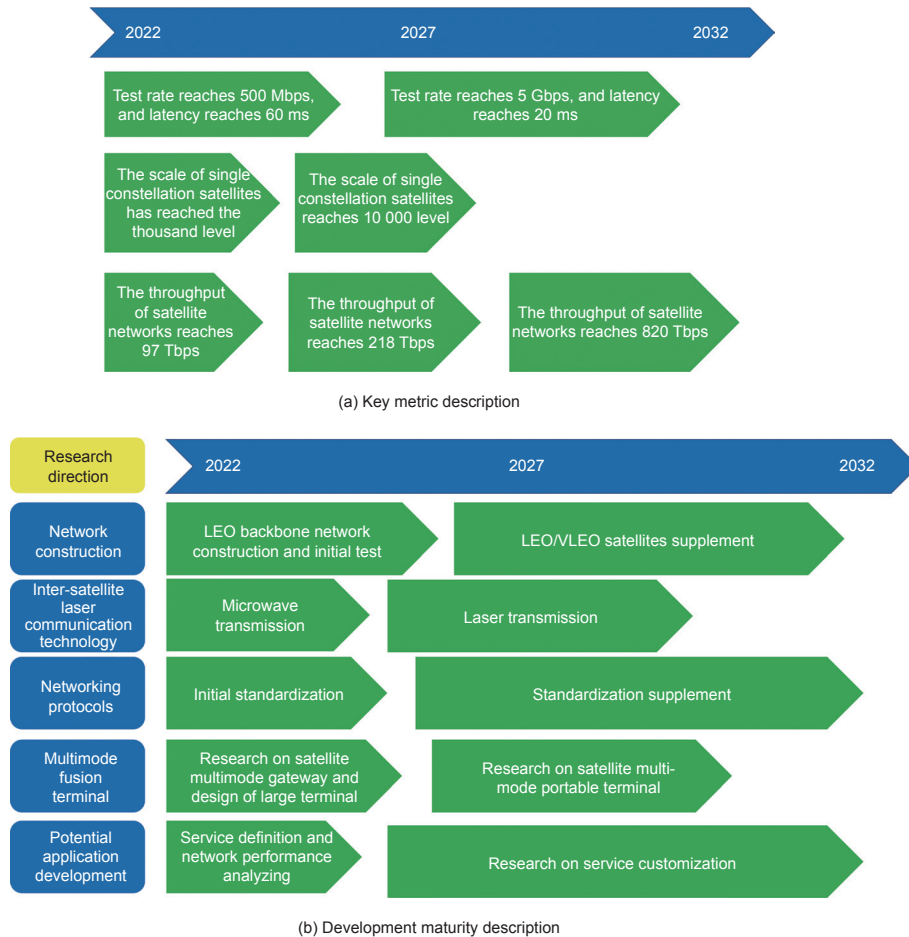


Figure 1.2.3 Roadmap of the engineering research front of “space–air–ground–sea integrated networking theory and technique”

theory and technology” include network construction, inter-satellite laser communication technology, space-air-ground-sea networking protocol designing, multimode fusion terminal design, and potential application development. The construction of the integrated network is currently in the initial stage, which includes the construction of the LEO satellite backbone network and the testing of the system terminal. It is expected that the construction of the backbone will be completed by the end of 2025, and more low- and super-low-orbit satellites will be launched according to application needs by 2032. The current inter-satellite communication technology in the LEO satellite network is also under development regarding inter-satellite laser communication technology, and the current communication technology is primarily microwave communication. Nevertheless, laser communication remains in the test stage, which is expected to be deployed by 2025. Furthermore, concerning satellite multimode fusion terminals, several requirements on mass, volume, compatibility in a heterogeneous network, and application integration must be satisfied to adapt to multi-system, multi-band, multi-network, and multi-application, among others. Recently, the satellite multimode technique is only in the preliminary stage, and the related products are limited to gateways and larger terminals; however, portable terminals are expected to be designed and introduced into the market from 2025 to 2032. Moreover, for potential application development, the current application scenarios for the SAGSIN mainly focus on wide-area broadband access, military communications, IoT, and the Internet of Vehicles, among others. However, in the future, more potential services will be explored to further exploit the potential capabilities of the SAGSIN. Additionally, with the support of international organizations, such as 3GPP and IMT-2030, the standardization of space-air-ground-sea integrated communication and networking has officially started, and part of the agenda is gradually being conducted. Therefore, relevant technologies, protocols, and index requirements will be further improved in the next 5–10 years.

1.2.2 Theories and algorithms for trustworthy AI

The AI field has been revolutionized by leaps and bounds, considering the great success of complex AI systems, such as deep neural networks. However, these systems are frequently regarded as black-box systems because of their complex architectures and massive parameters. Therefore, people

neither understand the internal decision logics of these systems nor explain the advantages and disadvantages of these systems based on representation capacity, such as why neural networks can achieve superior performance and are simultaneously highly vulnerable to adversarial attacks. Given the uninterpretability of AI systems in the decision-making process and the representation and optimization capabilities, the credibility, controllability, and security of these systems are greatly impaired, thereby hindering the widespread application of AI, particularly in intelligent healthcare, self-driving, and other high-risk areas.

Therefore, academia and industry are committed to enhancing the interpretability of AI systems and algorithms to build trustworthy, controllable, and secure AI. Specifically, trustworthy AI aims to enhance the interpretability and quantifiability of AI systems in knowledge representation, representation capacity, optimization, and learning ability, and the interpretability of the AI algorithms’ internal mechanism.

Recently, major research interests of trustworthy AI are as follows: ① qualitatively or quantitatively interpreting the knowledge representation modeled with AI systems, such as visualizing the semantic information contained in intermediate-layer features and quantifying the importance of input variables to final decisions; ② evaluating, explaining, and improving the representation capacity of AI systems, such as theoretically proving or empirically studying the boundaries of generalization and robustness, explaining the internal mechanisms of neural networks in generalization, robustness, and representation bottlenecks, and developing various methods (e.g., the adversarial training) to improve the robustness, fairness, or to avoid privacy leakage; ③ explaining the internal mechanism of the effective optimization of AI system algorithms, and exploring the latent defects in current empirical optimization algorithms, for example, to explain why optimization methods, such as stochastic gradient descent and dropout are effective and to identify potential mathematical defects in classical optimization operations, such as batch normalization; ④ designing interpretable AI systems and incorporating credibility into the system architecture in the system design stage, for example, with a specifically designed objective function for the convolutional neural network, each filter of the high-level convolutional layer automatically represents specific semantics.

Notably, the field of trustworthy AI has recently received extensive attention, achieving many achievements. Tables 1.2.5 and 1.2.6 present the countries and institutions, respectively, with the greatest output of core papers on this research front. Tables 1.2.7 and 1.2.8 present the countries and institutions with the greatest output of citing papers on this front, respectively. Typical institutions include MIT, Chinese Academy of Sciences, and Shanghai Jiao Tong University, among others, which are mainly in the USA and China. Additionally, many of the core papers are jointly produced by different research institutions in different countries. Figures 1.2.4 and 1.2.5 show the cooperation networks between major countries and institutions, respectively.

Although trustworthy AI has received extensive attention

recently, most studies remain at the level of engineering algorithms, such as visualizing neurons of a neural network, estimating the importance of input variables, and evaluating the robustness of neural networks using the accuracy under adversarial attacks. However, several critical and fundamental bottlenecks in trustworthy AI are rarely involved and explored, which include:

1) Exploring, identifying, and quantifying the essential factors that determine the representation capacity of AI systems: Specifically, many factors, such as network architectures and optimization tricks, affect the representation capacity of AI systems. However, such factors frequently produce complex and diverse effects at the representation capacity level. Therefore, determining the fundamental factors that impact

Table 1.2.5 Countries with the greatest output of core papers on “theories and algorithms for trustworthy AI”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	67	42.68	21 672	323.46	2018.9
2	China	36	22.93	1 990	55.28	2020.0
3	UK	19	12.10	1 389	73.11	2019.8
4	Germany	18	11.46	1 501	83.39	2019.5
5	Italy	12	7.64	319	26.58	2020.3
6	Austria	9	5.73	627	69.67	2020.0
7	South Korea	8	5.10	750	93.75	2019.8
8	Australia	7	4.46	1 170	167.14	2019.9
9	Canada	7	4.46	776	110.86	2019.3
10	Switzerland	7	4.46	282	40.29	2019.3

Table 1.2.6 Institutions with the greatest output of core papers on “theories and algorithms for trustworthy AI”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of California, Los Angeles	11	7.01	875	79.55	2019.2
2	Stanford University	8	5.10	2 638	329.75	2018.2
3	Korea University	6	3.82	716	119.33	2019.5
4	Medical University of Graz	6	3.82	586	97.67	2019.7
5	University of Pisa	6	3.82	199	33.17	2019.8
6	University of California, Berkeley	5	3.18	4 561	912.20	2017.2
7	Technical University of Berlin	5	3.18	710	142.00	2019.2
8	Fraunhofer Heinrich Hertz Institute	5	3.18	695	139.00	2019.4
9	Shanghai Jiao Tong University	5	3.18	123	24.60	2020.6
10	University of Granada	4	2.55	1 086	271.50	2020.2

Table 1.2.7 Countries with the greatest output of citing papers on “theories and algorithms for trustworthy AI”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	7 372	33.09	2020.4
2	USA	5 719	25.67	2020.2
3	UK	1 722	7.73	2020.3
4	Germany	1 471	6.60	2020.4
5	South Korea	1 130	5.07	2020.4
6	Australia	915	4.11	2020.4
7	Canada	901	4.04	2020.3
8	Japan	890	3.99	2020.3
9	Italy	771	3.46	2020.4
10	India	739	3.32	2020.4

Table 1.2.8 Institutions with the greatest output of citing papers on “theories and algorithms for trustworthy AI”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	750	22.27	2020.3
2	Zhejiang University	333	9.89	2020.4
3	Tsinghua University	325	9.65	2020.1
4	Harvard University	282	8.37	2020.4
5	Stanford University	276	8.19	2020.2
6	Shanghai Jiao Tong University	266	7.90	2020.3
7	Massachusetts Institute of Technology	260	7.72	2020.2
8	University of Electronic Science and Technology of China	245	7.27	2020.4
9	Peking University	216	6.41	2020.2
10	Wuhan University	212	6.29	2020.4



Figure 1.2.4 Collaboration network among major countries in the engineering research front of “theories and algorithms for trustworthy AI”

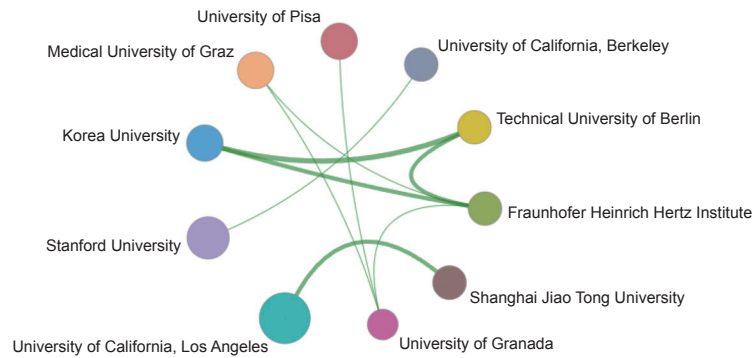


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “theories and algorithms for trustworthy AI”

representation capacity is challenging. Moreover, researchers can accurately evaluate and interpret the representation capacity of AI systems only when the decisive factors of the representation capacity are clearly identified.

2) Unifying and interpreting the internal mechanisms of various empirical AI algorithms: To address a specific research problem, scholars propose different AI algorithms from different empirical perspectives. Specifically, these algorithms often contain identical or similar internal mechanisms. The common essence of these algorithms may be revealed through the unification and explanation of the internal mechanisms of these different empirical algorithms, and the reliability of these algorithms can be evaluated and compared.

3) Theory-driven design and optimization of AI systems, particularly neural network systems: The current architecture design and training optimization of AI systems are mostly empirical, which implies that people develop effective architectural design and optimization algorithms based on several experimental observations. However, unified theoretical feedback is required to guide the design and optimization of AI systems so that the representation capacity of AI systems can meet the demands of specific tasks. Therefore, the controllability of AI systems is truly realized.

Specifically, a few international research teams have realized and considered the abovementioned key issues and conducted forward-thinking explorations on them. For example, the team from the Shanghai Jiao Tong University uniformly explained numerous algorithms for improving adversarial transferability, whereas those from University of California, Berkeley proposed that the principles of “self-consistency” and “simplicity” are the cornerstones of AI

systems and used these principles to guide AI systems’ design with interpretable representations and training.

In the past decade, much research progress has been achieved for trustworthy AI. However, from the perspective of the development process of the entire field, trustworthy AI remains in its infancy, and many key bottlenecks exist, which need to be urgently solved. Specifically, important research directions for the next 5–10 years include the following aspects (Figure 1.2.6).

First, further improve the explanation for knowledge representations. Most of current explanations stem from heuristics, which lack theoretical reliability. Additionally, these explanations have no ground-truth, making it impossible to verify the reliability of explanations. Therefore, future research priorities may include: ① unifying numerous existing empirical explanations and revealing their common mechanism; ② proposing new explanations with theoretical guaranties; ③ evaluating the reliability of explanations objectively.

Second, develop the explanation and quantification for representation capacity. Future research priorities may include: ① exploring and identifying the essential factors that affect the representation capacity of AI systems; ② uniformly explaining the internal mechanism of various AI algorithms proposed for improving representation capacities; ③ proposing precise quantitative metrics to evaluate the representation capacity of AI systems; ④ explaining and proving properties and defects of representation capacities of AI systems.

Third, conduct theory-driven design and optimization of AI systems. Today, effective architectural design and optimization methodologies are typically developed based on

experimental observations. However, trustworthy AI requires a unified theory, which can provide targeted feedback to guide the design and optimization of AI systems. Future research priorities in this area could be ① investigating the connection between network architectures and knowledge representations, ② investigating the connection between the model performance and knowledge representations, and ③ investigating the relationship between knowledge representations and various types of representation capacity, such as generalization, robustness, and fairness.

1.2.3 Silicon-based CMOS terahertz imaging technique

Traditional terahertz (THz) imaging methods are mainly based on pure electronic or photoelectric setups. The former mainly depends on Schottky diodes and III-V devices, whereas the latter focuses on photoconductance, optical rectification, and quantum cascade lasers. In reality, all the devices are expensive and bulky, and some even call for cooling equipment. Additionally, they are incompatible

with traditional microelectronics packaging methods, which further increase the difficulty of circuit integration. However, with the rapid development of silicon-based technology, the silicon-based CMOS THz imaging technique can achieve lower power consumption and a smaller size, which can meet the market demand for low cost and high integration density and has gradually become a hot research topic in the field of THz imaging.

Table 1.2.9 summarizes the research status on the silicon-based CMOS THz imaging technique. The top three countries in core papers are the USA, Germany, and China. In terms of citations, China is overtaken by Japan and France and drops to the fifth place. The main research institutions with the greatest output of core papers are shown in Table 1.2.10. The University of Wuppertal and the Vilnius University are the top two institutes with the greatest output of core papers. In China, only Nanjing University breaks into the top 10. Regarding total citations, the top three institutes are Princeton University, University of Wuppertal, and University of Michigan, while Nanjing University

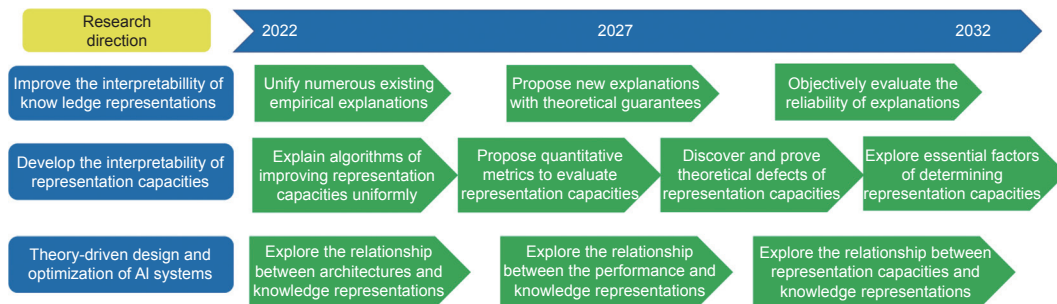


Figure 1.2.6 Roadmap of the engineering research front of “theories and algorithms for trustworthy AI”

Table 1.2.9 Countries with the greatest output of core papers on “silicon-based CMOS terahertz imaging technique”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	38	31.15	519	13.66	2018.3
2	Germany	33	27.05	359	10.88	2018.7
3	China	18	14.75	107	5.94	2018.4
4	France	10	8.20	147	14.70	2017.6
5	Poland	10	8.20	42	4.20	2020.4
6	Lithuania	10	8.20	41	4.10	2020.3
7	Israel	6	4.92	17	2.83	2016.8
8	Switzerland	6	4.92	12	2.00	2017.2
9	Japan	5	4.10	222	44.40	2018.8
10	UK	4	3.28	102	25.50	2017.0

of China ranks around tenth. Based on cooperation among major countries (Figure 1.2.7), the main partners of China is the USA. Germany has developed extensive cooperative ties with countries in Europe, America, and Asia. Based on cooperation among major institutions (Figure 1.2.8), stable cooperation has been established in continental Europe, including the General Jonas Žemaitis Military Academy of Lithuania, Vilnius University, and Institute of High-Pressure Physics of the Polish Academy of Sciences, while Cornell University built partnerships with University of California, Los Angeles and University of Michigan, as listed in the table. Institutions with the greatest output of citing papers on this front are shown in Table 1.2.11. China accounts for over a third of the publications and ranks first worldwide. The USA and Germany rank second

and third, respectively. In Table 1.2.12, China dominates the list of institutions, with seven in the world's top 10, whereas only two are in the USA, and one in Germany.

Three factors are primarily the focus of initial research on CMOS silicon-based THz imaging: high sensitivity, high integration density, and high resolution. Incoherent direct-detection technology was used initially, but its low sensitivity and high input power requirement are the main challenging factors for solid-state electronic design. Based on the 0.13 μm silicon germanide (SiGe) BiCMOS technology, a specific coherent imaging transceiver chip can upgrade the sensitivity by more than 10 times. The array's scale must be expanded to achieve a higher imaging resolution, but this is impossible for traditional coherent detection arrays because

Table 1.2.10 Institutions with the greatest output of core papers on “silicon-based CMOS terahertz imaging technique”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Wuppertal	20	16.39	294	14.70	2018.5
2	Vilnius University	9	7.38	39	4.33	2020.7
3	Princeton University	8	6.56	301	37.62	2018.8
4	Institute of High Pressure Physics, Polish Academy of Sciences	8	6.56	39	4.88	2020.8
5	University of California, Los Angeles	8	6.56	20	2.50	2019.6
6	University of Michigan	6	4.92	109	18.17	2018.0
7	General Jonas Žemaitis Military Academy of Lithuania	5	4.10	20	4.00	2020.8
8	Nanjing University	5	4.10	8	1.60	2018.6
9	University of Glasgow	4	3.28	102	25.50	2017.0
10	Cornell University	4	3.28	97	24.25	2017.5

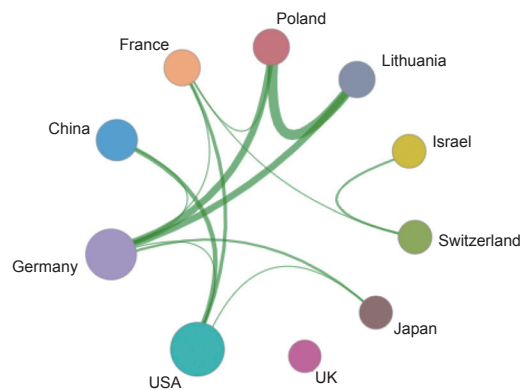


Figure 1.2.7 Collaboration network among major countries in the engineering research front of “silicon-based CMOS terahertz imaging technique”

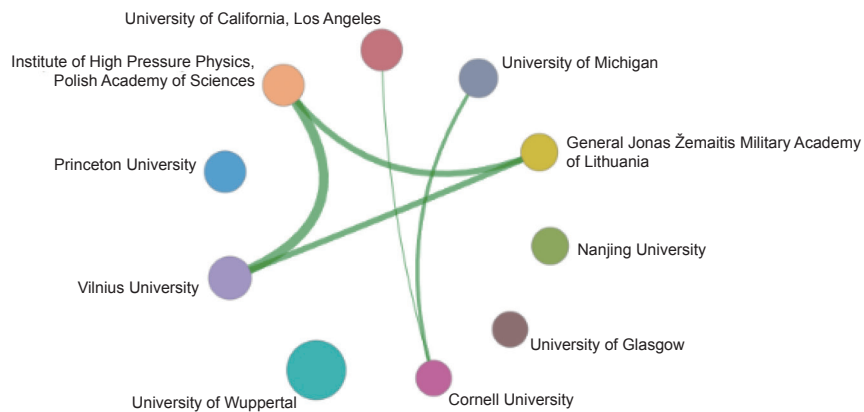


Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “silicon-based CMOS terahertz imaging technique”

Table 1.2.11 Countries with the greatest output of citing papers on “silicon-based CMOS terahertz imaging technique”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	464	34.73	2020.1
2	USA	276	20.66	2019.7
3	Germany	150	11.23	2019.7
4	Japan	76	5.69	2020.3
5	South Korea	76	5.69	2019.9
6	UK	63	4.72	2019.8
7	Spain	52	3.89	2019.9
8	India	51	3.82	2020.2
9	Italy	50	3.74	2020.0
10	France	44	3.29	2019.6

Table 1.2.12 Institutions with the greatest output of citing papers on “silicon-based CMOS terahertz imaging technique”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	89	23.67	2019.9
2	Huazhong University of Science and Technology	40	10.64	2019.8
3	University of Wuppertal	36	9.57	2019.3
4	Tianjin University	35	9.31	2019.9
5	University of Electronic Science and Technology of China	34	9.04	2020.2
6	Princeton University	29	7.71	2019.8
7	Peking University	26	6.91	2020.0
8	Zhejiang University	23	6.12	2020.2
9	Southeast University	23	6.12	2020.0
10	Massachusetts Institute of Technology	21	5.59	2019.6

of the limitation of the centralized design methods for local oscillator signals. Instead, the 32-element phase-locked dense heterodyne receiver array, based on 65 nm CMOS technology, enables the integration of two interleaved 4×4 arrays onto a chip of 1.2 mm^2 , significantly shrinking the whole receiver array. Based on lateral resolution improvement, the fully integrated ultra-wideband (UWB) inverse synthetic aperture imaging technology in terms of 55 nm BiCMOS technology can achieve a lateral resolution of 2 mm and a range resolution of 2.7 mm.

To date, many technological advances have been achieved to improve THz imaging resolution, but it is still restricted to a spot size in the range of millimeters, because of the diffraction limit in the silicon-based technique. Resolution in the micron range is necessary for biomedical or material characterization. It can be achieved using imaging from a far-field to a near-field method, with a lateral resolution of 10–12 μm .

The silicon-based CMOS THz imaging technique has grown rapidly in popularity over the past decade because of market demand for cheap cost and high integration density. Many investigations were conducted and prompted the development of THz imaging technology. With the ongoing advancement of technology, the development of the THz imaging technique is moving toward high integration density, high-accuracy, and a large array. However, it simultaneously encounters three unavoidable challenges:

1) At higher frequencies up to the THz range, the effectiveness of active device models is reduced, and the loss of passive devices is increased, which restricts the rapid development of the THz circuit by silicon-based technology. Simultaneously, multilayer metal and medium characteristics in silicon-based technology introduce complex parasitic and coupling effects into the devices operating at THz frequencies.

2) As the THz wavelength is so short, more circuit integration

space is available for the systems. However, THz circuits are more susceptible to distribution effects and surface roughness. Therefore, the system must be integrated according to innovative packaging and interconnection technologies.

3) When expanding from a single channel to an array chip, to achieve a high angle resolution, it is necessary to ensure the cooperation of multiple channels, which puts a higher requirement on the technology of source synchronization. Finally, more sophisticated calibration systems are needed to ensure the accuracy of signal detection and transmission.

According to the BCC Research forecast, the global market for the main terahertz technology may reach 3.5 billion dollars by 2029. However, the market shares from the silicon-based integrated circuit industry are not included here because of its relatively backward development and maturation. Figure 1.2.9 presents a roadmap for the evolution of the engineering research frontiers of the CMOS silicon-based THz imaging technology. The chip fabrication is expected to finish around 2029, and on-chip testing will be on schedule. By 2032, technology optimization and integration research will be performed with breakthroughs in chip size and resolution. In the next 10 years, the integration of the THz technique by CMOS silicon-based methods will push the THz imaging technology toward a much larger market size.

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the information

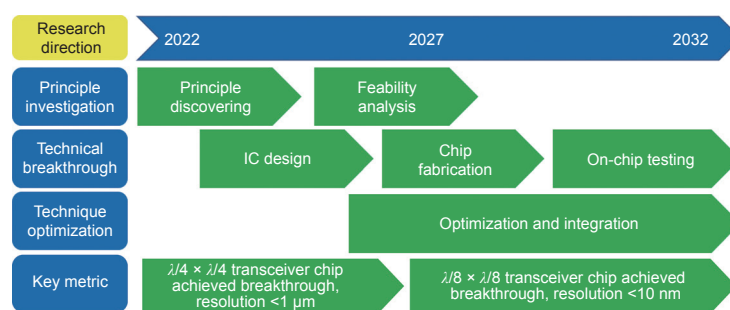


Figure 1.2.9 Roadmap of the engineering research front of "silicon-based CMOS terahertz imaging technique"

and electronic engineering field are summarized in Table 2.1.1, encompassing the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. The annual number of core patents published for the Top 10 engineering development fronts from 2016 to 2021 is

shown in Table 2.1.2.

(1) Super-large-scale digital twin visualization and simulation system

A technical “digital twin” enables dynamic interactions between physical and virtual entities. It allows real-time connection, two-way mapping, simulation analyses,

Table 2.1.1 Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Super-large-scale digital twin visualization and simulation system	483	2 865	5.93	2020.1
2	Integrated on-chip light source	832	1 548	1.86	2018.7
3	Localization by multisource information fusion	909	3 745	4.12	2018.7
4	Ubiquitous operating systems for human–cyber–physical computing	404	1 095	2.71	2018.6
5	Quantum microwave measurement technology	638	4 523	7.09	2017.3
6	Atomic and close-to-atomic scale manufacturing and measurement technologies for optical components	224	1 766	7.88	2017.8
7	Ultra-low power IoT chip technology	987	2 691	2.73	2019.3
8	Artificial intelligence for electronic design automation technology	954	4 468	4.68	2019.7
9	Reinforcement learning-based evolutionary algorithm for unmanned systems	990	5 867	5.93	2020.0
10	Medium- and low-orbit space communication network technology	908	4 957	5.46	2019.1

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Super-large-scale digital twin visualization and simulation system	6	7	28	69	164	209
2	Integrated on-chip light source	122	97	164	153	121	175
3	Localization by multisource information fusion	116	125	182	145	145	196
4	Ubiquitous operating systems for human–cyber–physical computing	73	50	78	52	85	66
5	Quantum microwave measurement technology	188	247	120	40	22	21
6	Atomic and close-to-atomic scale manufacturing and measurement technologies for optical components	62	46	44	34	26	12
7	Ultra-low power IoT chip technology	40	79	179	213	245	231
8	Artificial intelligence for electronic design automation technology	31	39	81	181	289	333
9	Reinforcement learning-based evolutionary algorithm for unmanned systems	15	29	54	192	266	434
10	Medium- and low-orbit space communication network technology	77	101	143	155	179	253

dynamic interaction, and feedback control. It can also map the structure, attribute, state, and behavior of physical entities or systems into the virtual environment to form a high-fidelity dynamic digital model. A digital twin provides effective technical tools for observing, understanding, learning, controlling, and transforming the physical world. The super-large-scale digital twin visualization and simulation technology is a key part of the digital twin technology system. It plays a vital role in scientific research and production manufacturing and is an important tool in the fields of geographic information, biomedical research, large-scale engineering design, production manufacturing, etc. With the development of cloud computing, GPU, and other technologies, the resulting huge parallel processing capacity combined with the technologies of space-time synchronization, distributed parallel simulation, visualization algorithms, data structures, and system architecture has made computationally intensive operations possible. It enables the distributed access, scheduling, and management of large-scale simulation data on the cloud computing platform and supports large-scale grids with hundreds of millions of triangles, enabling simulation and visualization to reach extremely high resolutions. Multiscale modeling and distributed high-performance computing have become necessary technologies for overcoming these issues. With the development of data-driven machine learning methods and IoT technology, more physical elements are being simultaneously digitized online. Unrestricted innovation potential is offered by integrating machine learning, multiscale modeling, and distributed computing technologies to solve the modeling, simulation, and visualization of super-large-scale digital twins. Moreover, it provides infinite possibilities for the sustainable evolution of the system itself.

(2) Integrated on-chip light source

With the advent of the post-Moore era, ICs are moving toward an integrated photonic chip, aiming to achieve photon generation, ultra-high-speed transmission, processing, and detection. Integrating the light source on the chip is a big problem in the field of integrated photonic chips. Silicon-based optoelectronic chips can be mass produced using the established CMOS technology, but the optical efficiency is poor because silicon is an indirect bandgap semiconductor. Carrier injection technology can improve silicon's luminescence intensity to integrate light-emitting devices on a chip. The reverse bias PN junction of polysilicon combined

with the avalanche doubling phenomenon is used to generate visible and infrared light. Another method is integrating III – V semiconductor lasers on silicon wafers by wafer bonding or epitaxial growth. Currently, the integration technology of InP, silicon nitride, InGaAs, and other materials on silicon wafers has been mature and commercialized. Recently, there have been new development trends and directions in the field of the on-chip integrated light source: ① multi-material integrated optoelectronic chips: according to the functional division of an integrated photonic chip, multiple semiconductor materials are integrated on a chip, considerably enhancing the chip's functionality and applicability; ② aiming at the urgent need for multi-wavelength output of the on-chip light source, an optical parametric oscillation-integrated chip is adopted to actualize an efficient nonlinear wavelength conversion on the chip through the weak pump light and the nonlinear impact of the material in the micro-cavity; ③ the on-chip spectrum output of multiple frequency laser combs is realized using an on-chip light source combined with optical frequency comb technology, widely used in optical atomic clock and on-chip precision detection; ④ integrating a single-photon quantum source in an optical quantum chip, using QDs or a color center light source to achieve a multifunction optical quantum chip.

(3) Localization by multisource information fusion

Multisource information fusion is the technique used to localize sources based on processing position-dependent information collected by multiple sensors distributed in space. Typical position-dependent information includes the time of arrival, time difference of arrival, angle of arrival, and received signal strength. The resulting nonlinear estimating issues can be solved in many ways to determine source positions by establishing mathematical models for these different kinds of information and adopting appropriate parameter estimation criteria. Research on performance improvement in this area mainly focuses on the following three aspects:

- 1) Accuracy: High-accuracy localization is generally the most crucial objective for any developed localization technique.
- 2) Robustness: Different uncertainties usually exist in measurements obtained in complex propagation environments; hence, the robustness of the developed localization techniques against different models and measurement errors is always a desired feature.
- 3) Easy implementation: Computational complexity is a crucial factor to consider for the developed localization techniques in

practical implementation scenarios.

The following three directions are trends for developing localization techniques in the future:

1) Heterogeneous and synchronized multisource information fusion by fusing different measurements from different types of sensors: This includes, for example, high-precision range and angle information that can be acquired in millimeter wave localization systems, making localization with centimeter precision possible. Additionally, a fusion of image and microwave information may provide the opportunity to meet the localization requirements in both visible and invisible environments.

2) Localization of multiple sources, group sources, and weak sources in complex scenarios: This includes, for example, the localization of multiple point sources and rigid bodies, or even group sources in mixed near- and far-field scenarios and localization of weak sources in deep space and underwater environments.

3) Data-driven intelligent localization: The rapid development of machine learning techniques and AI provides new solutions for complicated localization problems.

(4) Ubiquitous operating systems for human–cyber–physical computing

We have entered a new digitalization era with the fast development of new generation information technologies, such as the internet, big data, AI, and IoT. As a result, we are witnessing the emergence of many ubiquitous operating systems (UOSs) for human–cyber–physical systems, which are developed for various new application paradigms and new application scenarios. The UOS has the same functionality goals as traditional operating systems, such as Linux and Windows, because they both focus on managing heterogeneous resources while providing application development and runtime support. However, the UOS also represents the extensibility of the traditional operating system concept because many new computing paradigms and application scenarios need to be built for different operating systems. Conceptually, UOSs could also include operating systems built for computing devices with different scales, such as servers, personal computers (PCs), mobile devices, and sensors and for different application scenarios such as IoT, robotics, smart cities, and smart homes. However, in the specific context of human–cyber–physical computing, the

term “UOS” refers to new types of operating systems that follow the concept of ubiquitous computing while equipped with novel features such as ubiquitous sensing, ubiquitous interconnection, light-weight computation, light-weight cognition, feedback control, and natural interaction.

Multiple UOS instances have been proposed in different countries, for areas including IoT, smart robots, and smart cities. However, as they have not been investigated or deployed in large scale, there are not many systematic research outputs, uniform technical frameworks, or industry standards. In China, the UOS has received wide attention in academia and industry because it has received support from the National Natural Science Fund of China and National Key Research & Development Projects. Additionally, the most recent Five-Year Plan from the Ministry of Industry and Information includes the promotion of UOSs. Simultaneously, companies such as Tencent and Haier have been actively investigating the development of new UOSs in areas including IoT, cloud computing, smart cities, intelligent transportation, smart building, and smart homes, which have provided necessary system software support during the process of digital transformation for various industrial customers.

(5) Quantum microwave measurement technology

Quantum microwave measurement technology is a subject that generates, manipulates, transmits, and measures microwave in quantum systems according to quantum mechanical properties, especially quantum entanglement, quantum superposition, and quantum tunneling. This field combines the advantages of high correlation, high reuse, and strong robustness of quantum technology with the flexibility, all-weather, and easy regulation of microwaves. As a result, the microwave detection ability can be expanded from the current hundreds of kilometers to more than 2 000 kilometers, and the detection sensitivity can be increased by up to 50 dB compared to standard microwave technology. Compared with traditional microwave technology, the instantaneous bandwidth is increased by up to one order of magnitude, reaching 100 GHz, which significantly improves the capacity of existing microwave detection channels; three orders of magnitude increase the antidamage ability, and the reflection cross section is reduced by four orders of magnitude under the same detection power, realizing the “self-stealth” function. Therefore, it is considered a subversive technology for the cross-generational transformation of modern information

systems.

The two primary categories of quantum microwave measurement directions are as follows: one is to apply quantum systems (atoms, diamonds, photons, etc.) to microwave systems such as radar and electronic countermeasures and use the unique advantages of quantum systems to transmit and process microwave signals. The other is to realize the quantum correlation of the microwave frequency band signal using conventional systems (optical frequency comb and mechanical resonator) and expand the development of quantum information technology in the multifrequency domain. The further development of quantum microwave measurement will emphasize solving the scientific problems of the cross band, cross-medium, cross-scale, and cross-system faced by future microwave detection and information systems. It will develop toward multifunction, miniaturization, integration, networking, and collaboration.

Currently, quantum microwave detection guided by practical applications has been carried out worldwide. It has surpassed conventional microwave technology in terms of power sensitivity, damage resistance, dynamic range, and other technical indicators. The advantages of quantum microwave measurement engineering have also been put into a defined technical improvement plan regarding bandwidth and electric field sensitivity. Overall, quantum microwave technology will be the core technology in the new generation of the microwave information field. It has broad application prospects in military fields, such as radar detection, electronic countermeasures, and intensive communications, and commercial fields such as medical, security, navigation, and telecommunications.

(6) Atomic and close-to-atomic scale manufacturing and measurement technologies for optical components

High-end core optical components with ultra-smooth and damage-free surfaces and atomic scale functional features are urgently needed for modern optical engineering, represented by extreme ultraviolet lithography, sophisticated light sources, and super-lenses. Current optical manufacturing technology based on machine precision does not meet the demand for the atomic-level precision and performance of such optical components. The next-generation core technology for manufacturing such high-end optical components will be atomic and close-to-atomic scale manufacturing (ACSM), where the production tools and procedures directly affect

atoms to remove, add, or migrate materials at the atomic-level. The goal of ACSM for optical components is to pioneer optical manufacturing technologies to atomic-level precision and functional feature size, which requires investigating novel optical manufacturing approaches from common issues in the fields of intrinsic mechanisms, processes, characterization and measurement, and instrumentation and equipment. At the atomic and close-to-atomic scales, the fundamental theoretical framework of ACSM has radically changed from classical to quantum theory. The study of the intrinsic mechanism of single-atom manipulation, multi-atom interactions, and their connection with macroscopic scales in the ACSM process based on quantum theory will be the cornerstone for future research. The ACSM technology needs the direct application of energy to atoms to establish a multidimensional manufacturing system with a certain generality and the innovative use of inter-atomic forces to make atoms spontaneously form specific functional structures to achieve the goal of large-scale, high-efficiency, and high-precision manufacturing of advanced optical components. The ACSM high-precision measurement technology is a prerequisite for guaranteeing end-use performance and reliability of ACSM-based optics. Decoupling the perturbations introduced using the ACSM measurement process will become a key technical issue in improving the measurement accuracy because the quantum characteristics of ACSM can alter the state of the measurement object.

(7) Ultra-low power IoT chip technology

Based on artificial intelligent chips, intelligent IoT devices must support multiple functions, such as data perception, storage, computation, and decision-making. Traditional IoT systems consist of several discrete devices, including sensors, analog-to-digital conversion chips, processor chips, and memory chips. Therefore, the design of IoT systems is fragmented and lacks top-level optimizations to overcome the bottleneck of system power consumption and energy efficiency. The low power IoT chip fuses the sensing, storage, and computing into one integrated heterogeneous chip, effectively reducing the cost of data movement and invalid data processing and fundamentally breaking the system efficiency bottleneck. The cutting-edge technology directions in this research area include low power data acquisition technology, high-efficiency AI hardware acceleration technology, low power chip architecture technology, etc.

Through novel data acquisition circuit topologies, such as changing from the traditional “voltage domain” data conversion to the novel “charge domain” or “time domain” data conversion and changing from the traditional Nyquist conversion to the adaptive sampling conversion, the low power data acquisition technology seeks to lower power consumption and improve the data sensing accuracy. The high-efficiency AI hardware acceleration technology improves computing capacity and energy efficiency through lightweight hardware accelerator design. For instance, changing the traditional “von Neumann architecture” to the “computing in-memory” architecture can reduce the data movement overhead and enhance the computing performance. Through novel architecture design, low power chip architecture technology reduces chip power consumption, especially always-on standby power consumption. For example, changing from the traditional “synchronous computing” architecture to the “asynchronous event-driven” clockless low power architecture can considerably reduce the standby power as the chip activity matches the actual valid event. Additionally, cutting-edge research is continuing to investigate the co-design innovations across the data perception, computing, storage, and transmission to develop one integrated IoT chip that fuses “perception, computing, storage, and transmission” with high-efficiency and low power.

(8) Artificial intelligence for electronic design automation technology

Electronic design automation (EDA) refers to designing integrated circuits aided by computer algorithms and software, which are widely adopted in the design, verification, and manufacturing of modern very-large-scale integrated circuits. Artificial intelligence (AI) for EDA or AI-assisted EDA aims at leveraging AI technology to assist the modeling, optimization, and verification procedures in the design flow. It can effectively facilitate optimization, speed up design closure, and eventually improve the quality of results. According to the stages of the EDA algorithms in the design flow, research studies on AI for EDA can be roughly divided into six major categories: system-level design space exploration (DSE), synthesis, physical design, manufacturing, verification and testing, and runtime management. Since 2016, related publications on premier EDA conferences and journals have increased about 2x, especially on system-level DSE, synthesis, physical design, and manufacturing. Both industrial and academic research teams from China, the USA, Europe, Japan,

Korea, and so on have invested efforts in these directions. In the past two years, Synopsys and Cadence (two major EDA vendors) have announced commercial products, DSO.ai and Cerebrus, respectively, for design space exploration. With the continuous scaling of semiconductor technologies and circuit design complexity, AI for EDA is a promising direction to explore.

(9) Reinforcement learning-based evolutionary algorithm for unmanned systems

The reinforcement learning (RL)-based evolutionary algorithm for unmanned systems applies RL to create intelligent behavioral decision-making and control strategies without human intervention and to improve performance over time continuously. The interaction between a single agent or a group of agents in a predefined environment and an evaluation mechanism produces training data in RL algorithms.

RL-based evolution algorithms are not constrained using established approximations, such as linearization, and therefore, have wider working intervals and the ability to adapt to complex and changing scenarios in addition to conventional metrics widely considered for nonlearning control algorithms, such as convergence speed, accuracy, and anti-overfitting.

The RL-based evolutionary algorithm for unmanned systems faces additional constraints from the physical performance of the system, the difference between the simulation and reality domain, and safety issues within the strategies compared to RL applied to other industries. New challenges, such as sexuality and continuous evolution, in turn, generate new scientific questions and technological approaches.

As the computing performance of unmanned systems is commonly limited compared with dedicated computing devices, the RL-based evolutionary algorithm for unmanned systems requires lower computing scales to adapt to high frequencies and highly dynamic interactions. Consequently, technologies such as multi-task and multi-scene meta-learning, knowledge distillation, representation learning, cloud computing, and edge computing have emerged at this stage.

Simultaneously, early training is usually done with simulation to improve the efficiency of data collection and avoid mechanical damage. However, the inevitable difference between the simulation and reality domains is damaging to

the performance of RL-based strategies when migrating to real-world unmanned systems. Therefore, methodologies such as domain parameters online identification, adversarial domain randomization, distributed robust optimization, and auto-encoding transformations have improved robustness when crossing the reality gap.

Real-world scenarios put forward higher requirements for the security of RL-based evolutionary algorithms. Technologies such as multi-sensor risk detection, trust domain strategy optimization, and action space dynamic constraints have emerged at this stage.

Continuous evolution requires algorithms to be capable of continuously gathering data, optimizing strategies, and improving performance after deployment in the real-world. Additionally, higher data efficiency and the ability to adapt to dynamic systems and environment changes are demanded. Therefore, prior reward shaping, small sample transfer learning, and distributed computing have emerged at this stage.

The next development directions of the RL-based evolutionary algorithm for unmanned systems include the following: accurate simulation environment and online system identification; unmanned system ontology capabilities; embodied intelligence that incorporates prior knowledge of the dynamics of the unmanned system; multi-task comprehensive autonomous decision-making under complex scenes; heterogeneous unmanned system group intelligent cooperation; multi-agent information integration; and efficient, secure capability evolution in real scenarios.

(10) Medium- and low-orbit space communication network technology

Medium- and low-orbit space communication network technology refers to building a wide-area communication system through inter-satellite and satellite-ground links, where satellite constellations operate in medium- and low-earth orbits. It can actualize network access and the interconnection of space probes, manned spacecraft, satellites, ground stations, ground terminals, and high-altitude vehicles, which serve environment monitoring, military surveillance, space exploration, in-flight internet service, remote area communication, etc. The primary technical directions include space laser communication, inter-satellite routing, satellite beam management, handover control, etc. Space laser communication primarily includes

high-speed modulation, capture-tracking-alignment, laser signal detection, and other technologies. Inter-satellite routing principally includes satellite and end-user addressing, route planning, etc. Satellite beam management largely includes technologies such as multi-beam satellite antenna, precoding, agile beam hopping, and multi-color frequency multiplexing. Finally, handover control primarily includes inter-beam handover, inter-satellite handover, and inter-satellite link handover. Future development trends may be as follows:

- 1) The satellite constellation evolves from low to high density to improve network capacity. It is essential to carefully consider the problems of on-demand inter-satellite link establishment, interference avoidance, and frequent inter-satellite handover.
- 2) The network will be deeply integrated with SDN and virtualization techniques to achieve programmable spatial routing and flexible deployment of network functions. The research primarily focuses on software-defined satellite payload design, network function deployment strategies, etc.
- 3) The network with just communication function will develop into a network integrating communication, computing, sensing, and positioning, which can achieve low latency sensing information distribution and accurate positioning. Future research directions include the integrated design of communication and positioning signals, onboard intelligent processing of remote sensing information, and location-assisted communication improvement.

2.2 Interpretations for three key engineering development fronts

2.2.1 Super-large-scale digital twin visualization and simulation system

The digital twin is the deepening stage and future vision of enterprise digital transformation, which integrates multiple technologies to support the development of a data-centric business. The “twins” idea can be traced back to the Apollo Program of the National Aeronautics and Space Administration (NASA) in the 1960s. With the advancements in the computer simulation, network connection, and sensor technologies, Professor Michael Grieves proposed the digital twin concept and model in 2002 and applied it to product

lifecycle management. The digital twin concept was first suggested in the simulation-based system engineering chapter of the Area 11 technology roadmaps released by NASA in 2010. The concept is as follows: “A digital twin is an integrated multi-disciplinary, multiscale simulation that uses the best available physical models, sensor updates, operation history, etc., to mirror the life of its corresponding flying twin”. According to Gartner, a digital twin is defined as the digital mapping of physical entities or systems in the virtual world. It was one of the top ten strategic technology development trends from 2017 to 2019. Businesses, such as Siemens, GE, and Microsoft, among many others, have consistently promoted the idea and notion of digital twins and introduced related products.

The super-large-scale digital twin visualization and simulation system is the core of the digital twin and the key to the value, scale, and commercialization of the digital twin technology business. The digital twin involves three aspects, namely holistic mapping, simulation maintenance, and closed-loop control. Holistic mapping provides a God-like perspective that can observe and understand the world by utilizing the digital twin technology. It synchronizes together people, places, and things that are distributed in different spaces in the real world and presents them integrally in the virtual environment. It can also realize space folding and time collapse beyond reality, support on-site coordination across time and space, and enable people to immerse themselves in the production process with a more real and closer interaction. The simulation maintenance of digital twins is the simulated reproduction or prediction based on holistic interconnection. It is the integrated simulation of static and dynamic, virtual

and real, and past and present, which is driven by large-scale and refined data and optimization and intelligent algorithms. To some extent, it exceeds the traditional simulation. In terms of holistic mapping and simulation maintenance, super-large-scale digital twin visualization and simulation are the core basic capabilities of digital twins. For example, aircraft design and final assembly simulation have approximately 4 to 18 million components. Traditional technologies and methods cannot support the overall evaluation. Another typical case is building information modeling (BIM) visualization and structural analysis in the architecture field. At present, lightweight processing must be performed before using the BIM data for visualization or structural analysis, which greatly limits the possibility of overall research or full structural simulation. Similar practical problems exist in the fields of smart cities, city-level transportation, and ocean governance. The super-large-scale digital twin visualization and simulation system is the necessary core technology for achieving the integration of data and entity of the holistic digital twin.

Tables 2.2.1 and 2.2.2 show the distribution of the primary countries and institutions that published patents in the “super-large-scale digital twin visualization and simulation system” engineering development front, respectively. China, the USA, and Germany have prioritized this in national strategies; hence, fundamental research and application are relatively prominent, and these countries are clearly leading in patents. As for institutions, Siemens and GE have shown obvious leading advantages and achieved outstanding industrial implementation. Siemens considers the digital twin to be the core technical pillar of “Industry

Table 2.2.1 Countries with the greatest output of core patents on “super-large-scale digital twin visualization and simulation system”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	356	73.71	1 715	59.86	4.82
2	USA	68	14.08	747	26.07	10.99
3	Germany	24	4.97	196	6.84	8.17
4	South Korea	13	2.69	28	0.98	2.15
5	Japan	4	0.83	34	1.19	8.50
6	Australia	4	0.83	21	0.73	5.25
7	Finland	2	0.41	9	0.31	4.50
8	Switzerland	2	0.41	1	0.03	0.50
9	UK	1	0.21	78	2.72	78.00
10	Canada	1	0.21	17	0.59	17.00

4.0". Combined with its advantage in traditional software, Siemens exhibits a clear lead in intelligent manufacturing. Meanwhile, by implementing twin technologies to support condition detection and the predictive maintenance of aircraft engines relatively early, GE has gradually transitioned from selling engines to maintaining the product lifecycle, which is an upgrade of the business model from products to services. In China, universities like Beihang University and Beijing Institute of Technology mainly engage in theoretical and applied fundamental research, reflecting the application demand of digital twins in aerospace and national defense.

For applications, the energy and industrial fields have also shown great potential. The State Grid Corporation of China has already implemented unattended substations and quality inspection and maintenance equipment. Therefore, in the engineering development of a "super-large-scale digital twin visualization and simulation system", governments of all countries are prioritizing it. Businesses and relevant institutions for scientific studies have also made good progress. However, the cooperation network between countries in Figure 2.2.1 depicts that horizontal cooperation is relatively little, and there is no cooperation between the major

Table 2.2.2 Institutions with the greatest output of core patents on "super-large-scale digital twin visualization and simulation system"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Siemens Corporation	23	4.76	274	9.56	11.91
2	General Electric Company	22	4.55	305	10.65	13.86
3	Beihang University	17	3.52	89	3.11	5.24
4	State Grid Corporation of China	15	3.11	22	0.77	1.47
5	Guangdong University of Technology	11	2.28	196	6.84	17.82
6	Xi'an Jiaotong University	11	2.28	69	2.41	6.27
7	China Electronics Technology Group Corporation	8	1.66	94	3.28	11.75
8	Guangdong Power Grid Company Limited	8	1.66	22	0.77	2.75
9	Beijing Institute of Technology	8	1.66	21	0.73	2.62
10	International Business Machines Corporation	6	1.24	40	1.40	6.67

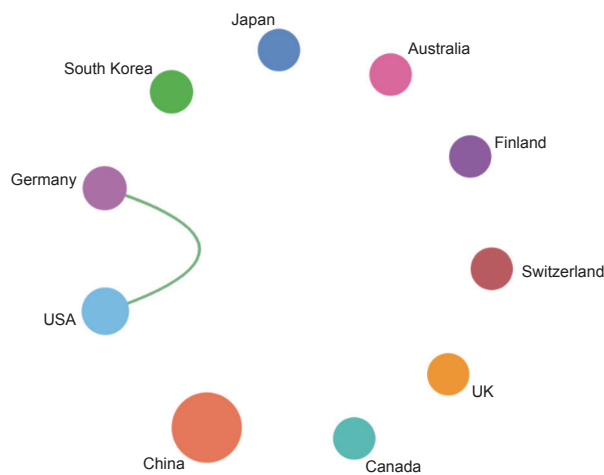


Figure 2.2.1 Collaboration network among major countries in the engineering development front of "super-large-scale digital twin visualization and simulation system"

institutions. At the national level, only the USA and Germany engage in some cooperation and exchanges.

One of the critical technologies used for constructing the mirror image, expansion, and extension of an actual society is the super-large-scale digital twin visualization and simulation system. The development of accurate modeling and analysis, real-time presentation, efficient computing, and flexible applications is currently being accelerated for the super-large-scale digital twin visualization and simulation system. Regarding visualization, refinement and immersion are the core development directions that improve the dynamic fidelity of virtual or virtual-real fusion scenarios through sight, hearing, touch, and other holographic technologies. Simultaneously, it will significantly change the interaction mode and add a new dimension to virtual reality. Simulation progresses throughout time from the single body and process simulation to a distributed group simulation, fusing mechanisms and data driven and virtuality and reality. This can better support the development of swarm and human-machine hybrid swarm intelligence. Meanwhile, distributed, parallel, and high-performance computing are continually combined with a digital twin visualization and simulation system to enhance the computing performance of digital twin systems. The IoT and the real-time integration of virtuality and reality can be actualized with the help of high-speed communication networks (e.g., 5G and 6G). A new range of business models and industrial types for digital transformation will be birthed because of the formation of a consensus on digital transformation in all walks of life, the further implementation of digital twins in urban governance, industrial manufacturing, retail, and medical care, and its gradual penetration into the entire industrial lifecycle. These developments have broad and promising prospects.

Figure 2.2.2 presents the roadmap of the engineering development front of the “super large-scale digital twin visualization and simulation system”. According to the report

published in 2019 by a consulting firm Markets & Markets, the digital twin market is expected to increase from 3.8 billion dollars in 2019 to 35.8 billion dollars in 2025. As the core of the digital twin technology, the super-large-scale digital twin visualization and simulation system should continue to permeate transportation, logistics, city, and manufacturing, moving from the application of a single scenario to that of the entire lifecycle of the industry. For example, the transportation field will involve road construction and design, traffic optimization analysis, asset intelligent operation and maintenance, safe driving intelligent assistance, and other scenarios. The city domain will contain design optimization and simulation, innovative construction sites, rain and flood simulation, intelligent emergency response, etc. Meanwhile, manufacturing include intelligent product development, production process optimization, workshop intelligent scheduling, predictive maintenance of equipment, safe factory production, etc. These all involve large-scale, wide-dimension, and precise visualization and simulation for better implementation of human-in-the-loop simulation and deduction and ultimately assist in decision-making. Additionally, the digital twin application will extend to various fields, such as medical care and agriculture.

2.2.2 Integrated on-chip light source

Since the introduction of the first transistor in 1947, IC technology has dramatically promoted scientific and technological progress, laying the essential groundwork for the information society. People’s demand for information is increasing in line with advancements in society and technology, which raises the bar for ICs’ capacity for information processing and acquisition. However, in the post-Moore era, ICs are constrained in using insurmountable electrical interconnections in terms of time and power consumption. Therefore, with the end of Moore’s law, people put forward the concept of using photons as information

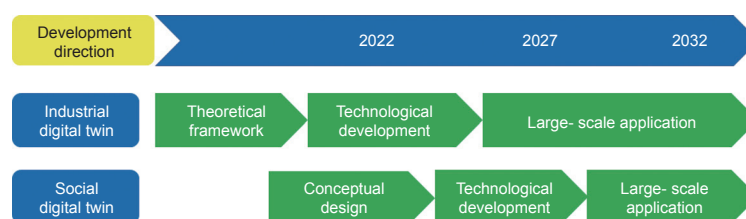


Figure 2.2.2 Roadmap of the engineering development front of the "super-large-scale digital twin visualization and simulation system"

carriers to substitute electrons, that is, through the fusion of optoelectronics and microelectronics, the application of an on-chip optical interconnection instead of the conventional electrical interconnection, to attain high-speed transmission of data, and reduce the parasitic resistance of electrical interconnection. For microelectronics, deep submicron power-off interconnects severe delay and power consumption difficulties; so, it is imperative to introduce optoelectronics to resolve the issue of electrical interconnect. For optoelectronics, it is essential to use mature microelectronic processing technology platforms to achieve large-scale, high integration, high-yield, and low cost mass production.

Over the past decade, optoelectronic integrated chips, which can produce photons, transmit, process, and detect optical information on a chip, have become one of the most popular directions in academia and industry. The on-chip integrated light source (which is among them) can provide a coherent light source for the photoelectric integrated chip to generate optical information. Its performance determines the chip's application space and implementation purpose. The integrated on-chip light source has great advantages in reducing size, mass, power consumption, and cost compared with traditional optical equipment through integrated design and modern semiconductor processing technology. Simultaneously, it promotes the industrial upgrading of advanced lithography technology, nanomanufacturing technology, micro/nano manufacturing technology, and material science development.

Silicon-based optoelectronic integrated chip technology refers to the design, manufacture, and integration technology of silicon-based optoelectronic chips. Monocrystalline silicon has become the most mature and broad platform for photonic chips because of its sizable optical bandwidth, robust scalability, low cost, efficient chip routing, and high refractive index. Silicon-based optoelectronic integration circuit (OEIC) is compatible with the CMOS process and can achieve large-scale production with the help of a mature microelectronic processing platform. It is the best solution to realize the integration of optoelectronics and microelectronics and optical interconnection because of its low cost, high degree of integration, and excellent reliability. Optical communication links will benefit from increased bandwidth density and speed because of wafer-integrated on-chip light source technologies in the field of optical interconnection and high-speed optical computing. Additionally, in the field of

precision measurement, the characteristics of miniaturization and low power usage will be accomplished, and the optical atomic clock and spectrometer will be relocated from the equipment to the chip. Multi-wavelength optical comb technology can achieve multi-wavelength parallel computing in optical computing and reach speedups of several orders of magnitude. On-chip light source technology will enable parallel lidar systems in the sensing sector to improve sampling rates, reduce power usage, and enable high-speed IoT sensing and processing for complex applications such as autonomous driving.

Silicon-based detectors, optical modulators, optical switches, optical waveguides, and other breakthroughs have been achieved so far. However, for on-chip silicon-based light sources, no mature options are currently available. The indirect bandgap characteristics of silicon material determine its low luminescence efficiency, and it is challenging to create high-performance luminescence devices as active materials. How to integrate light sources into silicon-based chips is a big challenge. Recently, researchers who are major in optics, materials, mechanical engineering, etc., have carried out a large amount of silicon-based light source research. From the initial silicon-based light-emitting diode, like the luminescence of PN junction, structure of metal-isolator-semiconductor, Schottky junction, to the luminescence of the carrier injection silicon avalanche multiplication-glow, silicon of rare earth-doped luminescence, the silicon nanocrystal laser, silicon germanium laser, etc., the luminescence efficiency is continuously improved. However, there is still a difference between these light sources' III-V lasers' performance. Therefore, the industry's solution is to use high-precision packaging to couple the external light source and the silicon optical chip into components before the integrated on-chip light source reaches maturity. So, how do we make a silicon-based optoelectronic chip with excellent performance combining low power consumption, long life, and a high-power light source?

Direct bandgap III-V semiconductors have excellent optical and electrical properties. Gallium arsenide (GaAs), indium phosphide (InP), quantum well, and QD lasers are commercially available. Despite the high quantum efficiency, the conventional III-V family light source is incompatible with the existing IC technology. The idea of incorporating an III-V semiconductor laser with silicon on a silicon wafer came naturally. Ensuring that the manufacturing process of the light

source is compatible with the existing IC process is a hot and difficult problem. According to current technology, mature III–V material lasers are added to silicon wafers either through hybrid integration (transfer of materials to silicon wafers, such as direct placement or wafer bonding) or monolithic integration (direct growth of materials on silicon wafers, such as epitaxial growth). Hybrid integrated technology is mature; for instance, through wafer bonding technology, people can be III–V and epitaxial layers using BCB auxiliary adhesive-bonding technology integration above the silicon chip; light can be produced with III–V materials using evanescent wave coupling into silicon photonic circuits, and finished on the hybrid integrated light source and silicon photonic chips. However, its high process cost makes it difficult to achieve large-scale integration. Monolithic incorporation is expected to use the process and technology of native III–V photonic devices to silicon photonic sources, and obtain outstanding on-chip light sources, considered the ultimate solution for the large-scale production of light sources on silicon chips. The primary issue affecting this technology is the severe lattice mismatch between the III–V material and silicon, which results in the generation of dislocations, antiphase domains, and other defects, severely limiting the life and performance of the III–V laser. A dislocation defect is one in which a dislocation-barrier layer or other buffer layer structure may be added between the substrate and the active region during growth. For antiphase domain defects, the selective growth technique can successfully limit the impact of the antiphase domain defects on the active region by epitaxizing the III–V material on the graphic silicon substrate. The main advantage of the monolithic integration scheme over the hybrid integrated

light source is that it can improve the integration degree while reducing the line width concurrently with the silicon photonic process. It has great potential in developing large-scale photonic integrated chips, which is also the primary development direction of silicon photonic technology. Currently, the integration technology of InP, silicon nitride (Si_3N_4), indium gallium arsenide (InGaAs), and other materials on silicon wafers has been mature and commercialized. Additionally, the SiN-on-Si platform with shallow loss, large-transmittance window, and remarkable nonlinear effect make up for the defects of Si transmittance window cut-off when the wavelength of Si is lower than 1 100 nm and has new applications in AR/VR, measurement, biomedicine, sensing, and other fields.

Table 2.2.3 shows the distribution of the major countries for producing patents in the development frontier of the “integrated on-chip light source”. China, the USA, and Japan rank in the top three. The number of China’s patents is more than three times that of the second-place USA, indicating China’s national strategy to prioritize the field of the integrated on-chip light source and its progress in the fields of materials, physics, optoelectronics, and precision manufacturing, among others. However, the mean number of citations is only a third of that in the USA, showing slightly insufficient originality. Regarding national cooperation (Figure 2.2.3), as the country with the most significant number of original technologies in integrated on-chip light sources, the USA has close cooperative relations with South Korea, the UK, and Australia. These countries have a clear division of labor in the on-chip integrated light source field, and their technological advantages can be complementary. There is no cooperation

Table 2.2.3 Countries with the greatest output of core patents on “integrated on-chip light source”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	565	67.91	724	46.77	1.28
2	USA	165	19.83	602	38.89	3.65
3	Japan	31	3.73	67	4.33	2.16
4	South Korea	20	2.40	14	0.90	0.70
5	Germany	7	0.84	45	2.91	6.43
6	Canada	7	0.84	21	1.36	3.00
7	UK	5	0.60	34	2.20	6.80
8	Singapore	5	0.60	19	1.23	3.80
9	India	5	0.60	0	0.00	0.00
10	Australia	3	0.36	6	0.39	2.00

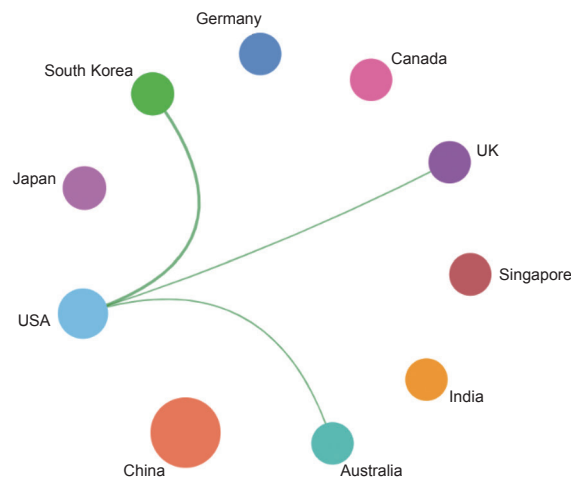


Figure 2.2.3 Collaboration network among major countries in the engineering development front of “integrated on-chip light source”

among major institutions at the top of the ranking, signifying that the competition in this area is ferocious, and that the top institutions are cautious in protecting their original technology. Remarkably, AIM Photonics, Intel, and HP LABS have several high-level silicon and optical process lines, from silicon and optical chip design training to production and packaging capabilities. For instance, Intel announced the first commercial silicon-based heterogeneous integration product in 2016, which realized the monolithic integration of the InP laser and Si high-speed Mach-Zehnder interferometer and the product series of 100 Gbps transceivers. Intel's accomplishments and vertically integrated business model have shown the technical possibility of silicon-based heterogeneous integration. Regarding scientific research and industrialization, China is progressively narrowing its gap with foreign countries. In terms of silicon and optical integration, China currently has silicon and optical platforms of Chongqing United Microelectronics Center Co., Ltd. (CUMEC), Institute of Microelectronics of the Chinese Academy of Sciences (IMECAS), and Shanghai Industrial μ Technology Research Institute (SITRI) with chip-processing capability. For instance, CUMEC has realized a silica-based narrow linewidth laser based on an independent process platform, with a wavelength tuning range of 1520–1580 nm, power > 10 dBm, linewidth < 100 kHz, and features of low phase noise, high integration, and low cost. It has broad application prospects in silicon optical lidar, high-speed coherent optical communication modules, gas detection, and fiber sensing based on coherent detection. Regarding scientific research institutions, Peking University, Zhejiang University, Shanghai Jiao Tong University, Institute

of Semiconductors Chinese Academy of Sciences, and other units have conducted numerous cutting-edge studies on the on-chip light source frequency comb and multi-material fusion chips, among others (Table 2.2.4).

New trends and directions exist in the field of on-chip integrated light sources (Figure 2.2.4).

First, the multi-material system incorporates the photoelectric chip to develop the integrated process technology of III–V compounds, silicon nitride, silicon dioxide, polymer, lithium niobate, aluminum potassium arsenic, and InP, on silicon wafers. The target can cover visible light, near-infrared, mid-infrared, THz, and other frequency bands. The methods employed include transfer printing processes according to reversible adhesion methods that incorporate thousands of devices made of different materials onto a single wafer. Multi-material integration is used to create a silicon/advanced photoelectric material (III–V, LiNbO₃, etc.) hybrid integration process platform.

Second, because of the urgent demand for the multi-wavelength output of the on-chip light source, the nanoscale optical parametric oscillator is created to realize the successful nonlinear wavelength conversion on the chip via the nonlinear effect of the weak pump light and the material in the micro-cavity. The wavelength output that is difficult to accomplish using the traditional silicon chip technology is widely applied in chip-based atomic clocks or portable biochemical analysis devices.

Third, semiconductor mode-locked laser combined with

Table 2.2.4 Institutions with the greatest output of core patents on “integrated on-chip light source”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations	Citations per patent
1	Inphi Corporation	26	3.12	50	3.23	1.92
2	Ningbo Daye Garden Equipment Company Limited	23	2.76	20	1.29	0.87
3	Zhejiang University	14	1.68	21	1.36	1.50
4	Institute of Semiconductors Chinese Academy of Sciences	13	1.56	27	1.74	2.08
5	International Business Machines Corporation	13	1.56	26	1.68	2.00
6	The Government of the USA of America as represented by the Secretary of the Navy	12	1.44	5	0.32	0.42
7	Peking University	11	1.32	21	1.36	1.91
8	Intel Corporation	9	1.08	57	3.68	6.33
9	Accelink Technology Company Limited	9	1.08	43	2.78	4.78
10	Shanghai Jiao Tong University	7	0.84	28	1.81	4.00

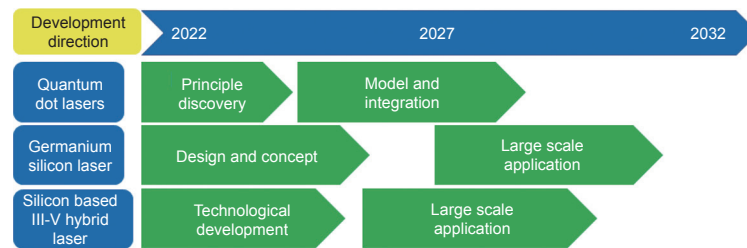


Figure 2.2.4 Roadmap of the engineering development front of “integrated on-chip light source”

integrated nonlinear optical frequency comb devices realize the compound semiconductor, silicon nitride, lithium niobate, etc., and silicon wafer monolithic integration and mixed integration and attain mass production to achieve low power usage and narrow linewidth ultrashort optical pulse, offer hundreds of isometric and coherence of the laser line, and can be accurate corresponding to the frequency of the comb line spacing. It can not only make optical atomic clocks to accurately measure time, but also reduce the interference between optical fiber communication channels, and upsurge the signal amount transmitted by a single optical fiber using various orders of magnitude. It is also commonly employed in technologies such as lidar, GPS, astronomical observation, and the investigation of gas composition. The current indicators can produce a QD laser comb with a comb tooth width of 12 nm and a thin line width outer cavity laser with a minimum linewidth of 140 Hz.

Fourth, in QD lasers, the discrete distribution of QDs causes QD-based lasers to have better temperature characteristics and lower threshold currents. For instance, a simple template-

free self-assembly method for glial QDs can be used to prepare resonators. Furthermore, indium arsenide QDs can be used as gain media to grow GaAs substrate epitaxially. Under the action of the optical pump, the micro- and nanochip laser is realized. The on-chip entanglement light source in the integrated optical quantum chip can also be realized by integrating high-quality semiconductor QDs, diamond color centers, and two-dimensional material defect states, among others. One potential future direction is to study the hybrid integrated on-chip quantum light source of polarized entangled photon pairs of self-assembled QDs. Currently, the best on-demand single-photon and entangled photon QD sources emit energies much higher than the silicon bandgap, so hybrid III-V integration technologies are required.

The application of lidar is a typical usage scenario of an on-chip integrated light source. The current lidar has a large volume, mass, power consumption, and cost. The trend is to use photonic integrated chips to substitute the current lidar built using discrete optical components, which can significantly reduce the volume, mass, power consumption,

and cost. This can be achieved by incorporating the on-chip light source through optical interconnection. The optical switch routes the on-chip optical signal to achieve chip-level integration of photon emission and reception. The light source and the germanium silicon photodetector are integrated into a chip. This chip is used to achieve the coherent detection of targets at different distances and achieve the scanning and ranging functions of the coherent lidar.

Sensor is another application scenario. On chip light source is needed to achieve the integration of optical sensing applications. To realize the on-chip integration of sensing chip, processing technologies such as heteroepitaxy/transfer printing/materials bonding are fully developed. Currently, the refractive index sensing detection limit of waveguide chip incorporated optical sensing detection chips has reached the order of 10^{-6} RIU, the detection limit of gas has reached the order of ppb (10^{-9}), and the detection of chemical and biological molecules has reached the order of pg/mm^2 , indicating good application potential. The chip can also be easily integrated into platforms such mobile phones and drones, enabling portable applications and robust on-site detection through big data, cloud computing, and IoT technologies. In optical communication, Fujitsu laboratory scholars Tanaka et al. designed a silicon photonic transmitter chip without a temperature regulator. They integrated the III-V material semiconductor optical amplifier on the Silicon-On-Insulator (SOI) substrate by high-precision backloading welding equipment. The hybrid integrated laser is aligned with the waveguide end and the SOI waveguide.

2.2.3 Localization by multisource information fusion

Source localization is a core function in conventional military applications, such as space-air early warning and accurate attacking, and is an indispensable technique in civilian applications such as autonomous driving and intelligent transportation. Moreover, new applications such as ultra-high-speed target tracking, unmanned aerial vehicles, robots, autonomous driving, and future 6G wireless communications have recently motivated even more efforts toward high-performance localization methods and improved their rapid developments.

Conventionally, source localization is primarily used in line-of-sight environments, and the research focuses on the mathematical formulation and solution of the resultant

nonlinear estimation problem. Traditional localization techniques, however, struggle to perform satisfactorily in contexts with complex propagation because of factors such as multipath propagation, low-precision measurements, and insufficient prior information. Hence, high-precision source localization in complex propagation environments has become a hot research topic. In such a situation, many low complexity, robust, and precise source localization techniques have been suggested and applied in practice. Specifically, the applications of new sensors, such as UWB sensors, millimeter wave radar, and high-precision vision sensors, have improved the measurement accuracy. However, they have also generated a large amount of redundant data. Many robust localization methods have been proposed and applied for the problem formulation to address the localization problem in dynamic nonline-of-sight (NLOS)/beyond-line-of-sight (BLOS) environments, where information is limited. For the solution side, convex optimization-based approaches have been proposed and used, significantly enhancing the localization performance at low signal-to-noise ratios and simultaneously maintaining relatively low complexity. Moreover, machine learning-based methods have been introduced to solve various localization problems. However, the excellent performance of these methods has not been well understood because of the black-box nature of many deep-learning structures.

Recently, the development of new sensors, such as a millimeter wave radar, UWB sensor, Bluetooth, and high-precision vision sensors, have enriched the study and application of localization techniques. For example, millimeter wave systems can generate high-precision range and angle information, which can be applied to simultaneous localization and mapping; a fusion of the measurements from UWB sensors and Bluetooth 5.1 equipment makes low cost indoor localization possible; and the fusion of image processing technique and electromagnetic wave positioning technology can meet the localization requirements in both visible and invisible environments.

Tables 2.2.5 and 2.2.6 list the countries and institutions with the greatest output of core patents on “localization techniques by multisource information fusion”, respectively. Table 2.2.5 shows that China holds most of the patents in this area, accounting for 73.60% of the total number. Additionally, the number of citations received by China exceeds half of the total, more specifically, 55.01%. These

two figures show that China is leading the development in this area. Furthermore, four of the Top 10 institutions with the largest core patents are from China, with Baidu Incorporation in the first rank. This trend also indicates that China is the most active in this area. Furthermore, the listed institutions include internet enterprises Baidu and Google and automotive companies GM, Hyundai, and Ford, which reveal the great importance of localization techniques in robotics and autonomous driving. Figure 2.2.5 presents the collaboration network among major countries. As shown, only a few countries collaborated on this topic. Also, there is

no collaboration among the major institutions. These signify that the R&D of this method is relatively independent among the countries and institutions.

Figure 2.2.6 shows the main paths in which "localization techniques by multisource information fusion" will grow over the next 5–10 years, including the followings:

(1) Localization scenarios

1) Millimeter wave localization: As 5G millimeter wave systems are commercially deployed, localization techniques for millimeter wave systems will also be implemented gradually.

Table 2.2.5 Countries with the greatest output of core patents on "localization by multisource information fusion"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	669	73.60	2 060	55.01	3.08
2	USA	97	10.67	1 046	27.93	10.78
3	South Korea	39	4.29	121	3.23	3.10
4	Germany	30	3.30	178	4.75	5.93
5	Japan	23	2.53	72	1.92	3.13
6	Netherlands	6	0.66	124	3.31	20.67
7	Canada	6	0.66	31	0.83	5.17
8	France	5	0.55	9	0.24	1.80
9	India	5	0.55	4	0.11	0.80
10	Sweden	4	0.44	37	0.99	9.25

Table 2.2.6 Institutions with the greatest output of core patents on "localization by multisource information fusion"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Baidu Incorporation	17	1.87	79	2.11	4.65
2	GM Global Technology Operations Limited Liability Company	7	0.77	46	1.23	6.57
3	Nanjing University of Posts and Telecommunications	7	0.77	19	0.51	2.71
4	Hyundai Motor Company	7	0.77	3	0.08	0.43
5	Google Incorporation	6	0.66	59	1.58	9.83
6	International Business Machines Corporation	6	0.66	54	1.44	9.00
7	Ford Global Technologies Limited Liability Company	6	0.66	29	0.77	4.83
8	Zhejiang University	6	0.66	17	0.45	2.83
9	South China University of Technology	6	0.66	11	0.29	1.83
10	Denso Corporation	6	0.66	6	0.16	1.00

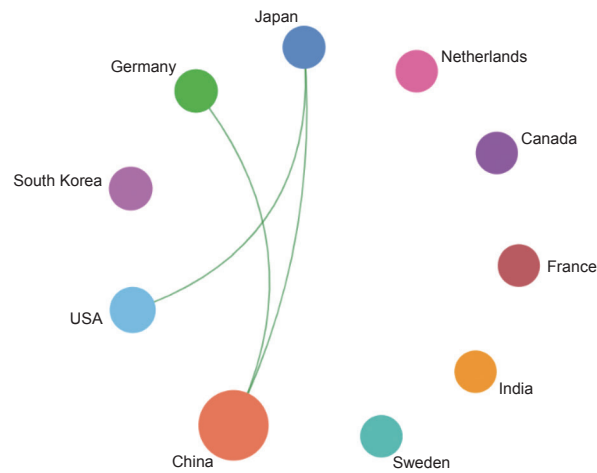


Figure 2.2.5 Collaboration network among major countries in the engineering development front of “localization by multisource information fusion”

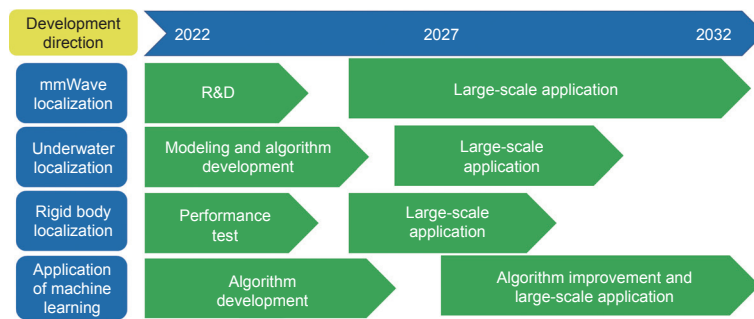


Figure 2.2.6 Roadmap of the engineering development front of “localization by multisource information fusion”

Moreover, millimeter wave localization can cooperate with the BeiDou Satellite Positioning System to realize high-precision indoor and outdoor localizations, facilitating emergency rescuing, smart transportation, and IoT applications.

2) Underwater localization: Given the unique characteristics of underwater propagation, localization techniques developed for electromagnetic wave signals may not be applied directly to underwater environments. Therefore, further development in underwater localization techniques is needed, which will be extremely important to the application of defense and surveillance in an oceanic environment.

(2) Source type

The source type will be moved from the point source to the rigid body and even group sources. Applications such as

autonomous driving and robotics require both position and orientation information. In such a situation, the object can no longer be regarded as a point source but as a rigid body. Therefore, rigid body localization will become an essential task in the future. Armed with high-precision radar, rigid body localization will be widely used in autonomous driving and robotics applications.

(3) Localization techniques

As machine learning-based methods mature and the chip computing ability becomes more powerful, localization problems in complex propagation environments will be solved using intelligent machine learning-based methods, which may revolutionize the area and significantly improve the performance with added value in various application scenarios.

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III. Chemical, Metallurgical, and Materials Engineering

1 Engineering research fronts

1.1 Trends in Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Tables 1.1.1 and 1.1.2. “Precise construction of catalyst surface active sites”, “next-generation high-energy-density battery cathode materials”, “high-efficiency nitrogen fixation driven by green energy in photocatalytic/electrocatalytic process”, and “autonomous inference of chemical industry big data” were chosen based on the core-paper statistics provided by Clarivate together with a panel of experts. The other eight fronts were recommended by the experts directly. Three of fronts provided by Clarivate have more than 150 citations per paper. The annual number of core papers for “precise construction of catalyst surface active sites” and “high-efficiency nitrogen fixation driven by green energy in photocatalytic/electrocatalytic processes” are increasing overall year by year.

(1) High-performance superconducting materials for energy storage

With the increasing energy demands of modern society and the worsening fossil-fuel crisis, renewable energy has seen rapid development. Specifically, driven by the Chinese government’s “double carbon” goal, the application scale and proportional usage of renewable energy are bound to increase significantly. Currently, renewable energy sources such as wind and solar power cannot generate electricity in a stable manner like traditional fossil-based energy sources. However, superconducting energy-storage technology promises to alleviate the negative impact of this intermittent nature, thereby improving power quality and grid stability to meet the needs of new power-system voltages and frequencies. At present, as the only technology that can store electrical energy directly as current, superconducting magnetic energy storage (SMES) is the major application form of superconducting energy storage. In SMES systems, superconducting coils are combined in series and parallel to form energy storage units. In the developmental stages of this technology, low-temperature superconducting magnets cooled by direct immersion in liquid helium were employed. However, the

Table 1.1.1 Top 12 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	High-performance superconducting materials for energy storage	92	5 972	64.91	2017.7
2	Green and low-carbon blast-furnace ironmaking technology	31	1 416	45.68	2018.4
3	Precise construction of catalyst surface active sites	110	17 290	157.18	2018.3
4	High-performance gas-separation membranes for CO ₂ capture	93	8 349	89.77	2017.3
5	Next-generation high-energy-density battery cathode materials	144	23 395	162.47	2017.5
6	High-efficiency nitrogen fixation driven by green energy in photocatalytic/electrocatalytic process	111	23 781	214.24	2018.6
7	Autonomous inference of chemical industry big data	61	4 748	77.84	2018.4
8	Material simulations for complex extreme service conditions	51	2 176	42.67	2017.5
9	Construction and application of multi-dimensional gradient metamaterials	81	7 997	98.73	2017.5
10	Bioadaptability of new implantable biomaterials for whole life cycles	97	10 186	105.01	2017.5
11	New steel materials for offshore engineering in deep-sea environments	25	763	30.52	2017.7
12	Supernormal enrichment and ultrapure preparation of critical metals	94	7 831	83.31	2017.7

Table 1.1.2 Annual number of core papers published for the Top 12 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	High-performance superconducting materials for energy storage	17	28	23	16	7	1
2	Green and low-carbon blast-furnace ironmaking technology	5	6	4	8	5	3
3	Precise construction of catalyst surface active sites	14	20	24	29	20	3
4	High-performance gas-separation membranes for CO ₂ capture	31	24	21	12	5	0
5	Next-generation high-energy-density battery cathode materials	39	40	36	21	6	2
6	High-efficiency nitrogen fixation driven by green energy in photocatalytic/electrocatalytic processes	1	16	29	50	14	1
7	Autonomous inference of chemical industrial big data	6	6	19	17	12	1
8	Material simulations for complex extreme service conditions	14	16	7	8	5	1
9	Construction and application of multi-dimensional gradient metamaterials	22	18	23	13	4	1
10	Bioadaptability of new implantable biomaterials for whole life cycles	27	25	21	16	5	3
11	New steel materials for offshore engineering in deep-sea environments	6	4	9	4	2	0
12	Supernormal enrichment and ultrapure preparation of critical metals	20	28	18	20	6	2

complex and expensive low-temperature refrigeration systems required greatly limit the application scale of SMES devices. SMES based on high-temperature superconductors can be operated above 20 K (−253.15 °C), and the operating efficiency and stability of the refrigeration systems can also be greatly improved, allowing SMES research to regain viability. However, the currently poor performance of high-temperature superconducting materials, high preparation costs, and insufficient large-scale producibility have prevented high-temperature SMES from exceeding the practical threshold of 10 MJ, and it has not found large-scale industrial application. To develop high-performance superconducting energy-storage materials, the following problems need to be solved: ① the low current-carrying capacity, poor mechanical properties, and poor electromagnetic properties of superconducting materials under high-field conditions; ② the poor large-scale production ability of high-performance, high-temperature superconducting materials; and ③ sufficient technological development of superconducting cables. The realization of large-scale preparation of high-temperature superconducting cables will provide a material foundation for the large-scale preparation of superconducting energy storage magnets.

(2) Green and low-carbon blast-furnace ironmaking technology

The blast furnace–basic oxygen furnace (BF-BOF) process has come to dominate modern iron and steel production. However, blast-furnace ironmaking is energy and resource intensive, and its carbon emissions account for ~66% of the total in the steel

industry. To achieve global carbon-emission reduction and reach carbon neutrality, developing green and low-carbon blast-furnace ironmaking technology, such as Japan's COURSE50, Germany's ThyssenKrupp hydrogen injection, and Baowu's hydrogen-enriched carbon recycling, has become an important research direction. Currently, the main areas of focus for research in this field include: ① improvement of key common technologies such as low-carbon briquetting process, high blast temperatures, oxygen-enriched coal injection, top gas recycling/injection, oxygen-enriched air smelting, and prolonged blast-furnace service life to further reduce the carbon fuel consumption and pollutant emission; ② the study of frontier technologies such as hydrogen metallurgy for blast furnaces and carbon capture utilization and storage (CCUS) for the waste gas from blast furnaces to move towards near-zero carbon emission.

(3) Precise construction of catalyst surface active sites

Driven by the energy issues and the demands of social development, science and technology are moving towards precision. The essence of precision is selectivity. In the field of catalysis, the precise and atom-economical synthesis of target products is demanded. Although using catalysts can effectively reduce the energy consumption of chemical syntheses, the development of catalysts currently entails a certain degree of trial and error and serendipity. The precise control of catalytic reaction activity will only be realized by the construction of tailored catalyst surface active sites. Current research on the precise construction of catalyst surface active

sites mainly focuses on the following aspects: ① precise control of the catalyst-preparation conditions to correctly evolve the desired catalyst surface structure; ② exploiting the actions of reactants, intermediates, and by-products to induce reconstruction of the catalyst; and ③ *in situ* construction of catalyst surface active sites using self-assembly and other methods. For future advances, it will be necessary to first precisely observe and identify catalyst structure, necessitating concerted multidisciplinary effort to develop *in situ* characterization techniques. Deepening understanding the catalyst structure–activity relationships and improving the reaction efficiency by precisely construction of catalyst surface active sites. In addition, intelligent and precise construction will be needed. Here, machine learning may facilitate precise, efficient construction and aid the rational design of high-performance catalysts. Furthermore, methods for *in situ* construction of catalyst surface active sites need to be developed, and these will require precise catalyst synthesis processes.

(4) High-performance gas-separation membranes for CO₂ capture

High-efficiency CO₂ separation technology is key for carbon capture and energy-industry gas purification, so it will make significant contributions to realizing carbon neutrality. Compared with traditional absorption methods for CO₂ separation, membrane technology is energy economical, no solvent evaporation is needed, it has a small footprint, and it is applicable for various processing capacities, so it has broad application prospects. At present, there are still many basic scientific problems in each stage of the technology chain that need to be further studied, mainly focusing on the following areas. ① Development of high-performance membrane materials and separation membranes. Informed by in-depth study on the structure–activity relationship between materials and separation performance, membrane materials must be designed at the molecular level, exploiting the synergy of multifunctional groups and multiple perm-selectivity mechanisms. Then, CO₂ membranes with high permeabilities and separation factors may be prepared by comprehensively adjusting their multi-layer membrane structures. ② Large-scale preparation of defect-free membranes. The industrial manufacture of high-performance and defect-free CO₂ separation membranes will require optimization of membrane production processes and improvement of the accuracy of the production equipment used. ③ Design of high-performance

membrane modules. Knowledge of the fluid mechanics and mass transfer behavior within the complex flow channels of modules will contribute to the development of high-performance membrane modules with low concentration polarization, low pressure drop, and high packing density. ④ Large-scale applicability to different scenarios. The different gas-source characteristics and capture requirements of different fields will necessitate novel integrated processes and complete construction of application-specific large-scale membrane separation systems that are highly efficient and energy saving.

(5) Next-generation high-energy-density battery cathode materials

With the rapid expansion of the electric/hybrid vehicle industry, developing batteries with high energy density, high power, long life, and low cost has become paramount. In terms of cathode materials for lithium batteries, currently used oxide cathode materials are limited by their low theoretical capacity and they cannot meet the performance requirements of next-generation batteries. In this context, to achieve higher energy density, it is necessary to develop new cathode materials with higher capacity. At present, research into cathodes for next-generation batteries is mainly focused on high-capacity materials such as high-voltage lithium cobaltate, high-nickel ternary compounds (including lithium nickel cobalt manganate and lithium nickel cobalt aluminate) and lithium-rich manganese. For improved discharge capacity and cycle stability of the batteries using high-voltage lithium cobaltate materials, it is necessary to use multi-element doping technology to break the upper voltage limit of lithium intercalation in lithium cobaltate. For high-nickel ternary materials with nickel contents equal to or greater than 80%, the specific capacity and cycle stability should be improved through synergistic means, such as element doping, surface coating, and crystal plane optimization or the use of single crystals. To ensure high specific capacity and long life for batteries built using lithium-rich manganese-based materials, it will be necessary to explore the mechanisms of charge and discharge processes, reduce the release of oxygen, and inhibit the migration of transition metal sites during charging, which may be achieved by combining element doping, crystal form optimization (O₂ or O₃), surface coating, and concentration gradient design. In addition to the above problems, it is vital to address the poor stability at the interface between the cathode materials and electrolytes. Moreover, because

the charging cut-off voltage of new cathode materials has exceeded the upper limit of the traditional liquid electrolyte voltage window, it is urgent to modify commonly used electrolytes or explore the use of solid-state electrolytes.

(6) High-efficiency nitrogen fixation driven by green energy in photocatalytic/electrocatalytic processes

Photocatalytic and electrocatalytic N_2 fixation technologies, with N_2 and H_2O as raw materials and renewable energy as the driving force, are environmentally friendly and economically optimal, and they must realize distributed NH_3 production at room temperature and pressure. Owing to its compressibility, high energy density, and zero carbon emission, ammonia plays an important role in modern agriculture, and thus it has the potential to become a central molecule in the future energy landscape. Photocatalysis and electrocatalysis generate high-energy electrons, which can pre-activate N_2 and greatly reduce the activation energy of its fixation processes. Chemical adsorption of N_2 on the surface of catalysts is difficult because N_2 molecules have high bond energy and weak catalyst-coordination ability, dramatically limiting the efficiency of N_2 fixation. Recent studies have mainly focused on improving the intrinsic activity of catalysts, promoting N_2 adsorption on the surface of catalysts to break the symmetry of electron distribution, weakening the $N \equiv N$ bond, and enhancing proton affinity. Various strategies for engineering such catalysts have been attempted, where interface control, surface engineering, and chemical modification have been used to optimize the intrinsic reaction activity of photocatalysts as well as for designing electrocatalysts. Despite the remarkable progress and achievements in this field, however, low catalytic efficiency and poor mechanistic knowledge remain major hurdles for the development of photochemical and electrochemical N_2 fixation. To accelerate development in this field, more research in the following areas is needed to broaden the application of photocatalytic and electrocatalytic N_2 fixation. ① Rational design and controllable synthesis of more efficient, cost-effective, environmentally friendly, and robust catalytic materials for reaction systems that achieve excellent catalytic performance. ② The development of *in situ* characterization techniques for photocatalytic and electrocatalytic N_2 fixation to probe reaction intermediate states and enable the identification of true active sites. This will facilitate the effective combination of theoretical analysis and experimental study, which is required to reveal the relevant

reaction mechanisms. ③ Rational design and structural optimization of reactors for different reaction systems to enhance their reaction efficiency and NH_3 accumulation. Despite being a great challenge, the heterogeneous catalytic synthesis of ammonia under mild conditions shows great promise as a means to reduce our reliance on fossil fuels and mitigate the impact of climate change.

(7) Autonomous inference of chemical industry big data

To meet the requirements of “carbon peak and carbon neutrality”, a move towards green and low-carbon practices in the chemical industry is imperative. Intelligent digital development may provide a means for the chemical industry to quickly achieve carbon emission reduction and improve process economics, and the core of this concept is the mining of big data generated by industrial production processes. At present, Europe, the USA, and China all have corresponding development strategies. In 2015’s *Made in China 2025* initiative, the deep integration of informatization and industry was taken as a focus, and the strategic importance of industrial data was acknowledged. However, how we might mine effective information from the high-dimensional and high-noise big data generated by the chemical industry; that is, to autonomously infer the implicit dynamic mechanisms that determine the behavior of complex industrial systems, is a crucial problem that needs to be solved. Here, it is necessary to develop a new data-driven algorithm to model the spatio-temporal dynamic characteristics of different process variables, understand the causal inference between them, determine the information transmission mechanisms, and build a hidden reaction network. Furthermore, we must then integrate such mechanistic knowledge and expert experience into a data-driven model to develop an interpretable and robust system to finally realize the autonomous inference of industrial big data and lay a foundation for the autonomous optimization and decision-making of industrial systems.

(8) Material simulations for complex extreme service conditions

Researching the behavior and properties of materials under complex extreme service conditions, such as those in nuclear reactors and aeronautical engines, weapons, and equipment, is a great challenge, mainly because it is difficult to accurately observe and test the evolution of material structure and physical properties in a considerable number of extreme environments. First, it is difficult to implement real-time and

in situ observation in extreme environments. Second, it is impossible to recreate those extreme environments in the laboratory. This makes it very difficult to develop materials for complex extreme service conditions by experimental research methods alone. Material simulations is an effective method to solve this problem. Accordingly, investigating the evolution of material microstructure and physical properties under complex extreme service conditions by these means has attracted a lot of attention. Studies in this area mainly focus on the following aspects. ① Neutron irradiation and hydrogen/helium damage of materials. In terms of fission reactors, research mainly focuses on the evolution of and damage to material structure caused by neutron irradiation in the process of core structure, nuclear fuel, and nuclear waste disposal. In a fusion reactor, the material structure evolution and damage to the first wall and divertor caused by neutron irradiation and the hydrogen/helium effect are mainly studied. Such research typically involves high-throughput cross-scale calculation of material structure evolution and damage, data collection, and database establishment. ② Effects of high strain rate on materials under impact load. This mainly involves high-throughput cross-scale calculation of constitutive relationships, strong plasticity, fracture failure, and coupling relationships with microstructure evolution and material phase transformation of various materials used in weapons equipment under dynamic load and high strain rate, collection of relevant data, and establishment of databases. ③ Effects of high temperature and high gravity on materials, which are mainly evaluated by high-throughput cross-scale calculation simulation (for example, the fatigue and creep characteristics of materials in aeronautical engines under the combined effects of high temperature and high gravity during high-speed turns), collection of relevant data, and establishment of databases. ④ The physical laws of condensed materials under extremely low temperature, strong magnetic fields, and ultra-high pressure. Through high-throughput cross-scale calculation and analysis, studying the key scientific problems and phenomena that occur in materials under those different extreme conditions, the new physical laws displayed by materials under these conditions will be revealed, providing a foundation for research and the development of relevant new materials.

(9) Construction and application of multi-dimensional gradient metamaterials

Gradient metamaterials are a new type of artificial composite

or material composed of a space gradient arrangement of basic units with unique geometry. They exhibit extraordinary physical properties that natural materials do not have, which is related not only to the intrinsic properties of the constituent materials, but also to the spatial arrangement and combination of the structural units. These novel artificially structured composite materials enable flexible regulation of light, sound, electromagnetism, and heat. The combination of multi-dimensional gradients and the construction of related metamaterials can allow more complex functions. For example, introducing a frequency gradient based on the above spatial gradient metamaterials can lead to new degrees of freedom that realize a more powerful and flexible manipulation of the electromagnetic beam, which can be used in smart skins, radar antennas, and electronic countermeasure fields. At present, research of multi-dimensional gradient metamaterials focuses on the coupling effect of gradient structure and performance in medium metamaterials, high-order optical nonlinear theory, and ultra-wideband perfect wave-absorbing materials (such as electromagnetic black holes). In the future, such research will seek to realize full-band and multi-dimensional control, improve theoretical model construction, and allow structural design and performance optimization strategies, ultimately providing large-scale and high-precision metamaterial manufacturing technology and thus the widespread application and industrialization of multi-dimensional gradient metamaterials.

(10) Bioadaptability of new implantable biomaterials for whole life cycles

Bioadaptability is a more comprehensive theoretical parameter of biomaterials based on the present concepts of biological safety and biocompatibility, and it represents a further level of requirement. The intrinsic meaning of bioadaptability can be expressed as follows: on the basis of fulfilling the general requirements of biological safety and biocompatibility, new biomaterials should actively adapt to and have an impact on various tissues, organs, and the physiological environment (histological, mechanical, chemical, and other related factors), to promote the effective repair or healing of diseased tissues and organs, and to restore normal physiological functions. Bioadaptability mainly includes, but is not limited to, three important aspects: the adaptability of the microenvironment created *in situ* by the biomaterial; the adaptability of the mechanical properties of the biomaterial to the native tissues; and the adaptability of

the degradation behavior of the biomaterial to the formation of new tissues. The future development trend for this field is precise bioadaptability, which requires that precisely adaptable biomaterials aimed at precision medicine should have spatiotemporally tailorable characteristics considering the mechanical and degradation behaviors, so as to precisely match the physiological process of tissue repair. In addition, it requires whole-life-cycle bioadaptability for implant materials. Under the guidance of the innovative concept of bioadaptability, the main characteristics of future biomaterials should contain the features of intelligence, accuracy, vitality, and versatility.

(11) New steel materials for offshore engineering in deep-sea environments

In the process of ocean development from offshore to open sea, from shallow to deep water, and from ocean to pole, it is very important to study the performance of ocean engineering materials. As the key structural material of ocean engineering equipment, steel is widely used in marine platforms, marine energy equipment, and submarine pipelines. The main types of steel are as follows: steel for marine oil and gas development equipment, steel for ships, steel for bridges and infrastructure, and steel for special marine equipment (including deep submersibles, seawater desalination, and deep-sea resource exploration). Owing to the complexity and particularity of the marine environment, there are generally strict requirements for ocean engineering steel, such as high thickness, high strength, high toughness, high service safety, and easy processing and welding performance. In addition, with the rapid development of deep-sea scientific research and polar sea and space exploration, study of the key technologies in terms of stable performance, specificity of shape and size, and adaption to extreme service conditions is crucial. Accordingly, ocean platform steel with ultra-high strength (above 690 MPa) and low-temperature toughness (-60°C and below) will become an important research focus. Thus, future research directions include: ① ocean platform steel with high strength and high toughness to meet the requirements of low-temperature environments with reduced construction and installation costs; ② low-cost and high-value-added products to reduce the need for the addition of Ni, Mo, and other precious alloy elements, while still meeting the safety performance requirements of deep- and polar-sea application; ③ ocean platform steel with low yield strength ratios that ensures sufficient ductility before plastic failure

and prevents catastrophic brittle fracture; ④ improved crack-arrest properties to prevent the occurrence of fracture accidents.

(12) Supernormal enrichment and ultrapure preparation of critical metals

The concept of a “critical metal” was recently developed from international politics and national strategy, and it refers to the rare and precious metals that are basic raw materials applied in high-tech industries such as new energy and electronics. The national security risks associated with critical metals are prominent, and special measures should be taken to secure an adequate supply. Most critical metals are rare and scattered elements and occur as concomitants or isomorphs, so their metallurgical extraction necessitates “supernormal enrichment”. Furthermore, the application of critical metals is specific to high purity metals or compounds with ppm impurities, making “ultra-pure preparation” a new feature of metallurgy. Unlike the traditional bulk-metal metallurgy with three high and one intense (high temperature, high pressure, high concentration, intense agitation) processes, the metallurgy of critical metals also involves “strong selectivity”, which describes the process of converting raw materials with ppm-level dispersed elements into metallurgical products with ppm-level impurity contents. According to the “reaction-selectivity principle” of chemical processes, highly selective enrichment and separation of critical metals can be achieved only in a weak-reactivity metallurgical system. The core scientific problem facing critical metal metallurgy mainly include: the occurrence of rare and rare scattered elements and supernormal enrichment mechanisms, the selective-separation dynamics of similar elements, impurity migration behavior, and process-control in the purification of critical metals.

1.2 Interpretations for three key engineering research fronts

1.2.1 High-performance superconducting materials for energy storage

SMES is the only technology that can store electrical energy as current directly, thus realizing almost zero current loss. Theoretically, SMES provides high power density in the range 500–2 000 W/kg, typical rated power of 1–10 MW, energy storage efficiency of more than 97%, and microsecond-

level response. However, the development of energy storage technology is relatively slow, which can mainly be attributed to the high-cost of superconducting materials as well as the poor availability of low-temperature high-magnetic-field systems. At present, promising high-temperature superconductor candidates for SMES include MgB_2 , Bi-based materials (Bi-2223 and Bi-2212), and YBCO. After nearly 40 years' development, high-temperature superconductors, represented by typical practical superconducting materials, such as Bi-based tapes and YBCO-coated conductors, have begun to enter the industrialization stage. Related practical applications such as in power systems, transportation, and large scientific devices have promoted these materials into the limelight of new materials research. Large-scale research and application demonstrations have been successfully carried

out in the USA, the European Union, and Japan, involving a large amount of manpower and material resources, and have achieved great results. In the future, to meet the material requirements of SMES applications, it is crucial to perform the corresponding research and development for high-temperature superconducting materials and cables, and the key technologies for large-scale production have to be focused upon.

The main output countries and institutes of core papers in recent years on "high-performance superconducting materials for energy storage" are listed in Tables 1.2.1 and 1.2.2, respectively. Among the major countries, China ranks first, with 41 core papers, accounting for 44.57% of the total, which is far more than that of the USA, the UK, Japan, and other countries. Among the main institutes, Chinese

Table 1.2.1 Countries with the greatest output of core papers on "high-performance superconducting materials for energy storage"

No.	Country	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	China	41	44.57	2 828	68.98	2017.7
2	USA	18	19.57	1 848	102.67	2017.8
3	India	13	14.13	539	41.46	2017.8
4	UK	10	10.87	647	64.70	2017.3
5	Japan	8	8.70	617	77.12	2017.2
6	Australia	6	6.52	430	71.67	2018.7
7	Germany	4	4.35	201	50.25	2018.8
8	Egypt	4	4.35	156	39.00	2017.8
9	France	4	4.35	151	37.75	2018.2
10	Singapore	3	3.26	180	60.00	2018.3

Table 1.2.2 Institutions with the greatest output of core papers on "high-performance superconducting materials for energy storage"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	9	9.78	549	61.00	2017.4
2	University of Bath	8	8.70	449	56.12	2017.1
3	Huazhong University of Science and Technology	7	7.61	350	50.00	2018.3
4	Peking University	6	6.52	390	65.00	2017.3
5	Sichuan University	6	6.52	170	28.33	2018.0
6	Wuhan University	5	5.43	474	94.80	2017.6
7	University of Maryland	4	4.35	432	108.00	2018.5
8	Beijing Institute of Technology	4	4.35	275	68.75	2019.0
9	Tsinghua University	4	4.35	231	57.75	2019.0
10	National Institute of Technology	4	4.35	192	48.00	2017.8

Academy of Sciences ranks first, followed by University of Bath and Huazhong University of Science and Technology. The major collaborations between countries and institutes are plotted in Figures 1.2.1 and 1.2.2, respectively. Among the relevant research countries, China and the USA have more collaboration, with China and the UK, and the USA and Japan also collaborating closely. Closer cooperation is observed between domestic institutes, such as between Chinese Academy of Sciences and Peking University, and between Huazhong University of Science and Technology and Wuhan University. According to Table 1.2.3, the top three countries with the most core-paper citations are China, the USA, and India, where the proportion for China is 44.21%, indicating that Chinese scholars pay close attention to the research trends of this frontier. The main institutes citing core papers are Chinese, including Chinese Academy of Sciences, Jilin University, and Tsinghua University (Table 1.2.4).

SMES systems use superconducting coils to store electromagnetic energy, and they have the advantages of fast response speed as well as flexible and adjustable active and reactive power. However, to date, high-temperature superconducting SMES has not yet exceeded the practical threshold of 10 MJ due to the low performance of high-temperature superconducting materials and their high production costs. The main problems include: ① the application of high-temperature superconducting materials requires lower AC loss and better thermodynamic and magnetic stability; ② the superconducting performance level and batch stability of mass-produced high-temperature superconducting materials still require improvement for practical application; ③ length and production scale of high-temperature superconducting wires are relatively small and cannot yet meet the requirements of customers, affecting the application development of superconducting materials; and

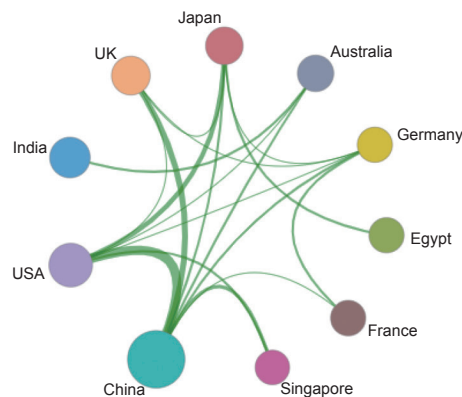


Figure 1.2.1 Collaboration network among major countries in the engineering research front of “high-performance superconducting materials for energy storage”

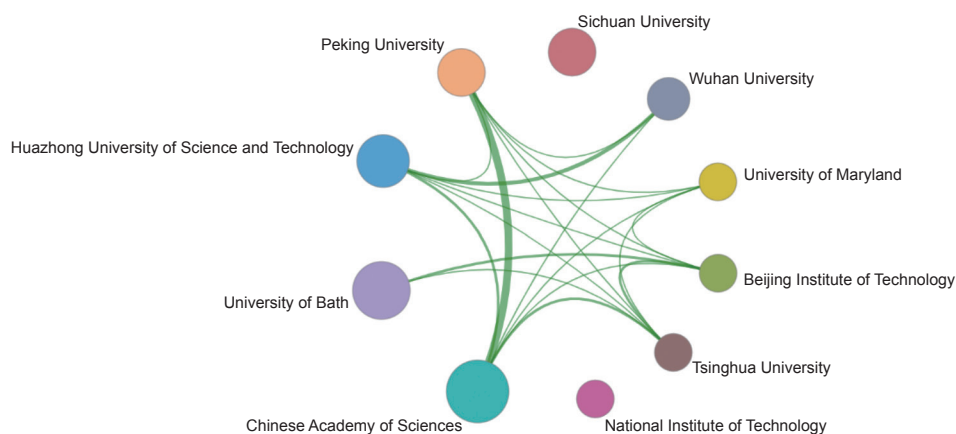


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “high-performance superconducting materials for energy storage”

Table 1.2.3 Countries with the greatest output of citing papers on “high-performance superconducting materials for energy storage”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 453	44.21	2019.9
2	USA	873	15.73	2019.6
3	India	515	9.28	2020.0
4	UK	298	5.37	2019.7
5	Germany	267	4.81	2019.9
6	Australia	251	4.52	2020.0
7	Japan	220	3.96	2019.7
8	South Korea	206	3.71	2020.0
9	Iran	166	2.99	2020.1
10	Canada	152	2.74	2019.8

Table 1.2.4 Institutions with the greatest output of citing papers on “high-performance superconducting materials for energy storage”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	318	27.94	2019.6
2	Jilin University	116	10.19	2019.8
3	Tsinghua University	112	9.84	2019.7
4	Peking University	100	8.79	2019.4
5	Tianjin University	90	7.91	2020.2
6	Huazhong University of Science and Technology	89	7.82	2019.7
7	Nanyang Technological University	64	5.62	2019.5
8	Lawrence Berkeley National Laboratory	63	5.54	2019.0
9	Hunan University	63	5.54	2020.1
10	University of Science and Technology of China	62	5.45	2019.6

④ at present, the price of high-temperature superconducting materials is relatively high, resulting in relatively narrow fields of applications, and no large-scale applications have yet been demonstrated. Therefore, in the future, it is necessary to overcome the technical difficulties associated with batch preparation of high-performance MgB_2 , Bi-based, and YBCO materials, which will not only greatly promote the development of SMES technology, but also provide reliable materials for high-field MRI, nuclear magnetic resonance, magnetic confinement nuclear fusion, particle accelerators, and other important devices. Accordingly, future research must provide: ① a means to control the plastic deformation of MgB_2 and Bi-based ceramic powder/metal multi-core composites, and a breakthrough in terms of the high-pressure heat treatment of superconducting wire; ② the optimization of coating structures for YBCO long tapes to improve its performance under high magnetic field;

and ③ high-temperature superconducting cable fabrication technology suitable for batch production. For details, see the roadmap shown in Figure 1.2.3.

1.2.2 Green and low-carbon blast-furnace ironmaking technology

The essence of blast-furnace ironmaking technology is the reduction process. Here, coal is used as fuel and a reductant to obtain iron ore or iron-containing raw materials from oxides or minerals, providing liquid pig iron at high temperature. After nearly 200 years of development, modern blast furnace ironmaking technology is relatively mature and has a low production cost, and its output accounts for over 91% of the world's total pig iron. As the largest steel producer and consumer in the world, China's BF-BOF process

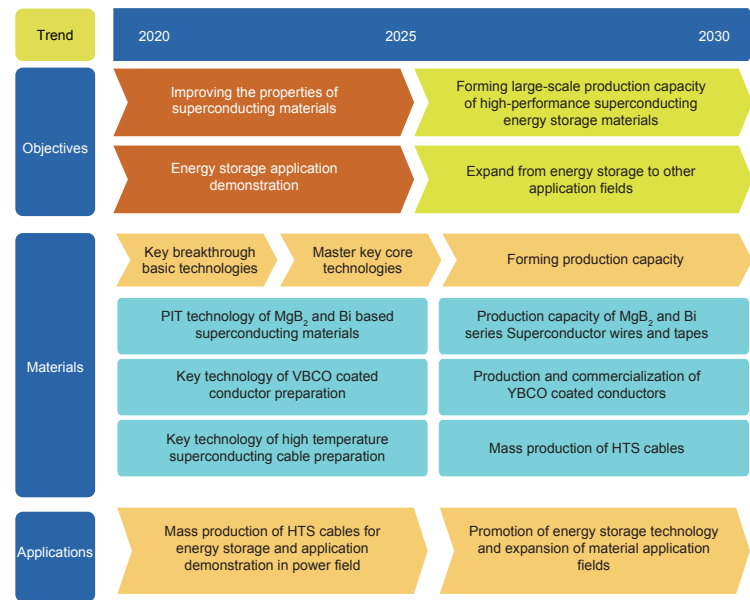


Figure 1.2.3 Roadmap of the engineering research front of "high-performance superconducting materials for energy storage"

plays a dominant role in the steel manufacturing process, and the output of blast furnace pig iron was 869 million tons in 2021, of which electric-furnace crude steel accounted for only ~10%.

The blast furnace ironmaking process is a major consumer of resources and energy in the steel manufacturing process. At present, CO_2 emissions from the steel industry account for ~7% of global emissions, and ~66% of the carbon emissions in the steel process come from the blast furnace ironmaking. Thus, in terms of global carbon emission reduction and carbon neutrality, blast furnace ironmaking is a major problem. Accordingly, the main iron and steel companies in the world have put forward strategic objectives and technical routes, with green and low-carbon blast furnace ironmaking technologies being central to such strategies. The COURSE50 project, which is being explored by Japanese iron and steel companies to reduce CO_2 emissions, is scheduled to realize the practical application of the first next-generation blast furnace in 2030, with widespread application scheduled for 2050. Germany's ThyssenKrupp tested injecting hydrogen into blast furnaces in 2019, realizing the replacement of coal with hydrogen to reduce CO_2 emissions. In 2020, China Baowu launched a new low-carbon metallurgical process at Xinjiang Bayi Iron & Steel Co., Ltd., carried out research on hydrogen-enriched carbon recycling blast furnace technology, and

conducted industrial production tests of ultra-high oxygen-rich and even pure oxygen blast furnaces.

The main countries and institutions with the greatest output of core papers on "green and low-carbon blast-furnace ironmaking technology" since 2016 are listed in Tables 1.2.5 and 1.2.6, respectively, and the collaborations between major countries and institutions are outlined in Figures 1.2.4 and 1.2.5, respectively; the main countries and institutions with the greatest output of citing papers on this front are shown in Tables 1.2.7 and 1.2.8, respectively. China, Malaysia, Britain, and France are the top four countries in this field, with China accounting for 41.94% of core papers, far ahead of other countries. Malaysia and Bangladesh boast the greatest level of cooperation, and collaboration networks between other countries are also well developed. The most cited core papers are by researchers from China, reaching 44.66%; the UK ranked second with 8.45% of core papers cited, with Germany, the USA, and Australia accounting for 6.49%, 6.49%, and 6.40%, respectively. Thus, China ranks No.1 in terms of both cited papers and citing core papers, which indicates that Chinese scholars lead this research and pay close attention to this frontier. Among the domestic institutions with the greatest output of cited papers, University of Science and Technology Beijing is ranked No.1, with the output reaching 21.14%, followed by Northeast University and Chongqing University, with outputs exceeding 10%.

Table 1.2.5 Countries with the greatest output of core papers on “green and low-carbon blast-furnace ironmaking technology”

No.	Country	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	China	13	41.94	483	37.15	2019.0
2	Malaysia	5	16.13	230	46.00	2017.8
3	UK	4	12.90	186	46.50	2018.8
4	France	3	9.68	118	39.33	2017.3
5	Sweden	2	6.45	203	101.50	2017.5
6	Bangladesh	2	6.45	124	62.00	2016.0
7	Saudi Arabia	2	6.45	81	40.50	2021.0
8	USA	2	6.45	78	39.00	2020.5
9	Finland	2	6.45	73	36.50	2019.5
10	Australia	2	6.45	65	32.50	2019.0

Table 1.2.6 Institutions with the greatest output of core papers on “green and low-carbon blast-furnace ironmaking technology”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	University of Malaya	3	9.68	156	52.00	2016.3
2	University of Lorraine	3	9.68	118	39.33	2017.3
3	Universiti Teknologi Petronas	2	6.45	77	38.50	2019.0
4	University of Science and Technology Beijing	2	6.45	77	38.50	2018.5
5	Tsinghua University	2	6.45	69	34.50	2019.5
6	Macquarie University	2	6.45	65	32.50	2019.0
7	Sichuan University	2	6.45	64	32.00	2019.5
8	Central Metallurgical Research & Development Institute	1	3.23	158	158.00	2016.0
9	Swerea MEFOS	1	3.23	158	158.00	2016.0
10	Islamic University of Technology	1	3.23	95	95.00	2016.0

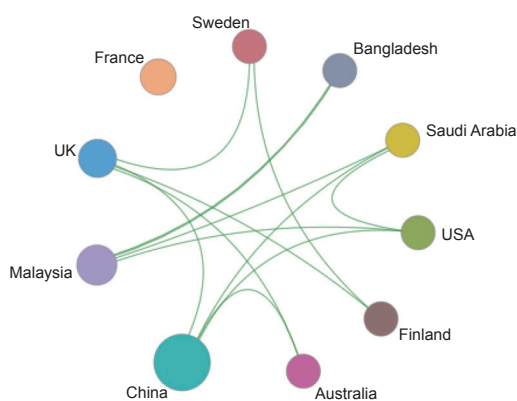


Figure 1.2.4 Collaboration network among major countries in the engineering research front of “green and low-carbon blast-furnace ironmaking technology”

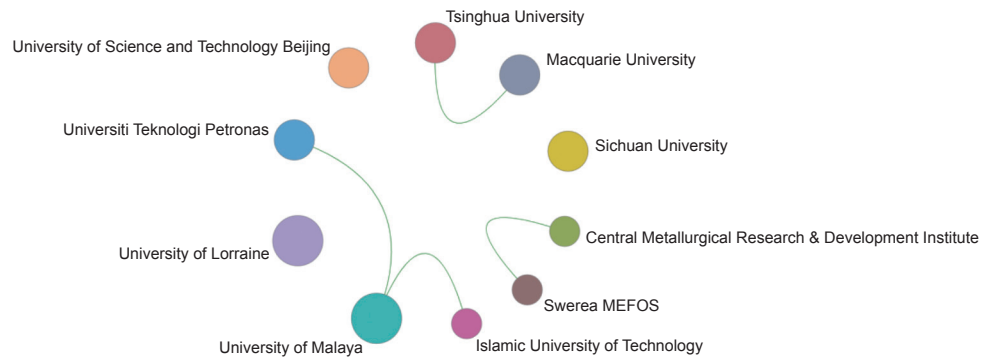


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “green and low-carbon blast-furnace ironmaking technology”

Table 1.2.7 Countries with the greatest output of citing papers on “green and low-carbon blast-furnace ironmaking technology”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	523	44.66	2020.2
2	UK	99	8.45	2020.1
3	Germany	76	6.49	2019.9
4	USA	76	6.49	2020.4
5	Australia	75	6.40	2020.2
6	Sweden	58	4.95	2019.9
7	South Korea	56	4.78	2020.0
8	Canada	55	4.70	2020.5
9	India	55	4.70	2020.6
10	Malaysia	50	4.27	2020.4

Table 1.2.8 Institutions with the greatest output of citing papers on “green and low-carbon blast-furnace ironmaking technology”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	University of Science and Technology Beijing	74	21.14	2020.3
2	Northeastern University	56	16.00	2020.2
3	Chongqing University	37	10.57	2020.8
4	Chinese Academy of Sciences	34	9.71	2019.8
5	Sichuan University	24	6.86	2020.0
6	Shandong University	24	6.86	2020.2
7	Prince Sattam bin Abdulaziz University	22	6.29	2021.0
8	Rheinisch-Westfälische Technische Hochschule Aachen	20	5.71	2019.8
9	Tsinghua University	20	5.71	2020.2
10	Far Eastern Federal University	20	5.71	2021.0

In the future, blast furnace ironmaking will begin to be replaced by non-blast furnace ironmaking technologies such as direct reduction and smelting reduction, and it will also have to face the gradual reduction of steel demand, the increase of EAF steel-making, and the need for carbon peaking and neutrality. However, considering iron ore, scrap steel, and other resources in the world, blast furnace ironmaking technology will still be the most dominant practice for the foreseeable future. Therefore, its survival and development depend on green and low-carbon ironmaking technology and reduction in its use and scale. The current and future directions of green and low-carbon blast-furnace ironmaking technology mainly include carbon resource optimization, energy efficiency improvement, and frontier technology research. This includes: ① the study of high-efficiency and low-carbon briquetting processes to optimize furnace burden structure and reduce the carbon consumption and pollutant emission of iron making; ② research on key common technologies such as high blast temperature, oxygen-enriched coal injection, top gas recycling/injection, and oxygen-enriched gas smelting to further reduce the carbon

fuel consumption of blast furnaces; ③ the study of biochar/pulverized coal mixed injection and the use of hydrogen-rich or pure-hydrogen gas to realize the replacement of carbon with hydrogen; ④ research on blast furnace long campaign technology to further extend the service life of blast furnaces; ⑤ rational study of the blast furnace ironmaking process to achieve long-term stable production practices; and ⑥ research on CCUS for the waste gas from blast furnaces. The roadmap of the engineering research front of “green and low-carbon blast-furnace ironmaking technology” is shown in Figure 1.2.6.

1.2.3 Precise construction of catalyst surface active sites

Catalysts improve reaction efficiency by reducing its activation energy, thereby reducing the input energy required to generate the target product. Clearly, this concept is of enormous importance to the current increasingly serious energy crisis. However, the design and development of catalysts have occurred mainly through serendipity or trial-and-error, which requires manpower, materials, and money.

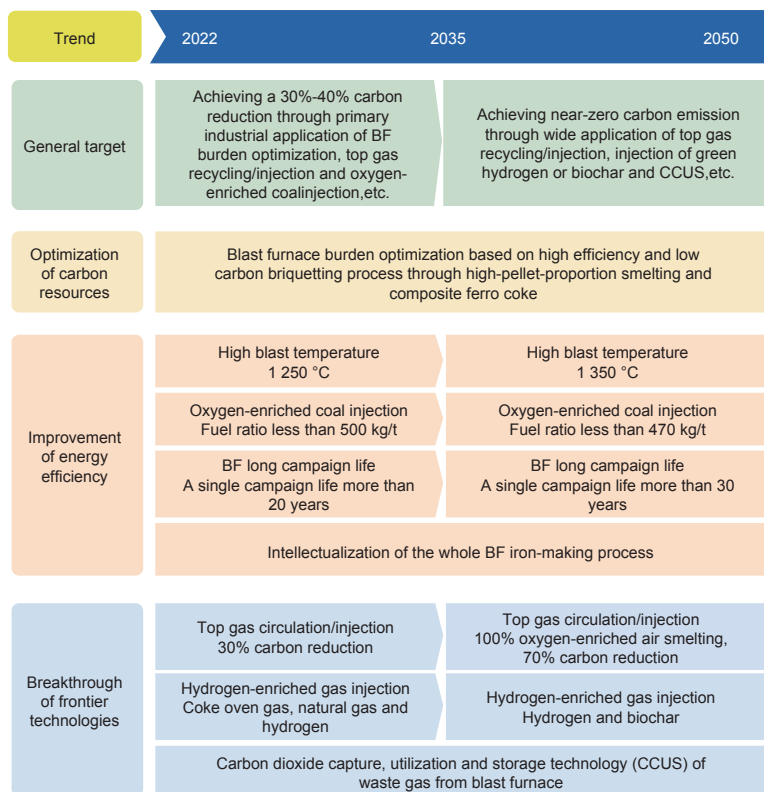


Figure 1.2.6 Roadmap of the engineering research front of “green and low-carbon blast-furnace ironmaking technology”

With deepening understanding of chemical synthesis, the rational design of efficient catalysts through precise construction of their surface-active sites is of increasing importance. The understanding of catalytically active sites has developed from being first in terms of matter, then molecules, then atoms, and finally to electrons, and it is mainly focused on the static structure of the active site. However, under real reaction conditions, the surface-active sites of a catalyst undergo dramatic and dynamic changes along with the surrounding reaction environment. Therefore, key to the precise construction of catalyst surface active sites is the combination of experimental and simulation methods to precisely identify, measure, and control the catalyst surface active sites under real reaction conditions. In view of the fact that the active sites on the catalyst surface are closely related to the surrounding reaction environment, the most direct method for constructing active sites is to control the

reaction conditions (such as temperature and pressure) and use the interactions of various substances involved in the reaction process (such as reactants, activating atmosphere, intermediates, and products) with the catalyst. In addition, the *in situ* precise construction of active sites on a catalyst surface can also be achieved by strategies such as self-assembly.

In recent years, the main producing countries and institutions of the core papers on “precise construction of catalyst surface active sites” are shown in Tables 1.2.9 and 1.2.10, respectively. China is foremost among the major producers of core papers, with a ratio of 86.36%, which is much higher than those of the USA and Australia. The Chinese Academy of Sciences ranks first among the main producers, with 22 core papers. The cooperation between major countries and institutions is shown in Figures 1.2.7 and 1.2.8, respectively. Among the relevant research countries, China has the most

Table 1.2.9 Countries with the greatest output of core papers on “precise construction of catalyst surface active sites”

No.	Country	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	China	95	86.36	15 316	161.22	2018.3
2	USA	20	18.18	3 818	190.90	2017.8
3	Australia	12	10.91	1 815	151.25	2018.2
4	Japan	7	6.36	1 924	274.86	2018.0
5	Germany	4	3.64	504	126.00	2017.5
6	Singapore	3	2.73	562	187.33	2018.7
7	Canada	2	1.82	833	416.50	2018.0
8	Saudi Arabia	2	1.82	215	107.50	2019.5
9	Poland	2	1.82	136	68.00	2016.5
10	Sweden	2	1.82	133	66.50	2017.5

Table 1.2.10 Institutions with the greatest output of core papers on “precise construction of catalyst surface active sites”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	22	20.00	4 064	184.73	2017.9
2	University of Science and Technology of China	6	5.45	2 076	346.00	2017.7
3	Tianjin University	6	5.45	1 592	265.33	2018.3
4	Soochow University	6	5.45	618	103.00	2018.8
5	Tsinghua University	5	4.55	1 777	355.40	2018.0
6	Wuhan University of Technology	5	4.55	1 293	258.60	2018.6
7	Beijing University of Chemical Technology	5	4.55	632	126.40	2019.2
8	Argonne National Laboratory	5	4.55	570	114.00	2017.6
9	Fudan University	5	4.55	545	109.00	2019.2
10	Xi'an Jiaotong University	4	3.64	1 117	279.25	2018.0

cooperative relationship with the USA, followed by Australia. For cooperation between institutions, that between Chinese Academy of Sciences and University of Science and Technology of China is relatively close. According to the citation situation of papers, the number of citing core

papers from China ranks first (Table 1.2.11), accounting for 67.12%, indicating that Chinese scholars pay close attention to this field. Among Chinese institutions, Chinese Academy of Sciences has the most citing core papers, accounting for 34.32%, followed by University of Science and Technology of



Figure 1.2.7 Collaboration network among major countries in the engineering research front of “precise construction of catalyst surface active sites”

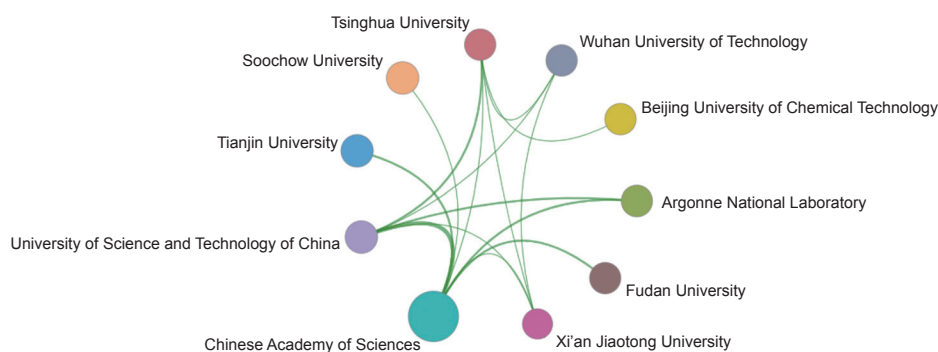


Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “precise construction of catalyst surface active sites”

Table 1.2.11 Countries with the greatest output of citing papers on “precise construction of catalyst surface active sites”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	11 566	67.12	2020.0
2	USA	1 495	8.68	2019.7
3	Australia	736	4.27	2020.0
4	South Korea	704	4.09	2020.0
5	India	626	3.63	2020.1
6	Japan	414	2.40	2019.9
7	Germany	383	2.22	2020.1
8	Singapore	376	2.18	2019.8
9	UK	335	1.94	2020.1
10	Canada	305	1.77	2020.1

China and Tianjin University (Table 1.2.12).

Research on the precise construction of catalyst surface active sites remains limited. This is largely because it is limited by the slow development of *in situ* characterization techniques and multi-scale simulation methods. Furthermore, such research involves multiple disciplines, such as catalysis, materials, and physics. The barriers between different disciplines also need to be broken down to promote their integration. Future research needs to focus on catalysts in model reaction systems to clearly identify the surface-active sites of catalysts under real reaction conditions, and then focus on realistic complex reaction systems to achieve controllable and precise synthesis of catalysts. Ultimately, the catalytic efficiency of the entire reaction system can be improved. In terms of technology,

the first step is to accurately quantify and identify the active sites on the catalyst surface as well as their structure–activity relationships to achieve precise regulation of catalytic reactions. During this research process, we must make full use of *in situ* characterization techniques as well as multi-scale simulation methods to fundamentally reveal the structure and evolution mechanism of catalyst surface active sites, and methods such as machine learning can provide intelligent support. Finally, the precise construction of catalyst surface active sites requires attention to *in situ* synthesis methods during the reaction process, which can highly improve the degree and efficiency of precise construction. The roadmap of the engineering research front of “precise construction of catalyst surface active sites” is shown in Figure 1.2.9.

Table 1.2.12 Institutions with the greatest output of citing papers on “precise construction of catalyst surface active sites”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	1 710	34.32	2020.0
2	University of Science and Technology of China	473	9.49	2019.9
3	Tianjin University	403	8.09	2020.0
4	Zhengzhou University	383	7.69	2020.2
5	Tsinghua University	375	7.53	2019.9
6	Beijing University of Chemical Technology	317	6.36	2019.9
7	Jilin University	284	5.70	2020.0
8	Zhejiang University	281	5.64	2019.8
9	Qingdao University of Science and Technology	261	5.24	2020.0
10	South China University of Technology	248	4.98	2019.7

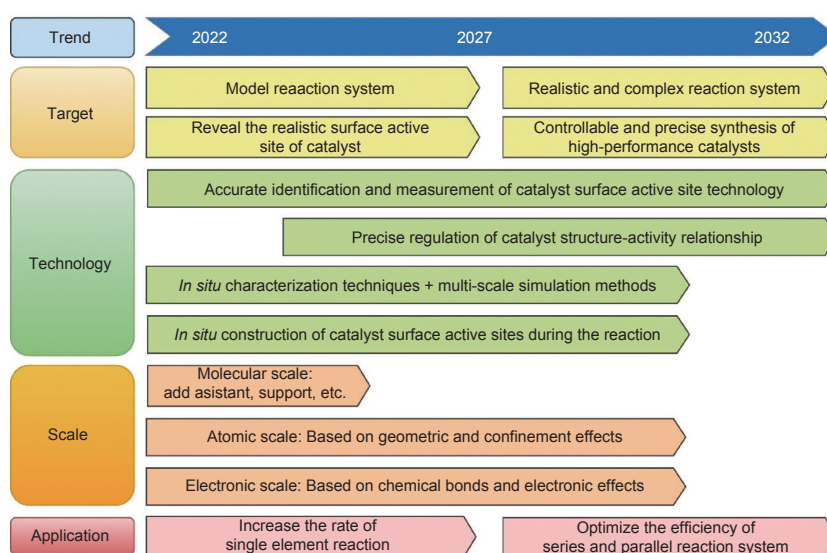


Figure 1.2.9 Roadmap of the engineering research front of “precise construction of catalyst surface active sites”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. The fronts related to energy and the environment are significant here. Works on flexible materials or devices are also prominent, for example “next-generation flexible display glass materials and technology development” and “key fabrication technologies for flexible display devices and their applications”. The annual numbers of core patents for all fronts show an overall growth trend, especially for “grid-scale molten salt energy storage technology” and “new generation of flexible display glass materials and technology development” are in faster growing (Table 2.1.2).

(1) Development and application of ultra-high temperature ceramics for extreme environments

Ultra-high temperature ceramic matrix composites (UHTCMCs) are multi-component structures composed of fibers, interfaces, and ultra-high temperature ceramic matrices. They exhibit the excellent properties of high temperature resistance, oxidation resistance, ablation

resistance, and high strength. Furthermore, they are endowed with non-brittle fracture characteristics similar to those of metals and high application reliability. They are internationally recognized as a new generation of lightweight structural materials suitable for extreme high temperature and mechanical-thermal coupling service environments. Research on UHTCMCs began in the 21st century. Over 20 years of development, great progress has been made in material fabrication and densification behavior, performance evaluation, oxidation and ablation mechanisms, and application technology development. As thermal structure/thermal protection materials, they have gradually entered the engineering application stage. The increasing application requirements and increasingly harsh service environments present new requirements for UHTCMCs technology. On the basis of further clarifying the service behavior of materials, it is vital that we design and develop new technologies for the fabrication of low-cost, short-cycle, and large-scale UHTCMCs; develop UHTCMCs with extremely high temperature resistance ($>2\,500\text{ }^{\circ}\text{C}$), near-zero ablation, and long-term reusability; develop ultra-high temperature ceramic fibers with ultra-high melting points (and their corresponding composites), and realize large-scale engineering application technology for UHTCMCs. With the development and advancement of new high-speed vehicle technologies, high-performance UHTCMCs and their components will be in mass demand in the coming years.

Table 2.1.1 Top 10 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Development and application of ultra-high temperature ceramics for extreme environments	308	631	2.05	2019.4
2	Smart manufacturing technologies for large complex refineries	553	939	1.70	2019.0
3	Selective and short-range recycling of spent power lithium-ion batteries	942	2 188	2.32	2019.4
4	Green recycling and upcycling of waste plastics	888	930	1.05	2019.0
5	Grid-scale molten salt energy storage technology	428	534	1.25	2019.1
6	Continuous manufacturing process for fine chemicals and APIs	905	574	0.63	2019.4
7	CO ₂ recovery and recycling technology in iron and steel processing	388	486	1.25	2018.8
8	Development and application of steel for key nuclear island equipment	138	289	2.09	2018.8
9	Next-generation flexible display glass materials and technology development	613	882	1.44	2019.5
10	Key fabrication technologies for flexible display devices and their applications	1 015	5 234	5.16	2018.7

Table 2.1.2 Annual numbers of core patents published for the Top 10 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Development and application of ultra-high temperature ceramics for extreme environments	15	25	50	58	67	93
2	Smart manufacturing technologies for large complex refineries	59	78	80	88	105	143
3	Selective and short-range recycling of spent power lithium-ion batteries	50	69	136	184	243	260
4	Green recycling and upcycling of waste plastics	72	111	176	168	150	211
5	Grid-scale molten salt energy storage technology	44	63	54	54	86	127
6	Continuous manufacturing process for fine chemicals and APIs	50	80	146	112	208	309
7	CO ₂ recovery and recycling technology in iron and steel processing	47	60	73	45	60	103
8	Development and application of steel for key nuclear island equipment	13	24	20	29	20	32
9	Next-generation flexible display glass materials and technology development	43	61	58	90	126	235
10	Key fabrication technologies for flexible display devices and their applications	135	157	161	188	180	194

(2) Smart manufacturing technologies for large complex refineries

Smart manufacturing technologies in refining plants mainly rely on automation technology, communication technology, artificial intelligence technology, and modern management science to improve product quality, production efficiency, and business economic and social benefits from multiple perspectives, including bottom-level perception, whole-process optimization and control, and top-level intelligent decision-making. In recent years, with the development of next-generation information technologies, such as big data, artificial intelligence, and 5G communication, all of which is of significant benefit to the refinery industry. Accordingly, there is active interest in the refinery field surrounding the application of smart manufacturing technologies to solve long-standing problems, such as high energy consumption, high carbon emission, and high pollution, as well as to improve operation and maintenance capacity and promote the green and sustainable development of refinery businesses. At present, the frontier directions for smart manufacturing technology in refineries include: ① real-time identification and perception of complex material properties; ② structure–activity analysis and the simulation of reaction processes with multiple fields and phases; ③ whole process collaborative optimization in uncertain environments; ④ risk-control technology; ⑤ carbon footprint traceability, monitoring, and collaborative carbon reduction technologies.

(3) Selective and short-range recycling of spent power lithium-ion batteries

With the rapid development of the new energy industry, the resource and environmental issues caused by spent power lithium-ion batteries have attracted widespread attention. Spent batteries have complex structures and components, but they contain a variety of critical metals. Traditional hydrometallurgical processes are subject to long process flow, high energy consumption, heavy pollution, and low metal-extraction rates. Thus, they are not suitable for new battery waste. In view of the diversification and complexity of spent batteries, developing a revolutionary new technology for the recycling of spent batteries with “short-range”, “high efficiency” and “cleanness” characteristics is of vital significance. This would also provide reference for the recycling of more complex and diverse new energy batteries in the future. The recycling of spent batteries in China was established a long time ago, and it developed rapidly in basic research and industrial applications. Accordingly, China is a world leader in large-scale industrial battery recycling. In the future, research into the short-process recycling of spent batteries should focus on three aspects: basic theoretical innovation, technological research breakthroughs, and data platform construction. Specifically, building a theoretical system for the low-carbon, green, and efficient recycling of spent batteries throughout the entire industrial chain; developing critical technologies for short-range, safe, and

low-carbon recycling of spent batteries to realize the short-range regeneration of positive and negative materials; and developing carbon-footprint analysis techniques for the whole industry and a data platform for the whole-process substance metabolism.

(4) Green recycling and upcycling of waste plastics

In recent years, along with rapid development of the world economy, global plastic production has risen exponentially, now amounting to some 400 million tons per year. Owing to the inherent difficulty of degradation or non-degradability, the vast majority of commodity plastics accumulates in the environment and will pollute it permanently. Therefore, the effective disposal of waste plastics is of great importance. At present, the main disposal methods for waste plastics globally are incineration, landfilling, and recycling. Incineration and landfilling quickly dispose of most plastic waste, but usually cause secondary pollution. Recycling not only does not cause secondary pollution it also realizes resource reuse of waste plastics, which has attracted much attention. However, traditional plastic recycling technology often suffers from high implementation temperature, low selectivity, and product performance degradation, so its industrial application is limited. In the future, the development of waste plastic recycling technology should mainly focus on implementing the following changes: ① from mechanical recycling with harsh raw material requirements to chemical recycling with wide adaptability of raw materials; ② from high-temperature thermochemical recycling to low-temperature catalytic recycling with high selectivity; ③ from down-recycling to grade preservation or even upcycling; ④ from intermittent small-scale recycling to continuous large-scale recycling.

(5) Grid-scale molten salt energy storage technology

With ongoing energy transformation, the proportion of renewable energy such as solar and wind power in energy supplies continues to increase. In some countries, the proportion of renewable electricity in the grid is close to or more than 50%. The large-scale access of fluctuating and intermittent renewable electricity to grids needs the support of grid-scale (GW·h level) energy storage technologies to reduce the risk of wind and light abandonment and grid failure, thus improving the economy and security of new energy systems. Molten salt energy storage is a reliable heat storage technology that uses the temperature difference of inorganic salt materials during heating or cooling in the

molten state to realize thermal energy storage (TES). As the second most used energy storage technology after hydro-pumped storage in terms of total global capacity, molten salt energy storage has the advantages of no geographical restrictions, low energy storage cost, and high operation safety and reliability. It has achieved a global capacity of more than 50 GW·h in concentrated solar power (CSP) plants. However, due to high-temperature thermal decomposition, the maximum operating temperature of commercial molten nitrate TES technology (such as commercial Solar Salt, a $\text{NaNO}_3\text{-KNO}_3$ salt mixture) is limited to $\sim 565^\circ\text{C}$. Furthermore, the price of nitrate materials is unstable due to the influence of the fertilizer market. Thus, the future development of molten salt energy storage technology should mainly address the following aspects. ① Next-generation molten chloride energy storage technology. Compared with the current commercial nitrate technology, chlorides have lower material cost and are more abundant. They also have a higher operating temperature (up to 800°C). Combined with advanced power cycle systems such as those based on supercritical CO_2 , its thermoelectric conversion efficiency could be increased to above 55%, thus greatly reducing the power generation cost of power stations such as the CSP. ② Grid-scale electricity storage systems (i.e., Carnot batteries) based on molten salt technology. Here, molten salt heat storage technology as the core technology is combined with molten salt electric heating technology (or high-temperature heat pump technology) and advanced power cycle systems to develop grid-scale Carnot batteries with high electricity storage efficiency (more than 70%), low electricity storage cost (equivalent to hydro-pumped storage), and no geographical restrictions.

(6) Continuous manufacturing processes for fine chemicals and APIs

With ongoing improvement of quality of life, the demand for fine chemicals and active pharmaceutical ingredients (APIs) has increased significantly, along with higher requirements in terms of product quality. Continuous manufacturing based on coupled design of multi-unit operations is a feasible way to achieve high-efficiency and high-quality production. At present, the USA, the UK, and Europe have all proposed their own developmental routes for continuous manufacturing, developing novel comprehensive strategies for the continuous manufacturing of fine chemicals and APIs and moves towards miniaturization, integration, and intellectualization. In recent years, China has also promoted the industrial

transformation of continuous manufacturing processes, focusing on developing integrated process technologies for fine chemicals and APIs. Some progress has been made in developing key technologies for continuous manufacturing, such as ppm-level purification of electronic-grade chemicals, continuous crystallization of small-molecule APIs, and intelligent design of integrated processes. However, there are still challenges to be overcome, such as poor manufacturing process stability and low modeling accuracy. In the future, the development and application of continuous manufacturing of fine chemicals and APIs will focus on process control, aiming to use integrated optimization control to optimize processes and product quality of the entire process and life cycle. However, it will be necessary to exploit advanced artificial intelligence methods to achieve the systematic, continuous, and integrated manufacturing of highly specific fine chemicals and APIs from raw materials.

(7) CO₂ recovery and recycling in iron and steel metallurgical processes

As a major energy consumer, the iron and steel industry generate a huge amount of CO₂, which can only be discharged into the atmosphere due to the lack of effective CO₂-utilization methods. In 2021, nearly 1.8 billion tons of CO₂ were emitted by the iron and steel industry in China, accounting for ~16% of the country's total emissions. At present, countries around the world are actively promoting the development of cutting-edge technologies for CO₂ recycling in the iron and steel industry, involving steel-chemical co-production and other strategies. In recent years, China has also vigorously promoted the development of CO₂ resource utilization technology in iron and steel processes. As a result China has made important progress in the development of key process technologies such as CO₂ resource utilization in converter steelmaking and electric arc furnace steelmaking, and built a demonstration production line validating the 'industrial tail gas→CO₂ recovery→steelmaking conversion→CO utilization' paradigm. However, there are still certain technical bottlenecks to be overcome. The future development of CO₂ recovery and recycling technology in steel processing will mainly focus on the following three aspects. ① The development of low-cost and high-efficiency CO₂ recovery technology. Specifically, it is to develop adsorbent compatible with the flue gas characteristics typical of the steel industry. This will further reduce the energy consumption and cost of CO₂ recovery and improve CO₂ recovery efficiency. ② Advancing CO₂ resource

utilization technology in the iron and steel industry, allowing the reclaimed CO₂ to be a functional resource for iron and steel metallurgy, perhaps to replace (or be used in conjunction with) gases used in steel-production processes like stainless steel smelting, vacuum refining, and blast furnace ironmaking. ③ The development of cross-field collaborative CO₂-utilization strategies, where the recovered CO₂ could be used by other industries, realizing steel-chemical co-production, agricultural carbon sinks, and other carbon-reduction strategies.

(8) Development and application of steel for key nuclear island equipment

Nuclear island steel is a key structural constituent of nuclear power plants, and thus it must meet the highest technical standards. Carbon steel, low-alloy steel, stainless steel, special steel, certain nickel-based alloys, titanium alloys, and zirconium alloys, among others, may be defined as nuclear island steels. It is used in plates, tubes, wires, rods, belts, and castings. The main equipment on a nuclear island, such as reactor pressure vessels and steam generators, must withstand high temperatures, high pressures, and/or irradiation for extended service lifetimes. Therefore, their shell materials must exhibit good fatigue resistance and toughness matching as well as sufficient resistance to neutron irradiation embrittlement to ensure long-term safe and reliable operation. However, the rapid development of fourth-generation nuclear energy technology has led to increased quality requirements for nuclear steel, especially for nuclear island steel. Accordingly, the main technical directions for the development and application of nuclear island steels are as follows: ① the development of structural materials for nuclear islands, including research on special alloys, preparation methodology, and nuclear-material technology; ② research on the mechanisms by which nuclear island steel is damaged, including stress corrosion, corrosion fatigue, flow accelerated corrosion, and interaction between radiation damage and corrosion; ③ research on the safety performance of nuclear steel components, including safety evaluation, life prediction, and life-extension methods.

(9) Next-generation flexible display glass materials and technology development

In recent years, flexible display technology has emerged as a highly active and exciting area of research and development. However, the production of key component materials such as flexible glass has become a bottleneck for the development

of the industry. Flexible display materials are next-generation, flexible/foldable glasses less than 100 μm in thickness. Their excellent hardness, temperature resistance, and chemical stability have led to them being broadly used in smartphones, in-vehicle networks, wearable devices, and VR displays, among others. Accordingly, these represent the focus of technological competition in the display field. At present, flexible display glass is manufactured by a two-step process. First, 100–200 μm raw glass sheets are prepared by the float and down-draw method, and then they are slimmed to below 70 μm for use in end products. In the future, the technological development of flexible display glass materials will address the following four aspects. ① Slimming, namely developing a method for mass producing 30–70 μm flexible glass through a one-step process while providing a quality that satisfies HD display demands. ② Reinforcing, namely applying new techniques such as glass ontological structure regulation and surface composite reinforcement to provide a glass strength that meets the demands of complex and sometimes harsh operating conditions. ③ Increasing size in order to meet the production demands of large end products like flexible laptops, rollable TVs, and 3D commercial displays. ④ Improving precision by applying developing technologies such as femtosecond laser cutting and roll-to-roll processing revolutionizing the glass manufacturing process.

(10) Key fabrication technologies for flexible display devices and their applications

A flexible display device is commonly composed of a soft substrate, a layer of display medium, and a protecting layer that effectively maintains the display functionality of the display medium upon bending, twisting, stretching, and winding. This makes it extraordinarily important for future display technologies. At present, a variety of technologies in the display industry are developing rapidly, such as liquid crystal displays (LCDs), organic light-emitting diode (OLED) displays, quantum dot (QD) displays, light-emitting diode (LED) displays, electronic paper (E-paper) displays, 3D displays, and laser display. With the demand of flexibility for the presentation of Internet-of-everything information, printing displays, micro-LED displays, and light field displays have become representative of next-generation display technologies. For commercialization and large-scale application, flexible display devices must be ultra-low energy consumers, ultra-thin, and multi-dimensionally deformable. Furthermore, their development will also require

good knowledge of advances in key materials and device integration technology as well as breakthroughs in equipment and manufacturing technology. With the rapid development of flexible display technology and the continuous exploration of human–computer interactions, flexible display devices will become integral to multi-functional simultaneous display, communication, and interaction. In combination with flexible sensors and flexible circuits, they will provide a means for the construction of new frameworks of flexible intelligent display modules.

2.2 Interpretations for three key engineering development fronts

2.2.1 Development and application of ultra-high temperature ceramics for extreme environments

The concept of designing and manufacturing UHTCMCs by combining ultra-high temperature ceramics (UHTCs) with fibers was first reported internationally at the beginning of the 21st century. Subsequently, this research direction has become a research hotspot in the field of high temperature structural materials. Researchers in numerous countries have carried out extensive research on UHTCMCs. Research on UHTCMCs in China dates back to 2007–2008, making China one of the first countries in the world to carry out research on such materials. UHTCMCs exhibit the same excellent properties of UHTCs, such as high temperature resistance, high strength, oxidation resistance, and ablation resistance. However, they are also endowed with non-brittle fracture characteristics, making them less susceptible to catastrophic damage. Accordingly, they are regarded as ideal materials for combined extreme temperature and mechanical stress conditions. Furthermore, they show application potential as structure and thermal protection materials for solid rockets and new high-speed vehicles, making them cutting-edge materials with huge and strategic engineering application value.

Early research on UHTCMCs mainly focused on the fabrication process, component design and optimization, and anti-oxidation ablation mechanisms. The reactive melt infiltration (RMI) method of fabricating UHTCMCs developed by the American Ultramet Company is the current industry leader. High performance Cf/Zr(Hf)C, Cf/Zr(Hf)-SiC, and other UHTCMCs and components have been successfully prepared

by the RMI method. The UHTCMC combustion chamber fabricated by Ultramet has been subjected to heat testing up to $\sim 2399^\circ\text{C}$ with no observable damage to its inner wall. Aiming at the problems of fiber/interface damage and large-scale metal residues in UHTCMCs fabricated by conventional RMI method, researchers from the Shanghai Institute of Ceramics, Chinese Academy of Sciences, have developed a new route of RMI for UHTCMCs based on sol-gel structure regulation. Through the regulation of interface structure, high-performance and low-cost UHTCMCs technology has been developed.

Very few reports on the engineering application of UHTCMCs are available because they are mainly applied for the thermal/structural protection new high-speed vehicles, which is a highly competitive and thus secretive field. The Italian Aerospace Research Center first reported the wind tunnel testing of continuous fiber reinforced UHTCMCs in 2011 and the flight testing of UHTCMCs in 2013, but there were no follow-up reports. In China, research on UHTCMCs started earlier. As a result of effective material design in the early stage and exploring the key mechanisms of high-temperature oxidation and ablation failure of materials, the UHTCMCs and related components have been verified by multiple environmental simulation assessments in recent years, and the flight test was successful. The successful application of various components in China shows that UHTCMCs and their related fabrication technologies can meet the needs of different extreme environments, and this also marks a major breakthrough in the field of ultra-high temperature thermal protection in China. Overall, China has developed

its own characteristics in terms of manufacturing technology and environmental simulation technology with UHTCMCs/components, and it is ranked among the top countries for overall technology of continuous fiber reinforced ceramic matrix composites. Furthermore, some key projects have been applied.

Table 2.2.1 shows the countries with the greatest output of core patents on “development and application of ultra-high temperature ceramic in extreme environment”. China’s patent disclosure and percentage of citations are much higher than those of the other countries and regions. There is no cooperation among main countries. Table 2.2.2 shows that the aerospace research institutions in China attach great importance to the research and development of UHTCMCs for extreme service environments. Represented by the Aerospace Research Institute of Special Materials and Processing Technology, a large number of patents have been disclosed. Figures 2.2.1 shows that there is little cooperation among domestic universities/research institutes in the study of UHTCMCs for extreme service environments, further indicating the important strategic position of UHTCMCs.

UHTCMCs have shown good application prospects in solid rocket motors and new high-speed vehicle thermal protection structures due to their excellent ultra-high temperature performance. UHTCMCs and thermal structural components developed by combining various processes can meet the operation requirements of existing high-speed vehicles. However, for large-scale engineering applications, there are still some key issues to address. ① The long fabrication cycle of UHTCMCs and high cost. ② UHTCMCs do not meet the

Table 2.2.1 Countries with the greatest output of core patents on “development and application of ultra-high temperature ceramic in extreme environment”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	271	87.99	586	92.87	2.16
2	USA	16	5.19	26	4.12	1.62
3	South Korea	7	2.27	1	0.16	0.14
4	Russia	3	0.97	2	0.32	0.67
5	India	3	0.97	0	0.00	0.00
6	France	1	0.32	6	0.95	6.00
7	Germany	1	0.32	5	0.79	5.00
8	UK	1	0.32	2	0.32	2.00
9	Poland	1	0.32	2	0.32	2.00
10	Japan	1	0.32	1	0.16	1.00

application requirements of higher temperatures because their temperature limit is generally $\sim 2\,200\text{--}2\,500\text{ }^{\circ}\text{C}$. ③ Batch manufacturing is not yet possible. All these factors restrict the development and application of UHTCMCs. Therefore, new low-cost, short-period, large-scale preparative technologies for UHTCMCs with high temperature ($>2\,500\text{ }^{\circ}\text{C}$) resistance, near-zero ablation, long-term reusability, ceramic fibers with ultra-high melting point and their corresponding composites, and large-scale engineering application technology for

UHTCMCs are the most important development directions for the future. Figure 2.2.2 shows the development roadmap of the engineering front of “development and application of ultra-high temperature ceramics for extreme environments”.

2.2.2 Smart manufacturing technologies for large complex refineries

The refinery industry is dominated by fossil energy, with a

Table 2.2.2 Institutions with the greatest output of core patents on “development and application of ultra-high temperature ceramics for extreme environments”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Aerospace Research Institute of Special Materials and Processing Technology	33	10.71	84	13.31	2.55
2	Northwestern Polytechnical University	19	6.17	19	3.01	1.00
3	Institute of Metal Research, Chinese Academy of Sciences	15	4.87	53	8.40	3.53
4	Central South University	13	4.22	75	11.89	5.77
5	Harbin Institute of Technology	9	2.92	26	4.12	2.89
6	Guangdong University of Technology	8	2.60	60	9.51	7.50
7	Shanghai Institute of Ceramics, Chinese Academy of Sciences	8	2.60	27	4.28	3.38
8	National University of Defense Technology	8	2.60	12	1.90	1.50
9	China Building Materials Academy	6	1.95	9	1.43	1.50
10	Suzhou Tunable New Materials Technology Company Limited	4	1.30	17	2.69	4.25

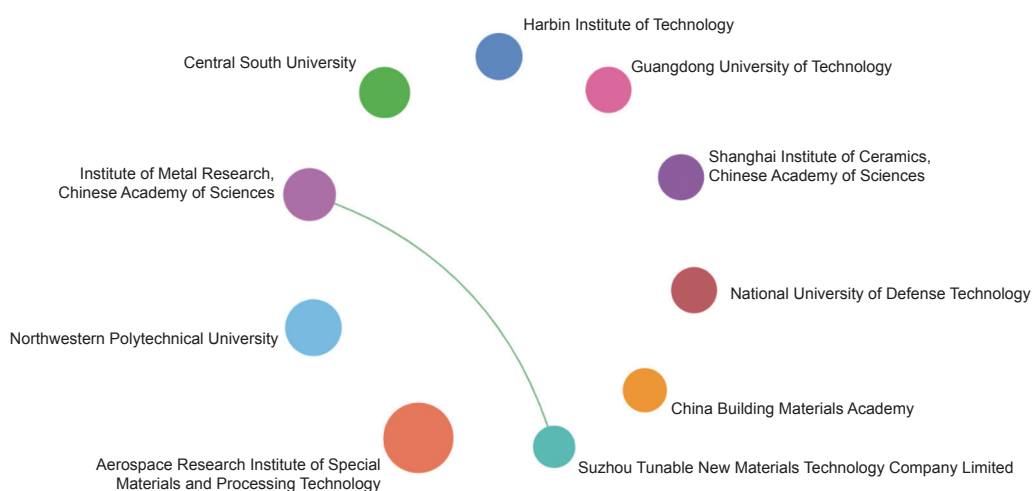


Figure 2.2.1 Collaboration network among major institutions in the engineering front of “development and application of ultra-high temperature ceramics for extreme environments”

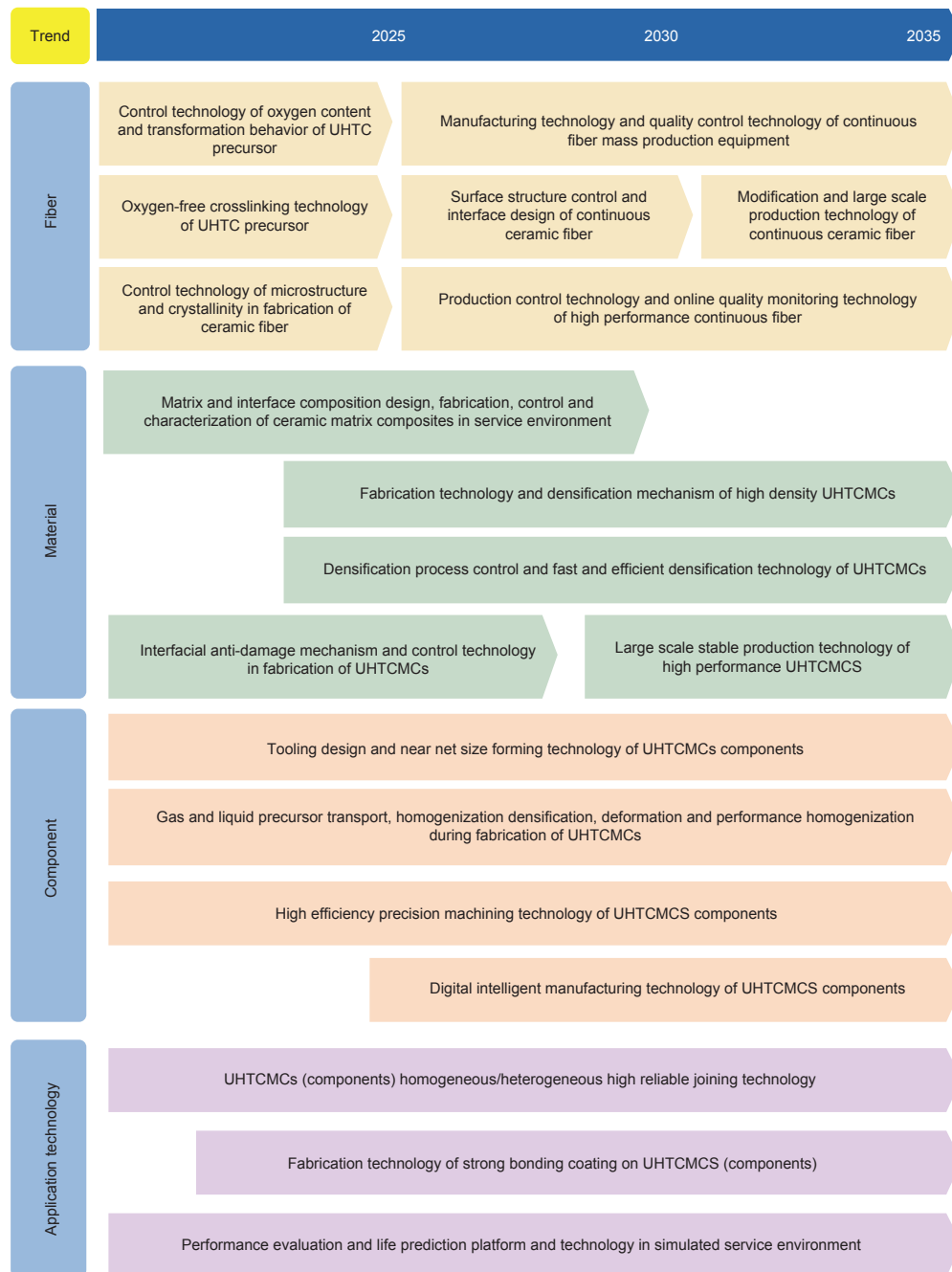


Figure 2.2.2 Roadmap of the engineering development front of “development and application of ultra-high temperature ceramics for extreme environments”

heavy industrial structure. Problems such as large production scale, long reaction chains, large spatial and temporal spans, many production elements, high energy consumption, and large carbon emissions are commonly seen. There is an urgent need to solve the problem of information silos through smart manufacturing technology, establish effective collaborations

from a multi-level and whole-process perspective, improve operation and maintenance capabilities, and promote green and sustainable development. In recent years, with the development of next-generation information technologies such as big data, artificial intelligence, and 5G communication, developed countries, including Germany, the USA, and Japan,

have developed “Industry 4.0”, the “advanced manufacturing national strategic plan,” and other smart manufacturing development strategies. China is now at a critical point in the digital transformation of its manufacturing industry. With the support of major national strategies such as “manufacturing power” and “new generation of artificial intelligence development plan”, China’s refinery industry is moving away from localized and rough production modes to whole-process and refined production modes by taking quality improvement, energy saving, and environmental protection as guiding principles.

Frontiers that need to be urgently developed in the area of smart manufacturing for the refinery industry are as follows.

① Real-time identification and analysis technologies for complex material properties. In the refinery industry, raw material components are complex. Many properties are to be measured. To solve these problems, it is necessary to develop molecular structure identification techniques based on multi-phase single-molecule properties, combined with classical physicochemical principles such as group contribution, maximum entropy, and large-scale multi-objective intelligent optimization. This will involve the study of real-time analysis methods for material molecular structure and composition; exploring online detection methods and technologies for determining raw material composition and product quality, providing technical support for process modeling, online optimization control, and scheduling. ② Multi-phase reaction process, constitutive cognition, and simulation technology. By establishing molecular reaction networks and kinetic equations, such developments would aid the study of multiple raw material components and complex reaction process mechanisms in the refinery process at the molecular level based on machine learning technology and first principles for typical reactions such as catalysis, reforming, and hydrocracking. On the basis of this, multi-scale dynamic simulation techniques for devices, reactors, and reaction processes that couple reaction, flow, and energy transfer will be possible. ③ Co-optimization technology for the whole process in open environments. In view of the strong uncertainty in terms of market demand, raw material price, and quality in the refinery industry, as well as the strong coupling of multiple units, it is necessary to study collaborative optimization methods for the whole process in an open environment to achieve optimal allocation of resources/energy. This would be based on robust optimization

and adaptive optimization strategies and suitable indicators of unit operation efficiency, energy consumption, safety, and environmental protection. ④ Safety risk control technology. Given that refinery processes involve a variety of flammable and explosive high-risk reactants, high environmental safety risks and difficulties, it is necessary to carry out dynamic scenario-based risk assessment technology. Furthermore, we must establish the fusion method and system framework of multi-source heterogeneous process data and abnormal working conditions disposal operation knowledge; develop big data-driven equipment and instrument reliability analysis methods; develop knowledge graph-driven abnormal condition causality analysis, deep learning, and operational risk analysis, to improve the analysis and risk management capability of on-site operational abnormalities and avoid serious accidents. ⑤ Carbon footprint traceability, monitoring, and collaborative carbon reduction technology must be developed. To solve the problems of high energy consumption and large carbon emission in the refining and chemical industry, it is necessary to conduct research on production energy consumption and carbon-emission-sensing technology for high-energy-consuming equipment; establish a smart prediction method of process energy consumption and carbon emission in an open environment; carry out research on carbon footprint traceability and monitoring of the whole industrial chain driven by big data; develop collaborative carbon reduction techniques for the whole production process that can synthesize multiple indexes including efficiency, quality, and carbon emission. Thus, a theoretical and technological foundation has been laid for the realization of smart low-carbon and efficient operation of production processes.

In the field of smart manufacturing in refining plants, the number of published patents in China is now the highest in the world, and most of the patents come from large state-owned enterprises such as China Petroleum & Chemical Corporation and Petro China Company Limited, as well as universities and research institutes such as China University of Petroleum (Tables 2.2.3 and 2.2.4). At present, the international cooperation in this field by China still needs to be strengthened. Internationally, there are closer exchanges and cooperation between the USA, Germany, the UK, and Saudi Arabia. In China, the cooperation between China University of Petroleum, Beijing and China Petroleum & Chemical Corporation is close, while other university-

Table 2.2.3 Countries with the greatest output of core patents on “smart manufacturing technologies for large complex refineries”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	367	66.37	473	50.37	1.29
2	USA	78	14.10	184	19.60	2.36
3	Saudi Arabia	34	6.15	215	22.90	6.32
4	South Korea	20	3.62	3	0.32	0.15
5	Canada	9	1.63	11	1.17	1.22
6	Germany	8	1.45	26	2.77	3.25
7	India	8	1.45	2	0.21	0.25
8	Japan	6	1.08	4	0.43	0.67
9	UK	4	0.72	7	0.75	1.75
10	France	3	0.54	13	1.38	4.33

Table 2.2.4 Institutions with the greatest output of core patents on “smart manufacturing technologies for large complex refineries”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Petroleum & Chemical Corporation	46	8.32	61	6.50	1.33
2	PetroChina Company Limited	42	7.59	25	2.66	0.60
3	Saudi Arabian Oil Company	34	6.15	215	22.90	6.32
4	China University of Petroleum, Beijing	23	4.16	50	5.32	2.17
5	Southwest Petroleum University	18	3.25	41	4.37	2.28
6	Nanjing Richisland Information Technology	18	3.25	17	1.81	0.94
7	China National Offshore Oil Corporation	13	2.35	8	0.85	0.62
8	Phillips 66 Company	9	1.63	8	0.85	0.89
9	Xi'an Shiyu University	8	1.45	35	3.73	4.38
10	East China University of Science and Technology	6	1.08	19	2.02	3.17

enterprise cooperations need to be strengthened (Figures 2.2.3 and 2.2.4).

As shown in Figure 2.2.5, in the next five years, smart manufacturing in refinery plants will mainly evolve from intelligence at the device level to collaborative manufacturing of the whole process, including identification of raw material attributes, online measurements, dynamic simulation of whole processes, and multi-objective collaborative optimization. In the next 10 years, smart manufacturing technology is expected to be oriented towards safety and environmental protection indicators and applied to plant-level risk control and carbon traceability, monitoring, and collaborative carbon reduction, providing a technical basis for the green and sustainable development of refining enterprises.

2.2.3 Selective and short-range recycling of spent power lithium-ion batteries

Power lithium-ion batteries are one of the main power sources for electric vehicles. The average life of these batteries is 8–10 years. Spent power batteries are important secondary resources for critical metals such as nickel, cobalt, manganese, and lithium. Spent batteries have complex structures and compositions. In addition to valuable metals, they contain toxic substances such as electrolytes and associated low-value elements. The current recycling process has a long route, high complexity, and obvious interdisciplinary characteristics. Among them, the recycling of spent lithium battery cathodes has received the most extensive research and attention. The three main types of recycling technologies

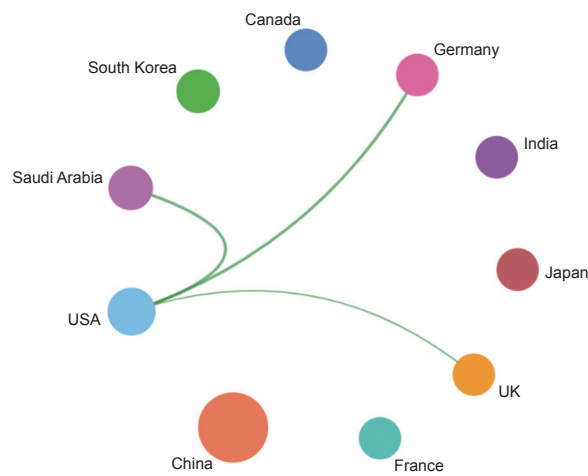


Figure 2.2.3 Collaboration network among major countries in the engineering development front of “smart manufacturing technologies for large complex refineries”

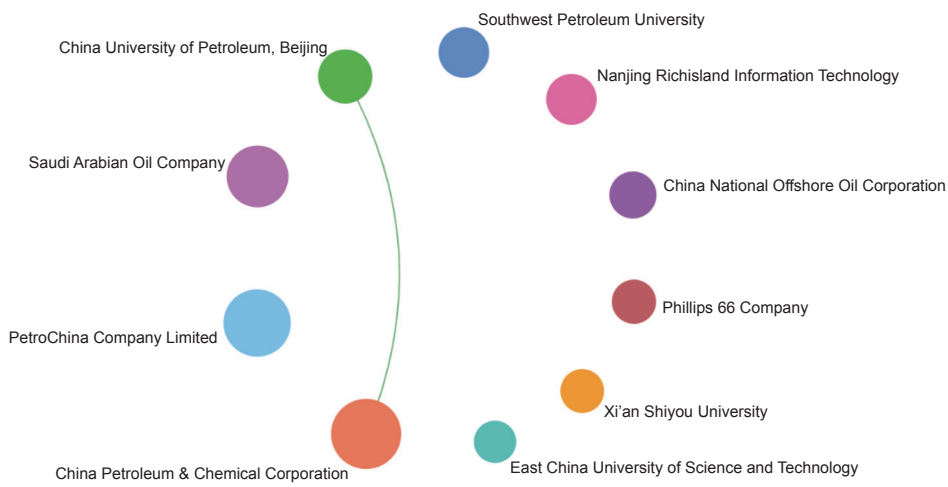


Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “smart manufacturing technologies for large complex refineries”

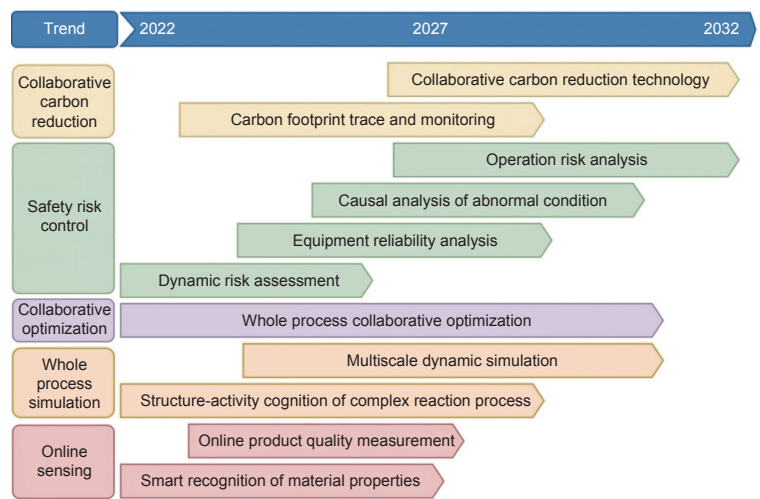


Figure 2.2.5 Roadmap of the engineering development front of “smart manufacturing technologies for large complex refineries”

are hydrometallurgy, pyrometallurgy, and direct regeneration. Umicore in Belgium uses pyrometallurgical technology to recycle metals without pretreatment, but it has high energy consumption and can release toxic and harmful gases, which poses great environmental risks. The hydrometallurgical process is relatively mature and has the advantages of low energy consumption and high recovery rate. It has a high application rate in the Chinese market. The recovery rate of metals such as nickel and cobalt can be more than 98%, while the recovery of lithium remains subject to low rates and high cost.

In recent years, attention on power lithium-ion battery recycling has continuously increased. The relevant institutions and enterprises have made many technological advances. From the perspective of resource extraction, research is mainly divided into two stages: total leaching of metal elements in early research and step extraction of metals with priority extraction of lithium in recent research. The Institute of Process Engineering, Chinese Academy of Sciences, and other institutions have done a lot of promotion work in this regard, developing a selective lithium extraction technology route for different wastes, such as LiCoO_2 , $\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$, LiFePO_4 , and LiMn_2O_4 . This constitutes a foundation-technology-equipment systematic research chain. By prioritizing lithium extraction, the lithium recovery process can be significantly shortened. The entire lithium battery recovery process can be further shortened, which is of great significance for the reduction of process pollution and carbon emission. For higher recycling efficiency, improving the effectiveness of pretreatment

methods and achieving the fine disassemble are important directions. The recently proposed technology pyrolysis-fine-sorting avoids the volatilization of toxic solvents in the pretreatment process, improves the dissociation efficiency of black mass and reduces the content of impurity elements. It can also achieve efficient sorting of positive and negative powders.

Discharge-free crushing has also received attention from the current industry, but it has mainly been used to handle LiFePO_4 . More research is needed in terms of safety, material adaptability, and economy. From the perspective of pollution reduction and carbon reduction, it is important to improve the efficiency of medium circulation and promote the treatment and utilization of ammonia nitrogen as well as high salt and high COD wastewater. It is also imperative to strengthen the utilization of waste salt, waste residue containing heavy metals, and waste graphite, among others. It is necessary to consider the carbon footprint of the obtained products and the carbon emissions of the whole process to further improve the technical level of the industry.

Table 2.2.5 lists the countries with the greatest output of core patents on “selective and short-range recycling of spent power lithium-ion batteries” in recent years. Among them, China and Japan have the largest patent outputs, with the number of patents for China being much higher than those of the other countries. Among the relevant countries, the research cooperation is relatively weak, and only China and Canada have cooperation (Figure 2.2.6). Table 2.2.6 lists

Table 2.2.5 Countries with the greatest output of core patents on “selective and short-range recycling of spent power lithium-ion batteries”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	822	87.26	2 028	92.69	2.47
2	Japan	64	6.79	84	3.84	1.31
3	South Korea	20	2.12	13	0.59	0.65
4	Germany	9	0.96	9	0.41	1.00
5	USA	8	0.85	7	0.32	0.88
6	India	5	0.53	29	1.33	5.80
7	Canada	4	0.42	16	0.73	4.00
8	Israel	3	0.32	1	0.05	0.33
9	Belgium	2	0.21	1	0.05	0.50
10	Poland	2	0.21	0	0.00	0.00

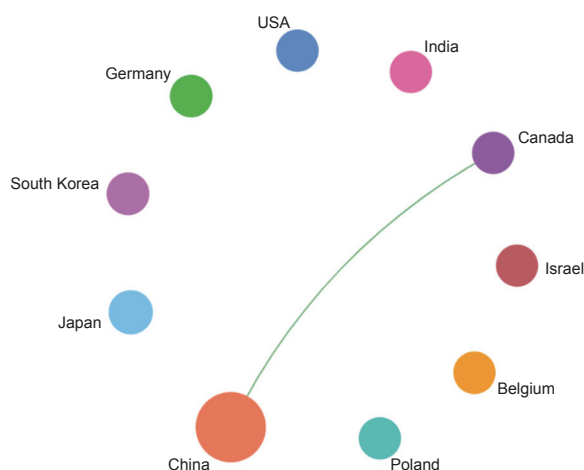


Figure 2.2.6 Collaboration network among major countries in the engineering development front of “selective and short-range recycling of spent power lithium-ion batteries”

Table 2.2.6 Institutions with the greatest output of core patents on “selective and short-range recycling of spent power lithium-ion batteries”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Central South University	55	5.84	184	8.41	3.35
2	Sumitomo Metal Mining Co., Ltd.	31	3.29	27	1.23	0.87
3	Institute of Process Engineering, Chinese Academy of Sciences	29	3.08	102	4.66	3.52
4	Hefei Guoxuan High-Tech Power Energy Co., Ltd.	27	2.87	74	3.38	2.74
5	Guangdong Brunp Recycling Technology Co., Ltd.	26	2.76	40	1.83	1.54
6	Kunming University of Science and Technology	19	2.02	35	1.60	1.84
7	BGRIMM Technology Group	17	1.80	64	2.93	3.76
8	State Grid Corporation of China	17	1.80	49	2.24	2.88
9	Taiheiyo Cement Corporation	17	1.80	29	1.33	1.71
10	GEM Company Limited	16	1.70	45	2.06	2.81

institutions with the greatest output of core patents on the “selective and short-range recycling of spent power lithium-ion batteries”. In terms of scientific research institutions, Central South University and the Institute of Process Engineering of the Chinese Academy of Sciences in China are at the forefront, while, in terms of enterprises, Japan's Sumitomo Metal Mining Co., Ltd. and China's Hefei Guoxuan Hi-Tech Power Energy Co., Ltd. and Guangdong Bangpu Recycling Technology Co., Ltd. are at the forefront. There has been no collaboration among the major institutions in this engineering research frontier.

In summary, much research and knowledge accumulation

has been carried out for spent battery recycling technologies, but there are still many issues that need to be solved. Under the background of the double carbon policy, the power battery industry chain faces new challenges and demands. As a key power and energy storage component, the short-range recycling of lithium-ion batteries is very important. How to ensure the sustainable development of the industry from the perspective of resource security, efficient utilization of resources, and carbon emission requires a new generation of green manufacturing technology for the whole industry chain. This will require further promotion of the improvement and application of the technology from the following aspects

(Figure 2.2.7): stepped pyrolysis-accurate sorting technology and corresponding equipment for spent power batteries; low-carbon and high-value utilization technology for complex nickel-cobalt-lithium waste; repair and regeneration technologies of spent cathode and anode materials; water-

gas-solid optimization integration technology for the whole industry chain of lithium battery materials; and establishing a feature database and standard system for the entire industry chain.

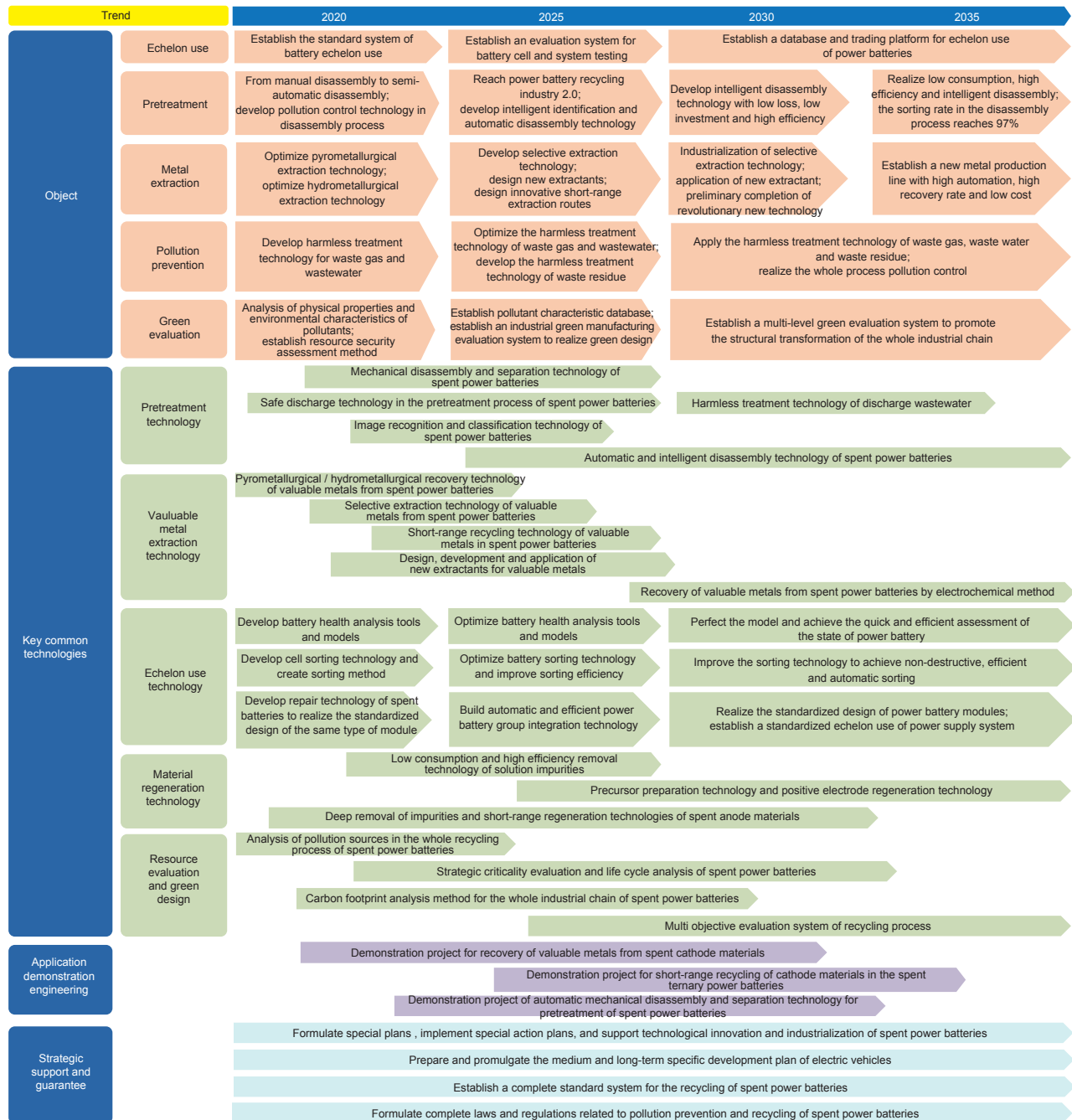


Figure 2.2.7 Roadmap of the engineering development front of “selective and short-range recycling of spent power lithium-ion batteries”

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IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, “core materials of high safety and high energy-density batteries”, “flexibility improvement of renewable energy power generation and power grid support theory”, and “synthesis of ammonia by electrochemical nitrogen reduction in organic system” represent energy and electrical science, technology, and engineering research fronts; “research on spent fuel reprocessing and high-level radioactive material separation process”, “research on

nuclear waste glass properties”, and “interaction mechanism between plasma and reactor materials” represent nuclear science, technology, and engineering research fronts; “3D fracture propagation model for hydraulic fracturing”, “hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources”, and “intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources” represent geology resources science, technology, and engineering research fronts; “induced mechanism and early warning method of rockburst in deep mining”, “mechanism of carbon dioxide flooding recovery-capture and storage of crude oil”, and “intelligent identification method for rock properties” represent research fronts of mining science, technology, and engineering.

The annual publication status of the core papers related to each front from 2016 to 2021 is shown in Table 1.1.2.

(1) Core materials of high safety and high energy-density batteries

The emergence of battery technology has changed our lives.

Table 1.1.1 Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Core materials of high safety and high energy-density batteries	177	10 783	60.92	2019.7
2	Research on spent fuel reprocessing and high-level radioactive material separation process	83	3 466	41.76	2017.8
3	3D fracture propagation model for hydraulic fracturing	239	4 020	16.82	2019.0
4	Induced mechanism and early warning method of rockburst in deep mining	214	3 374	15.77	2019.1
5	Flexibility improvement of renewable energy power generation and power grid support theory	188	3 058	16.27	2018.9
6	Synthesis of ammonia by electrochemical nitrogen reduction in organic system	20	930	46.50	2020.0
7	Research on nuclear waste glass properties	145	1 134	7.82	2018.8
8	Interaction mechanism between plasma and reactor materials	391	19 957	51.04	2017.6
9	Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources	157	2 931	18.67	2019.0
10	Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources	140	1 884	13.46	2018.7
11	Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil	94	1 618	17.21	2019.0
12	Intelligent identification method for rock properties	119	2 608	21.92	2019.7

Table 1.1.2 Annual number of core papers published for the Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Core materials of high safety and high energy-density batteries	7	8	20	31	49	62
2	Research on spent fuel reprocessing and high-level radioactive material separation process	15	20	21	19	8	0
3	3D fracture propagation model for hydraulic fracturing	26	20	45	42	52	54
4	Induced mechanism and early warning method of rockburst in deep mining	21	20	35	37	44	57
5	Flexibility improvement of renewable energy power generation and power grid support theory	18	27	31	43	25	44
6	Synthesis of ammonia by electrochemical nitrogen reduction in organic system	0	0	0	5	9	6
7	Research on nuclear waste glass properties	18	22	24	23	27	31
8	Interaction mechanism between plasma and reactor materials	92	109	78	77	32	3
9	Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources	22	17	21	21	35	41
10	Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources	22	15	24	27	22	30
11	Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil	5	16	12	19	24	18
12	Intelligent identification method for rock properties	2	8	15	17	30	47

It is a core component of electronic devices, electric vehicles, and smart grids. The energy density of existing lithium-ion batteries (LIBs) is close to its theoretical value, which is not adapted to the electric vehicle market. Safety issues have also become a significant obstacle hindering the development of battery technology in large-scale applications. Batteries are mainly composed of cathodes, anodes, and electrolytes. The energy density of batteries depends on the electrodes, whereas electrolytes determine their safety. The energy density of an electrode depends on voltage and capacity. To realize high energy-density cathodes, high-voltage cathode materials and high-capacity sulfur materials are being explored; concerning anodes, lithium metal anodes and silicon materials are being researched; finally, regarding electrolytes, solid-state electrolytes are being investigated. Solid-state electrolytes fundamentally solve safety problem of batteries, and they enable the use of high energy-density electrodes. Solid-state electrolytes can be divided into solid polymer electrolytes, solid inorganic electrolytes, and solid composite electrolytes. Solid composite electrolytes, which are actively researched for next-generation batteries, combine the advantages of good processability of polymer electrolytes

and high ionic conductivity of inorganic electrolytes.

(2) Research on spent fuel reprocessing and high-level radioactive material separation process

Nuclear fuel reprocessing aims to separate fission products in the spent fuel with chemical treatment methods, recover and purify valuable fissionable substances such as ^{235}U and ^{239}Pu , and remake them into fuel elements for the further use in the nuclear power plant (thermal reactor or fast reactor). This can jointly improve the utilization ratio of nuclear fuel and greatly save uranium resources; it can also extract transuranic elements and fission products required to develop isotopes for application in medical treatment, aerospace, etc. Nuclear fuel reprocessing can be categorized into aqueous reprocessing and non-aqueous reprocessing, based on whether it is carried out in an aqueous medium or not. Aqueous reprocessing refers to the chemical separation and purification processes in aqueous solutions, such as precipitation, solvent extraction, or ion exchange; non-aqueous reprocessing refers to the chemical separation and purification methods in an anhydrous state, such as fluorination volatilization, high-temperature metallurgical treatment, high-temperature chemical treatment, liquid

metal process, electrolysis of fused salts. Non-aqueous reprocessing has advantages in the treatment of high burnup spent fuel, especially in the reprocessing of fast reactor spent fuel. Research on “separation/transmutation” and “advanced nuclear fuel recycling” has been internationally conducted. In this case, the separation and recovery of minor actinides (MA) and long-lived fission products (LLFPs) from nuclear waste is a key step. Compared with existing spent fuel reprocessing and disposal methods, the integrated process of spent fuel reprocessing and high-level waste liquid separation is simpler and more economical, produces less secondary waste, and can better meet the separation requirements of advanced nuclear fuel recycling.

(3) 3D fracture propagation model for hydraulic fracturing

Hydraulic fracturing is a reservoir reconstruction technology that communicates natural fractures by pumping high displacement fluid into a formation to generate artificial fractures in the reservoir. Owing to the introduction of idealized assumptions concerning fracture geometry in the fracture height direction, the traditional two-dimensional and quasi-three-dimensional hydraulic-fracturing numerical models cannot describe the propagation process of the actual hydraulic fracturing. In a three-dimensional hydraulic fracturing model, the geometric constraints of the fracture are removed. Consequently, a more practical fracture design scheme can be obtained. At present, three-dimensional hydraulic-fracturing models can be divided into plane three-dimensional models and non-plane three-dimensional models. In a plane three-dimensional model, it is assumed that the hydraulic fracturing can only expand in the original fracture plane, while a non-plane three-dimensional model relaxes this condition and can simulate the non-plane deflection of the hydraulic fracturing. In a three-dimensional hydraulic-fracturing model, the crack propagation mode is more complex, and a mixed propagation mode is often coupled with three basic modes. Therefore, new crack propagation criteria need to be adopted. Hence, the fracture morphology of three-dimensional models is more complex than that of two-dimensional models and requires a new algorithm to accurately capture the crack front and calculate the stress field at the crack tip. In addition, problems addressed by two-dimensional models, such as the influence of in-situ stress, filtration effect, reservoir heterogeneity, and fracturing mode, on the expansion of hydraulic fractures,

migration of proppant still need to be further developed in three-dimensional models.

(4) Induced mechanism and early warning method of rockburst in deep mining

Rockburst is a phenomenon in which the elastic deformation potential energy accumulated in rock mass is suddenly and violently released under certain conditions, resulting in rockburst and ejection. It is a serious dynamic disaster. With the increase of mining depth, rockburst in coal mines is becoming increasingly dangerous. Research on the underlying mechanism of rockburst disasters, as well as on monitoring, early warning, and prevention and control technology, is increasingly important for safe coal mining. The main research topics in this field include dynamic response and catastrophe mechanisms of deep coal mine rockburst, intelligent monitoring of early warning theory and technology for the deep coal mine rockburst, and mechanisms and methods for prevention and control of deep coal mine rockburst. Regarding the underlying mechanism of rockburst, a new approach is based on the analysis of the sudden change mechanism of strain energy release of surrounding rock. Concerning rockburst early warning technology, future research lines will be based on integration of artificial intelligence algorithms, such as data mining and big data processing and analysis, to realize intelligent monitoring and early warning of rockburst disasters, and multi-field multi-dimensional perception.

(5) Flexibility improvement of renewable energy power generation and power grid support theory

The development of renewable energy generation, such as wind and solar power, is a promising approach for China to facilitate a clean and low-carbon transition of the energy and power industry and achieve the “30-60” carbon neutrality goal. Different from conventional electricity generators with continuous and controllable power output, the features of renewable generation are strong volatility and weak controllability. This fundamentally changes the physical form and operation mode of power systems. With the rapid development of centralized and distributed renewable generation, as well as the gradual decommissioning of thermal power units, the uncertainty continues to increase in both the generation and consumption sides of power systems, and flexible regulation resources are becoming increasingly scarce. The power supply-demand balance and secure economic operation of power systems are facing unprecedented

challenges. It is of utmost importance to investigate the theory and key technologies for flexibility improvement of renewable generation and power grid support, and for improvement of wide-area and efficient integration of a high proportion of renewable generation. Related research topics include mechanisms, operation strategies, and market mechanisms of flexibility balance in power systems; techno-economic analysis of the flexible transformation of thermal generation units and their conversion to regulating units; transient voltage support technology for large-scale wind and solar power generation systems; stability control technology of large-scale wind and solar power generation system; coordinated planning and operation of multi-period and multi-type energy storage technologies; and hierarchical aggregation, coordinated control, and distributed transaction of massive heterogeneous demand-side resources.

(6) Synthesis of ammonia by electrochemical nitrogen reduction in organic system

Ammonia is the second most produced commodity in the world. Motivated by the global shift toward sustainable energy, ammonia synthesis by electrochemical nitrogen reduction reaction (NRR) has attracted wide attention and is regarded as a promising alternative to traditional Haber-Bosch process. The electrochemical NRR can be performed in aqueous and organic systems and the later usually have higher Faradaic efficiency. Among the investigated modes of NRR, a lithium-mediated process in organic electrolytes distinguishes itself by outstanding ammonia yield rate and Faradaic efficiency. The lithium-mediated process takes place in three steps. Electrodeposition of metallic lithium first occurs, and then lithium-nitrogen based compound is produced by spontaneous reaction with reactive lithium. Based on this, the ammonia is formed by the protonation reaction. The performance of organic lithium-mediated systems is directly correlated with characteristics of lithium depositions. The study of lithium-mediated NRR is mainly focused on optimization of electrolytes, including the selection of proton donor, lithium salt, and additive. The highest reported current density and Faradaic efficiency are approximately $1 \text{ A}\cdot\text{cm}^{-2}$ and 100%, respectively, which are even better than the targets set by the REFUEL program of the US Department of Energy (current density is $0.3 \text{ A}\cdot\text{cm}^{-2}$; faradaic efficiency is 90%; energy efficiency is 60%). Before practical use, higher energy efficiency and better durability must be accomplished.

(7) Research on nuclear waste glass properties

The safe treatment and disposal of high-level radioactive waste liquid is a common challenge faced by all countries in the world, and it is also one of the key factors restricting the sustainable development of the nuclear industry. Glass solidification is currently the only industrially applied high-level waste liquid treatment method in the world. Glass has a short-range-ordered and long-range-disordered network structure, and most of the nuclides in the periodic table can enter the network of the glass. Therefore, Glass solidification used for treatment of high-level waste liquid have been extensively studied by scholars domestically and abroad, involving aluminosilicate glass, phosphate glass, silicate glass, and borosilicate. Phosphate glass has a relatively low melting temperature and are easy to prepare; however, they are seriously corrosive to other equipment. To date, only Russia has adopted phosphate glass solidification. Silicate glass contains more SiO_2 , although it has good anti-leaching performance. However, its solidification process is relatively complicated, and the solidification of high-level waste liquid with high cesium content is poor. Borosilicate glass has the advantages of good stability, simple preparation process, high mechanical strength, and large waste packaging capacity. It has become a solidified material widely used in the treatment of high-level waste liquid. Borosilicate glass is the substrate of choice. The first vitrification plant in China has now entered the operation stage, and research on the solidification behavior and anti-leaching performance of glass solidified bodies is of great significance for the safe production, temporary storage, and disposal of such bodies.

(8) Interaction mechanism between plasma and reactor materials

Controlled fusion energy is the ideal clean energy source of the future. Currently, the most likely method to achieve controlled thermonuclear fusion is magnetic confinement fusion. Solving the material problem of tokamak devices and future reactors is a key issue to realize magnetic-confinement fusion energy. The solution strongly depends on the deep understanding of the processes and mechanisms of plasma-wall interactions (PWIs), which occur mainly in the boundary plasma beyond the outermost closed magnetic surface of the tokamak field, also known as the scrapped-off layer (SOL), and in the region of the plasma-facing material in direct contact with the SOL. PWIs directly determine the operation safety of fusion

devices, development process of wall material components, and future wall lifetime. The understanding of the various physical processes and underlying mechanisms of PWIs and their effective control is one of the most important aspects in the realization of future fusion energy. The International Tokamak Physics Activity (ITPA) Working Group on scraped-off layer/divertor (SOL/Div) is dedicated to identifying the PWI issues and coordinating joint efforts at international scale. The results will have important implications for the design, manufacture, and operation of future fusion demonstration plants and commercial reactors. Currently, the main research directions include selection of plasma-facing materials, basic physical processes of boundary plasma, surface damage and structural effects under plasma irradiation, impurities and dust, and wall conditioning. Although a lot of research work on PWI process has been conducted domestically and abroad, there are still many issues to be solved; for example, the data on atomic-molecular processes in boundary plasma are not perfect, and the behavior of particle transport and redeposition is not completely clear. In view of the urgent demand for PWI-related data for national fusion projects and ITER, it is necessary to conduct comprehensive and in-depth basic research on PWIs both domestically and abroad as soon as possible.

(9) Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources

The long-term hydrogen-carbon cycle in deep earth is closely related to the short-term hydrogen-carbon cycle on the earth's surface. As the "processing plant" of the earth material cycle, the plate subduction zone is a window for understanding the deep earth. However, its internal complexity also restricts the understanding of the "generation, transportation, and accumulation" process of the earth's deep material. The exchange of material and energy between the ocean-sphere, lithosphere, and atmosphere is strengthened in the subduction "plant". Volatile components such as H_2O and CO_2 are brought into the mantle along with crustal sediments in the subduction zone. The products of deep-seated action are recycled into and out of the crust through the magmatic system of island arc volcanoes and rift basins, deep sea, and hydrothermal systems. By clarifying the link and correlation between plate subduction processes, deep geological processes, and inorganic origin oil and gas resources, the dynamics and material energy exchange mechanism across the lithosphere, and the possibility of

independent accumulation of inorganic origin oil and gas can be revealed. In the future, the work in this research field will focus on various sedimentary basins in the east of China that are under the influence of the subduction zone. By analyzing the direct or indirect relationships between these basins and deep geological processes, the interaction and dynamic mechanisms between the ocean-sphere, lithosphere, and atmosphere under the framework of the subduction "plant" will be revealed, and the resource effect of material-energy exchange between the lithosphere and asthenosphere will be clarified. Meanwhile, the hydrocarbon cycle process under organic-inorganic interaction between the ocean-sphere, lithosphere, and atmosphere, as well as the enrichment mechanism of inorganic origin oil and gas, and geothermal and other resources under plate subduction background can be clarified. Thus, the evaluation standard of inorganic-origin oil and gas resources and selection method of enrichment area can be established.

(10) Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources

Terrestrial potassium-lithium salts are formed in a terrestrial sedimentary environment. At present, China's potassium salt resource industry is based on modern terrestrial salt lakes mainly located in the Qaidam basin. Recently, Paleocene-Neogene deep-brine-type terrestrial potassium-lithium salts in western Qaidam have been discovered. The future trend of this type of resource-industry development is to carry out intelligent mineral search and comprehensive quantitative research.

Big data, artificial intelligence, blockchain, and other new technologies will be used to conduct efficient and intelligent collaborative research on key technologies for deep-brine potassium-lithium resources. In particular, new technologies will be applied to achieve deep data mining and multi-dimensional intelligent evaluation of deep-brine potassium-lithium resources. Therefore, it is of great significance to support intelligent mineral search and comprehensive quantitative research on deep-brine potassium-lithium resources and safeguard the national strategic resource security.

The next steps are as follows. First, using potassium and lithium exploration combined with seismic and logging data for oil and gas exploration will allow mapping the distribution of the reservoir brine layer. Second, well investigation

and water release tests will be conducted to obtain hydrogeological parameters of the aquifer section, determine the water richness, brine composition, aquifer permeability coefficient (K), specific yield (m), storage coefficient (S), coefficient of recharge from precipitation (a), irrigation infiltration coefficient (b), evaporation limit depth of diving (D), and other key parameters for resource evaluation. Third, core calibration or nuclear magnetic logging will be used to identify original and movable water saturations. Fourth, tectonic and lithium-bearing reservoir phase models will be created to obtain comprehensive well data, seismic data, and various types of results. Fourth, a phase-control and trend-control constraint modeling method, reservoir property model, and the use of intelligent means will be combined to achieve batch-computing quantitative evaluation of potassium and lithium resources.

(11) Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil

Carbon dioxide-enhanced oil recovery with carbon capture and storage technology refers to the injection of captured carbon dioxide into low-permeability reservoirs to achieve carbon dioxide burial and storage while enhancing the recovery of oil. This technology is a win-win solution to help reduce carbon emissions and enhance the production from oil and gas wells, which is of great significance for China to enhance “carbon peaking and carbon neutrality goals”. Carbon dioxide flooding technology was first developed in the USA in the early 1950s. By now, the carbon dioxide injection capacity amounts to 68 million tons/year and has become the main method of enhanced recovery in low-permeability and very-low-permeability blocks in the USA. There are abundant low-permeability oil reserves in China that approximately represent half of the total resources. However, the reservoir conditions of the onshore low-permeability reservoirs are complex and feature special crude oil properties. Likewise, existing carbon dioxide flooding technology is complicated. Carbon dioxide capture and transportation incur high cost, and carbon dioxide is difficult to bury, which limits the scale of carbon dioxide flooding storage. Therefore, it is urgent to explore mechanisms of carbon dioxide flooding and carbon capture and storage for the low-permeability reservoirs in China. The main research areas include efficient carbon dioxide capture technology, secure carbon dioxide transport technology, carbon dioxide enhanced oil recovery technology, and efficient carbon dioxide storage mechanism.

Understanding of the mechanism of carbon dioxide flooding recovery-capture and storage of crude oil, and accelerating the widespread promotion of carbon dioxide flooding and carbon capture and storage technology in China’s onshore low-permeability reservoirs will lead to important contributions to the optimization of energy structures and realization of “carbon peaking and carbon neutrality goals”.

(12) Intelligent identification method for rock properties

Rock lithology classification identification is the primary task of underground engineering. This identification is the basis of quantitative analysis of rock engineering geology and an important aspect in geological safety evaluation. The main research areas in lithology identification mainly includes physical methods, such as ultrasonic, rebound index, density, and other physical test methods; mathematical and statistical methods, such as statistics, analysis, and comparison of the main elements of stratum rocks; and lithology intelligent identification methods. These development trends show that intelligent recognition methods are more dependent on sample data, and the generalization ability of models is easily affected when the sample data are insufficient; moreover, the classification error of rock lithology is larger when only a single feature type of the rock is considered, such as image optical features. Therefore, it is also necessary to analyze other physical features or properties of the rock to improve the classification accuracy. Coupling rock image recognition models and rock audio intensity regression models achieves rapid recognition of rock lithology and effectively improves the generalization ability and accuracy of models. Combined with the recognition results of comparative expert methods, it assists engineers to make the correct classification of rock properties.

1.2 Interpretations for four key engineering research fronts

1.2.1 Core materials of high safety and high energy-density batteries

Safety and energy density are two obstacles hindering the development of the battery industry. Batteries are mainly composed of cathodes, anodes, and electrolytes. The energy density of batteries depends on the electrodes, and electrolytes determine the safety of batteries. LIBs, the most extensively employed battery system, are essentially a

rocking-chair battery in which lithium ions are intercalated back and forth between the positive and negative electrodes. As early as 1990, Sony Company commercialized the first LIBs. The development of batteries has shaped our lives. It is a core component of electronic devices, electric vehicles, and smart grids. The most widely used anodes of LIBs are graphite and lithium titanate. Carbonate electrolytes are typically employed, and the positive electrodes are oxides such as lithium iron phosphate, lithium cobalt oxide, and lithium nickel cobalt manganese oxide.

The energy density of electrodes is determined by voltage and capacity. The main research areas in high energy-density cathodes are high-voltage cathode materials and high-capacity sulfur materials; in anodes, the main research areas are lithium metal anodes and silicon materials. High-voltage cathode materials include lithium-rich manganese-based cathodes, lithium nickel manganese oxides, and high-voltage lithium cobalt oxides; high-capacity cathode materials are mainly sulfur cathodes. The cost of cathode materials accounts for more than 40% of the total cost of batteries. Ideal cathode materials featuring both high capacity and high voltage still need to be explored. Lithium-metal and silicon anodes have been extensively studied both in academia and industry in recent years. However, dendrite problems for lithium-metal anodes and long-cycling problems for silicon anodes at large scale hinder their commercialization. A possible tradeoff involves the use of Si/C composite anodes. Besides, the overall capacity of Si/C composite anodes can be

improved by adding a certain proportion of silicon material.

The main research area in electrolytes is the development of solid-state electrolytes. These electrolytes can fundamentally solve the safety problem of batteries. In addition, they enable the use of high energy-density electrodes. Solid-state electrolytes can be categorized into solid polymer electrolytes, solid inorganic electrolytes, and solid composite electrolytes. On the one hand, solid polymer electrolytes have good processing ability, wide electrochemical window, and excellent stability. On the other hand, they are severely impeded by their limited ionic conductivity and transference number at room temperature. The ionic conductivities of inorganic solid electrolytes have reached values close to those of liquid electrolytes, but their poor stability and huge interfacial impedance with electrode materials seriously hinder their application. Composite solid electrolytes combine the advantages of polymer electrolytes and inorganic electrolytes. They are expected to achieve a breakthrough in the technology of all-solid-state battery industry if the solid interface between electrolytes and electrodes and the active loading of electrodes can be improved.

In the engineering research front of “core materials of high safety and high energy-density batteries”, the top three countries in terms of the number of core papers published (Table 1.2.1) are China, the USA, and Germany, all of which have been cited more than 60 times. Among the Top 10 countries with the most published papers, the

Table 1.2.1 Countries with the greatest output of core papers on “core materials of high safety and high energy-density batteries”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	154	87.01	9 718	63.10	2019.6
2	USA	18	10.17	1 673	92.94	2019.3
3	Germany	10	5.65	1 183	118.30	2019.3
4	Australia	9	5.08	805	89.44	2019.7
5	Canada	8	4.52	984	123.00	2019.4
6	Singapore	5	2.82	410	82.00	2019.6
7	South Korea	5	2.82	152	30.40	2019.8
8	Japan	5	2.82	63	12.60	2020.4
9	Spain	2	1.13	676	338.00	2018.5
10	Saudi Arabia	2	1.13	65	32.50	2021.0

USA and China have more cooperation, followed by China and Australia (Figure 1.2.1). The institutions that produce a large number of core papers include Chinese Academy of Sciences, Central South University, and Huazhong University of Science and Technology (Table 1.2.2). Among these 10 institutions, Chinese Academy of Sciences has more cooperation with the Tsinghua University (Figure 1.2.2). In the amount of citing core papers, the top three countries are China, the USA, and South Korea (Table 1.2.3). The main output institutions of citing core papers are Chinese Academy of Sciences, Zhengzhou University, and Central South University (Table 1.2.4).

Material innovation is indispensable for new developments in the battery industry. Concerning lithium batteries, cathode materials will evolve from high-voltage cathode materials to low-cost high-capacity sulfur cathodes, and anode materials will evolve from Si/C composite anodes to pure silicon anodes and finally to lithium metal anodes. Electrolytes will evolve from solid composite electrolytes to all-solid-state inorganic electrolytes. Terminal all-solid-state high-voltage lithium metal batteries or lithium-sulfur batteries are expected to be used in electronic devices, electric vehicles, and smart grids. Figure 1.2.3 shows the roadmap of the engineering research front of “core materials of high safety and high energy-density batteries”.



Figure 1.2.1 Collaboration network among major countries in the engineering research front of “core materials of high-safety and high energy-density batteries”

Table 1.2.2 Institutions with the greatest output of core papers on “core materials of high safety and high energy-density batteries”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	26	14.69	1 639	63.04	2019.1
2	Central South University	10	5.65	109	10.90	2020.9
3	Huazhong University of Science and Technology	9	5.08	349	38.78	2019.0
4	Beijing Institute of Technology	8	4.52	328	41.00	2019.8
5	Tsinghua University	6	3.39	916	152.67	2019.5
6	The Hong Kong Polytechnic University	6	3.39	531	88.50	2019.3
7	Wuhan University of Technology	6	3.39	460	76.67	2018.8
8	Zhengzhou University	6	3.39	215	35.83	2020.7
9	Fudan University	5	2.82	2 759	551.80	2017.6
10	Nankai University	5	2.82	618	123.60	2019.2

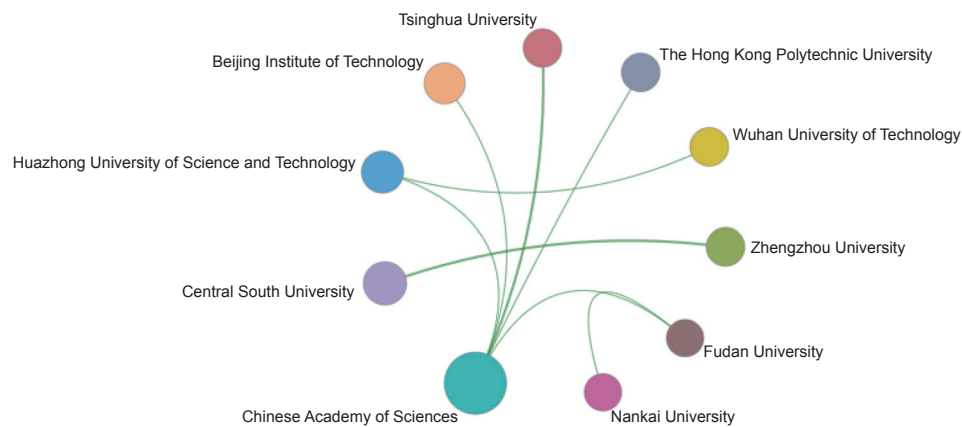


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “core materials of high safety and high energy-density batteries”

Table 1.2.3 Countries with the greatest output of citing papers on “core materials of high safety and high energy-density batteries”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	6 177	63.87	2020.1
2	USA	866	8.95	2020.1
3	South Korea	498	5.15	2020.3
4	India	408	4.22	2020.2
5	Australia	385	3.98	2020.1
6	Germany	377	3.90	2020.3
7	Japan	233	2.41	2020.1
8	Singapore	221	2.29	2020.1
9	UK	213	2.20	2020.3
10	Canada	178	1.84	2020.1

Table 1.2.4 Institutions with the greatest output of citing papers on “core materials of high safety and high energy-density batteries”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	742	29.22	2020.2
2	Zhengzhou University	244	9.61	2020.3
3	Central South University	241	9.49	2020.6
4	Tsinghua University	204	8.03	2020.2
5	University of Science and Technology of China	191	7.52	2020.2
6	Nankai University	184	7.25	2020.2
7	City University of Hong Kong	161	6.34	2020.2
8	Huazhong University of Science and Technology	161	6.34	2020.0
9	Tianjin University	150	5.91	2020.2
10	Beijing Institute of Technology	135	5.32	2020.4

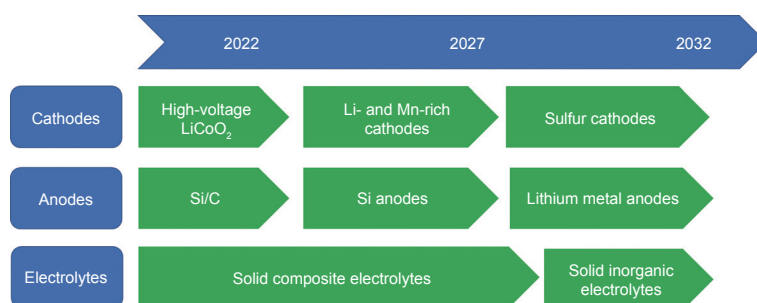


Figure 1.2.3 Roadmap of the engineering research front of “core materials of high safety and high energy-density batteries”

1.2.2 Research on spent fuel reprocessing and high-level radioactive material separation process

(1) Spent nuclear fuel reprocessing research

World-wide industrial-scale spent fuel reprocessing has a history of more than 40 years. A total of 17 countries have developed spent fuel reprocessing and built 32 reprocessing plants, including intermediate and experimental devices. The total reprocessing capacity is approximately 4 800 tons/year. Britain and France are the world leaders in terms of large-scale commercial spent fuel reprocessing.

The development of spent fuel reprocessing in China has gone through two stages: production reactor reprocessing and power reactor reprocessing. This development has been basically determined by the three-stage idea of “pilot scale–demonstration scale–large commercial scale”. The successful thermal commissioning and operation of the pilot plant shows that China has mastered the core technology of power-reactor spent fuel reprocessing, which is a milestone. The reprocessing industrial demonstration plant is expected to be completed in 2023, when China will have industrial-scale spent fuel reprocessing capability. China will complete the technology integration during the “14th Five-Year Plan” period. As a whole, it will have the ability to independently design and build large-scale post-processing plants.

In terms of technology development trends, spent fuel reprocessing methods can be categorized into two types: aqueous reprocessing and non-aqueous reprocessing, according to the state of the spent fuel being processed in the main stage. Aqueous reprocessing is mostly based on the PUREX process, whereas non-aqueous reprocessing uses electrolytic melting of halogen salts to separate fissionable material and fission products. Considering the differences in the spent fuel reprocessing objects and improvement in

fuel consumption, the mainstream development directions of aqueous reprocessing are as follows. First, improving the separation efficiency of U and Pu, strengthening the separation of Np and Tc, and improving and strengthening the control of ^{14}C and ^{129}I radioactive gas emissions. Second, to reduce the toxicity and volume of the final radioactive waste, MA and LLFP require “separation/transmutation”. In addition to the improvement of the conventional spent fuel reprocessing—PUREX process, the concept of “advanced spent fuel reprocessing” has been proposed internationally in terms of the “separation/transmutation” of MA and LLFP. It includes separation-based and transmutation-based spent fuel reprocessing technologies. Concerning fast reactor and accelerator technology, separation can be realized through two schemes, namely “total separation” and “spent fuel reprocessing—high-level waste liquid separation”. In addition, the design concept, key equipment, instrument control, waste management, nuclear safety, and other aspects of reprocessing plants are constantly improving and developing.

Non-aqueous reprocessing mainly includes halogenated volatilization, pyrometallurgy, and electrolytic refining. Electrodeposition and electrolytic refining are generally considered to be the most promising, feasible, economical, and reliable non-aqueous reprocessing technologies. As such, they have been widely studied internationally. At present, most countries are still in the laboratory research stage in terms of non-aqueous reprocessing. Only the USA has completed laboratory-scale and engineering-scale simulation experiments, and is preparing for pilot-scale thermal experiments.

(2) Research on separation of high-level waste liquid

The USA, France, Russia, Japan, and China have proposed their own high-level waste liquid separation processes. In the 1990s, Russia built a pilot-scale facility (UE-35) for separation

of high-level radioactive waste using CCD-PEG (chlorinated cobalt dicarbollide and polyethylene glycol) in Mayak to recover Sr and Cs from high-salt waste liquid. At present, only the USA has completed research on high-level waste liquid separation technology from laboratory to engineering scale. The high-level waste liquid separation plant was built at the Savannah River National Laboratory, and over 4 000 cubic meters of high-level waste liquid have been treated there by June 2016.

Since the 1980s, Tsinghua University in China has conducted research on the separation technology of high-level radioactive waste liquid, and proposed a separation process with independent intellectual property rights. At present, experimental research on the separation of high-level waste liquid of power reactor is being carried out, setting a solid foundation for thermal verification and application of high-level waste liquid separation technology, and meeting the conditions for engineering applications.

Concerning technology development trends, the separation process of transuranic elements (TRU) includes American TRUEX-TALSPEAK (Transuranic Extraction Process-Trivalent Actinide Lanthanide Separation by Phosphorous reagent Extraction from Aqueous Komplexe) and its improved process, American ALSEP (Actinide Lanthanide Separation Process) process, French DIAMEX-SANEX (DIAMide Extraction-Selective Actinide Extraction) process, European GANEX (Group Actinide Extraction) process, Japanese ARTIST (Amide-based Radio-Resources Treatment with Interim Storage of Transuranics) process, and Russian dibutyl zirconium phosphate extraction

process. The Sr and Cs separation process includes the Russian CCD-PEG process, French CSSEX process, American FPEX (Fission Product Extraction) process, and Japanese extraction chromatography process.

In China, the trialkylphosphine oxide (TRPO) process for separating actinides, crown ether process for separating strontium, and calixarene crown ether process for separating cesium have been proposed. At present, China has basically completed research on the separation process and equipment of high-level waste liquid, and is investigating on thermal experimental verification of the separation process of high-level waste liquid in power reactors. China aims to master the engineering technology by 2030 and then realize industrial applications of high-level waste liquid separation.

As shown in Table 1.2.5, the top four countries in terms of the number of core papers published on this research topic are China, the USA, the UK, and Germany. Among them, China occupies the first place, with more than 30%. The USA, the UK, and Germany exceed 10%. It can be seen from Table 1.2.6 that the top six institutions in terms of the number of core papers on this research topic are the Chinese Academy of Sciences, The University of Manchester, Sichuan University, Forschungszentrum Julich, National Nuclear Energy Laboratory, and Eidgenössische Technische Hochschule Zürich.

As shown in Figure 1.2.4, China, the USA, Japan, Germany, the UK, France, and Spain pay more attention to cooperation among countries in this field. The number of published papers in the USA is relatively large, mainly in cooperation with China, France, Germany, the UK, and Japan. As shown in Figure 1.2.5,

Table 1.2.5 Countries with the greatest output of core papers on “research on spent fuel reprocessing and high-level radioactive material separation process”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	25	30.12	1 067	42.68	2017.8
2	USA	14	16.87	800	57.14	2017.6
3	UK	12	14.46	459	38.25	2017.8
4	Germany	10	12.05	348	34.80	2017.7
5	Spain	8	9.64	512	64.00	2017.0
6	France	7	8.43	373	53.29	2018.1
7	Japan	6	7.23	354	59.00	2017.7
8	India	4	4.82	136	34.00	2018.8
9	Canada	4	4.82	133	33.25	2017.8
10	Switzerland	4	4.82	124	31.00	2019.5

Table 1.2.6 Institutions with the greatest output of core papers on “research on spent fuel reprocessing and high-level radioactive material separation process”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	5	6.02	168	33.60	2018.0
2	The University of Manchester	4	4.82	104	26.00	2018.0
3	Sichuan University	3	3.61	136	45.33	2017.3
4	Forschungszentrum Julich	3	3.61	134	44.67	2018.3
5	National Nuclear Laboratory	3	3.61	129	43.00	2018.3
6	Eidgenössische Technische Hochschule Zürich	3	3.61	98	32.67	2019.3
7	University of Texas at Austin	2	2.41	229	114.50	2018.0
8	Hokkaido University	2	2.41	147	73.50	2017.5
9	Japan Science and Technology Agency	2	2.41	147	73.50	2017.5
10	Massachusetts Institute of Technology	2	2.41	121	60.50	2017.5



Figure 1.2.4 Collaboration network among major countries in the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”

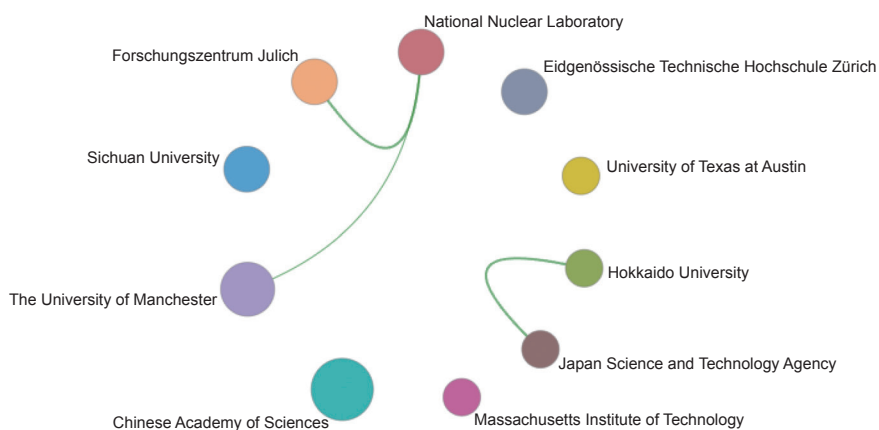


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”

The University of Manchester, Forschungszentrum Julich, and National Nuclear Energy Laboratory also cooperate.

Table 1.2.7 shows that China, which is the main output country, accounts for 32.28%, whereas the USA accounts for 20.47%. As shown in Table 1.2.8, the institutions with the main output of citing papers are Chinese Academy of Sciences, Chongqing University, Qingdao University of Science and Technology, Tsinghua University, University of New South Wales, University of Texas at Austin, and Shandong University of Science and Technology. Among them, Chinese Academy of Sciences, Chongqing University, and Qingdao University of Science and Technology all account for more than 10% on average.

From the above data analysis, it can be concluded that China

and the USA are at the forefront of the world in the number of core papers on “research on spent fuel reprocessing and high-level radioactive material separation process”, and the number of the output of citing core papers by institutions in China is relatively large.

With different reprocessing objects and the improvement of fuel burnup, the mainstream development direction of aqueous reprocessing is to strengthen the separation of Np and Tc on the basis of improving the separation efficiency of U and Pu. To reduce the toxicity and volume of the final radioactive waste, it is necessary to perform “separation/transformation” on MA and LLFP. Separation technology can be realized through two schemes, namely “total separation” and “spent fuel reprocessing—high-level waste

Table 1.2.7 Countries with the greatest output of citing papers on “research on spent fuel reprocessing and high-level radioactive material separation process”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	123	32.28	2019.2
2	USA	78	20.47	2018.8
3	Australia	31	8.14	2018.9
4	France	24	6.30	2018.8
5	Germany	24	6.30	2018.8
6	Italy	21	5.51	2019.0
7	Spain	20	5.25	2018.6
8	UK	19	4.99	2018.8
9	India	19	4.99	2018.7
10	Japan	12	3.15	2018.5

Table 1.2.8 Institutions with the greatest output of citing papers on “research on spent fuel reprocessing and high-level radioactive material separation process”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	11	12.94	2018.7
2	Chongqing University	9	10.59	2019.0
3	Qingdao University of Science and Technology	9	10.59	2018.9
4	Tsinghua University	8	9.41	2018.5
5	University of New South Wales	8	9.41	2019.0
6	University of Texas at Austin	8	9.41	2018.6
7	Shandong University of Science and Technology	8	9.41	2019.0
8	Consejo Superior de Investigaciones Científicas	6	7.06	2018.5
9	Massachusetts Institute of Technology	6	7.06	2018.3
10	The Hong Kong Polytechnic University	6	7.06	2019.3

liquid separation”. Most countries are still in the laboratory research stage in terms of non-aqueous reprocessing. Only the USA has completed laboratory-scale and engineering-scale simulation experiments, and is preparing for pilot-scale thermal experiments. By 2025, the spent fuel reprocessing industrial demonstration plant will be completed and put into stable operation, conduct special work on reprocessing scientific research, and have the ability to independently build large reprocessing plants. By 2030, the objectives are to carry out further pilot-scale thermal verification of the high-level waste liquid separation process and master the engineering technology. By 2035, the objectives are to realize special scientific research technology of spent fuel reprocessing and master the core technology of large-scale spent fuel reprocessing plants. China will independently construct a large-scale reprocessing plant. By 2050, research on advanced aqueous reprocessing technology will be conducted, verification of non-aqueous reprocessing technology and demonstration of non-aqueous reprocessing projects will be realized, and advanced and complete reprocessing process and radioactive waste treatment along with disposal technologies and industries will be established. Figure 1.2.6 shows the roadmap of the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”.

1.2.3 3D fracture propagation model for hydraulic fracturing

Since the 1950s, research on fracture propagation models for hydraulic fracturing has been conducted both analytically and numerically. PKN (Perkins-Kern-Nordgren), KGD (Khristianovic-Geertsma-de Klerk), and Penny are three classical hydraulic fracturing models that were developed in early stages. In the 1980s, with the progress of computational

solid mechanics technology, fracture propagation models that consider the phase change of fracturing fluid and reservoir heat exchange were gradually developed. In 1983, Cleary established a 3D fracture propagation model for hydraulic fracturing that included singular integral equations to describe the deformation of rock, and finite element methods to simulate the fluid flow in the fracture. This model is used to analyze the effect of stress difference and bedding on fracture propagation and can be directly used in fracture design. Several researchers, including Settari, Hongren Gu, and Donsov, have developed various 3D fracture propagation models for hydraulic fracturing that account for proppant, heat transfer, and fracturing fluid compressibility using finite differences, a finite element mesh, and implicit level set algorithms. The research objective is to closely combine the characteristics and actual conditions of hydraulic fracturing, achieve a comprehensive description of hydraulic fracture geometry, and master the law of hydraulic fracturing. Many countries around the world have conducted extensive research on 3D fracture propagation model for hydraulic fracturing. In particular, China and the USA have made the most remarkable efforts and published most of the core papers. Statistical data (Table 1.2.9 and Figure 1.2.7) show that China and the USA are the countries that pay most attention to the research on 3D fracture propagation model of hydraulic fracturing and produce most relevant core papers. Chinese core papers amount to 143, accounting for 59.83% of the total number of papers, whereas American papers amount to 90, accounting for 37.66%. Together, both countries account for 97.49% of the global production. The main institutions in terms of core papers related to 3D fracture propagation model for hydraulic fracturing also comprise mostly universities and research centers in China and the USA. The data (Table 1.2.10 and Figure 1.2.8) show that there are 6 Chinese universities and 3 American universities in the Top 10. Among them, China

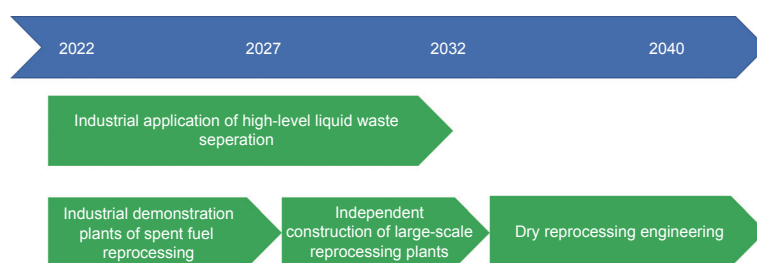


Figure 1.2.6 Roadmap of the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”

Table 1.2.9 Countries with the greatest output of core papers on “3D fracture propagation model for hydraulic fracturing”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	143	59.83	2 128	14.88	2019.3
2	USA	90	37.66	2 151	23.90	2018.6
3	Canada	18	7.53	160	8.89	2019.2
4	Australia	14	5.86	331	23.64	2018.9
5	Germany	11	4.60	580	52.73	2018.8
6	Russia	7	2.93	19	2.71	2018.6
7	UK	6	2.51	65	10.83	2019.5
8	Vietnam	4	1.67	369	92.25	2019.2
9	France	4	1.67	92	23.00	2017.8
10	Switzerland	3	1.26	204	68.00	2019.0

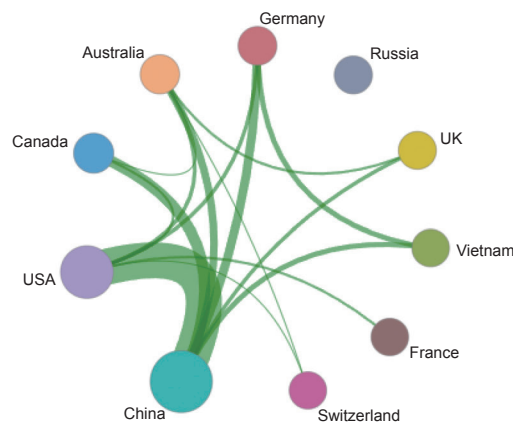


Figure 1.2.7 Collaboration network among major countries in the engineering research front of “3D fracture propagation model for hydraulic fracturing”

Table 1.2.10 Institutions with the greatest output of core papers on “3D fracture propagation model for hydraulic fracturing”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Petroleum	32	13.39	432	13.50	2019.3
2	Southwest Petroleum University	28	11.72	281	10.04	2019.2
3	Texas A&M University	22	9.21	456	20.73	2019.4
4	University of Texas at Austin	20	8.37	869	43.45	2017.6
5	China University of Petroleum East China	12	5.02	160	13.33	2019.2
6	University of Oklahoma	10	4.18	135	13.50	2019.1
7	Chongqing University	10	4.18	76	7.60	2019.5
8	Tongji University	8	3.35	431	53.88	2019.2
9	China University of Mining & Technology	8	3.35	167	20.88	2019.2
10	Commonwealth Scientific and Industrial Research Organisation Energy Centre	7	2.93	228	32.57	2018.6

University of Petroleum (Beijing) has 32 papers, accounting for 13.39% of the total number of papers, and Texas A&M University has 22 papers, accounting for 9.21% of the total number of papers. These are the institutions that present the largest production of core papers in China and the USA. Likewise, China and the USA are also the countries producing most citing papers on 3D fracture propagation model for hydraulic fracturing (Tables 1.2.11 and 1.2.12). Chinese citing papers amount to 1 676, accounting for 55.77%, while the citing papers from USA are 617, accounting for 20.53%. Together, both countries account for 76.3% of the global production. Among the Top 10 universities, 8 are from China and 2 from the USA. The above data clearly demonstrate that China and the USA pay attention to 3D hydrofracture propagation model as a cutting-edge engineering research topic.

Domestic research on 3D fracture propagation model for hydraulic fracturing started earlier. To date, different studies have revealed factors that influence models. A large amount of simulations has been realized using tools such as the ABAQUS large calculation software. However, the development speed is notably slow, mainly because 3D fracture propagation model for hydraulic fracturing involves coupling several complex problems. Strong knowledge of mathematics and mechanics related to coupling is required. In the next 5 to 10 years, 3D fracture propagation model research will still be focused on the mechanisms underlying influence factors such as proppant, heat transfer, fluid compressibility, three-phase flow, and hydraulic and natural fractures. Verification of 3D fracture propagation model by a large number of physical simulation experiments will be required. After ensuring the accuracy of model prediction and achieving reliable high-

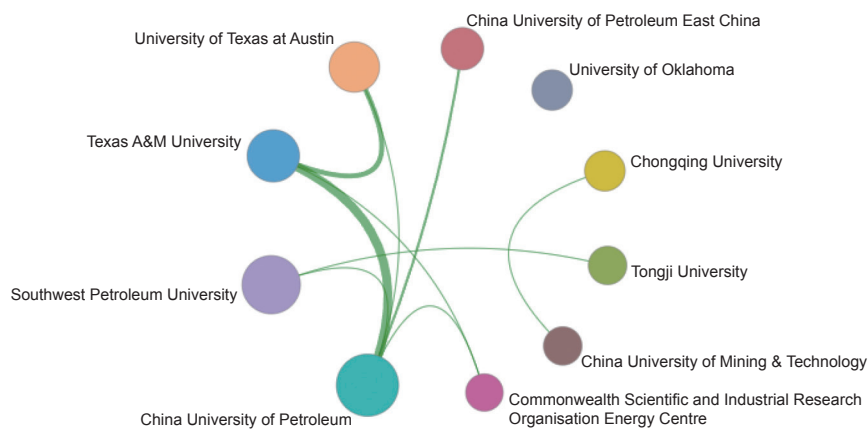


Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “3D fracture propagation model for hydraulic fracturing”

Table 1.2.11 Countries with the greatest output of citing papers on “3D fracture propagation model for hydraulic fracturing”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 676	55.77	2020.0
2	USA	617	20.53	2019.7
3	Canada	136	4.53	2019.9
4	Australia	134	4.46	2019.8
5	Germany	104	3.46	2020.0
6	UK	95	3.16	2019.9
7	Iran	60	2.00	2019.9
8	Russia	58	1.93	2019.9
9	France	51	1.70	2019.6
10	India	38	1.26	2020.1

performance computer and software, multi-factor coupled model software will be developed to carry out high-precision 3D hydraulic pressure fracture prediction, setting a theoretical basis for hydraulic fracturing technology transformation. Figure 1.2.9 shows the roadmap of the engineering research front of “3D fracture propagation model for hydraulic fracturing”.

1.2.4 Induced mechanism and early warning method of rockburst in deep mining

Rockburst is a phenomenon in which the elastic deformation potential energy accumulated in rock mass is suddenly and violently released under certain conditions, resulting in rockburst and ejection. It is a serious dynamic disaster. With the increase of mining depth, rockburst in coal mines is becoming increasingly dangerous. Research on the mechanism of rockburst disaster, monitoring, early warning and prevention, and control technology is increasingly important for safe coal mining.

At present, among the main coal-producing countries in the world, China faces the most deep mining conditions, and the

most serious potential harm from rockburst. To improve the monitoring, early warning, and control level of rockburst, China has conducted extensive scientific research on the induced mechanism and early warning methods of rockburst in deep mining. The country with the highest output of core papers in this field is China, which has produced 78.5% of the core papers, followed by Canada and Australia (Table 1.2.13). Portugal has the highest citation frequency with 35.67 times (Table 1.2.13). Institutions with high output of core papers are mainly Chinese universities, among which China University of Mining and Technology, Shandong University of Science and Technology and University of Science and Technology Beijing occupy the top three in the output of core papers in this field (Table 1.2.14). Among the countries with greatest paper output, China and Australia have more cooperation, followed by China and Canada, China and the USA (Figure 1.2.10). Among the institutions, China University of Mining and Technology and Shandong University of Science and Technology, University of Science and Technology Beijing and North China Institute of Science and Technology have the closest cooperation (Figure 1.2.11). The top two countries with greatest output of cited core papers are China and

Table 1.2.12 Institutions with the greatest output of citing papers on “3D fracture propagation model for hydraulic fracturing”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Petroleum	314	22.57	2020.0
2	Southwest Petroleum University	198	14.23	2019.8
3	China University of Petroleum East China	139	9.99	2019.9
4	China University of Mining & Technology	138	9.92	2020.0
5	Chinese Academy of Sciences	116	8.34	2020.1
6	University of Texas at Austin	101	7.26	2019.2
7	Chongqing University	97	6.97	2020.1
8	Texas A&M University	95	6.83	2019.7
9	China University of Geosciences	73	5.25	2020.0
10	Tongji University	61	4.39	2020.0

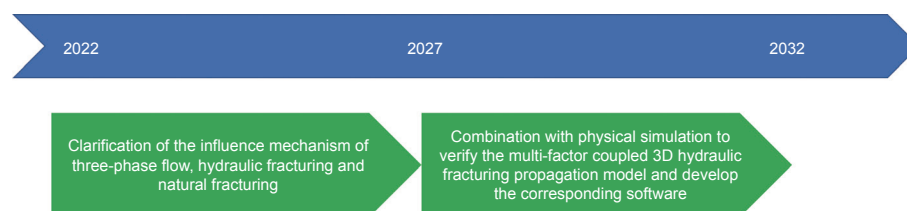


Figure 1.2.9 Roadmap of the engineering research front of “3D fracture propagation model for hydraulic fracturing”

Table 1.2.13 Countries with the greatest output of core papers on “induced mechanism and early warning method of rockburst in deep mining”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	168	78.50	2 860	17.02	2019.2
2	Canada	21	9.81	516	24.57	2018.5
3	Australia	18	8.41	486	27.00	2019.1
4	USA	12	5.61	153	12.75	2018.8
5	Poland	11	5.14	82	7.45	2018.9
6	Czech Republic	9	4.21	117	13.00	2018.0
7	Russia	6	2.80	16	2.67	2017.7
8	South Africa	4	1.87	27	6.75	2018.8
9	Portugal	3	1.40	107	35.67	2018.0
10	Japan	3	1.40	32	10.67	2019.3

Table 1.2.14 Institutions with the greatest output of core papers on “induced mechanism and early warning method of rockburst in deep mining”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Mining and Technology	43	20.09	720	16.74	2018.7
2	Shandong University of Science and Technology	28	13.08	536	19.14	2019.0
3	University of Science and Technology Beijing	21	9.81	230	10.95	2019.3
4	Central South University	10	4.67	322	32.20	2019.9
5	North China Institute of Science and Technology	10	4.67	153	15.30	2019.4
6	Anhui University of Science and Technology	10	4.67	92	9.20	2020.0
7	China University of Mining and Technology-Beijing	9	4.21	147	16.33	2019.6
8	Xi'an University of Science and Technology	9	4.21	58	6.44	2020.1
9	Chinese Academy of Sciences	8	3.74	112	14.00	2019.4
10	Czech Academy of Sciences	7	3.27	109	15.57	2018.3

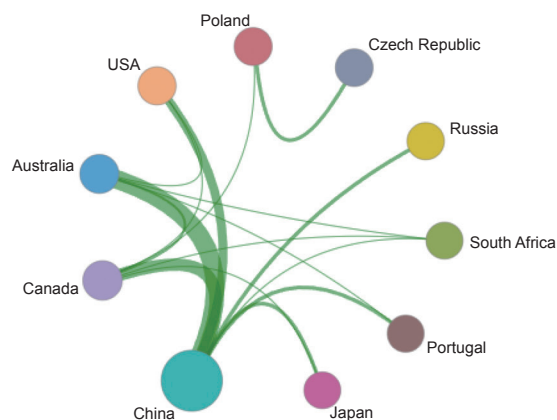


Figure 1.2.10 Collaboration network among major countries in the engineering research front of “induced mechanism and early warning method of rockburst in deep mining”

Australia, accounting for over 80%; the average citation year is 2020 (Table 1.2.15). The top three institutions with greatest output of cited core papers are China University of Mining and Technology, Central South University, and Shandong University of Science and Technology, accounting for 53.07% (Table 1.2.16).

Concerning the occurrence mechanism and prevention technology of rockburst, current research mainly focuses on the dynamic response and catastrophe mechanism of deep coal mine rockburst, intelligent monitoring and early warning theory and technology of deep coal mine rockburst, and prevention and control mechanism and method of deep coal mine rockburst. Regarding the mechanism of rockburst, a recent breakthrough is the study of the mechanism of

rockburst by analyzing the sudden change of strain energy release of surrounding rock. With respect to research directions of rockburst early warning technology, artificial intelligence algorithms, such as data mining and big data processing and analysis, are being integrated to realize intelligent monitoring and early warning of rockburst disasters and multi-field multi-dimensional perception. Conducting in-depth research and making breakthroughs in the field of induced mechanism and early warning methods of rockburst in deep mining will help to release deep mineral resources and fulfill the objective of realizing sustainable development of energy and resources in the future. Figure 1.2.12 shows the roadmap of the engineering research front of “induced mechanism and early warning method of rockburst in deep mining”.

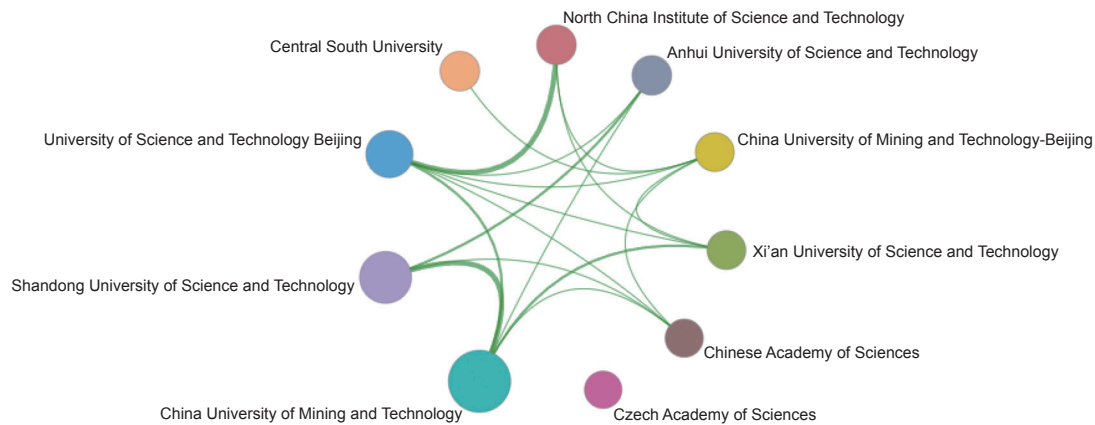


Figure 1.2.11 Collaboration network among major institutions in the engineering research front of “induced mechanism and early warning method of rockburst in deep mining”

Table 1.2.15 Countries with the greatest output of citing papers on “induced mechanism and early warning method of rockburst in deep mining”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 073	74.49	2020.2
2	Australia	164	5.89	2020.1
3	Canada	102	3.67	2019.9
4	USA	101	3.63	2019.9
5	Iran	73	2.62	2020.2
6	Vietnam	62	2.23	2020.5
7	Poland	59	2.12	2020.3
8	UK	42	1.51	2020.0
9	Russia	41	1.47	2020.2
10	Malaysia	37	1.33	2020.4

Table 1.2.16 Institutions with the greatest output of citing papers on “induced mechanism and early warning method of rockburst in deep mining”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Mining and Technology	469	25.93	2019.9
2	Central South University	265	14.65	2020.4
3	Shandong University of Science and Technology	226	12.49	2019.9
4	Chongqing University	145	8.02	2020.0
5	China University of Mining and Technology-Beijing	130	7.19	2020.3
6	University of Science and Technology Beijing	122	6.74	2020.1
7	Henan Polytechnic University	101	5.58	2020.3
8	Northeastern University	97	5.36	2020.3
9	Anhui University of Science and Technology	94	5.20	2020.4
10	Chinese Academy of Sciences	85	4.70	2020.0

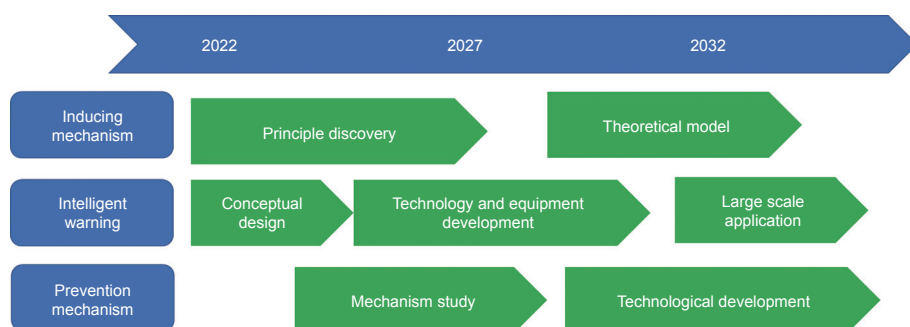


Figure 1.2.12 Roadmap of the engineering research front of “induced mechanism and early warning method of rockburst in deep mining”

2 Engineering development fronts

2.1 Trends in Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 engineering development fronts, “large scale wind solar complementary power generation and stable grid connection technology”, “fast and flexible peak shaving technology for coal-fired units”, and “ammonia-fuelled engine technology” represent the engineering development front of energy and electrical science; “multipurpose new concept micro nuclear reactor”, “technical system for high-

level radioactive waste repository and disposal”, and “tritium production technology by nuclear fusion” represent the engineering development front of nuclear science, technology, and engineering; “high precision prediction system for shale oil and gas production capacity”, “high-precision intelligent 3D visual exploration system”, and “intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources” represent the engineering development front of geology resources science, technology, and engineering; “research and development of looking-around and looking-ahead while-drilling technology”, “research and development of efficient fracturing technology for shale reservoirs”, and “coal mine layer long borehole fracturing, permeability enhancement and extraction technology” represent the engineering development front of mining science, technology, and engineering.

The disclosure of core patents involved in each development front from 2016 to 2021 is presented in Table 2.1.2.

Table 2.1.1 Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Large scale wind solar complementary power generation and stable grid connection technology	70	89	1.27	2018.6
2	Multipurpose new concept micro nuclear reactor	60	150	2.50	2018.6
3	High precision prediction system for shale oil and gas production capacity	145	589	4.06	2019.5
4	Research and development of looking-around and looking-ahead while-drilling technology	128	344	2.69	2017.9
5	Fast and flexible peak shaving technology for coal-fired units	157	124	0.79	2019.8
6	Ammonia-fuelled engine technology	70	53	0.76	2020.3
7	Technical system for high-level radioactive waste repository and disposal	140	172	1.23	2018.7
8	Tritium production technology by nuclear fusion	94	110	1.17	2018.5
9	High-precision intelligent 3D visual exploration system	129	311	2.41	2018.8
10	Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources	162	336	2.07	2018.9
11	Research and development of efficient fracturing technology for shale reservoirs	190	766	4.03	2019.3
12	Coal mine layer long borehole fracturing, permeability enhancement and extraction technology	192	329	1.71	2019.5

Table 2.1.2 Annual number of core patents published for the Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Large scale wind solar complementary power generation and stable grid connection technology	9	6	19	9	19	8
2	Multipurpose new concept micro nuclear reactor	13	6	9	9	5	18
3	High precision prediction system for shale oil and gas production capacity	9	23	27	19	27	40
4	Research and development of looking-around and looking-ahead while-drilling technology	29	30	29	12	20	8
5	Fast and flexible peak shaving technology for coal-fired units	2	11	18	19	42	65
6	Ammonia-fuelled engine technology	2	2	2	2	16	46
7	Technical system for high-level radioactive waste repository and disposal	18	22	23	21	27	29
8	Tritium production technology by nuclear fusion	17	17	14	9	14	23
9	High-precision intelligent 3D visual exploration system	23	15	18	14	20	39
10	Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources	16	17	29	32	28	40
11	Research and development of efficient fracturing technology for shale reservoirs	9	20	24	40	41	56
12	Coal mine layer long borehole fracturing, permeability enhancement and extraction technology	8	9	31	31	50	63

(1) Large scale wind solar complementary power generation and stable grid connection technology

Wind power and solar power are naturally complementary. Wind-solar-storage complementary power generation systems formed with energy storage systems can overcome the volatility and randomness of wind and solar resources, smooth overall power fluctuations in the large-scale wind-solar bases, and ensure the stable operation of new energy high-penetration power system. In recent years, with the continuous increase of the proportion of wind and solar power generation, wind and solar hybrid power generation has evolved towards high voltage levels and multi-station coordination. In addition, the forms of energy storage used for coordination and complementarity are also changing to green and low carbon; this is the case of large-scale hydrogen storage and pumped storage stations. The key technologies involve in the large-scale wind-solar-storage hybrid power generation system including site selection and capacity determination of wind farms, photovoltaic power stations and energy storage power stations; wind-solar-storage coordinated control, dispatch and economic operation technology; the active power grid supporting technology of wind-solar-storage hybrid power generation system; unplanned and off-grid seamless switching technology of wind-solar-storage hybrid power generation system; stable control technology of wind-solar-storage hybrid power generation system.

In the future, the focus of large-scale wind-solar-storage hybrid power generation will be, among other topics, on the development of active grid-supporting technology, unplanned grid-connected and off-grid seamless switching technology, and broadband oscillation suppression to support the steady operation of high-energy-penetration-rate power systems.

(2) Multipurpose new concept micro nuclear reactor

International Atomic Energy Agency (IAEA) generally refers to a reactor with a power generation below 10 MW and with modular features as a micro nuclear reactor. Micro nuclear reactors are neither miniaturized versions of large nuclear power plants nor prototype reactors to verify technical feasibility. They are innovative reactors with advanced technical features that can provide megawatt-level energy in innovative application scenarios according to user needs. Micro nuclear reactors have broad application prospects and unique advantages with respect to other energy sources. They are also one of the important supports for the realization

of national strategies. IAEA and major international nuclear energy countries have recognized the development prospects of micro nuclear reactors and strongly supported their development. The USA, Canada, and the UK have developed technical routes for micro nuclear reactors and provided long-term policy and financial support. The USA has studied the challenges faced by key activities of micro reactor deployment, such as technology development and license application, engineering design procurement and construction, and fuel cycle. They have also put forward suggestions. By cooperating with users, project approval units, nuclear safety review units, technology development units and operating units, it is planned to build and operate at least one micro nuclear reactor demonstrator by the end of 2027.

(3) High precision prediction system for shale oil and gas production capacity

Productivity prediction is an important part of the theoretical system of petroleum development. Whether the prediction result is reliable is one of the core factors that affects the asset evaluation and development scheme design. Commonly used methods for shale oil and gas productivity prediction include numerical simulation, decline analysis, and analytical models. Researchers have conducted extensive research in aspects such as numerical model building, modern production performance, data analysis, and inter-well interference risk prediction, aiming to explore the influence of factors such as fractures, cluster spacing, pore media, compaction, and fluid phase state on productivity. However, shale reservoirs are characterized by complex lithology, diversity hydrocarbon occurrence with large pore-scale span, and complex development processes such as horizontal well and volume fracturing, which lead to deviation between productivity prediction results and actual production. Therefore, it is urgent to develop a high-precision system suitable for shale oil and gas productivity prediction. Four possible trends are expected: ① continuously deepen and improve the research on shale oil and gas occurrence characteristics and seepage mechanism to set a solid foundation for realizing reliable prediction of shale oil and gas production; ② use artificial intelligence technology to analyze big data of geological parameters and engineering parameters in order to explore the main control output factors, establish correlation models, and predict the output; ③ develop non-deterministic prediction methods of shale oil and gas productivity, combine uncertain mathematical theory and physical methods, and

establish uncertain production capacity analytical models or numerical models to realize production prediction; ④ physical simulation and theoretical research on three-dimensional development of shale oil and gas by horizontal wells to promote the realization of systematic theoretical research on methods of production prediction for three-dimensional development.

(4) Research and development of looking-around and looking-ahead while-drilling technology

Measurement while drilling (MWD) refers to technology that realizes real-time measurement and upload of drilling trajectory information and geological parameters during the drilling process. Look-ahead-while-drilling and look-around-while-drilling technologies can be used for geosteering and evaluation of the oil and gas content of complex wells and complex formations. They have become a hot topic in industry. Foreign look-ahead-while-drilling and look-around-while-drilling technologies have been greatly developed, Schlumberger, Halliburton, and other companies have developed various technologies. The detection distance of the look-around-while-drilling technology can reach 60 m, whereas the detection distance of the look-ahead-while-drilling technology can reach 30 m. China's current oil and gas exploration and development are gradually turning to deep and ultra-deep complex formations, deep sea, and unconventional reservoirs, thereby setting more demanding requirements for drilling. Look-ahead-while-drilling and look-around-while-drilling technologies are expected to become key to improve the drilling-encounter ratio and oil and gas production. At present, China has made progress in some stages, but as a whole, these technologies are still lagging behind those of foreign countries. The main research directions are development of downhole test instruments, test process improvement, data transmission and storage, data analysis and interpretation, etc. The development trend of look-ahead-while-drilling and look-around-while-drilling technologies is to reduce costs, increase efficiency, and improve the level of intelligence. This can be used for geosteering and reservoir depiction while-drilling, which are expected to become an important part of smart oilfield and intelligent drilling and of great practical and strategic significance for building a solid foundation of oil and gas resources for China's energy security.

(5) Fast and flexible peak shaving technology for coal-fired

units

Rapid and flexible peak shaving of coal-fired units is a coal-fired power generation technology with capabilities of rapid response and safe and stable operation at low loads according to the load change command of the power grid. For countries/regions that use coal-fired power generation at large scale, this technology is the only one, and consequently key, to increase the proportion of renewable energy power generation and ultimately achieve carbon neutrality.

Renewable energy has the characteristics of fluctuation, intermittence, and uncertainty. Besides, there is a significant space-time difference between the supply of renewable energy and energy consumption of terminal users. Therefore, to ensure the safety of the power grid and stable supply of energy, it is necessary to rely on coal-fired units for rapid and flexible peak shaving in an extensive period of time as long as the energy storage technology remains immature and expensive. The main technical development directions include: ① ultra-low load pulverized coal boiler combustion technology and circulating fluidized bed combustion technology under various coal qualities; ② hydrodynamic safety and reliability, and economy of coal-fired units, under ultra-low load and varying load operation; ③ rapid start and stop technology of coal-fired units; ④ rapid response mechanism of unit load and coupling technology of coal-fired units and various energy storage systems; ⑤ influence of rapid load change of coal-fired units on heating surface materials; ⑥ full-load ultra-low emission technologies and carbon dioxide emission reduction assessment of coal-fired units; ⑦ economic and efficient thermal power decoupling technology and wide load peak shaving technology for thermal power coal-fired units. The core indicators of fast and flexible peak shaving technology are the response speed to the load change command of the power grid. The development trend is a progressively faster peak shaving speed, in which the supercritical unit reaches above 5% PE/min (rated load/min), and the subcritical unit reaches above 8% PE/min (rated load/min).

(6) Ammonia-fuelled engine technology

Fossil fuel-based engines, which are commonly used in power generation, land transportation, ship power, aerospace industry, and other sectors, are one of the major contributors to carbon dioxide emissions. Ammonia, a carbon-free fuel, is viewed as a viable approach to minimize carbon emissions

with respect to traditional carbon-based fuels. However, the combustion of ammonia may encounter some issues, including poor stability and misfire due to high self-ignition temperature and slow flame propagation speed. In addition, the emissions of nitrogen oxides (NO_x) from ammonia engines is generally high because the fuel molecule itself contains nitrogen, which also hinders the development of ammonia to substitute engine fuels.

Dual-fuel technology, which combines ammonia with high-reactivity additives to improve combustion stability, is a potential path to the realization of ammonia-fueled engines. Compared with other high-reactivity fuels, hydrogen has the advantage of being another carbon-free fuel that can be produced online through ammonia cracking. High-efficiency catalytic techniques that convert ammonia into hydrogen is gaining attention. However, owing to the strong diffusivity of hydrogen and high latent vaporization heat of ammonia, the concentration and temperature distribution of ammonia-hydrogen fuel in the engine combustion chamber is often highly inhomogeneous. Therefore, a proper fuel injection strategy to achieve a reasonable distribution of ammonia fuel in the engine and effectively control the combustion phase is a key technology to be accomplished. Although the addition of high-reactivity fuels such as hydrogen improves the combustion stability of ammonia, it also increases the combustion temperature and therefore increases NO_x emissions. Under fuel-rich conditions, NO_x emissions may reduce to a certain extent, but it simultaneously leads to other problems such as poor combustion economy and increased unburned ammonia emissions. Therefore, it is imperative to couple after-treatment methods such as selective catalytic reduction (SCR) and ammonia slip catalyst (ASC) in ammonia-fueled engines to reduce NO_x and unburned ammonia emissions.

In general, single ammonia-fuelled engine technology is still facing many challenges. To achieve the efficiency and emission optimization of ammonia fueled engines, several advanced technologies should be realized, including: ① fast and efficient ammonia on-line cracking to produce high-reactivity hydrogen; ② proper fuel injection strategies, such as high-temperature rich-fuel jet through pre-chamber and multi-stage injection in the main chamber considering the existence of strong turbulences; ③ moderate or intense low oxygen dilution (MILD) combustion, which allows high temperature and low-oxygen concentration to simultaneously

reduce NO_x emission and enhance combustion stability; ④ a strategy to prevent pre-ignition and knocking of ammonia-hydrogen fuel in large space of marine engines; ⑤ after-treatment system, such as SCR and ARC (Ammonia Slip Catalysts), with wide operation window and high conversion efficiency for NO_x and unburned ammonia emissions.

(7) Technical system for high-level radioactive waste repository and disposal

The safe disposal of high-level radioactive waste is a major issue for the sustainable development of nuclear energy and environmental protection. High-level radioactive waste is a special waste with strong radioactivity, high toxicity, long half-life, and heat. Safe disposal is extremely difficult and faces a series of challenges involving science, technology, engineering, humanities, and sociology. In response to this problem, most nuclear-armed countries have carried out a large number of fruitful research and development studies based on the formulation of laws and regulations. They have established management systems, implemented agencies, and financed mechanisms. They have also developed long-term plans and underground laboratories as well as other R&D platforms to ensure safe disposal of waste. Since the research and development of geological disposal of high-level radioactive waste began, in the 1960s, extraordinary achievements have been made in geological disposal site selection and evaluation, engineering barriers, repository design and construction technology, underground laboratory construction and experiments, and safety evaluation research. The most prominent countries in the implementation of repository engineering are Finland, France, and Sweden. Core technologies include site evaluation; high-precision hydrogeological parameter measurement systems; fracture network simulation; ultra-low-concentration radionuclide migration evaluation; engineering barrier design and manufacturing; disposal container design; evaluation and manufacturing; safety evaluation; ultra-long-term and ultra-large-scale safety evaluation simulation; key equipment development (such as disposal pit excavation, waste container placement), and high-precision and high-reliability hydrological parameter testing system.

(8) Tritium production technology by nuclear fusion

Tritium plays an important role in the military, energy, industry, and scientific research fields, among others. Natural

tritium is extremely rare and difficult to utilize and is often produced through man-made means such as gas pedals and nuclear fission reactors. Compared to other approaches, nuclear fusion reactions can directly produce high-energy neutrons and have more advantages in tritium production. Tritium production by nuclear fusion is a process that uses the nuclear reaction of high-energy neutrons with Li-6 to produce tritium. It also extracts and purifies the tritium in a safe and inclusive manner. The main directions involved in the development of fusion tritium technology include design and fabrication of tritium-producing cladding for nuclear fusion reactors, tritium extraction, separation and purification, and safe containment. According to tritium production efficiency requirements, the tritium-producing blanket of nuclear fusion reactors can be designed as a conventional or hybrid blanket: a conventional blanket presents clean features but tritium production efficiency needs to be improved. One of the goals of the ITER, currently under development, is to test tritium production in a tritium breeder blanket. Likewise, the main objective of China's proposed China Fusion Engineering Test Reactor (CFETR) is to achieve tritium self-sustainability through tritium production in the blanket. A hybrid blanket is chain-amplified by introducing fission fuel to the neutron yield. This can achieve efficient tritium production but is less clean. Tritium extraction, separation, and purification and safe inclusion technologies are critical factors that affect tritium self-sustainability. Therefore, the development of fusion-tritium production technology still needs to focus on tritium-production blanket design, fabrication, and verification, tritium-permeation retention reduction, tritium extraction and separation and purification efficiency, and safe inclusion of tritium operation.

(9) High-precision intelligent 3D visual exploration system

A high-precision intelligent 3D visual exploration system refers to a prospecting system with enhanced precision based on artificial intelligence technology for comprehensive exploration data related to mineral exploration, such as those employed in geophysics, multispectral and hyperspectral remote sensing, infrared spectral detection, and geochemistry and geology, under the guidance of the theory of mineral deposits. It includes hardware and software. The main research line is to continuously improve the accuracy of exploration through the development of sensor hardware technology and software algorithms. Hardware development is mainly focused on high-performance sensors, reliable

performance of core chips, data acquisition accuracy, and power. Software development consists mainly in algorithmic innovations for deep-seated ore prospecting information mining. Finally, 3D exploration is realized through independent and controllable artificial intelligence prospecting and exploration software. Future development trends are as follows: ① constant improvement of the performance of hardware related to exploration for more accurate collection of geological exploration information; ② higher exploration precision of all types of information for in-depth excavation, especially in the proposed target area; ③ artificial intelligence encapsulation of expert knowledge to realize simple and user-friendly interfaces; ④ latest exploration data displayed in real-time 3D visualization systems.

(10) Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources

Potassium salt is a strategic mineral resource related to food security that has been classified as a large and scarce strategic mineral by China. Lithium salt is also a new strategic energy mineral, and its foreign dependence remains high, which seriously threatens the national security of mineral resources. The difficulties in exploring deep potassium/lithium salt resources in China are mainly multiple resource endowment states (solid and liquid phases), complex late tectonic deformation, and strong non-homogeneity of brine reservoirs, which have hindered the achievement of breakthroughs for a long time.

To date, there are no international evaluation criteria for new deep miscellaneous halite potash and lithium-rich brines. Intelligent identification and comprehensive resource evaluation technology of new potassium halite and lithium-rich brines are established on the basis of long-term practice. They take advantage of the geophysical and drilling data characteristics of new deep miscellaneous halite potash ores: high gamma, high potassium, high resistance, low thorium, low uranium, and large well diameter. They also establish “three high, two low, and one large” comprehensive logging identification technologies. For the geological characteristics of lithium-rich potash brines, “three high, four low (high neutron porosity, high acoustic time difference, high gamma energy spectrum potassium, low natural gamma, low natural potential, low resistivity, low density)” logging comprehensive intelligent

identification technology is established. Combined with massive 3D seismic data to carry out planar intelligent identification prediction, new deep miscellaneous halite potash and lithium-rich brine layers can be found, obtaining information on the depth, thickness, mineral content, and porosity of brine reservoirs in the target layer. On this basis, the necessary parameters for the evaluation of deep potash/lithium resources are obtained and a comprehensive evaluation is completed. This technology was first created by Zheng Mianping's team in the Xuanhan area of northeast Sichuan and achieved a major breakthrough in deep potassium/lithium resource exploration. This technology is helpful to break the bottleneck of comprehensive evaluation of deep sea-phase potassium and lithium resources in China.

The next step is to improve the prediction accuracy, increase the landmark parameters, improve the existing set of deep geological exploration technologies, and create relevant norms for deep solid and brine salts. The objective is to promote the formation of the first large-scale "comprehensive industrial base of lithium and potassium resources in the marine phase" in China, and produce pioneering results domestically and abroad.

(11) Research and development of efficient fracturing technology for shale reservoirs

Shale is dominated by micro-nano pore throats, and the brittle mineral content is generally greater than 35%. Fracturing is the core technology to shorten the seepage distance of oil and gas and realize the economic exploitation of shale. Shale reservoir reconstruction is required to form interlaced fracture networks and has become the industry consensus. Horizontal well staged multi-cluster fracturing is the main technology for reservoir reconstruction. In recent years, the number of stages, clusters, and sand addition in fracturing design has been increasing. Likewise, the proportion of sliding water fracturing has been gradually increased and the spacing of fracturing and clusters has been shortened. Different from the stable tectonic conditions in the North American Plain, the shale strata in China have poor continuity and strong segmentation. Domestic shale development cannot copy the mode of multi-well staged network fracturing. Therefore, it is necessary to form a full-well fracture network mode to achieve high yield with fewer wells. Maximizing the distribution of fracture networks is key

for efficient fracturing, but it faces the following challenges, among others: non-synchronous initiation of fractures, formation of main fractures, and inter-fracture interference and fracture steering near the wellbore zone. In view of the above problems, the research directions mainly include the following technologies: branch well fracturing, high-speed channel fracturing, variable displacement fracturing, repeated fracturing, synchronous fracturing, zipper fracturing, steering fracturing, and small well spacing three-dimensional development. Each fracturing process has its own limitations. Only by realizing an integrated reservoir solution that matches geology and engineering, optimal reservoir reconstruction volume can be achieved and efficient development of shale oil and gas in China can be promoted.

(12) Coal mine layer long borehole fracturing, permeability enhancement and extraction technology

With the deepening of coal mining in China, the proportion of high gas and low permeability coal seam expands constantly. In this new situation, the problem of gas control and efficient extraction needs to be solved urgently. Anti-reflection extraction and extraction technology based on long drilling holes in coal seam uses directional drilling machines to construct horizontal long drilling holes in coal seam and capsule hole sealers to seal holes in sections. Fracturing fluid is thus delivered to the sealing hole section through a high-pressure sealing drill pipe to perform sectional fracturing on coal body. This can effectively change the development of coal seam fractures, increase the permeability of coal seam, and greatly increase the drilling concentration and flow rate. The main research directions are the development of deep-hole fracturing tool strings, optimization of fracturing proppant, development of downhole fracturing pump with high pressure and large flow rate, and exploration of gas-liquid collaborative fracturing technology. In the future, anti-reflection extraction technology based on long borehole fracturing in underground coal mines will greatly improve the efficiency of gas advanced control in coal mine areas and shorten the time of gas extraction reaching the standard. Current conventional hydraulic anti-reflection measures such as hydraulic slit, cavitation, and punching are expected to be replaced. The realization of anti-reflection extraction of low-permeability coal seam will lead to faster, efficient, and energy-saving characteristics.

2.2 Interpretations for four key engineering development fronts

2.2.1 Large scale wind solar complementary power generation and stable grid connection technology

Owing to the randomness and volatility of wind and solar power output, direct grid connection will have an impact on the power system. To ensure the stable operation of the power grid, related companies often restrict the grid connection of wind and photovoltaic power generation through dispatching means or provide backup services by thermal power units. Although the stable operation of the system is thus ensured, the abandonment of wind and light has caused serious waste. Wind power and photovoltaics have certain complementarity. Integrated wind-solar-storage power generation combined with energy storage devices constitutes a high-quality power source under the action of intelligent regulation technology. The coordination of wind-solar complementary power generation and energy storage can improve the consumption rate of wind-solar resources and stabilize the power supply capacity. Denmark, the UK, and other European countries with rich wind resources have planned a large number of wind-solar-storage integrated power plants in coastal areas. Denmark's Eurowind Energy has planned the deployment of more than 1 GW of wind-solar-storage onshore energy centers and considered the use of hydrogen electrolysis as large-scale energy storage. General Electric has built a 380 MW large-scale wind-solar-storage project in Oregon, and Australia's Walcha Energy has built a 4 GW wind-solar-storage project in New South Wales (NSW). The earliest wind-solar-storage hybrid power generation project in China was a 54 MW/100 kWp wind-solar hybrid power plant built by Huaneng Nanao in December 2004. With the national policy biased towards renewable energy generation, integrated wind-solar-storage power generation technology has been fully developed and applied. Limited by the geographical layout, most of the wind-solar-storage hybrid power generation systems in China are distributed in northwest and coastal areas

with sufficient solar or wind resources. In the future, wind-solar-storage power generation will be jointly planned and designed with transmission systems. China's first 10- million-kilowatt-level wind-solar-storage-transmission multi-energy complementary integrated energy base was officially launched in Gansu in 2021. China Energy Engineering Group Co., Ltd., China Energy Investment Corporation, Shanxi International Energy Group Co., Ltd., Beijing Energy Holding Co., Ltd., China Power Investment Corporation and State Nuclear Power Technology Corporation, and other 15 central and state-owned enterprises have signed 27 wind-solar-storage projects, with a total project planning scale of 42.49 GW.

At present, as shown in Table 2.2.1, the top three countries in terms of patent production in this field are China, India, and South Korea. China has published 63 related patents, accounting for 90% of the public disclosure. There are 6 related patents published in India, accounting for 8.57%. There is 1 relevant patent published in South Korea, accounting for 1.43%. China has the highest patent citation frequency and average citation frequency, 86 and 1.37 respectively, and the citation frequency ratio is 96.63%. There is no cooperation among countries. According to Table 2.2.2, the major institutions of patent output are State Grid Corporation of China, Hohai University, Sungrow Power Supply Company Limited. State Grid Corporation of China and Zhuji Dongbai Power Installation Engineering Company Limited have carried out related engineering cooperation, as shown in Figure 2.2.1.

In the next 5–10 years, large-scale photovoltaic-wind-storage hybrid power generation systems will become an important component to ensure safe operation and support the stability of voltage and frequency of power systems. Considering both the capacity of consumption and active support of the power grid is the key development direction of future photovoltaic-wind-storage hybrid power generation systems, involving the following key technologies:

1) Large-scale photovoltaic-wind-storage hybrid high-proportioned absorption technology to smooth the output

Table 2.2.1 Countries with the greatest output of core patents on "large scale wind solar complementary power generation and stable grid connection technology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	63	90.00	86	96.63	1.37
2	India	6	8.57	3	3.37	0.50
3	South Korea	1	1.43	0	0.00	0.00

Table 2.2.2 Institutions with the greatest output of core patents on “large scale wind solar complementary power generation and stable grid connection technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	State Grid Corporation of China	8	11.43	18	20.22	2.25
2	Hohai University	2	2.86	3	3.37	1.50
3	Sungrow Power Supply Co., Ltd.	2	2.86	1	1.12	0.50
4	Shanghai University of Engineering Science	1	1.43	13	14.61	13.00
5	Nantong University	1	1.43	7	7.87	7.00
6	Nanjing Institute of Technology	1	1.43	6	6.74	6.00
7	Harbin Electric Co., Ltd.	1	1.43	5	5.62	5.00
8	Guangdong Electric Power Design Institute	1	1.43	4	4.49	4.00
9	Huaxia Wuwei Cultural Industries Co., Ltd.	1	1.43	4	4.49	4.00
10	Zhuji Dongbai Power Installation Engineering Co., Ltd.	1	1.43	4	4.49	4.00

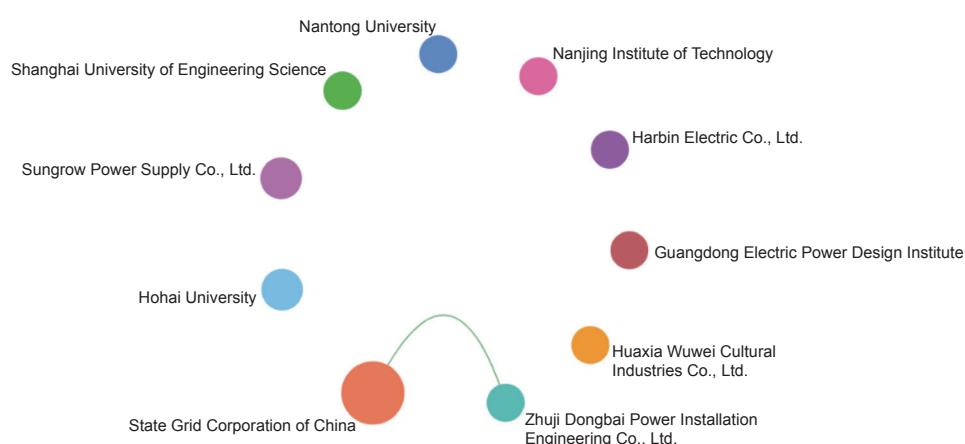


Figure 2.2.1 Collaboration network among major institutions in the engineering development front of “large scale wind solar complementary power generation and stable grid connection technology”

fluctuations of new energy sources, compensate the power prediction error, reduce the wind and light curtailment rates, and increase the number of new energy grid connections and the delivery capacity.

2) Grid-connected technology of photovoltaic-wind-storage with inertial control. Dynamic disturbance control technology represented by virtual synchronous machine control and variable droop control dynamically adjusts to incorporate the frequency and voltage of bus bar for improving the fault ride-through capability of new energy.

3) High-energy-density and high-reliability energy storage systems to improve the manufacturing process, operation ability, and safety performance of single equipment components such as energy storage battery, battery management system, and energy storage converter.

Under the background of building a new type of power system with new energy as the main body in China, the proportion of renewable energy generation in China will increase from 30% to 50%, or even higher. Large-scale photovoltaic-wind-storage hybrid power generation and stable grid-connected

technology will become the core technologies of energy construction in the future. The new photovoltaic-wind-storage project will reach more than 50 million kilowatts. In the future, China will build a photovoltaic-wind-storage power generation base, photovoltaic-wind-storage hybrid base, wind-photovoltaic-hydrogen-storage complementary base, and other related projects.

Figure 2.2.2 shows the roadmap of the engineering development front of “large scale wind solar complementary power generation and stable grid connection technology”.

2.2.2 Multipurpose new concept micro nuclear reactor

Micro nuclear reactors are neither miniaturized versions of large nuclear power plants nor prototype reactors to verify technical feasibility. They are innovative reactors with advanced technical features that can provide megawatt-level energy in innovative application scenarios according to user needs. To meet user needs in innovative application scenarios, the design of micro nuclear reactors must consider multiple factors, such as safety improvement, simplification of on-site construction, flexible deployment, and simplified operation. Moreover, this design generally has innovative technical characteristics: high inherent safety; easy modularization and expansion; transportability; ease of deployment; autonomous operation.

Micro nuclear reactors can meet flexible and diverse energy needs for multiple nuclear energy innovation fields and can provide small-capacity or distributed green and clean power and heat sources for remote islands and mining areas, border posts and bases, and other important remote areas. They can also provide emergency relief after disasters or to war victims. They can provide emergency or backup power after damage to important infrastructures. As an energy module with high capacity density, small size, and reduced maintenance during operation, a micro nuclear reactor can provide long-endurance autonomous operation power for important applications such

as deep-sea exploration and space exploration; it can also be used as high-energy density equipment. Providing a long-life power supply with flexible deployment has been a research and development hot topic in the international nuclear energy industry in recent years.

As early as in the 1960s and 1970s, the USA and the Soviet Union had developed micro nuclear reactors for space exploration and military bases; this ended with the end of the Cold War. Around 2015, leveraging key technological breakthroughs of space heat pipe reactors in the USA and the emergence of new demands for land-based nuclear power sources, micro nuclear reactors have become a research and development hot topic in the world, revealing the characteristics of a diversity of reactor types and system configurations.

At present, the micro nuclear reactors disclosed domestically and abroad include high-temperature gas-cooled reactors, heat pipe reactors, sodium-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, and light water reactors. In addition to power generation capabilities, various micro nuclear reactors are designed with transport and mobility in mind. In general, when designing micro nuclear reactor thermoelectric conversion systems and waste heat removal systems, compact and lightweight designs are especially considered, and transportability is a key objective to be fulfilled as much as possible. Specifically, factors such as the choice of reactor vessel, reactor type, fuel type and enrichment, reflector material, and control rods and drums affect the size of the reactor vessel and thus the transportability of the reactor design. For thermoelectric conversion systems, compact heat exchangers and Rankine cycles, supercritical carbon dioxide, nitrogen, and helium closed or open Brayton cycles are mainly used. Concerning waste heat removal systems, natural circulation or thermal radiation/thermal conduction transfers the core heat to the periphery. The heat is then dissipated through passive air cooling or metal fins.

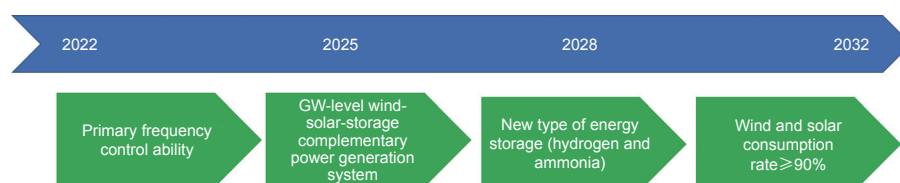


Figure 2.2.2 Roadmap of the engineering development front of “large scale wind solar complementary power generation and stable grid connection technology”

As shown in Table 2.2.3, the countries with the largest number of core patents in this research topic are China, the USA, and South Korea. Among them, the proportion of core patents in ① China exceeds 60%, ② the USA and South Korea both exceed 14%, and ③ other countries are less than 2%. There is no cooperation among countries. It can be seen from Table 2.2.4 that the institutions with the largest number of core patents in this research topic are Xi'an Jiaotong University, Xi'an Thermal Power Research Institute, Westinghouse Electric Company, South China University of Technology, and Nuclear Power Institute of China. They have a proportion exceeding 4% on average. As shown in Figure 2.2.3, the cooperation among institutions in this field is mainly domestic.

Most of the domestic and abroad micro nuclear reactors are currently in key technology research stage. The first demonstration and verification tests are expected to be conducted after 2025–2027. According to the technological

development trends in large nuclear power plants in China and the innovative technical characteristics of small and micro nuclear reactors, the technological development trends in micro nuclear reactors are to improve the inherent safety, compact and lightweight design, easy transportation, and ease of deployment for users, and use flexibility. After further analysis, the identified key technologies include: new fuels (such as accident-resistant fuels), main circuit integration, new thermoelectric conversion, passive safety systems, intelligent operation and maintenance, and coupling of nuclear energy and other energy sources. Different micro nuclear reactors are employed for development and verification of the above-mentioned key technologies and equipment based on the reactor characteristics and technological maturity. Figure 2.2.4 shows the roadmap of the engineering development front of “multipurpose new concept micro nuclear reactor”.

Table 2.2.3 Countries with the greatest output of core patents on “multipurpose new concept micro nuclear reactor”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	39	65.00	65	43.33	1.67
2	USA	9	15.00	80	53.33	8.89
3	South Korea	9	15.00	1	0.67	0.11
4	Switzerland	1	1.67	4	2.67	4.00
5	Germany	1	1.67	0	0.00	0.00
6	Japan	1	1.67	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “multipurpose new concept micro nuclear reactor”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Xi'an Jiaotong University	5	8.33	8	5.33	1.60
2	Xi'an Thermal Power Research Institute	4	6.67	3	2.00	0.75
3	Westinghouse Electric Company	3	5.00	22	14.67	7.33
4	South China University of Technology	3	5.00	8	5.33	2.67
5	Nuclear Power Institute of China	3	5.00	3	2.00	1.00
6	Shenzhen Alpha BioPharm Co., Ltd.	2	3.33	13	8.67	6.50
7	Yunnan Jici Institute of Regenerative Medicine	2	3.33	13	8.67	6.50
8	Liaoning Dahua Guorui New Materials Co., Ltd.	2	3.33	11	7.33	5.50
9	TerraPower Limited Liability Company	2	3.33	11	7.33	5.50
10	China Aerospace Academy of Systems Science and Engineering	2	3.33	1	0.67	0.50

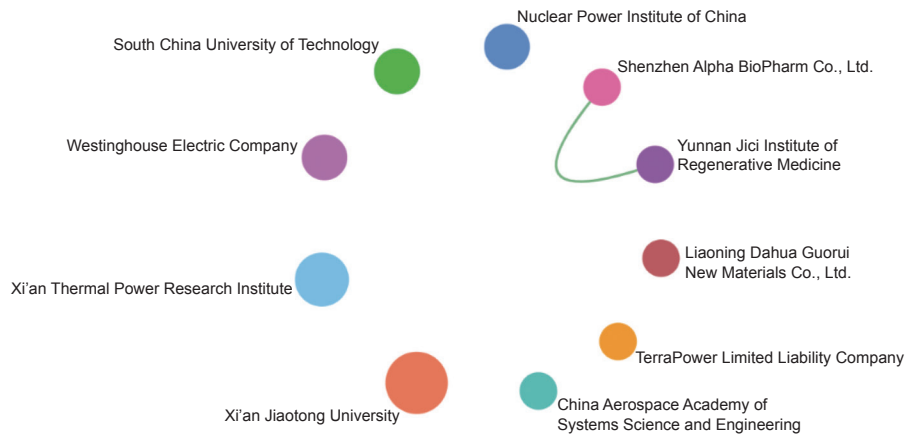


Figure 2.2.3 Collaboration network among major institutions in the engineering development front of “multipurpose new concept micro nuclear reactor”

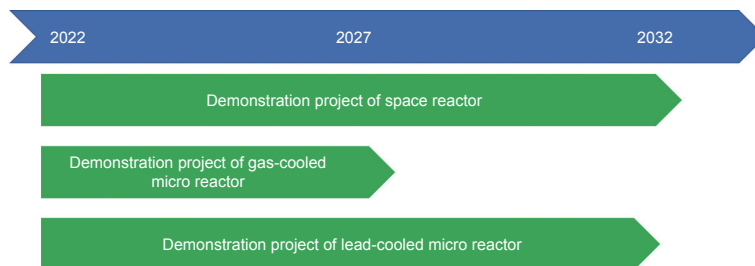


Figure 2.2.4 Roadmap of the engineering development front of “multipurpose new concept micro nuclear reactor”

2.2.3 High precision prediction system for shale oil and gas production capacity

Predictivity is an important prerequisite for shale oil and gas resource evaluation and development scheme designs. An accurate estimate of production capacity and output is key for shale oil and gas development and can provide effective support for scientific arrangement and deployment of various tasks, formulation of reasonable production systems, and realization of sustainable development. The characteristics of ultra-low porosity, low permeability, and multi-stage fracturing of shale reservoirs give rise to unsteady flows in long production cycles of oil and gas wells. No conditions exist to achieve quasi-steady flow for production capacity testing. The production decline law is not clear, especially in later stages. Strong fracturing reconstruction makes shale fracture systems complex and difficult to identify. It is also difficult to select multiple sets of production capacity prediction models, and uncertain numerical simulation is caused by the uncertainty of the flow mechanism. Therefore, the prediction of shale oil and gas production capacity is difficult and highly

uncertain. Conventional prediction methods are not adaptable to shale oil and gas. It is appropriate to pay attention to mine production data, build the relationship between production capacity and geological engineering parameters, strengthen dynamic analysis, and integrate multiple prediction methods to build a high-precision prediction system.

At present, China is the main producing country of patents in the development frontier of “high precision prediction systems of shale oil and gas production capacity”, with 120 patents, accounting for 82.76%. South Korea and the USA rank second and third with 12 and 10 pieces, accounting for 8.28% and 6.90%, respectively (Table 2.2.5). The largest patent-output institution is China. There is no cooperation among countries. Among the Top 10 institutions in terms of output, nine are oil and gas-related Chinese companies or universities. Among them, China Petroleum and Chemical Corporation rank first with 32 patents, accounting for 22.07% (Table 2.2.6). China’s oil and gas related companies and universities cooperate closely. The most cooperative institutions are Sichuan Changning Natural Gas Development Co., Ltd. and

Chengdu Chuanyou Ruifei Technology Co., Ltd. (Figure 2.2.5).

In the next 5–10 years, high-precision prediction systems for shale oil and gas production capacity will mainly have two key development directions: first, deepening the understanding of shale oil and gas geology and engineering theory; second, establishing a comprehensive evaluation method and prediction model for shale oil and gas production capacity (Figure 2.2.6). These directions can be divided into the following four topics: ① deepening and improving the research on the occurrence characteristics and flow mechanism of shale oil and gas, and setting a solid foundation for promoting the reliable prediction of shale gas production capacity; ② using artificial intelligence technology to carry out big data analysis of geological parameters and engineering

parameters, exploring the main control factors of production, establishing relevant relationship models, and finally predicting production; ③ conducting research on prediction methods of uncertain production capacity, and combining uncertain mathematical theory and physical methods to derive an analytical or numerical model of uncertain production capacity to realize prediction of uncertain production capacity; ④ developing physical simulation and theoretical research on three-dimensional development of shale oil and gas horizontal wells, promoting the generation of systematic research results on production capacity evaluation methods for three-dimensional development of shale oil and gas horizontal wells. Considering the actual conditions and uncertain factors of shale oil and gas reservoir development,

Table 2.2.5 Countries with the greatest output of core patents on “high precision prediction system for shale oil and gas production capacity”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	120	82.76	485	82.34	4.04
2	South Korea	12	8.28	39	6.62	3.25
3	USA	10	6.90	63	10.70	6.30
4	France	1	0.69	2	0.34	2.00
5	Australia	1	0.69	0	0.00	0.00
6	Saudi Arabia	1	0.69	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “high precision prediction system for shale oil and gas production capacity”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Petroleum & Chemical Corporation	32	22.07	129	21.90	4.03
2	Southwest Petroleum University	21	14.48	73	12.39	3.48
3	PetroChina Co., Ltd.	20	13.79	125	21.22	6.25
4	China University of Petroleum-Beijing	9	6.21	17	2.89	1.89
5	Chongqing University of Science & Technology	6	4.14	32	5.43	5.33
6	Sichuan Changning Natural Gas Development Co., Ltd.	4	2.76	1	0.17	0.25
7	Yangtze University	3	2.07	15	2.55	5.00
8	China University of Geosciences (Beijing)	3	2.07	9	1.53	3.00
9	Korea Institute of Geoscience and Mineral Resources	3	2.07	8	1.36	2.67
10	Chengdu Chuanyou Ruifei Technology Co., Ltd.	3	2.07	0	0.00	0.00

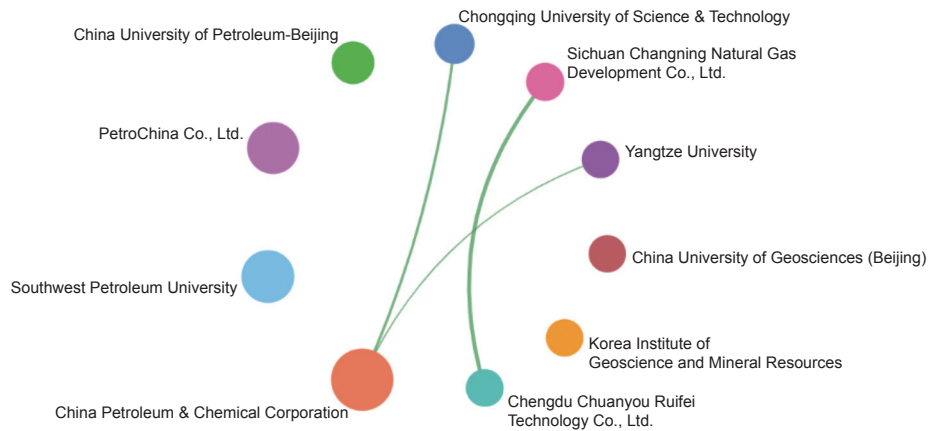


Figure 2.2.5 Collaboration network among major institutions in the engineering development front of “high precision prediction system for shale oil and gas production capacity”

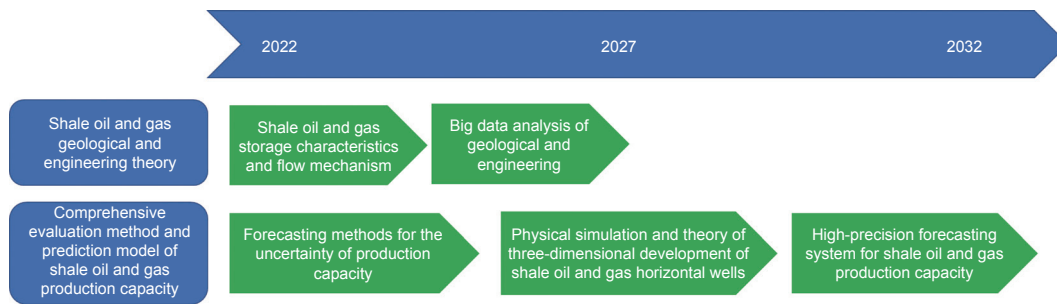


Figure 2.2.6 Roadmap of the engineering development front of “high precision prediction system for shale oil and gas production capacity”

comprehensive evaluation methods and prediction model of shale oil and gas production capacity can be used to achieve an accurate prediction of production capacity and provide scientific guidance for promoting the increase of reserves, production, and economic development of continental shale oil and marine shale gas in China.

2.2.4 Research and development of looking-around and looking-ahead while-drilling technology

Measurement while drilling (MWD) refers to the technology that realizes real-time measurement and upload of drilling trajectory information and geological parameters during the drilling process. Look-ahead-while-drilling and look-around-while-drilling technologies can be used for geosteering and evaluation of oil and gas content of complex wells and formations. It has become a hot topic in the industry. Look-ahead-while-drilling technology makes use of logging

instruments to detect the stratigraphic interface of an unexplored formation in front of a drill bit. The detection direction is the same as that of wellbore/drilling, mainly used for geosteering. Look-around-while-drilling technology makes use of logging instruments to detect fluid and formation boundaries as well as other formation information in a long range from the wellbore. In this case, the detection direction is perpendicular to the wellbore direction, mainly used for reservoir description and formation evaluation.

Foreign look-ahead-while-drilling and look-around-while-drilling technologies have been greatly developed. Schlumberger, Halliburton, and other companies have developed Geosphere, Earthstar, IriSphere and other technologies. The detection distance of the look-around-while-drilling technology can reach 60 m, whereas the detection distance of the look-ahead-while-drilling technology can reach 30 m. China's current oil and gas exploration

and development is gradually turning to deep and ultra-deep complex formations, deep sea, and unconventional reservoirs, which puts forward higher requirements for drilling. Look-ahead-while-drilling and look-around-while-drilling technologies are expected to become key to improve the drilling-encounter ratio and oil and gas production. In 2006, China set up the “Research on Seismic While Drilling Technology” project in the National High-tech R&D Program (863 Program), and made a certain breakthrough in the vertical seismic profiling (VSP). In 2014, Greatwall Drilling launched GW-LWD (BWRX) with a detection distance of 2–3 m, thereby reaching the international advanced level. In 2016, Bohai Drilling Engineering Co., Ltd. (BHDC) launched the Azimuth Detection Acoustic Imaging Logger, which can make reservoir predictions. At present, China has made progress in different stages, but overall, the technology is still lagging behind foreign countries. The main research directions of the technology are development of downhole test instruments, test process improvement, data transmission and storage, data analysis and interpretation, etc.

The top two countries with most published core patents for looking-around and looking-ahead while-drilling technology are the USA (63) and China (56), with proportions of 49.22% and 43.75%, respectively. The proportion of core patents of other countries is below 6.00%. The USA has the highest number of citations (206) and highest percentage of citations (59.88%) for published core patents. The percentage of citations in China and Canada are 35.47% and 11.92%, respectively, and the percentage of citations for related

technologies in other countries are less than 10%. The top country with the highest citations per patent is Canada (5.86) (Table 2.2.7). Institutions with most published core patents include Halliburton Energy Services Incorporation (32), Schlumberger Technology Corporation (18), PetroChina Co., Ltd. (10), China Petroleum & Chemical Corporation (9), Institute of Geology and Geophysics Chinese Academy of Sciences (7). The top institution in terms of citation percentage is Halliburton Energy Services Incorporation (27.62%) and in terms of highest number of citations per patent is Institute of Geology and Geophysics, Chinese Academy of Sciences (8.29) (Table 2.2.8). Countries that focus on cooperation include the USA, Netherlands, Canada, and France (Figure 2.2.7), and cooperative research between institutions is concentrated in China National Offshore Oil Corporation and Hangzhou Xunmei Technology Co., Ltd. (Figure 2.2.8).

Look-ahead-while-drilling and look-around-while-drilling technologies have broad development prospects in the fields of geosteering and complex oil and gas evaluation. In the next 5–10 years, the key development directions of the technology are to reduce costs, increase efficiency, and improve the intelligence level. Combining look-ahead-while-drilling and look-around-while-drilling technologies with “one-trip logging” and “one-trip drilling” technology can simplify the operation process and reduce the cost. Research and development of new instruments and processes can efficiently produce logging information and realize fluid and core sampling, which is expected to greatly improve the

Table 2.2.7 Countries with the greatest output of core patents on “research and development of looking-around and looking-ahead while-drilling technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	63	49.22	206	59.88	3.27
2	China	56	43.75	122	35.47	2.18
3	Canada	7	5.47	41	11.92	5.86
4	France	7	5.47	31	9.01	4.43
5	Netherlands	7	5.47	31	9.01	4.43
6	Russia	2	1.56	1	0.29	0.50
7	Norway	2	1.56	0	0.00	0.00
8	Germany	1	0.78	3	0.87	3.00
9	Saudi Arabia	1	0.78	2	0.58	2.00

Table 2.2.8 Institutions with the greatest output of core patents on “research and development of looking-around and looking-ahead while-drilling technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Halliburton Energy Services Incorporation	32	25.00	95	27.62	2.97
2	Schlumberger Technology Corporation	18	14.06	78	22.67	4.33
3	PetroChina Co., Ltd.	10	7.81	16	4.65	1.60
4	China Petroleum & Chemical Corporation	9	7.03	9	2.62	1.00
5	Institute of Geology and Geophysics, Chinese Academy of Sciences	7	5.47	58	16.86	8.29
6	China National Offshore Oil Corporation	5	3.91	6	1.74	1.20
7	Baker Hughes Incorporated	4	3.12	20	5.81	5.00
8	Hangzhou Xunmei Technology Co.,Ltd.	3	2.34	5	1.45	1.67
9	Institute of Acoustics, Chinese Academy of Sciences	3	2.34	4	1.16	1.33
10	University of Electronic Science and Technology of China	2	1.56	9	2.62	4.50

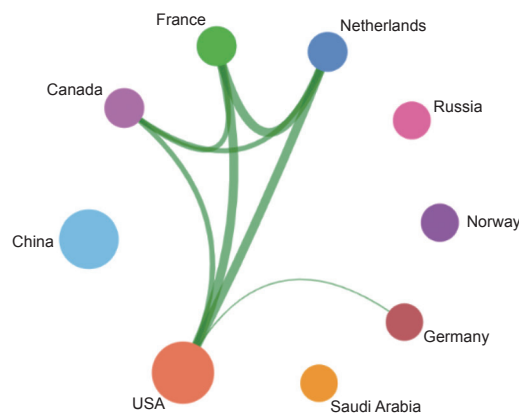


Figure 2.2.7 Collaboration network among major countries in the engineering development front of “research and development of looking-around and looking-ahead while-drilling technology”

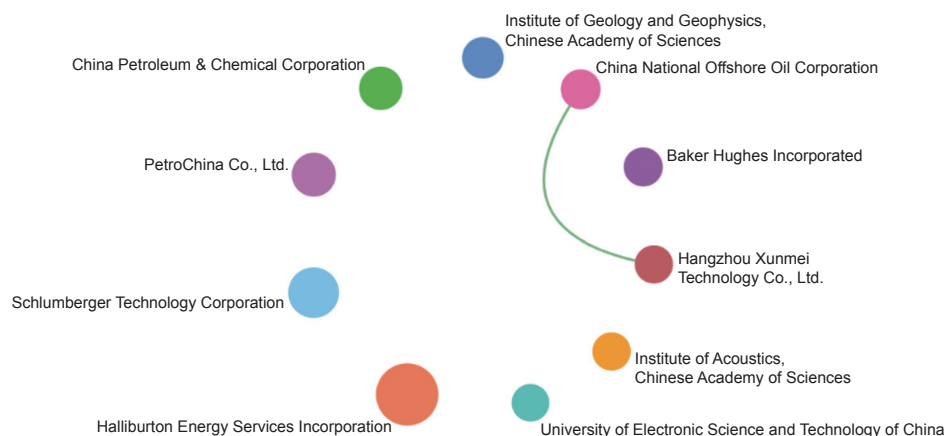


Figure 2.2.8 Collaboration network among major institutions in the engineering development front of “research and development of looking-around and looking-ahead while-drilling technology”

drilling-encounter ratio and oil and gas production. Combined with big data and cloud computing, improving the level of intelligence and strengthening the research and development of relevant software such as data measurement and information interpretation can lead to achieve efficient and high-precision

data acquisition and analysis. This is expected to become an important part of intelligent drilling and smart oilfield. Figure 2.2.9 shows the roadmap of the engineering development front of “research and development of looking-around and looking-ahead while-drilling technology”.

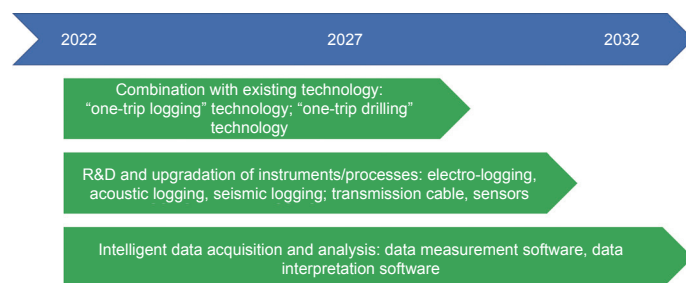


Figure 2.2.9 Roadmap of the engineering development front of “research and development of looking-around and looking-ahead while-drilling technology”

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V. Civil, Hydraulic, and Architectural Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including geotechnical engineering, transportation engineering, architectural design and theory, surveying and mapping engineering, urban planning and landscaping, hydraulic engineering, structural engineering, municipal engineering, and engineering mechanics. Five of them were from experts' nomination: "disaster mechanism and protection of vital transportation infrastructure", "hybrid computing theory and methods in intelligent surveying and mapping", "theory of urban renewal for high-density and complex space", "theory and realization path of regional water balance under changing environments", and "low-carbon resource utilization of urban sewage sludge". The other five fronts were identified using the co-citation clustering method

applied to the top 10% of highly citing papers, and they were confirmed in expert panel meetings. Table 1.1.2 presents annual statistics on the core papers published between 2016 and 2021 that are relevant to these Top 10 research fronts.

(1) Disaster mitigation and risk control of underground engineering in extreme environments

The extreme environments of underground engineering refer to the extremely complex geological environments confronted during underground construction and the extreme natural hazards suffered during operation. Unlike typical unfavorable geological conditions, the extreme environments of underground engineering are of great uncertainty and complexity in evolutionary and cluster mechanisms. In recent years, in the construction of underground engineering represented by the Sichuan-Tibet Railway in China and the operation of underground engineering represented by the Heavy Rainstorm in Zhengzhou, China, the extreme environments have posed serious risks to underground engineering. It is of great significance to study the disaster mitigation and risk control of underground engineering in extreme environments. The current research focuses

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Disaster mitigation and risk control of underground engineering in extreme environments	85	3 722	43.79	2019.9
2	Disaster mechanism and protection of vital transportation infrastructure	37	1 451	39.22	2018.8
3	Intelligent and responsive architecture for the elderly health	13	329	25.31	2018.8
4	Hybrid computing theory and methods in intelligent surveying and mapping	56	1 671	29.84	2019.8
5	Theory of urban renewal for high-density and complex space	20	1 245	62.25	2018.5
6	Theory and realization path of regional water balance under changing environments	30	1 200	40.00	2018.3
7	Intelligent evaluation of engineering structures performance	29	1 249	43.07	2018.8
8	Low-carbon resource utilization of urban sewage sludge	28	2 584	92.29	2018.3
9	High-efficiency energy-absorbing composite structures for impact resistance	31	1 233	39.77	2019.0
10	Intelligent monitoring and risk early-warning for dam safety	65	2 110	32.46	2019.4

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Disaster mitigation and risk control of underground engineering in extreme environments	3	2	5	13	31	31
2	Disaster mechanism and protection of vital transportation infrastructure	7	6	2	4	8	10
3	Intelligent and responsive architecture for the elderly health	2	1	2	2	4	2
4	Hybrid computing theory and methods in intelligent surveying and mapping	1	2	5	8	21	19
5	Theory of urban renewal for high-density and complex space	2	5	3	4	3	3
6	Theory and realization path of regional water balance under changing environments	8	3	5	6	3	5
7	Intelligent evaluation of engineering structures performance	3	5	2	9	4	6
8	Low-carbon resource utilization of urban sewage sludge	7	4	1	8	5	3
9	High-efficiency energy-absorbing composite structure for impact resistance	4	1	8	3	9	6
10	Intelligent monitoring and risk early-warning for dam safety	2	5	10	10	21	17

on: ① inversion analysis of high geo-stress fields in soft and hard rocks and risk prediction; ② characterization of the geothermal field of underground engineering, and optimization of supporting structures; ③ risk evaluation and control of tunnels in high-altitude cold areas; ④ seismic design and risk control of tunnels in areas of high seismic intensity; ⑤ risk assessment and control system of extraordinary waterlogging disasters in urban underground space. The development trend in the future is to identify geological conditions prone to disaster and clarify the catastrophic mechanisms in extreme environments. On this basis, multi-information is integrated for disaster prediction and mitigation. Meanwhile, attentions are also paid to accelerating the intelligentization of comprehensive management of underground space, strengthening the safety management of emergency response in underground space, and building a comprehensive management system for underground space. Between 2016 and 2021, 85 core papers relevant to this research front were published. These papers received 3 722 citations, with an average of 43.79 citations per paper.

(2) Disaster mechanism and protection of vital transportation infrastructure

The research on this front is devoted to reveal performance deterioration and disaster-causing mechanism of vital transportation infrastructure (e.g., highway, railway, and

airport) that undergoes extreme weathers, natural hazards (e.g., earthquakes and hurricanes), or emergencies due to engineering accidents or pipe leaking-induced collapse, and meanwhile to develop techniques for retaining or rapidly recovering functions of the affected transportation infrastructure. It is crucial to ensure long-term stable and safe operation of transportation, and reduce the impact of disaster on people's travel. The main research directions include: ① disaster-causing mechanism of vital transportation infrastructure under extreme weathers, adverse geological conditions, and emergencies; ② assessment of function loss and traffic impact of vital transportation infrastructure during disasters; ③ key technologies for accurate inspection, monitoring, and early warning of service status of vital transportation infrastructure in complex environments; ④ key technologies for disaster mitigation and resilience maintenance of transportation infrastructure undergoing disasters. At present, this research front has been listed as a topic of urgent need that draws increasing attention and investigation over the next stage of transportation sector. In the future, progress of this front could be made in three aspects: ① the understanding on the mechanisms of infrastructure disaster may extend from single-factor leading mechanisms to multi-factor coupling mechanisms; ② the tools for infrastructure disaster assessment may evolve from numerical analyses and quantitative evaluation to fuzzy

assessment and digital twin analyses of disaster evolution; ③ the methods for disaster prevention and control may advance from a single means focusing on monitoring and early warning to multiple means involving resilience design, intelligent operation and maintenance, and post-disaster recovery. Between 2016 and 2021, 37 core papers relevant to this research front were published. These papers received 1 451 citations, with an average of 39.22 citations per paper.

(3) Intelligent and responsive architecture for the elderly health

Intelligent and responsive architecture for the elderly health is to intelligently regulate building environment and initiatively improve human health through comprehensive health monitoring and spatial response with the aid of environmental control technologies and intelligent response algorithms based on behavioral characteristics and health needs of the elderly. It is emerging as a key research direction for the development of healthy buildings. The relevant subjects include: ① integrated building health monitoring and spatial response mechanism via portable health monitoring and environmental sensing, which focuses on exploring the comprehensive perception and response mechanism of human health status and physical environment parameters; ② digital and intelligent environmental control based on Internet of Things (IoTs) for achieving a comprehensive control of the physical environment such as air, sound, light, heat, and color; ③ intelligent response algorithms and smart control systems for health monitoring processing and decision-making mechanism. The future development of this front is to integrate multi-disciplinary knowledge (e.g., intelligent building and construction, computer and artificial intelligence, communication technology, and environmental science) for improving the health performance of buildings. Achievements in this direction would enable not only the adaptive transformation of existing buildings but also intelligent design and construction of new buildings. Between 2016 and 2021, 13 core papers relevant to this research front were published. These papers received 329 citations, with an average of 25.31 citations per paper.

(4) Hybrid computing theory and methods in intelligent surveying and mapping

Hybrid computing theory and methods in intelligent surveying and mapping use knowledge engineering, deep learning, logical reasoning, swarm intelligence, and other new artificial

intelligence technologies and means, to extract, describe and express the natural intelligence formed in human surveying and mapping activities. Combined with digital algorithms and models, the hybrid intelligent computing paradigm is built to realize the perception, cognition, expression and behavior computing in surveying and mapping. The subjects covered in this research front include: ① the analysis and modeling of natural intelligence in surveying and mapping; ② the knowledge system construction of the intelligent surveying and mapping; ③ the construction of the hybrid computing paradigm; ④ the implementation of the hybrid computing paradigm; ⑤ the mechanism and path of empowering production. In the future, this research could advance surveying and mapping data collection, processing, and service technologies from geometric information collection based on traditional measuring instruments to dynamic perception supported by ubiquitous smart sensors, from model and algorithm-led data processing to the knowledge-oriented and algorithm-based hybrid intelligent computing paradigm, and from the platform data information service to the online intelligent knowledge service. Between 2016 and 2021, 56 core papers relevant to this research front were published. These papers received 1 671 citations, with an average of 29.84 citations per paper.

(5) Theory of urban renewal for high-density and complex space

Urban renewal is an important and effective approach to solve the problems associated with high-density and complex urban space. It helps clarify the space operation mechanism of high-density and complex space, reshape the image of the built environment, improve the urban environment quality, and revitalize the space value of the built environment. The theory of urban renewal for high-density and complex space is to improve the quality and efficiency in planning, design and construction of the high-density built environment in accordance with the law of urban development especially in areas or for subjects that cannot satisfy or meet the needs of social and economic development. The main research interests include: ① operation rule and principle of high-density and complex urban space; ② the new methodology and approach of urban renewal for high density and complex urban space; ③ multi-dimensional and refined analysis technological system of the built environment based on urban multi-source big data; ④ urban renewal planning and design method of high-density and complex space supported by

digital technology; ⑤ intelligent platform based construction management and control approach of urban renewal. The future development trends of this research include: ① to establish a theoretical system and working path of urban renewal for high-density and complex space with healthy, green and sustainable development goals; ② to enable objective and quantitative analysis for high-density and complex space features recognition and sign diagnosis based on multi-source urban big data; ③ to promote applications of urban renewal planning, design and optimization of high-density and complex space based on virtual and real interactive digital technology; ④ to develop a periodic intelligent platform for urban renewal planning, construction and control of high-density and complex spaces; ⑤ through above ways to promote high-quality and sustainable development of high-density urban built environment. Between 2016 and 2021, 20 core papers relevant to this research front were published. These papers received 1 245 citations, with an average of 62.25 citations per paper.

(6) Theory and realization path of regional water balance under changing environments

Regional water balance refers to the spatial storage, the exchange between revenue and expenditure, and the transformation characteristics of water in the regional water cycle system and its various circles under the coupled action of natural and human factors. The state of regional water balance not only affects the water resources carrying capacity, but also is an “indicator” and “barometer” that informs us the utilization of regional water resources exceeding the carrying capacity. Due to the complexity and uncertainty in the interaction and feedback among water resources-ecological environment-socioeconomic system, strengthening the rigid constraints of water resources and achieving a healthy regional water balance in changing environments becomes one of the basic prerequisites for promoting the ecological civilization from concept to practice, ensuring the overall national security, and facilitating green development. The main subjects of this front include: ① regional water balance mechanism and its constitutive relationship; ② the relationship between the state and the carrying capacity of water resources; ③ dynamic evaluation and regulation of regional water balance under changing environments; ④ the path of building the healthy regional water balance. The future development trends mainly include: ① to strengthen dynamic monitoring and analysis of the basic elements of

regional water balance and water resources carrying capacity; ② to improve the theory and the method of water balance evaluation and early warning; ③ to construct the collective strategy for increasing regional water resources carrying capacity and optimizing water balance status; and ④ to work out the strategic goals and development paths of land use and restoration under rigid constraints of water resources. Between 2016 and 2021, 30 core papers relevant to this research front were published. These papers received 1 200 citations, with an average of 40.00 citations per paper.

(7) Intelligent evaluation of engineering structures performance

Traditional performance evaluation methods for engineering structures are limited in accuracy and efficiency due to limitation of theoretical development, structural complexity, limited data, and random deviation of structures. Emerging information technologies such as artificial intelligence, sensing technology and big data are profoundly changing design, construction and maintenance of engineering structures. The relevant research involves intelligent evaluation of mechanical performance at different levels, such as material, cross section, structural member, connection and structure. Intelligent evaluation of engineering structures improves efficiency of design, construction, operation and maintenance of structures, and increases accuracy of structural performance evaluation. The main research subjects include: ① intelligent evaluation algorithm and theory of engineering structural performance; ② multiscale mechanical performance evaluation of engineering structures under different hazards, such as earthquakes, fires, winds and geo-hazards; ③ damage state and bearing capacity evaluation of engineering structures under daily service conditions. The future development trends include such as: ① intelligent design of engineering structures and systems; ② physics-informed neural network for intelligent evaluation of engineering structures. Between 2016 and 2021, 29 core papers relevant to this research front were published. These papers received 1 249 citations, with an average of 43.07 citations per paper.

(8) Low-carbon resource utilization of urban sewage sludge

Low-carbon resource utilization of urban sewage sludge refers to the full use of energy and resource such as organic matters and nutrient elements contained in the sludge to realize low-carbon treatment and disposal of sludge. Urban sewage

sludge has the dual properties of pollutant and resource. Its improper treatment and disposal are prone to generate greenhouse gases such as methane with high warming potential. Meanwhile, sludge has good potential for resource utilization. Facing the challenges brought by global climate change, the low-carbon resource utilization of multiple substances of sludge has become an important approach and research hotspot to achieve energy self-sufficiency and carbon cycle of sewage treatment plants. The main research subjects include: ① mechanism and technology of deep development of sludge biomass energy based on efficient regulation of anaerobic flora, targeted strengthening of methanogenic metabolic pathways, and synergistic complementation of sludge and organic wastes, which improves biomass conversion rate of low organic matter sludge to above 40% stably; ② mechanism and technology of efficient and low-carbon sludge drying and incineration based on staged combustion for excavating sludge calorific value while reducing the emission of non-carbon dioxide greenhouse gases, multi-stage recovery and comprehensive utilization of heat from drying exhaust gas and incineration flue gas, and dynamic regulation and optimization of energy allocation; ③ land use technology of sludge treatment products or derivative products, and morphological transformation law, product-environment interaction mechanism and secondary pollution risk control technology of key substances with resource and environmental attributes; ④ high value extraction and recycling technology of carbon, nitrogen and phosphorus in sludge. The main development trend in the future is to integrate interdisciplinary development, and further carry out research on key technologies for improving the efficiency of sludge energy and resource recovery, safety risk assessment and control of resource utilization, which helps to realize the efficient recycling of sludge energy and resource, and improve the low-carbon level of sludge treatment and disposal. Between 2016 and 2021, 28 core papers relevant to this research front were published. These papers received 2 584 citations, with an average of 92.29 citations per paper.

(9) High-efficiency energy-absorbing composite structure for impact resistance

With their capacity of irreversible deformations that absorb the kinetic energy, high-efficiency energy-absorbing composite structures provide a solution to possible accidents, explosions or impacts during life cycles of engineering structures. Compared with traditional metal-based energy-

absorbing structures, they have higher specific strength and stiffness, and exhibit advantages such as environmental friendliness, vibration and noise suppression, presenting obvious superiority for the objective of carbon peaking and carbon neutrality. Typical structural types of high-efficiency energy-absorbing composite structures include fiber/matrix composite structures, metal and fiber-reinforced polymer composite structures, foam and architected core sandwich structures, etc. The evaluation of their impact resistance involves a variety of behaviors such as fiber fracture, matrix cracking, interface failure and their coupling effects, and is related to different loading rate conditions, namely the quasi-static, low-speed and high-speed impact. The main topics of this research includes: ① failure modes of high-efficiency energy-absorbing composite structures and influence of the design and manufacturing process; ② simulation of the impact process of high-efficiency energy-absorbing composite structures and evaluation methods of impact resistance; ③ health monitoring and maintenance of high-efficiency energy-absorbing composite structures considering sustainability. The future research trend is to carry out the impact resistance performance evaluation considering the life-cycle performance demand of engineering structures, and especially to solve the failure criterion under high-speed impact conditions. Meanwhile, the failure modes and the assessment for new materials (e.g., nanocomposites, functional gradient materials, negative Poisson's ratio materials) and new manufacturing process (e.g., additive manufacturing) should be considered, and the multi-objective optimization design could be conducted. Between 2016 and 2021, 31 core papers relevant to this research front were published. These papers received 1 233 citations, with an average of 39.77 citations per paper.

(10) Intelligent monitoring and risk early-warning for dam safety

The construction and safe operation of dams, as critical infrastructure, are crucial to flood mitigation as well as economic, ecological and public safety. Dam safety management is becoming more digitalized, network-based and intelligent. Dam safety intelligent monitoring system utilizes modern information technologies, such as IoTs, cloud computing and big data, being able to perceive multi-source information in an all-round way. Data fusion helps to build an intelligent monitoring system featuring deep perception, comprehensive interconnection, deep fusion,

wide-scope sharing, smart application and ubiquitous service. The system provides functions of forecasting, early-warning, rehearsal and emergency plan, and supports high-quality development of dam safety management covering the whole-process and the full-chain of development. Based on physics-informed data-driven model, risk early-warning enables evaluation of the real-time dam risk, sends early-warning signals in time upon risk beyond design levels, and implements emergency plans as necessary. The main topics of this research include: ① multi-source information fusion and diagnosis of dam safety; ② dam structural performance evolution, prediction and early-warning; ③ intelligent diagnosis and decision-making on dam safety based on big data; ④ application of modern information technology in dam safety management; ⑤ formulation of risk early-warning indicators; ⑥ risk emergency response and decision-making mechanism. The future research may focus on breakthroughs in bottleneck technologies, such as numerical identification of dam damages, virtual scenario construction for rapid and accurate diagnosis of safety performance, and strengthened capabilities in deep perception, risk assessment and early-warning to effectively guarantee the safe operation of dams with scientific and technological supports. Between 2016 and 2021, 65 core papers relevant to this research front were published. These papers received 2 110 citations, with an average of 32.46 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Disaster mitigation and risk control of underground engineering in extreme environments

The worldwide development and utilization of underground space is in great demand and has broad prospects. With the increase in construction scales, the worldwide development of underground space is gradually extended to the regions with harsh geological conditions. Extreme environments characterized with high geo-stresses that stimulate large deformation in soft rock or rockburst in hard rock, and high ground temperature pose huge risks to underground engineering. Besides, extreme weathers affect the world at an increasing frequency, and add additional challenges to the operation and management of underground projects. The research of disaster mitigation and risk control of

underground engineering under extreme environments is of great significance to ensure safety and shorten construction.

Currently, the major topics of this research front include:

1) Inversion analysis of high geo-stress fields in soft and hard rocks and risk prediction. Geo-stresses are largely random and uncertain, and the local measurement of geo-stresses has great uncertainty. The following issues are of interest: ① reasonably selecting the measured indexes for geo-stress inversion in underground engineering with different lithologies; ② analyzing the inversion criteria of initial geo-stress fields in different lithologies; ③ obtaining geo-stress distribution; ④ predicting large deformation in surrounding rock and rockburst.

2) Characterization of geothermal fields in underground engineering and optimization of supporting structures. Efforts are devoted to ① infer geothermal fields from field measurements, ② study the influence of high geothermal temperature on the thermal stresses and the mechanical properties (e.g., strength and durability) of concrete supporting structures, and ③ simultaneously improve the structures' capacity in thermal insulation and stability in heated environments.

3) Risk evaluation and control of tunnels in high-altitude cold areas. This topic is to ① depict the temperature change in linings and surrounding rock, ② explore the mechanism of freezing damage, ③ optimize the engineering measures for mitigating freezing damage during construction and operation, and ④ ensure safe operation of the tunnels by minimizing traffic interruption due to freezing.

4) Seismic design and risk control of tunnels in areas of high seismic intensity. This topic is to ① develop reliable theories and methods for seismic analysis of tunnels in areas prone to strong motions, ② reveal seismic response of tunnels and the resulting disaster, and ③ improve mitigation measures.

5) Risk assessment and control system of extraordinary waterlogging disasters in urban underground space. This topic is to ① identify main causes of disasters in urban underground space during extremely flood seasons, ② establish methods for risk assessment and disaster control, ③ integrate intelligent networks of underground engineering towards a waterlogging disaster prevention and control system, and ④ plan post-disaster recovery.

As shown in Table 1.1.1, 85 core papers concerning “disaster mitigation and risk control of underground engineering in extreme environments” were published between 2016 and 2021, with each paper being cited 43.79 times on average. The top five countries in terms of output of core papers on this topic are China, Iran, Malaysia, Vietnam, and the USA (Table 1.2.1). China is one of the most active countries, having published 69.41% of the core papers. The five countries with the highest average citations were Norway, Australia, Malaysia, Iran, and Vietnam. The papers published by Chinese authors were cited 43.81 times on average, which is slightly above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers

were Chang’an University, Xi’an University of Architecture and Technology, Amirkabir University of Technology, Universiti Teknologi Malaysia, and Chongqing University (Table 1.2.2). Chang’an University and Xi’an University of Architecture and Technology have focused on the structural response of underground engineering under adverse geological conditions dominated by loess areas and the design of new supporting structures for underground engineering. Amirkabir University of Technology has focused on application of new intelligent technologies such as neural networks in prediction, optimization and design of underground engineering. As illustrated in Figure 1.2.2, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.3, the five most active countries in terms of paper citations were China, Iran, the USA, Vietnam, and Australia. The top five institutions in terms of citations of core

Table 1.2.1 Countries with the greatest output of core papers on “disaster mitigation and risk control of underground engineering in extreme environments”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	59	69.41	2 585	43.81	2020.0
2	Iran	19	22.35	1 036	54.53	2019.8
3	Malaysia	16	18.82	1 049	65.56	2019.6
4	Vietnam	9	10.59	426	47.33	2020.2
5	USA	8	9.41	358	44.75	2019.5
6	Australia	6	7.06	418	69.67	2019.2
7	Norway	4	4.71	324	81.00	2020.5
8	India	4	4.71	177	44.25	2019.5
9	Canada	3	3.53	98	32.67	2019.0
10	Italy	3	3.53	75	25.00	2019.7



Figure 1.2.1 Collaboration network among major countries in the engineering research front of “disaster mitigation and risk control of underground engineering in extreme environments”

Table 1.2.2 Institutions with the greatest output of core papers on “disaster mitigation and risk control of underground engineering in extreme environments”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chang'an University	20	23.53	455	22.75	2020.3
2	Xi'an University of Architecture and Technology	19	22.35	443	23.32	2020.3
3	Amirkabir University of Technology	17	20.00	1 001	58.88	2019.7
4	Universiti Teknologi Malaysia	16	18.82	1 049	65.56	2019.6
5	Chongqing University	11	12.94	885	80.45	2019.6
6	China University of Mining and Technology	8	9.41	427	53.38	2019.9
7	Duy Tan University	8	9.41	358	44.75	2020.2
8	China Railway First Survey & Design Institute Group Co., Ltd.	7	8.24	233	33.29	2020.0
9	Central South University	6	7.06	240	40.00	2020.5
10	Xi'an University of Architecture and Technology	5	5.88	130	26.00	2020.6

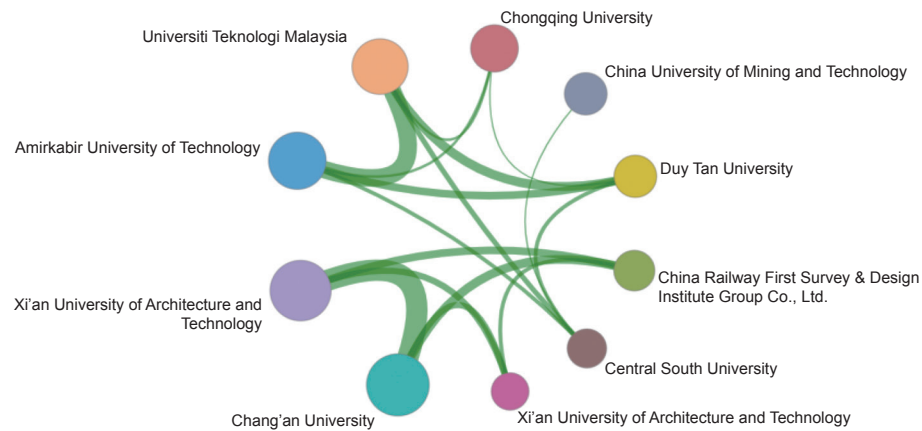


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “disaster mitigation and risk control of underground engineering in extreme environments”

Table 1.2.3 Countries with the greatest output of citing papers on “disaster mitigation and risk control of underground engineering in extreme environments”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 178	48.48	2020.5
2	Iran	263	10.82	2020.3
3	USA	178	7.33	2020.4
4	Vietnam	171	7.04	2020.4
5	Australia	158	6.50	2020.4
6	Malaysia	114	4.69	2020.2
7	India	102	4.20	2020.5
8	Russia	78	3.21	2020.7
9	Italy	66	2.72	2020.7
10	UK	62	2.55	2020.6

papers were Duy Tan University, Central South University, China University of Mining and Technology, Chongqing University, and Chang'an University (Table 1.2.4). China ranked the first in the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this front.

Summarizing the above statistics, Chinese scholars have performed well and become the leader in the research of “disaster mitigation and risk control of underground engineering in extreme environments”.

In the next ten years, the key directions of this research front lie in

identification of disastrous geological conditions and clarification of the catastrophic mechanism under extreme environments, establishment of urban underground space disaster assessment and control systems under extreme weathers, and promotion of the intelligent construction of underground engineering. Meanwhile, in terms of the development trend, the front will gradually develop towards refinement, systematization and intelligentization. The outcomes of this front are of great potential and will be widely used in underground projects, which are threatened by increasingly harsh environments during their construction and increasingly frequent extreme weathers during their operation (Figure 1.2.3).

Table 1.2.4 Institutions with the greatest output of citing papers on “disaster mitigation and risk control of underground engineering in extreme environments”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Duy Tan University	125	13.87	2020.3
2	Central South University	119	13.21	2020.5
3	China University of Mining and Technology	106	11.76	2020.1
4	Chongqing University	101	11.21	2020.6
5	Chang'an University	94	10.43	2020.4
6	Xi'an University of Architecture and Technology	70	7.77	2020.5
7	Islamic Azad University	65	7.21	2020.3
8	Amirkabir University of Technology	65	7.21	2019.9
9	Universiti Teknologi Malaysia	64	7.10	2019.9
10	Ton Duc Thang University	51	5.66	2020.3

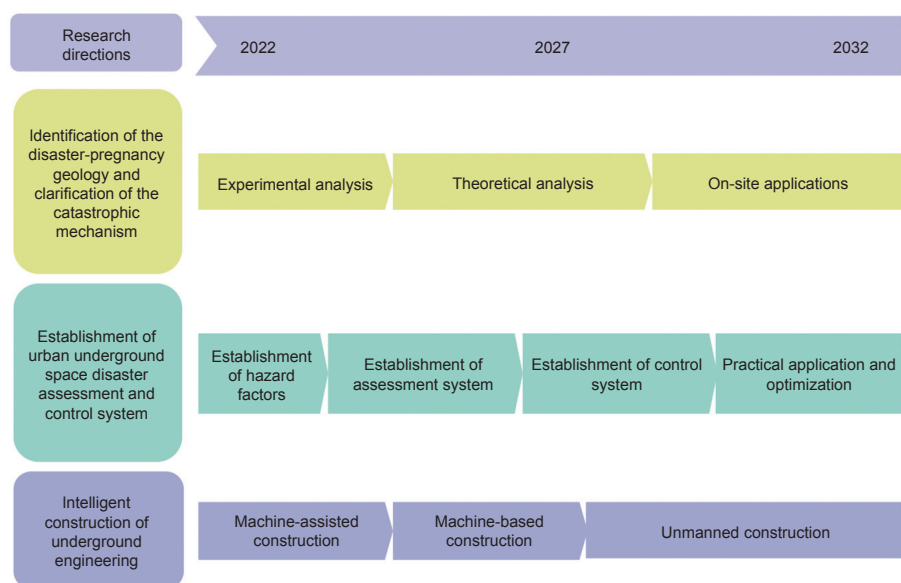


Figure 1.2.3 Roadmap of the engineering research front of “disaster mitigation and risk control of underground engineering in extreme environments”

1.2.2 Disaster mechanism and protection of vital transportation infrastructure

The transportation infrastructure including highway, railway, and airport frequently experiences complex environments and hazards, and the vital transportation infrastructure often suffers from serious damage and sudden reduction in service life due to insufficient resilience. This not only increases the life-cycle cost of vital transportation infrastructure, but also reduces the post-disaster service capacity of entire transportation system. Currently, systematic research on catastrophe mechanism and protection of vital transportation infrastructure is still in the preliminary stage. It is of great significance to clarify the service performance degradation and disaster-causing mechanism for vital transportation infrastructure under emergencies due to extreme weathers or natural hazards, and further develop methods for maintaining safety and rapid recovery during emergencies. At present, the relevant research has been expanded from the single-disaster resistance design to more systematic research involving disaster recognition, assessment, monitoring and early warning, prevention and control. The main topics include:

- 1) Disaster-causing mechanism of vital transportation infrastructure under extreme weathers and adverse geological conditions. Various tools, such as small scale modelling, in-situ tests and numerical simulations, are deployed to reveal the damage mechanism of vital transportation infrastructure caused by earthquakes, typhoons, freeze-thaw, debris flows, engineering disturbance, torrents, foundation damage, and accidents, and formulate the evolving functionality or performance of vital transportation infrastructure.
- 2) Assessment of function loss of vital transportation infrastructure and traffic impact. This topic is to ① identify proper assessment index driven by big data with physical support using advanced methods such as fuzzy evaluation and numerical analyses, ② improve the methods for accurately evaluating the function loss and the traffic delay due to natural hazards and sudden accidents, and ③ establish the twin theory and model for disaster occurrence and evolution of vital transportation infrastructure.
- 3) Accurate monitoring and early warning for the service status of vital transportation infrastructure in complex environments. This topic aims to ① innovate the theory of non-destructive detection and real-time monitoring of the service status of vital transportation infrastructure under natural hazards and

traffic loads, ② create a new generation of “space-sky-earth” integrated disaster intelligent monitoring theory and method with the help of Beidou system, and ③ build a digital system for time-dependent service performance prediction and real-time warning based on big data mining for vital transportation infrastructure.

- 4) Disaster mitigation and resilience maintenance of vital transportation infrastructure. This topic aims to ① propose a universal mechanism for efficient repair and rapid reinforcement of damaged parts of vital transportation infrastructure in complex post-disaster scenarios, ② innovate the theory of temporary maintenance, rapid rescue, and function recovery of vital transportation infrastructure after disasters, and ③ clarify the principles of resilience design, recovery and improvement of vital transportation infrastructure in disaster affected environments.

As shown in Table 1.1.1, 37 core papers concerning “disaster mechanism and protection of vital transportation infrastructure” were published between 2016 and 2021, with each paper being cited an average of 39.22 times. The top five countries in terms of output of core papers on this topic are the USA, Italy, China, Singapore, and Greece (Table 1.2.5). China is very active, having published 5.41% of the core papers. The five countries with the highest average citations were Serbia, China, Saudi Arabia, Japan, and Malaysia. The papers published by Chinese authors were cited 76.50 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.4, close cooperation was observed among the most productive top 10 countries.

The five institutions that published the most core papers were The University of Texas at Arlington, The University of Oklahoma, University of Illinois, Texas A&M University, and Florida International University (Table 1.2.6). The University of Texas at Arlington has focused on the disaster resilience analysis of infrastructure, the weight analysis of the key process of infrastructure post-disaster reconstruction, and the influencing factor of post-disaster environment on infrastructure reconstruction; The University of Oklahoma has focused on the resilience-based infrastructure disaster resilience and risk mitigation analysis; University of Illinois has focused on the assessment of disaster resilience and post-disaster impact of transportation infrastructure in city based on mathematical and empirical methods. Cooperation is rare

Table 1.2.5 Countries with the greatest output of core papers on “disaster mechanism and protection of vital transportation infrastructure”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	27	72.97	1 041	38.56	2019.3
2	Italy	3	8.11	48	16.00	2019.3
3	China	2	5.41	153	76.50	2019.0
4	Singapore	2	5.41	58	29.00	2019.5
5	Greece	2	5.41	42	21.00	2018.0
6	Serbia	1	2.70	105	105.00	2017.0
7	Saudi Arabia	1	2.70	75	75.00	2019.0
8	Japan	1	2.70	45	45.00	2017.0
9	Malaysia	1	2.70	45	45.00	2019.0
10	Germany	1	2.70	41	41.00	2018.0

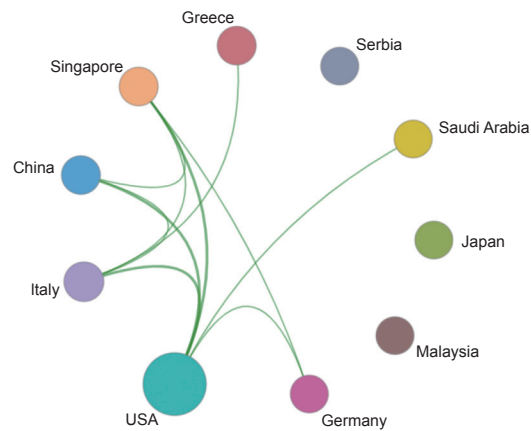


Figure 1.2.4 Collaboration network among major countries in the engineering research front of “disaster mechanism and protection of vital transportation infrastructure”

Table 1.2.6 Institutions with the greatest output of core papers on “disaster mechanism and protection of vital transportation infrastructure”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	The University of Texas at Arlington	6	16.22	42	7.00	2020.3
2	The University of Oklahoma	3	8.11	321	107.00	2017.0
3	University of Illinois	3	8.11	87	29.00	2019.7
4	Texas A&M University	2	5.41	24	12.00	2020.5
5	Florida International University	2	5.41	13	6.50	2018.5

among major institutions.

As shown in Table 1.2.7, the five most active countries in terms of paper citations were USA, China, UK, Iran, and Canada.

The top five institutions in terms of citations of core papers were Texas A&M University, Tsinghua University, The Hong Kong Polytechnic University, University of Illinois, and Tongji

University (Table 1.2.8). According to the number of citations of core papers, there are differences between the top five countries in terms of output of core papers and the five most active countries in terms of paper citations, which indicates that this front has received common attention from scholars from different countries.

Based on the above statistics, the proportion of paper citations in China is far higher than the core papers, indicating that Chinese researchers paid close attention to this front.

In the next 5–10 years, the engineering research front of

“disaster mechanism and protection of vital transportation infrastructures” will focus on the development direction of disaster-causing mechanisms, disaster evaluation system, monitoring and early warning platform, and disaster prevention and resilience recovery technology (Figure 1.2.5).

1.2.3 Intelligent and responsive architecture for the elderly health

Building for the elderly has become an important research direction in recent years aiming to improve the health

Table 1.2.7 Countries with the greatest output of citing papers on “disaster mechanism and protection of vital transportation infrastructure”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	438	30.80	2020.0
2	China	425	29.89	2020.1
3	UK	97	6.82	2020.1
4	Iran	93	6.54	2020.0
5	Canada	72	5.06	2020.2
6	India	60	4.22	2020.2
7	Australia	55	3.87	2019.9
8	Italy	54	3.80	2019.8
9	South Korea	53	3.73	2019.9
10	Germany	41	2.88	2020.1

Table 1.2.8 Institutions with the greatest output of citing papers on “disaster mechanism and protection of vital transportation infrastructure”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Texas A&M University	37	14.92	2020.1
2	Tsinghua University	27	10.89	2020.3
3	The Hong Kong Polytechnic University	25	10.08	2020.0
4	University of Illinois	23	9.27	2020.4
5	Tongji University	22	8.87	2020.2
6	Chinese Academy of Sciences	22	8.87	2020.0
7	The University of Texas at Arlington	21	8.47	2021.0
8	University of Tehran	20	8.06	2019.9
9	Delft University of Technology	18	7.26	2020.4
10	The University of Oklahoma	17	6.85	2019.6

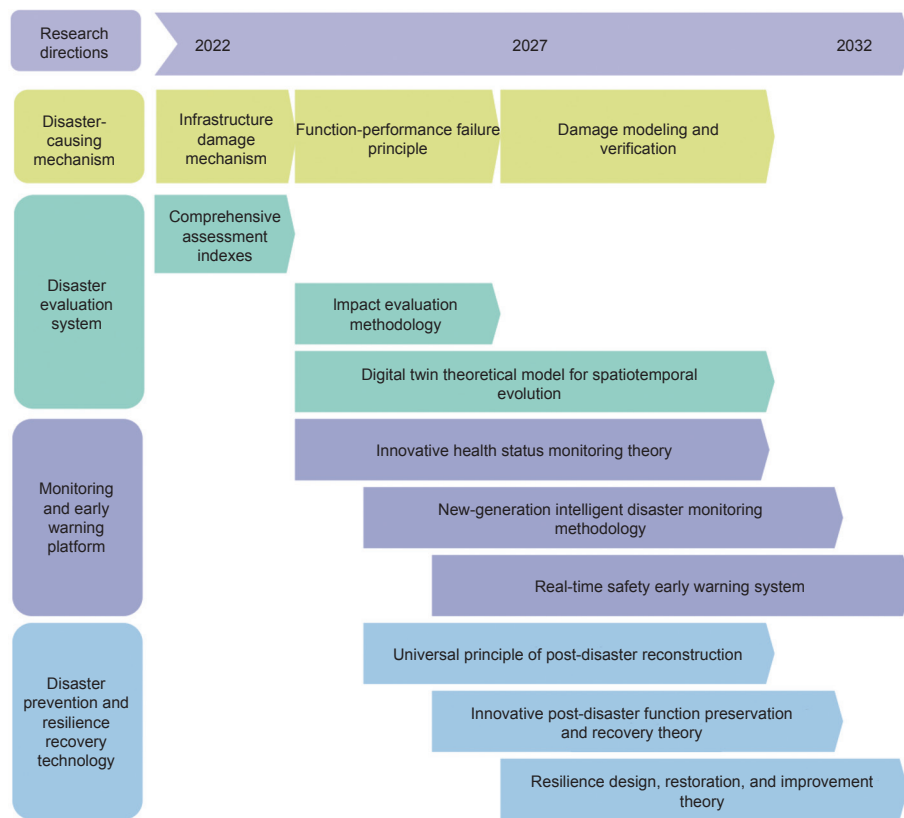


Figure 1.2.5 Roadmap of the engineering research front of “disaster mechanism and protection of vital transportation infrastructure”

performance of buildings and promote the well-being of the elderly. Intelligent and responsive architecture for the elderly health is to intelligently regulate building environment and initiatively improve human health through comprehensive health monitoring and spatial response using environmental control technology and intelligent response algorithms based on behavioral characteristics and health needs of the elderly. Relevant studies and insights provide effective support for the aging adaptation and intelligent empowerment of a large number of existing buildings with billions of square meters, as well as the intelligent design and construction of new buildings. Existing studies of buildings for the elderly mainly focus on behavioral characteristics, physical space and facilities adaption, which are difficult to dynamically adjust and respond to their health needs in real time. Nevertheless, with the technological innovation of wearable biosensors and IoTs, low-cost portable physical and mental health monitoring and environmental data acquisition become possible in daily lives. Accordingly, intelligent and responsive regulation of

indoor environment to achieve active health intervention has become a hot direction for buildings for the elderly. The relevant topics are as follow:

- 1) Integrating building health monitoring and spatial response mechanism. Portable health monitoring equipment and environmental sensors are utilized for achieving comprehensive perception of human health status and physical environmental parameters, with special attention to the personalized characteristics of different user groups such as the disabled, the demented, and the active elderly. In particular, a focus is placed on intelligent early warning and real-time response mechanisms for accidental risks such as falls and strokes.
- 2) Digital and intelligent environmental control. Instant control of physical environment of buildings (e.g., air, sound, light, heat, color, and vegetation) are enabled based on the environmental health data obtained from real-time monitors. Furthermore, it becomes possible to achieve optimized and intelligent configuration of the built environment via multi-

system comprehensive control instead of single-system control.

3) Intelligent response algorithms and smart control systems. Building intelligent infrastructure is developed based on deep learning and reinforcement learning. In order to fully meet the need of environmental health monitoring, responsive facilities in buildings and health monitoring equipment are managed and controlled in a comprehensive manner. Besides, mechanisms are established for information transmission, processing and decision making mechanism for the ultimate goal targeting the integration of information system and physical system.

As shown in Table 1.1.1, 13 core papers concerning “intelligent and responsive architecture for the elderly health” were published between 2016 and 2021, with each paper being cited an average of 25.31 times. The top five countries in terms of output of core papers on this topic are USA, Italy, China, France, and India (Table 1.2.9). China is very active, having published 15.38% of the core papers. The five countries with the highest average citations were France, India, Greece, Italy, and Spain. The papers published by Chinese authors were cited 23.50 times on average, which is slightly lower than the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.6, close

Table 1.2.9 Countries with the greatest output of core papers on “intelligent and responsive architecture for the elderly health”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	3	23.08	31	10.33	2018.3
2	Italy	2	15.38	107	53.50	2020.5
3	China	2	15.38	47	23.50	2019.5
4	France	1	7.69	99	99.00	2020.0
5	India	1	7.69	99	99.00	2020.0
6	Greece	1	7.69	68	68.00	2016.0
7	Spain	1	7.69	50	50.00	2016.0
8	Singapore	1	7.69	27	27.00	2019.0
9	Tunisia	1	7.69	16	16.00	2020.0
10	Egypt	1	7.69	9	9.00	2017.0

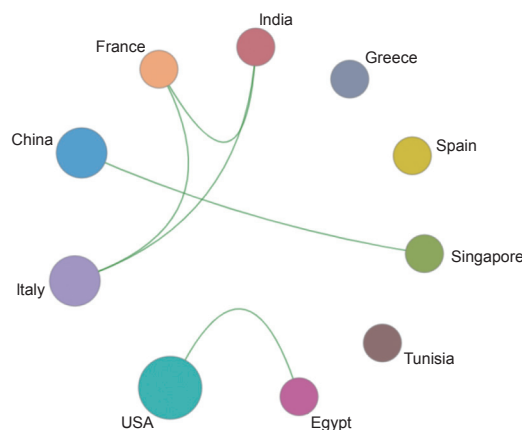


Figure 1.2.6 Collaboration network among major countries in the engineering research front of “intelligent and responsive architecture for the elderly health”

cooperation was observed among the most productive Top 10 countries.

The five institutions that published the most core papers were Great Lakes Institute of Management, Paris School of Business, Link Campus University, University of Turin, and The Aristotle University of Thessaloniki (Table 1.2.10). As illustrated in Figure 1.2.7, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.11, the five most active countries in terms of paper citations were China, Spain, Italy, Greece,

and the UK. The top five institutions in terms of citations of core papers were The Aristotle University of Thessaloniki, The University of Castilla-La Mancha, University of Waterloo, Nanyang Technological University, and Shanghai Jiao Tong University (Table 1.2.12). According to the number of citations of core papers, there are differences between the top five countries in terms of output of core papers and the five most active countries in terms of paper citations, which indicates that this front has received common attention from scholars from different countries.

Table 1.2.10 Institutions with the greatest output of core papers on “intelligent and responsive architecture for the elderly health”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Great Lakes Institute of Management	1	7.69	99	99.00	2020.0
2	Paris School of Business	1	7.69	99	99.00	2020.0
3	Link Campus University	1	7.69	99	99.00	2020.0
4	University of Turin	1	7.69	99	99.00	2020.0
5	The Aristotle University of Thessaloniki	1	7.69	68	68.00	2016.0
6	The Greek Association of Alzheimer’s Disease and Related Disorders	1	7.69	68	68.00	2016.0
7	Conservatorio Profesional de Música Maestro Gómez Villa	1	7.69	50	50.00	2016.0
8	University of Carlos III Madrid	1	7.69	50	50.00	2016.0
9	The University of Castilla-La Mancha	1	7.69	50	50.00	2016.0
10	Nanyang Technological University	1	7.69	27	27.00	2019.0

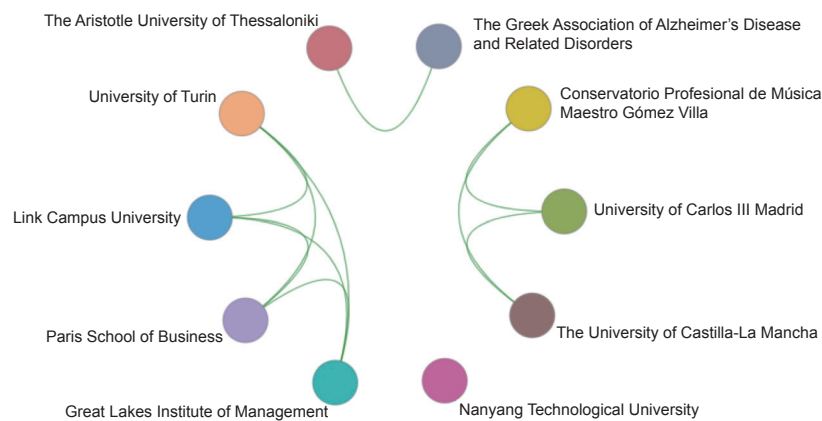


Figure 1.2.7 Collaboration network among major institutions in the engineering research front of “intelligent and responsive architecture for the elderly health”

Based on the above statistics, China ranked third in the quantity of core papers, and ranked first in the number of citations of core papers, indicating that Chinese scholars have paid close attention to this research front.

The key development directions of engineering research frontier “Intelligent and responsive architecture for the elderly health” in the next five to ten years are ① integrated health monitoring and spatial response mechanisms in

buildings, ② digital and intelligent environmental control technologies, and ③ intelligent responsive algorithms and building management systems. It is expected that the aging-appropriate renovation of existing buildings and the intelligent design and construction of new buildings will be carried out at the same time from 2022 to 2027. After that, the comprehensive evaluation system and standard guidelines could be formulated from 2025 to 2032 (Figure 1.2.8).

Table 1.2.11 Countries with the greatest output of citing papers on “intelligent and responsive architecture for the elderly health”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	58	18.12	2020.4
2	Spain	49	15.31	2019.0
3	Italy	32	10.00	2020.0
4	Greece	30	9.38	2017.7
5	UK	30	9.38	2019.7
6	India	30	9.38	2020.4
7	USA	22	6.88	2020.4
8	Germany	19	5.94	2019.0
9	France	18	5.62	2020.4
10	Canada	16	5.00	2020.1

Table 1.2.12 Institutions with the greatest output of citing papers on “intelligent and responsive architecture for the elderly health”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	The Aristotle University of Thessaloniki	26	28.26	2017.4
2	The University of Castilla-La Mancha	23	25.00	2018.4
3	University of Waterloo	6	6.52	2020.5
4	Nanyang Technological University	6	6.52	2020.3
5	Shanghai Jiao Tong University	6	6.52	2020.3
6	Biomedical Research Networking Center in Mental Health	5	5.43	2019.8
7	University of Seville	4	4.35	2017.0
8	Sapienza University of Rome	4	4.35	2019.2
9	King Saud University	4	4.35	2019.5
10	University of Valencia	4	4.35	2018.5

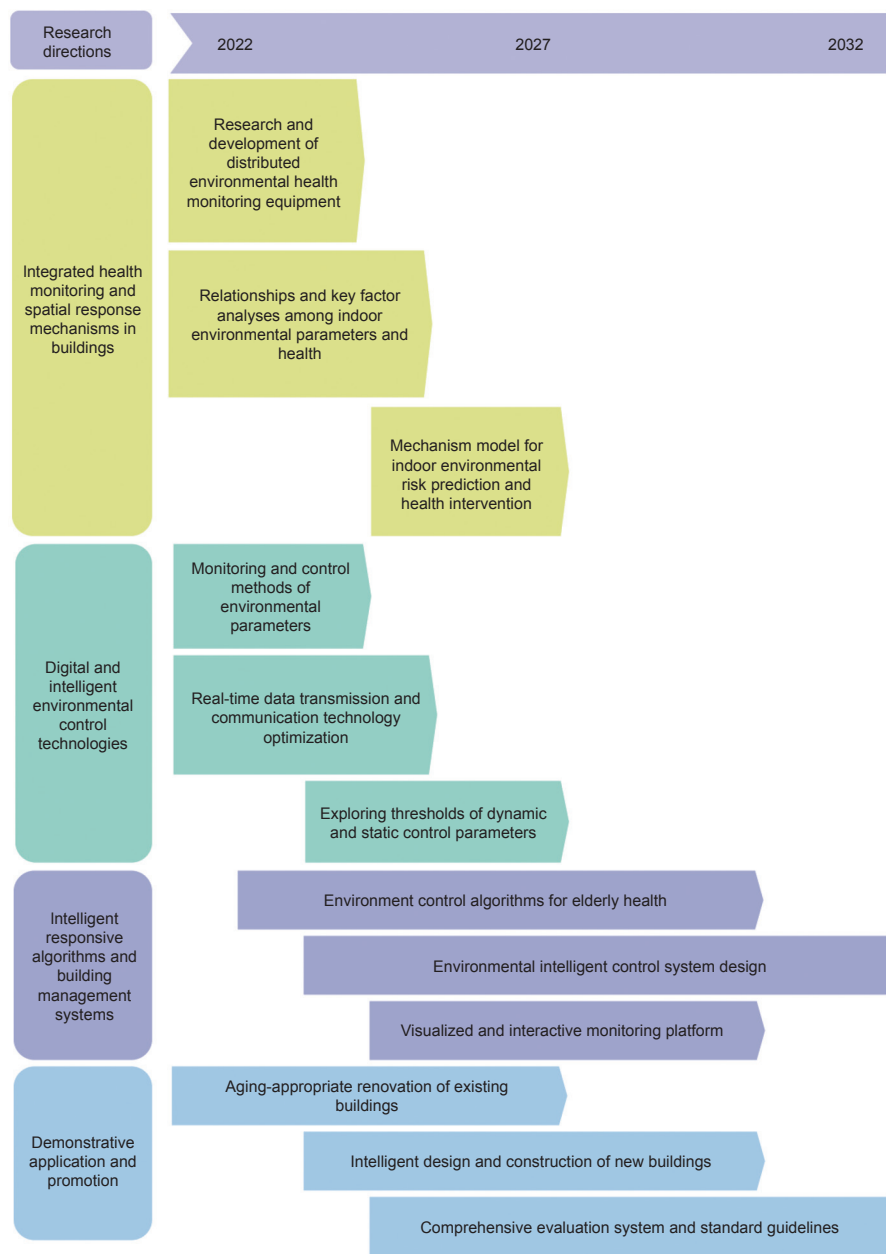


Figure 1.2.8 Roadmap of the engineering research front of “intelligent and responsive architecture for the elderly health”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines,

including geotechnical and underground engineering, hydraulic engineering, architectural design and theory, surveying and mapping engineering, construction materials, transportation planning, urban planning and landscaping, municipal engineering, and bridge engineering. The following development fronts were from experts’ nomination: “intelligent monitoring and early warning technologies for hidden defects of transportation infrastructure” and “control of algal and odor pollution in urban water supply system”.

The remaining fronts were identified from patent maps and confirmed in expert panel meetings. Table 2.1.2 presents annual statistics on patents registered between 2016 and 2021 related to these Top 10 development fronts.

(1) Active prevention and control of geohazards along the Sichuan-Tibet Railway

The active prevention and control of geohazards refers to the technologies that employ advanced measures to eliminate

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Active prevention and control of geohazards along the Sichuan-Tibet Railway	279	860	3.08	2019.4
2	Riverway ecological environment conservation and restoration	296	1 273	4.30	2019.6
3	Modeling and optimization of urban building energy consumption and carbon emission	13	275	21.15	2018.4
4	Autonomous positioning and navigation of unmanned systems	37	376	10.16	2018.8
5	Intelligent perception and prediction of multi-source information on underground engineering status	87	164	1.89	2019.8
6	Healing materials and techniques for different service environments	65	207	3.18	2019.0
7	Intelligent monitoring and early warning for hidden defects of transportation infrastructure	18	85	4.72	2018.8
8	Dynamic measurement and performance enhancement of green infrastructure ecosystem services	62	110	1.77	2019.2
9	Control of algal and odor pollution in urban water supply system	41	26	0.63	2019.0
10	Reliability evaluation and maintenance for bridge structures	79	131	1.66	2018.76

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Active prevention and control of geohazards along the Sichuan-Tibet Railway	18	21	37	44	70	89
2	Riverway ecological environment conservation and restoration	12	26	32	41	87	98
3	Modeling and optimization of urban building energy consumption and carbon emission	3	1	1	4	4	0
4	Autonomous positioning and navigation of unmanned systems	4	8	3	8	6	8
5	Intelligent perception and prediction of multi-source information of underground engineering status	4	6	10	12	10	45
6	Healing materials and techniques for different service environments	6	4	11	18	18	8
7	Intelligent monitoring and early warning for hidden defects of transportation infrastructure	1	4	2	5	2	4
8	Dynamic measurement and performance enhancement of green infrastructure ecosystem services	6	7	8	10	7	24
9	Control of algal and odor pollution in urban water supply system	2	8	8	5	8	10
10	Reliability evaluation and maintenance for bridge structures	6	14	13	17	18	11

hidden risks before forming geological disasters. The principle of these technologies is to use digitalized, informatized, mechanized and intelligentized techniques to establish an information database of geohazard source characteristics. The goal of being active and predictive is achieved through deployment of standardized modeling, network interaction, visual cognition, high-performance computing, and intelligent decision-making among other technologies in various core tasks such as quantitative assessment, intelligent monitoring, risk analysis, disaster warning, prevention and control, and emergency response. Driven by the digital chain, it becomes possible to enable integration and coordination of detection, assessment, monitoring, early warning, prevention and control, and emergency rescue against geohazards, and ultimately raise the level of disaster prevention and control by avoiding, transferring, and minimizing geohazards risk. The Sichuan-Tibet Railway is threatened frequently by geohazards such as landslides, debris flows, rockfalls, earthquakes, high geostress rockbursts and excessive deformations, high geothermal damages, active fault dislocations, and inrush of water and mud. The applications of the active prevention and control technologies against the geohazards involve: ① quantitative assessment of geohazards risk under coupling dynamic interaction of intensive internal and external forces; ② three-dimensional comprehensive intelligent monitoring and early warning of geohazards; ③ active prevention and control in advance and intelligent construction for complex bridges, tunnels, and high-steep slopes; ④ rapid and intelligent emergency rescue for geological disaster chain in mountainous areas. The key of these technologies is to deeply and extensively utilize modern technologies, such as the IoTs, big data, artificial intelligence, and building information modelling (BIM), to innovate upon new materials, new structures, and new techniques applicable in the key components (e.g., bridges, tunnels and high-steep slope) of the Sichuan-Tibet Railway and adaptive to harsh environment, and thus to achieve life-cycle early detection, warning and precise control of geohazards. Between 2016 and 2021, 279 patents relevant to this research front were registered. These patents received 860 citations, with an average of 3.08 citations per patent.

(2) Riverway ecological environment conservation and restoration

Riverway ecological environment conservation and restoration is critical for maintaining the ecological security boundary

of territorial space, maintaining or assisting the restoration of river ecosystem to the natural or near-natural state, so as to maintain and improve its ecological integrity and sustainability. It is also a scientific and technological frontier of international common concern, and its main technical directions include: ① the intelligent integration technology of riverway monitoring, evaluation and smart collaborative watershed management system; ② riverway green low-carbon and naturalization restoration technology; ③ riverway ecosystem function and biodiversity of conservation and restoration technology. New technologies, such as artificial intelligence, support of river ecological environment conservation and restoration technology, and accelerate the river ecological management of precision, fine, systematic transformation, which provides effectively technical support to guarantee the sustainability of river ecosystem and land ecological security, and achieves the ecological civilization goal of harmonious coexistence of man and nature. Between 2016 and 2021, 296 patents relevant to this research front were registered. These patents received 1 273 citations, with an average of 4.30 citations per patent.

(3) Modeling and optimization of urban building energy consumption and carbon emission

Modeling and optimization of urban building energy consumption and carbon emission is to establish physics-based models of energy consumption of buildings, and optimize design and operation of buildings through quantitative analyses of the impact of different factors on energy consumption and carbon emission of buildings. It is a key technical means to achieve energy saving and emission reduction in field of building engineering. The main topics of this front include: ① buildings' big data acquisition and digital city construction, which facilitates digital collection of building information and establishment of digital cities; ② automatic modeling of energy consumption of buildings at regional scale, which enables rapid modeling and automatic model calibration based on operational data; ③ regional energy system design and operation optimization, which supports intelligent response of energy consumption and power supply in buildings; ④ carbon emission prediction and optimization of urban building clusters, and analysis of the emission reduction potential brought by different energy-saving technologies. The future development trend is to upgrade the physical models of regional building energy consumption, improve regional building energy efficiency by integrating

multi-disciplinary knowledge from energy-saving buildings, geographic information science, computer technology, and artificial intelligence, and help promote the carbon peaking and carbon neutrality goals. Between 2016 and 2021, 13 patents relevant to this research front were registered. These patents received 275 citations, with an average of 21.15 citations per patent.

(4) Autonomous positioning and navigation of unmanned systems

Autonomous positioning and navigation of unmanned systems is the general term of real-time positioning, autonomous map construction and path planning method. It is one of the key technologies of autonomous mobile unmanned systems and one of the development fronts in the field of surveying and mapping engineering. There exist a wide range of application needs in autonomous mobile systems such as unmanned aerial vehicles, unmanned ships and unmanned submarines. Development trends in this front include: ① high-precision autonomous positioning technology, which determines the position and attitude of unmanned systems in the workspace by using global navigation satellite systems (GNSS), simultaneous localization and mapping (SLAM), dead reckoning, space beacon positioning and other technologies independently or in combination; ② map building technology in a dynamic environment, which is oriented to dynamic scenes, senses the surrounding spatial information through various sensors and models the environment map; ③ efficient local path planning algorithm, with which the unmanned system uses dynamic path algorithm to plan the optimal moving route according to the perceived environmental information. Between 2016 and 2021, 37 patents relevant to this research front were registered. These patents received 376 citations, with an average of 10.16 citations per patent.

(5) Intelligent perception and prediction of multi-source information on underground engineering status

Intelligent perception and prediction of multi-source information on underground engineering status refers to sensing the characteristic indicators of the multi-factor status through various smart sensors and fusing multi-source heterogeneous data to clean and correlate the status data for a consistent interpretation of underground engineering status. Through machine learning and big data algorithms, one can comprehensively evaluate underground engineering status, quickly diagnose and accurately identify faults, and thereby

realize intelligent prediction of underground engineering status. In practice, complex and dynamically changing responses of underground structures arise from highly variable geological conditions and surrounding engineering disturbances. Intelligent perception and prediction of multi-source information enables comprehensive evaluation of underground engineering operating status and supports decision making for underground engineering management. The main subjects involved in this front include: ① the holographic perception method and technological system of sensing underground engineering status based on wireless sensing, optical fiber, electromagnetic wave, sound wave, camera, laser, etc.; ② the technologies (such as the Internet of Things, edge computing, and deep learning) in characterization, fusion, and dynamic update of multi-source heterogeneous sensing data across time, space, scale, and media to achieve consistent interpretation of underground engineering status; ③ the physics-informed machine learning algorithms (such as Bayesian and Convolutional neural networks) to establish an evolution model of underground engineering status considering the influence of time and space in an uncertain environment, and realize fast evaluation, prediction and early warning of engineering status; ④ underground digital platforms and underground engineering digital bases via BIM, city-scale urban information model (CIM), and digital twin models to realize 3D visualization feedback and update of underground engineering status. The technologies for perception and prediction of underground engineering status developed rapidly in recent years. The real-time intelligent perception and efficient prediction technology integrating multi-smart sensors has gradually become an effective means to reduce risks and avoid accidents in underground engineering. It is in the mainstream future trend of intelligent management and control of underground engineering safety. Between 2016 and 2021, 87 patents relevant to this research front were registered. These patents received 164 citations, with an average of 1.89 citations per patent.

(6) Healing materials and techniques for different service environments

Concrete deteriorates in service safety and durability due to accelerated damage and structural failure, as it is exposed to largely fluctuating temperature, strong radiation or/and severely corrosive environments in high plateau, ocean, desert or deep ground. It is vital to repair degraded parts in time to achieve long-term safety of concrete structures. At

present, the development for concrete healing materials and techniques mainly involves: ① design of healing materials, such as polymer-cement based composite healing material, grouting healing material, fiber reinforced composite healing material; ② analysis of healing behavior, such as the characterization of crack healing behavior and the anti-corrosion behavior; ③ performance evaluation, such as mechanical properties, impermeability, corrosion resistance properties; and ④ simulation for predicting long-term repair of concrete. The existing healing materials and techniques suffer from the lack of intelligent healing methods, vagueness in healing behavior, destructive technique for performance evaluation, and the insufficiency of data platform and high-throughput simulation methods. Thus, the development trend of this field will revolve around intelligent repair design, in-situ nondestructive assessment, data platform construction and high-throughput operation. Between 2016 and 2021, 65 patents relevant to this research front were registered. These patents received 207 citations, with an average of 3.18 citations per patent.

(7) Intelligent monitoring and early warning for hidden defects of transportation infrastructure

Under the coupling effect of traffic loads and environmental variation, the base layer and soil foundation of transportation infrastructure are prone to internal diseases, such as cracking, void and settlement. These diseases are often unobservable directly from the surface, and they are often defined as hidden defects which are difficult to be monitored and positioned. Supported with big data and artificial intelligence, the intelligent monitoring and early warning of such hidden defects aims at accurate monitoring, rapid diagnosis, and real-time early warning of hidden defects based on the work flow of sensor monitoring, three-dimensional positioning, inversion diagnosis, health assessment, and decision making for early warning. The main topics of this front involve: ① equipment for accurate detection, three-dimensional positioning and digital sensing of hidden defects; ② analytical inversion theory and high-precision diagnosis algorithms; ③ database of typical hidden defects and cloud computing aided prediction systems; ④ platforms for health assessment and decision making for early warning. In the future, the relevant equipment may be no more multi-segment, large-scale and wired, and become intensive, light-weight and wireless. The passive detection means that heavily relies on man power could be replaced by intelligent, sensing and active means for

prediction and early warning. Besides, the platforms may be transformed from the ones mechanized and processed for data collection into intelligent and automatic ones that support monitoring and early warning. Between 2016 and 2021, 18 patents relevant to this research front were registered. These patents received 85 citations, with an average of 4.72 citations per patent.

(8) Dynamic measurement and performance enhancement of green infrastructure ecosystem services

In the context of climate change and the demanding need for improving global ecosystems, green infrastructure (GI) is considered to be one of the most important strategies to actively respond to climate change, increase carbon sinks, ensure national ecological security, and achieve sustainable development. The focus of GI development is to achieve more accurate quantification and more efficient provision of ecosystem services. GI highlights the “life supporting” functions of natural environment, forms an interconnected blue-green space network with comprehensive ecological functions, and integrates with regional landscape structures and other land uses in urban environment. GI provides provisioning ecosystem services (such as water supply), regulating ecosystem services (such as stormwater regulation, water quality regulation, air purification, soil contamination mitigation, soil and water conservation, carbon sink), supporting ecosystem services (such as supporting biodiversity) and cultural ecosystem services (such as promoting livability and providing recreational activities). In order to improve the efficiency of global ecosystem services provision, the most challenging issue is to reveal the mechanism of multi-scale coupling and multi-functional synergy of the ecosystem services provided by GI based on high-precision, all-factor, and whole-process dynamic quantification. The main topics of this front involve: ① quantitative analysis and dynamic metrics of GI ecosystem services supply; ② “space-air-ground” measurement equipment and intelligent perception system for GI ecosystem services; ③ spatiotemporal evolution and simultaneously global comparison of GI ecosystem services efficiency; ④ highly-efficient integrated technical system for GI construction. In response to climate change, increasing attention is paid to the performance and efficiency of key ecosystem services of GI, such as carbon emission reduction and carbon sink increase, stormwater regulation and storage, and water purification. Between 2016 and 2021, 62 patents relevant to this research front were registered. These patents

received 110 citations, with an average of 1.77 citations per patent.

(9) Control of algal and odor pollution in urban water supply system

Algal and odor pollution in urban water supply system refers to a series of drinking water quality problems caused by algal and odor substances in source water and water supply system, which undermine stable operation of drinking water treatment plants. Algal and odor pollution is aggravated by declining dissolved oxygen and intensified eutrophication in source water as a result of global temperature rising and accelerated urbanization. Effective control of algae and odor pollution in urban water supply system is key for health and safety of drinking water. The main topics of this front include: ① systematic ecological management and water source protection at the scale of city clusters; ② upgrading conventional treatment processes to strengthen the treatment of algae and odor pollution; ③ chemical treatment technologies based on active substances with strong oxidizing capacity (e.g., ozone catalytic oxidation, permanganate oxidation, ferrate oxidation, and photocatalysis) to achieve effective degradation of algae toxins and odor substances; ④ development of novel membranes and adsorbents based on the principles of physical separation and adsorption, such as ceramic membranes, activated carbon and bio-char; ⑤ low-cost biological treatment technologies with outstanding environmental adaptability; ⑥ intelligent monitoring-treatment system for algae and odor pollution by integrating advanced sensors, artificial intelligence, and automatic control technology. The focus of future development in this field aims at targeted source control with the support of accurate analysis and traceability of algae and odor substances, and highly automated, intelligent, low-cost, efficient, and easy-to-maintain technologies by conducting inter-disciplinary research among water treatment engineering, microbiology, chemistry, physics, and artificial intelligence. Between 2016 and 2021, 41 patents relevant to this research front were registered. These patents received 26 citations, with an average of 0.63 citations per patent.

(10) Reliability evaluation and maintenance for bridge structures

The reliability of a bridge structure refers to the ability of the bridge structure to complete its predetermined function in face of many uncertain events and factors in planning,

design, construction, management and maintenance during its life cycle. Structural reliability assessment is the process of modeling and analyzing the influence of these uncertain events and factors on structural behavior, and evaluating the life-cycle performance of structural engineering. The main technical directions include: ① uncertainty simulation of bridge construction process and behavior control of green construction process; ② uncertainty simulation of bridge completion and operation load process and maintenance of structural limit and fatigue reliability; ③ uncertainty simulation of deflagration process of bridge structure and guarantee of stability of components and structures; ④ risk scenario analysis of wind-induced catastrophic load process of cable bridge and the guarantee of structural aeroelastic stability; ⑤ the uncertain simulation of bridge earthquake and ship impact damage process and the maintenance of structural toughness and reliability. In recent years, the development trend has paid more attention to the branch evolution analysis of the behavior mode of green bridge structure under the consideration of uncertainty factors, the evaluation of the inducement failure and reliability maintenance of the continuous failure behavior of soft bridge structure under the disaster risk events, the reliability evolution analysis and damage control of the bridge structure system. Between 2016 and 2021, 79 patents relevant to this research front were registered. These patents received 131 citations, with an average of 1.66 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Active prevention and control of geohazards along the Sichuan-Tibet Railway

Traditional technologies for geohazard prevention and control cannot meet the need of construction safety and efficiency in the Sichuan-Tibet Railway due to unsatisfactory results, difficult implementation during construction, low-level intelligence, and passivity. Alternatively, it has become a priority to develop active approaches to prevent and control geohazards along the Sichuan-Tibet Railway. Currently, the new generation of the information technologies represented by IoTs, big data, artificial intelligence and BIM is accelerating the advancement in civil engineering technologies characterized by new materials, new structures,

and new techniques. The fusion across multiple disciplines is profoundly changing the theory and the technology for disaster prevention and mitigation. Accordingly, the way for preventing and controlling geohazards along the Sichuan-Tibet Railway changes from passive to active with an aim at comprehensive disaster prevention at full scales rather than for individual critical parts.

The core of active prevention and control of geohazards along the Sichuan-Tibet Railway is “being active”. The relevant subjects involved in this front are as follows:

- 1) Quantitative risk assessment, which includes: ① data- and model-driven identification of geohazards, such as landslides, debris flows, rockfalls, earthquakes, high geo-stress rockbursts and excessive deformations, high geothermal damage, active fault dislocations, and water and mud inrush; ② quantitative and rapid assessment of geohazard risk under coupling dynamic interaction of intensive internal and external forces.
- 2) Intelligent monitoring and early warning, including variable-frequency intelligent monitoring and early warning technology for geohazards, “space-sky-surface-interior” three-dimensional comprehensive intelligent monitoring and early warning technology for geohazards, artificial intelligence and decision-making technology, intelligent perception and data mining technology, and technology integration and information modelling.
- 3) Advanced prevention and control, which includes: ① anti-slide piles and retaining walls, and active rockfall netting protection technology; ② debris flow blocking and drainage technology; ③ damping flexible lining, and light-weight concrete; ④ ventilation and mechanized cooling technology of high geothermal tunnels; ⑤ pressure relief blasting technology, stress release and relief technology; ⑥ layered support and active pressure yielding support technology for large-deformation tunnels; ⑦ flexible protection technology for rockbursts, and kinetic energy release technology for active fractures; ⑧ advanced pre-grouting technology for water and mud inrush, curtain grouting, and high-pressure split grouting technology.
- 4) Intelligent construction, including intelligent construction technology, robot system and automation technology, modular and refined construction technology, precise control and decision-making technology.
- 5) Intelligent emergency rescue, including comprehensive

intelligent command system for emergency rescue, rapid recovery technology for infrastructure and grid power system, emergency escape and refuge technology, and intelligent removal technology for hidden dangers.

As listed in Table 2.1.1, 279 patents related to this topic were registered between 2016 and 2021, with each patent being cited 3.08 times on average. The three countries that registered the most patents were China, South Korea, and the USA (Table 2.2.1). Among these countries, China was at the forefront of development, contributing 91.40% of the patents. The average citation frequency of Chinese patents was 2.64. Cooperation is rare among major countries.

The five organizations that produced the most patents were Gansu Province Academy of Sciences Institute of Geological and Natural Disasters Prevention, China Institute of Geoenvironment Monitoring, Chongqing Geological Bureau of Geology and Minerals Exploration, Shandong Geological Environment Monitoring Station, and Kunming University of Science and Technology (Table 2.2.2). From the above ranking of core patent output institutions, Gansu Province Academy of Sciences Institute of Geological and Natural Disasters Prevention has focused on debris flow disaster prevention, landslide hazard assessment and stability monitoring and early warning in the Loess area; China Institute of Geoenvironment Monitoring has focused on protection measures for high level landslide debris flow disasters, monitoring and warning of regional geological disasters and cave-ins and rockfalls; Chongqing Geological Bureau of Geology and Minerals Exploration has focused on monitoring and warning of underground water, landslides, collapses, ground fractures and other disasters in mines and karst areas. Cooperation among these organizations is rare (Figure 2.2.1).

As shown in Figure 2.2.2, the future development of this front in the coming five to ten years involves quantitative risk assessment, intelligent monitoring and early warning, advanced prevention and control, intelligent construction, intelligent emergency rescue.

2.2.2 Riverway ecological environment conservation and restoration

Protecting the ecological security of territorial space is a basic national policy in many countries including China, and conserving riverway is the core artery of ecological

Table 2.2.1 Countries with the greatest output of core patents on “active prevention and control technology of geohazards along the Sichuan-Tibet Railway”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	255	91.40	674	78.37	2.64
2	South Korea	10	3.58	6	0.70	0.60
3	USA	9	3.23	163	18.95	18.11
4	Japan	2	0.72	4	0.47	2.00

Table 2.2.2 Institutions with the greatest output of core patents on the “active prevention and control technology of geohazards along the Sichuan-Tibet Railway”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Gansu Province Academy of Sciences Institute of Geological and Natural Disasters Prevention	29	10.39	27	3.14	0.93
2	China Institute of Geoenvironment Monitoring	21	7.53	74	8.60	3.52
3	Chongqing Geological Bureau of Geology and Minerals Exploration	15	5.38	17	1.98	1.13
4	Shandong Geological Environment Monitoring Station	14	5.02	21	2.44	1.50
5	Kunming University of Science and Technology	9	3.23	25	2.91	2.78
6	Chengdu University of Technology	7	2.51	33	3.84	4.71
7	Sichuan College of Architectural Technology	7	2.51	30	3.49	4.29
8	Gansu Geological Disaster Prevention Engineering Exploration and Design Institute	7	2.51	3	0.35	0.43
9	Shandong University	5	1.79	39	4.53	7.80
10	China Chemical Geology and Mine Bureau Shandong Geological Prospecting Institute	5	1.79	1	0.12	0.20

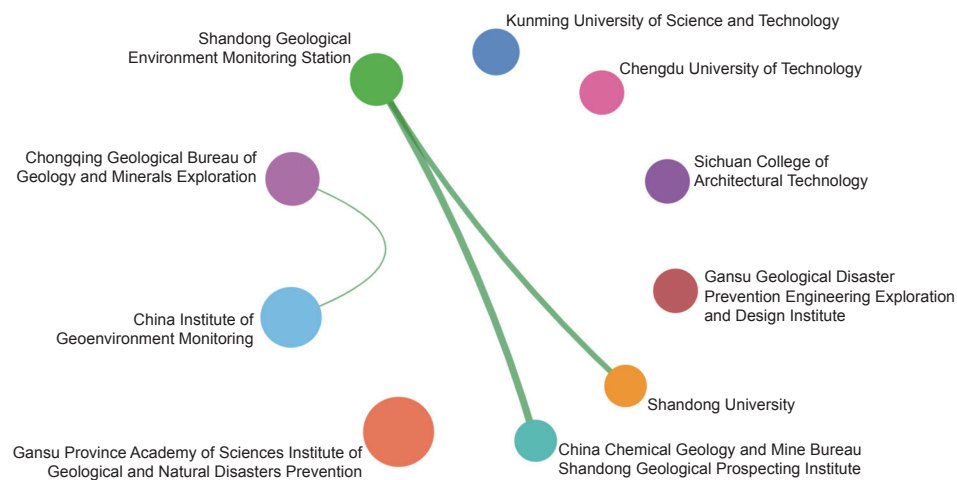


Figure 2.2.1 Collaboration network among major institutions in the engineering development front of “active prevention and control technology of geohazards along the Sichuan-Tibet Railway”

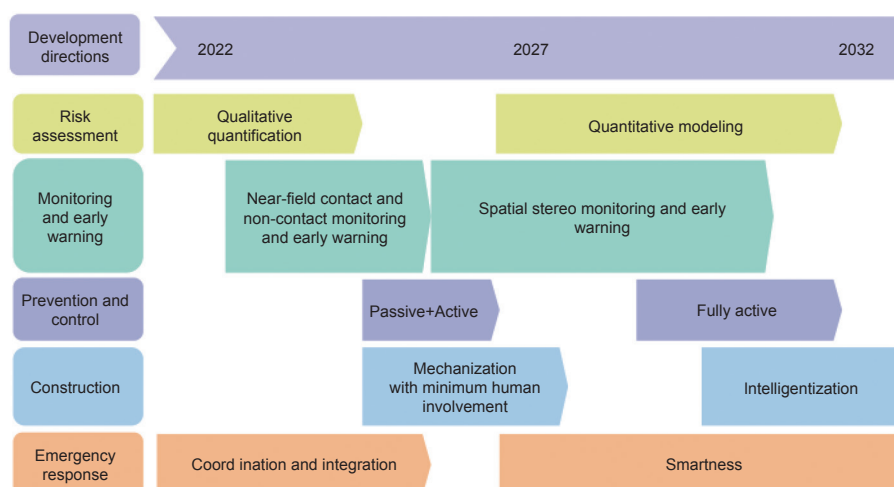


Figure 2.2.2 Roadmap of the engineering development front of "active prevention and control technology of geohazards along the Sichuan-Tibet Railway"

security of the life community of mountains, rivers, forests, fields, lakes, plants and sediments. The global research and practice on river ecological management dates back to 1960s, while the principle and strategy for sustainable riverway ecological conservation and restoration considering regional variation has been developed in China since 21st century by learning lessons from traditional riverway governance. Nowadays it has become an international consensus to fundamentally reversing and changing traditional modes of river development and governance that damage the health of river ecosystems. Identifying the scientific and technological frontiers in this field, and solving the bottleneck problems of river ecological governance are important supports for ensuring the ecological security of territorial space.

It is a scientific goal and a national strategic need to protect or restore the resilience of river ecosystem to facilitate the sustainable development of beautiful territorial space. The frontiers of river ecological environment conservation and restoration technology mainly focus on the following directions:

1) The intelligent integration technology of riverway monitoring, evaluation and smart collaborative watershed management system, which includes high-precision and rapid monitoring and evaluation, river ecological model construction and simulation based on big data and digital twins, water control projects and systematic collaborative technology, efficient and intelligent collaborative integration technology of watershed management.

2) Riverway green low-carbon and naturalization restoration technology, which includes restoration technology based on hydrological rhythm and spatial heterogeneity of geomorphology, riverside wetland conservation and restoration technology based on green and low-carbon concept, ecological conservation and restoration technology based on three-dimensional connectivity.

3) Riverway ecosystem function and biodiversity of conservation and restoration technology, which includes river habitat identification and conservation, aquatic food chain structure evaluation, food chain conservation and restoration technology, retroactive fish habitat conservation and restoration, natural simulation and efficient fish facilities construction with ecological flow precision regulation technology.

As listed in Table 2.1.1, 296 patents related to this front were registered between 2016 and 2021, with each patent being cited 4.3 times on average. The three countries that registered the most patents were China, the USA, and South Korea (Table 2.2.3). Among these countries, China was at the forefront of development, contributing 95.27% of the patents. The average citation frequency of Chinese patents was 3.91. Cooperation is rare among major countries.

The five organizations that produced the most patents were China Institute of Water Resources and Hydropower Research, Hohai University, Sinohydro Bureau 11 Co., Ltd., North China University of Water Resources and Electric Power, and Nanjing University (Table 2.2.4). From the above

Table 2.2.3 Countries with the greatest output of core patents on “riverway ecological environment conservation and restoration”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	282	95.27	1 102	86.57	3.91
2	USA	6	2.03	150	11.78	25.00
3	South Korea	4	1.35	4	0.31	1.00
4	Australia	2	0.68	5	0.39	2.50
5	India	1	0.34	10	0.79	10.00
6	Netherlands	1	0.34	2	0.16	2.00

Table 2.2.4 Institutions with the greatest output of core patents on “riverway ecological environment conservation and restoration”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Institute of Water Resources and Hydropower Research	7	2.36	19	1.49	2.71
2	Hohai University	6	2.03	30	2.36	5.00
3	Sinohydro Bureau 11 Co., Ltd.	6	2.03	22	1.73	3.67
4	North China University of Water Resources and Electric Power	3	1.01	18	1.41	6.00
5	Nanjing University	3	1.01	14	1.10	4.67
6	China First Metallurgical Group Co., Ltd.	3	1.01	13	1.02	4.33
7	Chinese Academy of Fishery Sciences	3	1.01	9	0.71	3.00
8	Shandong Jianzhu University	2	0.68	30	2.36	15.00
9	Institute of Hydroecology, MWR & CAS	2	0.68	19	1.49	9.50
10	Research Institute of Forest Ecology Environment and Protection, Chinese Academy of Forestry	2	0.68	18	1.41	9.00

ranking of core patent output institutions, China Institute of Water Resources and Hydropower Research focuses on river ecological corridor and ecological slope protection, riverway habitat feature identification using remote sensing, and habitat biodiversity restoration, Hohai University focuses on the real-time diagnosis and self-restoration of riverway health, riverway ecological slope protection, ecological flow and river ecological connectivity related technical products. Cooperation among major institutions is rare.

In the next five to ten years, the key development directions involved in this front are the intelligent integration technology of riverway monitoring, evaluation and smart collaborative watershed management system,

riverway green low-carbon and naturalization restoration technology, riverway ecosystem function and biodiversity of conservation and restoration technology. In terms of application, it is expected that the intelligent integration technology of riverway monitoring, evaluation and smart collaborative watershed management system will gradually reach maturity by 2027, and achieve large-scale applications afterwards. It is expected that riverway green low-carbon and naturalization restoration technology and riverway ecosystem function and biodiversity of conservation and restoration technology will be advanced from concept design to technology development until 2030, and receive large-scale applications afterwards (Figure 2.2.3).

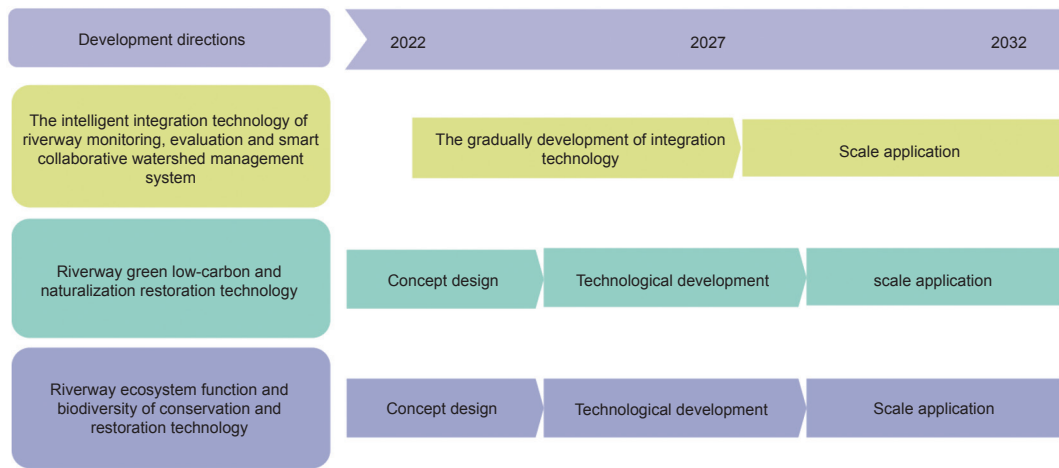


Figure 2.2.3 Roadmap of the engineering development front of “riverway ecological environment conservation and restoration”

2.2.3 Modeling and optimization of urban building energy consumption and carbon emission

Energy saving and emission reduction in buildings is crucial to achieve the carbon peaking and carbon neutrality goals. Modeling and optimization of urban building energy consumption and carbon emission is to establish physically-based models of energy consumption of buildings, and optimize design and operation of buildings through quantitative analyses of the impact of different factors on energy consumption and carbon emission of buildings. The ultimate goal of this development front is to achieve energy saving and emission reduction at urban scale, promote green, low-carbon and high-quality regional development, and technically support government to formulate policies and measures for energy saving and emission reduction. The current regional scale simulation is characterized by massive input data, complex model, and intensive computation. Thus, automation in model generation, light-weight model, “one model for multiple uses”, and new energy systems (such as electric vehicles, photovoltaic, energy storage, and microgrid) are the hot issues in this front.

The main topics involved in this front include the following:

1) Buildings big data acquisition and digital city construction. The relevant work is intended to ① acquire image data through remote sensing from unmanned aerial vehicle (UAV), satellite images, or street view images, ② automatically extract building information (e.g., building geometry, building type, and construction age) from the image data

in combination with GIS-based buildings big data (e.g., city information points and building outlines) by using artificial intelligence technologies such as machine learning, deep learning, and computer vision, and ③ ultimately establish a digital twin city.

2) Automatic modeling of energy consumption of buildings at regional scale. Regional building energy consumption and carbon emission models are automatically generated from based on the extracted building information and relevant standards with GIS and building energy simulation tools for rapid modeling at regional scale and automating model calibration with actual measurement data.

3) Regional energy system design and operation optimization. The energy demand of building groups is obtained through building regional energy consumption simulation, and optimization is made in the design of photovoltaic power generation system, energy storage system, electric vehicle charging and discharging system, and combined heat and power supply system. Ultimately, building energy consumption regulation is optimized according to electrovalence and demand response to achieve intelligent response and intelligent matching of building energy consumption and power supply.

4) Carbon emission prediction and optimization of urban building clusters. Regional building operation carbon emissions is calculated based on building energy consumption simulation and carbon emission factor database, and meanwhile the emission reduction potential brought by

different energy-saving technologies is analyzed.

As listed in Table 2.1.1, 13 patents related to this front were registered between 2016 and 2021, with each patent being cited 21.15 times on average. The three countries that registered the most patents were China, the USA, and South Korea (Table 2.2.5). Among these countries, China was at the forefront of development, contributing 61.54% of the patents. Cooperation is rare among major countries.

The five institutions that produced the most patents were Southeast University, Xi'an University of Architecture and Technology, Anguleris Technologies Limited Liability Company, Cenergistic Incorporation, and Johnson Controls Technology Company (Table 2.2.6). Cooperation is rare among

major institutions.

The development frontier of the “modeling and optimization of urban building energy consumption and carbon emission” for the next 5–10 years are: building big data acquisition and digital city construction, automated urban building energy modeling, community scale energy system design and operation optimization, and carbon emission prediction and optimization of urban buildings. To be more specific, on the data side, the research and application frontiers are twofold. First, how to introduce new data sources such as drone-aided remote sensing, satellite image, street view into building energy modeling and how to extract useful information from those new data sources using rapid evolving technologies such as deep learning, computer vision etc. Second, how to

Table 2.2.5 Countries with the greatest output of core patents on “modeling and optimization of urban building energy consumption and carbon emission”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	8	61.54	48	17.45	6.00
2	USA	4	30.77	227	82.55	56.75
3	South Korea	1	7.69	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “modeling and optimization of urban building energy consumption and carbon emission”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Southeast University	3	23.08	5	1.82	1.67
2	Xi'an University of Architecture and Technology	2	15.38	2	0.73	1.00
3	Anguleris Technologies Limited Liability Company	1	7.69	107	38.91	107.00
4	Cenergistic Incorporation	1	7.69	61	22.18	61.00
5	Johnson Controls Technology Company	1	7.69	58	21.09	58.00
6	Jiangsu Emap Geographic Information Technology Company Limited	1	7.69	32	11.64	32.00
7	Harbin Institute of Technology	1	7.69	9	3.27	9.00
8	Research Foundation of the City University of New York	1	7.69	1	0.36	1.00
9	Beijing Institute of Technology	1	7.69	0	0.00	0.00
10	Korea Advanced Institute of Science and Technology	1	7.69	0	0.00	0.00

better leverage data from multiple sources for data fusion and calibration. The research frontier of modeling is how to automate the model development and calibration process. In terms of optimization, the frontiers are twofold. First, how to leverage BIM technology to co-optimize the energy system design and operation. Second, how to more efficiently integrate the electrical vehicle, and distributed renewable

generations into building energy system. As for the carbon emission reduction, the emerging trend is how to accurately audit and predict carbon emission from building energy consumption at the urban scale, based on which to design a feasible and effective roadmap to achieve carbon peaking and carbon neutrality goal. For details, please refer to the Figure 2.2.4.

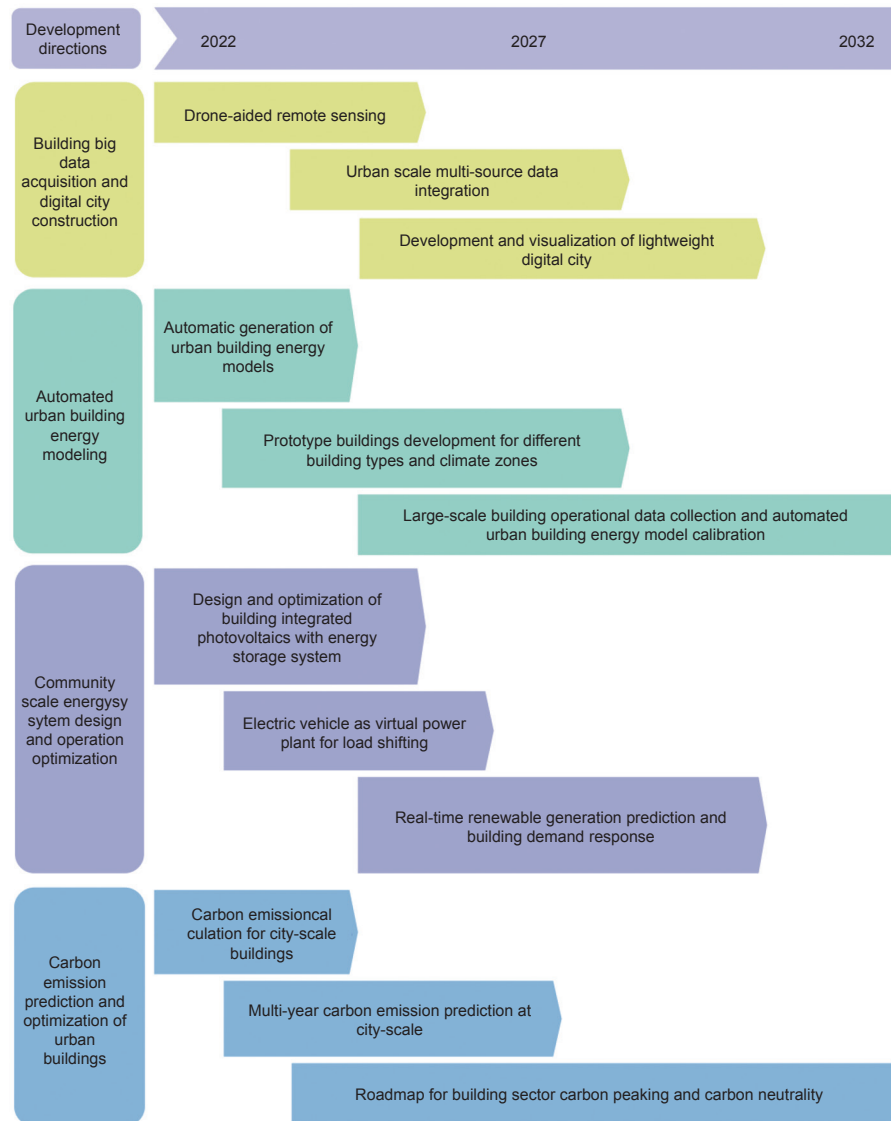


Figure 2.2.4 Roadmap of the engineering development front of "modeling and optimization of urban building energy consumption and carbon emission"

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VI. Environmental and Light Textile Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of environmental and light textile engineering include the subfields of environmental science, meteorological science, marine science, food science, textile science, and light industry science. The citation statistics for these research fronts and the annual number of core papers for each research front between 2016 and 2021 are summarized in Tables 1.1.1 and 1.1.2, respectively.

(1) Mechanisms of multi-media transport and transformation of new pollutants

New pollutants (or emerging pollutants) refer to newly discovered or noticed pollutants that pose risks to the ecological environment or human health, and have not yet been incorporated into management or existing management

measures are insufficient to effectively prevent and control their risks. With the increasing understanding of the environmental and health hazards of chemical substances and the continuous development of environmental monitoring technology, the number of new pollutants that can be identified will continue to increase. Therefore, the development of efficient and universal analytical methods for discovering new pollutants is an important research direction in the field of new pollutant management.

The production and use of toxic and hazardous chemical substances are the main sources of new pollutants. Literature shows that higher levels of new pollutants such as environmental endocrine disruptors, antibiotics, and microplastics have been monitored successively in the atmosphere, water, and soil in some regions of China. Transfer of new pollutants among different environmental media often occurs, implying that one medium can become the pollution source for the next environmental medium, leading to differences in fate and contamination levels for new pollutants in different media. However, the migration and transformation

Table 1.1.1 Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Mechanisms of multi-media transport and transformation of new pollutants	117	7 863	67.21	2017.8
2	Treatment and resource recovery techniques for hypersaline wastewater	81	4 877	60.21	2019.0
3	Mechanism and critical path of synergies between atmospheric pollution control and carbon emission mitigation	918	80 741	87.95	2017.8
4	Ecological effects and risks of microplastics in coastal wetlands or offshore waters	20	463	23.15	2020.5
5	Carbon sequestration of coastal wetland ecosystem	73	4 816	65.97	2018.3
6	Application of machine learning in earth system observation and prediction	96	9 270	96.56	2017.9
7	Vital characteristics and ecological effects of microorganisms in extreme marine environments	17	1 378	81.06	2017.9
8	Research on the cleaner production technology of tanning agent-free leather making	24	130	5.42	2019.8
9	Study on the mechanisms of food functional factors and chronic metabolic syndrome	18	1 524	84.67	2018.2
10	Extraction and development of new natural cellulose fibers	43	5 705	132.67	2017.5

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Mechanisms of multi-media transport and transformation of new pollutants	36	16	25	22	13	5
2	Treatment and resource recovery techniques for hypersaline wastewater	0	0	31	30	13	7
3	Mechanism and critical path of synergies between atmospheric pollution control and carbon emission mitigation	202	204	203	158	109	35
4	Ecological effects and risks of microplastics in coastal wetlands or offshore waters	0	0	1	3	2	14
5	Carbon sequestration of coastal wetland ecosystem	0	17	28	21	5	2
6	Application of machine learning in earth system observation and prediction	10	12	13	30	17	0
7	Vital characteristics and ecological effects of microorganisms in extreme marine environments	0	6	7	4	0	0
8	Research on the cleaner production technology of tanning agent-free leather making	0	0	4	5	8	7
9	Study on the mechanisms of food functional factors and chronic metabolic syndrome	3	4	4	2	3	2
10	Extraction and development of new natural cellulose fibers	13	8	11	8	3	0

behaviors and mechanisms of most new pollutants among multi-media are unclear, and the health risks are unclear. Around the management of new pollutants, it is necessary to further strengthen the research on environmental screening, traceability studies, environmental risk assessment and control, and research on ecological and environmental hazard mechanisms such as antibiotics and microplastics; it is also a necessary to develop with the help of mathematical methods or models to better describe the cross-media migration and transformation of new pollutants released into the atmosphere.

(2) Treatment and resource recovery techniques for hypersaline wastewater

Hypersaline wastewater usually refers to wastewater containing dissolved salts above 3.5% (w/v). It is extensively present in the chemical industry and often contains a large number of hazardous substances such as refractory organic matters and heavy metals. In recent years, with the policies on “zero liquid discharge” and wastewater recycling vigorously promoted across the world, the development of technologies for treating and recycling hypersaline wastewater has now become a high priority in the area of water treatment.

The high-concentration inorganic ions in hypersaline wastewater would not only inhibit bacterial growth but also

quench hydroxyl radicals, thus constraining organic pollutant degradation. Regarding organic pollutants removal, the current research is mostly focused on advanced oxidation technologies such as persulfate-based Fenton and spatially confined electro-catalysis. The core concept is to increase the lifetime of active species and accelerate the mass transfer of reactants for enhanced pollutants degradation. Besides, more halotolerant and halophilic bacteria have been screened and domesticated, which contributes to the removal of organic pollutants in combination with bioaugmentation technologies such as membrane bioreactors and granular sludge reactors.

Since salts and water in hypersaline wastewater are valuable resources, their separation is essential for establishing a sustainable water treatment process. Two of the important research fields are the concentration of hypersaline wastewater and the separation of mixed salts. Regarding these demands, membrane separation technologies, including nanofiltration, reverse osmosis, selective electrodialysis, and membrane distillation, have attracted much attention. To realize the industrial application of membrane technologies in the recycling of hypersaline wastewater, it's essential to fabricate high-performance membrane materials and develop membrane fouling control technologies.

It is noteworthy that the recycling of hypersaline wastewater is highly impacted by its complex composition. Therefore, multi-

process integrated approaches should be developed based on the actual water quality to accomplish the recycling of hypersaline wastewater in a green, low-carbon, and efficient manner.

(3) Mechanism and critical path of synergies between atmospheric pollution control and carbon emission mitigation

Both atmospheric pollutant emissions and CO₂ emissions show agglomeration effects in space, and the grids of hotspots are highly consistent. These hotspots are mainly distributed in large and medium-sized cities such as provincial capitals (capitals of autonomous regions) and key urban agglomerations. Similar to pollutant emissions, PM_{2.5} pollution and O₃ pollution in China also show obvious regional characteristics, and the areas with heavy air pollution and CO₂ emission areas are highly overlapped. The same root and homology of greenhouse gases and atmospheric pollutants makes the emission reduction work direction highly consistent, and the coordinated governance work can simultaneously achieve the dual goals of in-depth pollution prevention and control and “carbon peaking and carbon neutrality”, and promote the reduction of carbon emissions. Synergistic effect of pollution reduction and carbon reduction.

Considering that environmental pollutants and greenhouse gases have the same root and the same source, pollution reduction and carbon reduction are highly consistent in terms of management and control ideas, management methods, task measures, etc., and can be planned, integrated, and coordinated to achieve cost reduction and efficiency. Therefore, it is necessary to reveal the comprehensive impact mechanism of the application of pollution reduction and carbon reduction technology on social economy, ecosystem and human health through key research, as well as the feedback mechanism of cross-system element coupling and linkage on different technologies, and calculate the energy saving and emission reduction potential of the circular economy development model. Quantitative simulation and targeted regulation methods for the synergy of material energy flow and pollution reduction and carbon reduction in the coupled system of man and nature, develop a coupled multi-scale economy-energy-environment-climate model, and combine multi-source data from the Internet of Things and the Internet to reduce atmospheric pollution and carbon emissions. Carry out accurate detection and evaluation, develop technologies and methods for collaborative governance of greenhouse gases and air pollutants, explore

key paths for collaborative governance, and form a technical system and decision-making system support to achieve the goal of carbon neutrality.

(4) Ecological effects and risks of microplastics in coastal wetlands or offshore waters

Microplastics are plastic particles, fibers, films or fragments less than 5 mm in diameter, which are difficult to degrade in the natural environment and can persist and migrate over long distances as microplastics are petroleum-based and carbon-chain polymers. Microplastics can alter the physicochemical properties of the abiotic environment and cause toxic damage to the growth traits and physiological and biochemical characteristics of plants, animals and microorganisms. Meanwhile, microplastics can release chemical additives such as Bisphenol A (BPA), phthalates and antioxidants during natural aging. In addition, microplastics are able to carry pathogenic microorganisms and other contaminants such as heavy metals, antibiotics and endocrine disruptors, and finally form complex contamination.

In recent years, there have been increasing studies on the environmental behavior and toxicological effects of microplastics in terrestrial and marine ecosystems. In contrast, few works have been conducted on microplastic pollution in coastal wetlands or offshore waters. Coastal wetlands and offshore waters play an important role in maintaining the balance between land and sea, protecting biodiversity, and improving the coastal environment. Seaward rivers have been identified as an important transport pathway for terrestrial plastic debris into the ocean. As a transition zone between terrestrial and marine ecosystems, coastal wetlands and offshore waters have become filters and sinks for microplastics. Offshore pollution from ship traffic, fisheries, oil well exploration, coastal agriculture and tourism is another important source of microplastics in the marine environment. At the same time, microplastics in the ocean can be transported back to coastal wetlands and offshore waters by wind-driven, ocean current circulation and tidal flows. Microplastic pollution in coastal wetlands and offshore waters is becoming more and more serious, but the ecological risks posed by microplastics to coastal wetlands or offshore waters are not yet clear. Therefore, the distribution characteristics and transport pathways of microplastics in coastal wetlands and offshore waters need to be further investigated, and the toxic mechanisms and ecological effects of microplastics on the ecosystem structure and function of coastal wetlands and

offshore waters need to be further clarified.

(5) Carbon sequestration of coastal wetland ecosystem

Out of all the biological carbon captured in Earth's ecosystems, over half (55%) is captured by marine living organisms, which is called "blue carbon" (relative to the "green carbon" fixed by terrestrial ecosystems). The coastal wetland ecosystems mainly including mangroves, salt marsh wetlands and seagrass beds. The carbon captured by them is called coastal blue carbon. Compared with other ecosystems, the coastal wetland ecosystems have a very high carbon sequestration rate. In addition, the coastal wetland ecosystems are located between the sea and land, which are significantly affected by sea-land interactions. They are also eco-fragile regions and sensitive environmental areas that are greatly affected by human activities and climate change. Protecting and repairing the coastal wetland ecosystems and restoring the lost wetlands are contribute to carbon neutrality goals. Therefore, the study of carbon sequestration in coastal wetland ecosystems has received extensive attention in recent years.

At present, there have been many studies on blue carbon storage and carbon sequestration potential, but the carbon measurement methods used in different regions are not the same, which is not conducive to the comprehensive comparison and global analysis of coastal blue carbon. Besides, the carbon sink capacity of coastal wetland ecosystem is dynamic, and its carbon sequestration potential under the dual impact of climate change and human activities is also full of uncertainty. In response to these problems, the current main research directions and development trends include: first, it is necessary to study how to reduce the uncertainty in assessment of blue carbon in the coastal wetland ecosystems, deepen the understanding of carbon sequestration mechanism, and establish carbon sink measurement and assessment systems; second, it is necessary to analyze the impact of climate change and human activities on coastal wetland ecosystems and explain its evolution; third, it is necessary to study the technologies of carbon sequestration, assess the potential and stability of carbon sink enhancement in coastal wetland ecosystems, explore the protection, restoration and management methods for coastal wetland ecosystems based on natural solutions, and realize the synergistic improvement of the carbon sequestration and sink enhancement function of coastal wetland ecosystems and other important ecosystem functions; forth, it is necessary

to select typical coastal wetlands, conduct evaluation and technology demonstration, and finally realize engineering and large-scale application.

(6) Application of machine learning in earth system observation and prediction

Driven by an in-depth understanding of the mechanisms of the climate system, observational data, reanalysis data, and numerical simulations of the Earth system have grown rapidly over the past 40 years. In particular, a large number of climate models have participated in the fifth and the sixth phase of the International Coupled Model Intercomparison Project (CMIP5 and CMIP6), providing tens of billions of bytes of data resources for research on climate change, climate prediction and climate projection. How to extract useful information and acquire new knowledge from "big data" poses new challenges to traditional analysis methods, and brings new opportunities for machine learning and artificial intelligence. Machine learning can summarize key information and main features from the "big data" of the earth system, so as to make accurate identification and prediction. For example, the sea surface temperature information of a key area can improve the climate prediction skills of a certain area on the land in the coming months; on this basis, artificial intelligence can provide automated early warning of extreme weather and climate events. At present, machine learning, especially deep learning, has been widely studied in convective short-term nowcasting, extreme event detection and improvement of numerical weather models and their forecast error correction. The next step will be to change the traditional meteorological observation model, to accelerate and improve the processing of meteorological observation data, improve the quality of numerical weather forecasting, and advance the intersection of earth sciences.

(7) Vital characteristics and ecological effects of microorganisms in extreme marine environments

Extreme marine environments such as the deep sea, Polar Regions, submarine hydrothermal regions, and cold springs are characterized by harsh environmental conditions, including abnormal salinity, pressure, temperature, acidity, alkalinity, and radiation intensity. Nonetheless, a large number of extremophilic microorganisms survive these conditions. Investigating microorganisms that inhabit extreme marine environments, with their diversity, unique biological structures, and novel metabolic mechanisms,

provides a valuable source of knowledge for exploring the origin, adaptation, and evolution of life. Moreover, marine extremophiles can produce novel active substances, including enzymes and other natural products, with broad potential uses. In addition, marine extremophiles are responsible for mineralizing and reusing organic matter in specific habitats as drivers of the transfer of nutrients, energy, and biogeochemical cycles.

At present, the primary research focuses are community structure and ecological functions of marine extremophiles, their symbiotic relationships with benthic organisms, their adaptation and evolutionary mechanisms for survival in extreme environments, the extraction of active substances from extremophiles, and their participation in biogeochemical cycling processes and environmental effect. In the future, it will be necessary to improve marine extremophile isolation and cultivation capabilities and to analyze their genetic structures and physiological metabolisms. It will also be essential to characterize the mode of action of their active products, explore their roles and interactions in the ecological processes of extreme environments, and elucidate their influence and regulatory functions on extreme environmental ecosystems.

(8) Research on the cleaner production technology of tanning agent-free leather making

Chrome tanning technology based on the theory of “cross-linking tanning” occupies a dominant position in leather manufacturing, but the conventional chrome tanning technology suffers from the chrome emission issue. To address this problem, tanning chemists have developed chrome-free tanning agents represented by non-chrome metal tanning agents and organic tanning agents, which is aimed to replace conventional chrome tanning agents to form cross-linkages among collagen fibers to obtain tanning effects so as to fundamentally solve the problem of chrome emission. Nevertheless, the existing chrome-free tanned leathers fail to provide comparable thermal stability, mechanical strength and other leather properties to chrome-tanned leathers. In addition, the chrome-free tanning techniques still suffer from the emission problems of metals and organic pollutants. Aiming at the bottleneck of chrome-free tanning technologies based on the existing “cross-linking tanning” theory, it is of great significance to develop new tanning theories and tanning technologies to achieve cleaner production in the leather

industry. During the conversion of raw hide into leather, its water content is significantly reduced, which also shows obviously improved fiber dispersion and porosity. Therefore, the tanning process can be regarded as a “controllable dehydration” process involved with reduced hydrophilicity and improved fiber dispersion. In these considerations, controllable removal of free water in raw hides with suitable dehydration media is expected to impart collagen fibers with high dispersibility and porosity, thereby significantly enhancing the thermal stability, mechanical strength and other leather properties without the usage of cross-linking agents. Hence, the pollutant emission problems in leather industry are able to be radically resolved, thus boosting the realization of cleaner production of tanning agent-free leather making. Polar organic solvents have the capabilities to provide efficient dehydration role, which are able to be applied in reducing the water content of raw hide effectively. However, the water distribution between organic solvent and raw hide will gradually reach a balance along with the dehydration to proceed, which requires multiple organic solvent changes to achieve deep dehydration performance, thus resulting some problems such as excessive consumption of organic solvents, complicated dehydration process and difficulty in recycling of waste solvents. To this end, the composite dehydration media composed of porous materials and polar organic solvents was developed for realizing the one-step controllable deep dehydration. The porous materials are capable of selectively adsorbing and storing the captured water in the organic solvents, thereby breaking the distribution balance of water between the organic solvent and raw hide. Moreover, the used composite dehydration media were facilely recycled through the solid-liquid separation and reused for tanning agent-free leather making after regeneration. In the future, it is essential to further develop novel composite dehydration media to strengthen the controllable deep dehydration performance of raw hides and consummate the technical routes of tanning agent-free leather making, which in turn lays the foundation for the industrial application of cleaner production technology of tanning agent-free leather making so as to promote the sustainable and green development of the leather industry.

(9) Study on the mechanisms of food functional factors and chronic metabolic syndrome

Food functional factors such as polysaccharides, polyphenols and flavonoids in animals, plants and fungi have many excellent biological activities such as preventing obesity and

diabetes, regulating glucolipid metabolism, and improving obesity induction, which have positive effects on improving human health. Therefore, it is important to study the mechanism of food functional factors in the prevention of chronic metabolic syndrome at molecular, cellular and overall levels to provide theoretical and technical support for the early prevention and nutritional intervention of nutrition-related chronic diseases. Meanwhile, the enrichment of food functional factors and their bioactive system evaluation will be studied and functional foods with applications for the prevention of metabolic syndrome will be developed. Rapid and efficient screening and identification of natural functional components (such as terpenoids, flavonoids, phenols, alkaloids, saponins, etc.) in new food ingredients that act on obesity, diabetes, immunity, hypertension, lipid dysfunction and cancer through modern molecular biology, cell biology, metabolomics, molecular nutrition and other biological, chemical, physical and chemical technologies.

(10) Extraction and development of new natural cellulose fibers

Since petrochemical resources are becoming more scarce and environmental problems are becoming increasingly significant, natural cellulose fibers have gained increasing attention for their green, clean, and environmentally friendly characteristics, unique properties, renewable raw materials, natural degradation after disposal, and non-toxic and harmless properties. Natural cellulose fiber is a type of natural fiber containing cellulose as the main component. Since it is derived from plants, it is also referred to as plant fiber. The natural cellulose fiber is environmentally friendly. It is of great significance to the sustainable use of natural resources and the protection of the environment to conduct research and development of new natural cellulose fibers.

There are currently several research difficulties associated with the cellulose science field: one is the extraction of natural cellulose fibers; the second is the research of cellulose dissolving systems; and the third is the development of new functional natural cellulose fibers. It is particularly important to know how to cleanly and efficiently separate cellulose from plant cell walls (natural fibers). Plants have a very complex cell wall structure. The outer layer is protected by wax and inorganic salts. Chemical components such as hemicellulose and lignin are closely related to the inner cellulose. All of these factors pose obstacles to the separation and extraction of cellulose. There are two types of separation and extraction techniques

that are commonly used today: biological and chemical. After biological extraction, cellulose contains a significant amount of gum, and the activity of biological enzymes is poor. The chemical method is the most widely used, but it also involves a complex process and consumes a great deal of energy. To further realize the development of high value-added functional natural cellulose fiber textiles, it is necessary to pursue the green and efficient separation, extraction, and research and development of new natural cellulose fibers.

1.2 Interpretations for three key engineering research fronts

1.2.1 Mechanisms of multi-media transport and transformation of new pollutants

New pollutants (or emerging pollutants) refer to newly discovered or noticed pollutants that pose risks to the ecological environment or human health, and have not yet been incorporated into management or existing management measures are insufficient to effectively prevent and control their risks. With the increasing understanding of the environmental and health hazards of chemical substances and the continuous development of environmental monitoring technology, the number of new pollutants that can be identified will continue to increase. Therefore, the development of efficient and universal analytical methods for discovering new pollutants is an important research direction in the field of new pollutant management. Figure 1.2.1 is the roadmap of the engineering research front of “mechanisms of multi-media transport and transformation of new pollutants”.

The production and use of toxic and hazardous chemical substances are the main sources of new pollutants. Literature shows that higher levels of new pollutants such as environmental endocrine disruptors, antibiotics, and microplastics have been monitored successively in the atmosphere, water, and soil in some regions of China. Transfer of new pollutants among different environmental media often occurs, implying that one medium can become the pollution source for the next environmental medium, leading to differences in fate and contamination levels for new pollutants in different media. However, the migration and transformation behaviors and mechanisms of most new pollutants among multi-media are unclear, and the health risks are unclear. Around the management of new pollutants, it is necessary to

further strengthen the research on environmental screening, traceability studies, environmental risk assessment and control, and research on ecological and environmental hazard mechanisms such as antibiotics and microplastics; it is also a necessary to develop with the help of mathematical methods or models to better describe the cross-media migration and transformation of new pollutants released into the atmosphere.

Table 1.2.1 shows countries with the largest output of core papers on “mechanisms of multi-media transport and transformation of new pollutants”. Among them, China ranked

first with 42.74% of core papers and 3 637 citations. There is a large gap between other countries and China, which indicates that China has strong research advantages in this field. In terms of citations per paper, although the number of core papers in Spain is small, its citations per paper rank first, which also shows the importance of publishing high-level core papers recognized by peers from one side.

Table 1.2.2 shows the main output institutions of core papers in this engineering research frontier. Six of the top ten output institutions are from Chinese research institutions, namely, Chinese Academy of Sciences, East China Normal University,

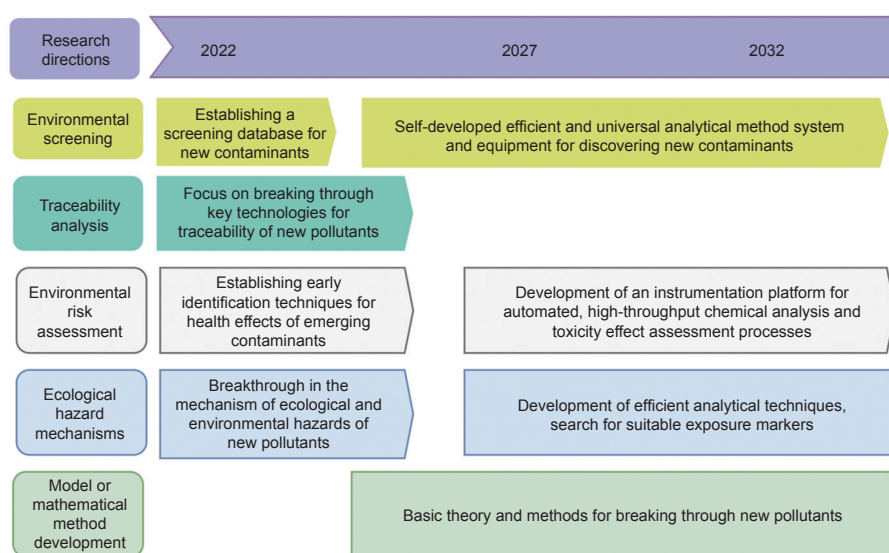


Figure 1.2.1 Roadmap of the engineering research front of “mechanisms of multi-media transport and transformation of new pollutants”

Table 1.2.1 Countries with the greatest output of core papers on “mechanisms of multi-media transport and transformation of new pollutants”

No.	Country	Core papers	Percentage of core/% papers	Citations	Citations per paper	Mean year
1	China	50	42.74	3 637	72.74	2018.0
2	USA	17	14.53	1 093	64.29	2018.2
3	India	10	8.55	590	59.00	2017.6
4	UK	8	6.84	509	63.62	2017.9
5	Germany	8	6.84	430	53.75	2017.9
6	Spain	7	5.98	585	83.57	2018.0
7	France	7	5.98	360	51.43	2017.9
8	Italy	6	5.13	357	59.50	2016.7
9	Norway	6	5.13	347	57.83	2016.5
10	Turkey	6	5.13	325	54.17	2017.3

Tsinghua University, Guangdong University of Technology, Northwest A&F University, and Nankai University. Among them, Chinese Academy of Sciences ranked first in the number of institutions with 20 core papers.

As can be seen from Figure 1.2.2, more emphasis is placed on inter-country cooperation in this research area by China, the USA, India, and the UK. China has the highest number of published papers, mainly with India, the UK, and Germany for collaborative publication. According to Figure 1.2.3, Chinese Academy of Sciences, Norwegian Institute of Air Research, Nankai University, and East China Normal University have cooperative relations.

Based on Table 1.2.3, the country with the highest output of

citing core papers is China, with 46.41% of citing core papers, followed by the USA with 12.31%. As presented in Table 1.2.4, the institution with the highest output of citing core papers is Chinese Academy of Sciences, with 36.12% of citing core papers, followed by Hunan University, with 12.15% of citing core papers.

The results of the above data analysis show that China is the forefront of the world in the output and the number of citing core papers on the mechanism of multi-media transport and transformation of new pollutants, followed by the USA.

1.2.2 Carbon sequestration of coastal wetland ecosystem

The carbon fixed by the coastal wetland ecosystems such

Table 1.2.2 Institutions with the greatest output of core papers on “mechanisms of multi-media transport and transformation of new pollutants”

No.	Institution	Core papers	Percentage of core/% papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	20	17.09	945	47.25	2017.3
2	East China Normal University	4	3.42	453	113.25	2018.5
3	Tsinghua University	4	3.42	388	97.00	2019.2
4	Norwegian Institute for Air Research	4	3.42	259	64.75	2016.2
5	Environment and Climate Change Canada	4	3.42	237	59.25	2016.8
6	Central University of South Bihar	4	3.42	206	51.50	2016.5
7	Guangdong University of Technology	3	2.56	527	175.67	2018.3
8	Northwest A&F University	3	2.56	382	127.33	2019.7
9	Masaryk University	3	2.56	245	81.67	2016.0
10	Nankai University	3	2.56	188	62.67	2018.7

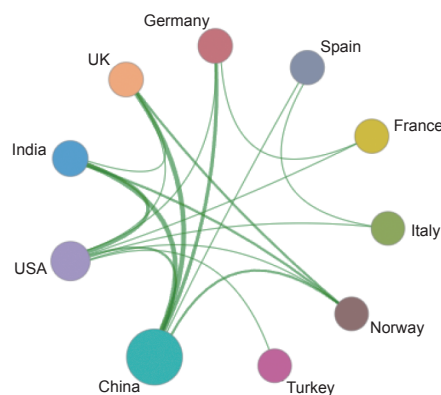


Figure 1.2.2 Collaboration network among major countries in the engineering research front of “mechanisms of multi-media transport and transformation of new pollutants”

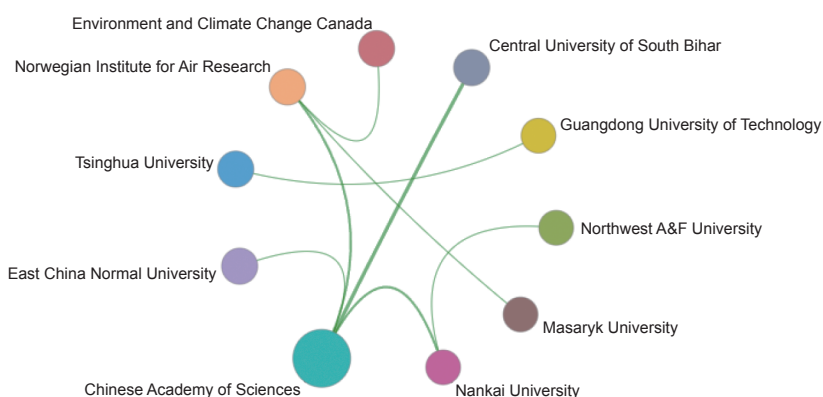


Figure 1.2.3 Collaboration network among major institutions in the engineering research front of “mechanisms of multi-media transport and transformation of new pollutants”

Table 1.2.3 Countries with the greatest output of citing papers on “mechanisms of multi-media transport and transformation of new pollutants”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	3 083	46.41	2020.1
2	USA	818	12.31	2020.0
3	India	445	6.70	2020.1
4	Germany	332	5.00	2019.9
5	UK	321	4.83	2020.0
6	Canada	314	4.73	2019.8
7	Spain	293	4.41	2020.0
8	Italy	287	4.32	2019.8
9	Australia	260	3.91	2020.1
10	France	256	3.85	2019.9

Table 1.2.4 Institutions with the greatest output of citing papers on “mechanisms of multi-media transport and transformation of new pollutants”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	523	36.12	2019.8
2	Hunan University	176	12.15	2019.0
3	Tsinghua University	109	7.53	2019.9
4	Nanjing University	88	6.08	2020.1
5	Northwest A&F University	86	5.94	2020.5
6	East China Normal University	83	5.73	2020.0
7	Jinan University	83	5.73	2019.9
8	Nankai University	79	5.46	2020.2
9	Peking University	78	5.39	2020.0
10	Tongji University	72	4.97	2020.1

as mangrove, salt marsh wetland and seagrass bed are the coastal blue carbon. The term “blue carbon” was first coined in 2009. Compared with the “green carbon” fixed by terrestrial ecosystems, it emphasizes the important contribution of ocean to carbon sequestration. The carbon sequestration of coastal wetland ecosystems is mainly reflected in plant carbon sequestration and sediment carbon burial in the vertical direction, and carbon exchange with seawater in the horizontal direction. The reciprocating tidal can slow down the decomposition of organic matter, continuously accumulate of the sediments and create an anaerobic environment in the coastal wetlands. The decomposition of organic matter is inhibited, and the carbon in the sediments can be kept in a stable state for a long time under certain conditions and realize continuous carbon storage. Compared with other ecosystems, the coastal wetland ecosystems have a very high carbon sequestration rate. In addition, the coastal wetlands also provide ecosystem service functions such as storm protection, wave dissipation, climate regulation, water purification, spiritual and aesthetic, and nutrient cycling, which has significant social and economic benefits.

The protection and restoration of the coastal ecosystems under human intervention is an operable way to increase carbon sinks. The existing technologies for coastal wetland restoration to increase carbon sinks include rebuilding high biomass plant communities, amending the sediment, conserving the beach, improving the wetland soil and the water environment. At present, the “nature-based solutions” are mainly advocated to realize the synergistic improvement

of the carbon sequestration and sink enhancement of coastal wetland ecosystems and other important ecosystem functions. Figure 1.2.4 is the roadmap of the engineering research front of “carbon sequestration of coastal wetland ecosystem”.

The main research directions and development trends at present include: ① analyzing the carbon source and carbon fixation mechanism, establishing the monitoring network, the big data platform, and carbon assessment systems, achieving long-term real-time monitoring; ② based on the spatial-temporal pattern of blue carbon, exploring the key regulatory factors of climate change and human activities that affect the blue carbon, deepening the understanding of carbon sequestration mechanism and evolution, and assessing the potential and sustainability of coastal wetland ecosystems in increasing carbon sinks; ③ studying the technologies of carbon sequestration, assessing the potential and stability of carbon sink enhancement in coastal wetland ecosystems, establishing the frameworks for coastal wetlands protection, restoration and management based on natural solutions, studying the service value evaluation methods of the coastal wetland ecosystems, exploring how to protect the integrity of coastal wetland ecosystems functions, and realizing the coordinated improvement of carbon sequestration and sink enhancement and other ecosystem functions; ④ selecting typical coastal wetlands, conduct evaluation and technology demonstration, and realizing the engineering and large-scale application of technologies for synergistic improvement of various ecosystem functions.

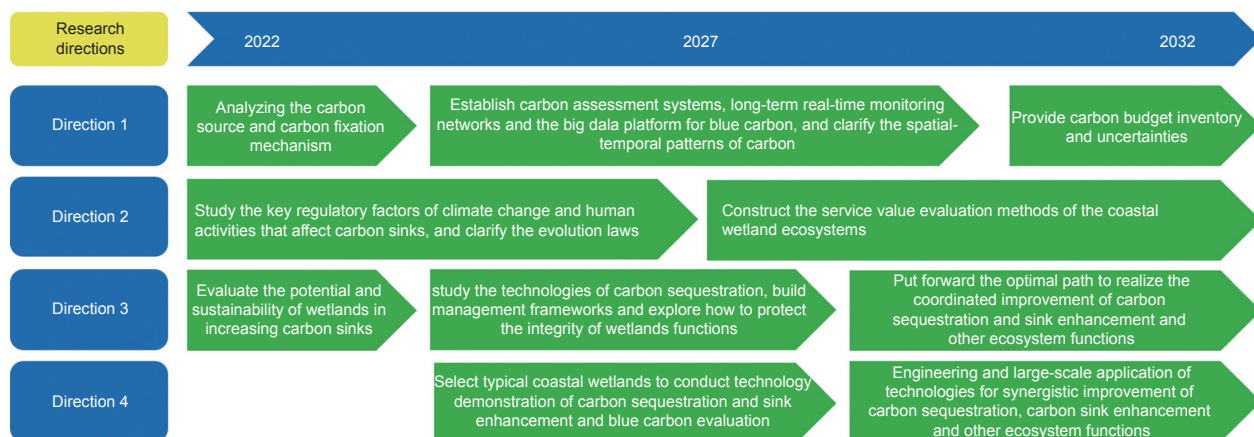


Figure 1.2.4 Roadmap of the engineering research front of “carbon sequestration of coastal wetland ecosystem”

Among the countries with the greatest output of core papers on this research (Table 1.2.5), the number of core papers and citation frequency of the USA are the first, and the number of core papers of China is the second. The total number of core papers of China and the USA accounts for more than half of the total number of the top 10 countries. In terms of the collaboration network among major countries on this research (Figure 1.2.5), the cooperation among the top 10 countries is close. In terms of institutions with the greatest output of core papers on this research (Table 1.2.6), the top 10 institutions with core papers are concentrated in China and the USA. In the collaboration network among

major institutions (Figure 1.2.6), there is close cooperation among various institutions. In the ranking of countries with the greatest output of citing papers (Table 1.2.7), China ranks first, while the Chinese Acad Sci, Beijing Normal Univ and East China Normal Univ rank first, second and fifth respectively in the ranking of institutions with the greatest output of citing papers (Table 1.2.8). In short, although the USA is still in the leading position in the world, China has also accelerated the pace of catching up. China still needs to accelerate its development, narrow the gap with the USA, and improve the international influence and discourse power of research in this field.

Table 1.2.5 Countries with the greatest output of core papers on “carbon sequestration of coastal wetland ecosystem”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	43	58.90	3 311	77.00	2018.1
2	China	30	41.10	1 728	57.60	2018.4
3	Australia	18	24.66	1 944	108.00	2018.5
4	UK	9	12.33	1 525	169.44	2018.3
5	Germany	8	10.96	522	65.25	2018.2
6	Netherlands	7	9.59	1 323	189.00	2018.0
7	Canada	7	9.59	487	69.57	2018.6
8	Spain	5	6.85	310	62.00	2018.6
9	Belgium	4	5.48	276	69.00	2018.0
10	Brazil	3	4.11	977	325.67	2018.3



Figure 1.2.5 Collaboration network among major countries in the engineering research front of “carbon sequestration of coastal wetland ecosystem”

Table 1.2.6 Institutions with the greatest output of core papers on “carbon sequestration of coastal wetland ecosystem”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	9	12.33	519	57.67	2018.8
2	University of Maryland	8	10.96	1 204	150.50	2017.9
3	Nature Conservancy	7	9.59	1 389	198.43	2018.1
4	U.S. Geological Survey	7	9.59	430	61.43	2018.0
5	Beijing Normal University	6	8.22	294	49.00	2018.7
6	University of Aberdeen	5	6.85	1 261	252.20	2018.6
7	Smithsonian Environmental Research Center	5	6.85	346	69.20	2018.6
8	University of California, Berkeley	5	6.85	328	65.60	2018.4
9	Woods Hole Research Center	4	5.48	1 236	309.00	2018.5
10	University of Florida	4	5.48	1 016	254.00	2017.8

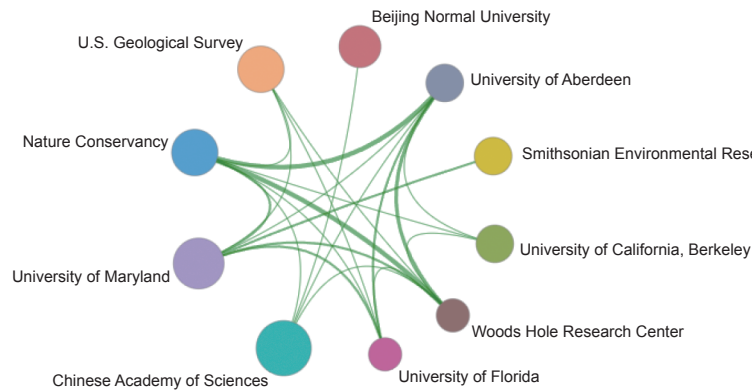


Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “carbon sequestration of coastal wetland ecosystem”

Table 1.2.7 Countries with the greatest output of citing papers on “carbon sequestration of coastal wetland ecosystem”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 411	26.56	2020.3
2	USA	1 395	26.26	2020.2
3	UK	513	9.66	2020.3
4	Australia	478	9.00	2020.2
5	Germany	389	7.32	2020.3
6	Canada	260	4.89	2020.3
7	France	197	3.71	2020.3
8	Netherlands	191	3.60	2020.2
9	Spain	171	3.22	2020.3
10	Italy	160	3.01	2020.3

Table 1.2.8 Institutions with the greatest output of citing papers on “carbon sequestration of coastal wetland ecosystem”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	465	35.33	2020.3
2	Beijing Normal University	129	9.80	2020.3
3	U.S. Geological Survey	126	9.57	2020.0
4	University of California, Berkeley	102	7.75	2020.2
5	East China Normal University	88	6.69	2020.5
6	Nature Conservancy	83	6.31	2020.0
7	University of Maryland	69	5.24	2020.0
8	U.S. Forest Service	69	5.24	2020.1
9	University of Queensland	66	5.02	2020.0
10	Stanford University	60	4.56	2020.2

1.2.3 Research on the cleaner production technology of tanning agent-free leather making

Tanning refers to the qualitative transformation process of converting raw hide into leather, which is one of the most important sections in the leather manufacturing. Chrome tanning technology based on the usage of chrome salts as tanning agents occupies a dominant position in leather manufacturing for a long time due to its excellent cross-linking tanning effect. However, chrome emission is a persisting problem in chrome tanning process, which is suffered by the limited absorption capability of raw hide to chrome tanning agent. To address this issue, great efforts have been dedicated to developing chrome-free tanning techniques based on the “cross-linking tanning” theory, which is aimed to replace conventional chrome tanning agents to form cross-linkages among collagen fibers to obtain tanning effects so as to fundamentally solve the problem of chrome emission. At present, the already reported chrome-free tanning agents mainly include non-chrome metal tanning agents and organic tanning agents, while these chrome-free tanned leathers fail to provide comparable thermal stability, mechanical strength and other leather properties to chrome-tanned leathers. In addition, the chrome-free tanning techniques still suffer from

the emission problems of metals and organic pollutants. Figure 1.2.7 is the roadmap of the engineering research front of “research on the cleaner production technology of tanning agent-free leather making”.

Aiming at the bottleneck of chrome-free tanning technologies based on the existing “cross-linking tanning” theory, it is of great significance to develop new tanning theories and tanning technologies to achieve cleaner production in the leather industry. Extensive tanning practices indicate that the tanned leather has lower water content as compared with raw hide, which also shows obviously improved fiber dispersion and porosity. Therefore, the tanning process can be regarded as a “controllable dehydration” process involved with reduced hydrophilicity and improved fiber dispersion. In these considerations, controllable removal of free water in raw hides with suitable dehydration media is expected to impart collagen fibers with high dispersibility and porosity, thereby significantly enhancing the thermal stability, mechanical strength and other leather properties without the usage of cross-linking agents. Hence, the pollutant emission problems in leather industry are able to be radically resolved, thus boosting the realization of cleaner production of tanning agent-free leather making.

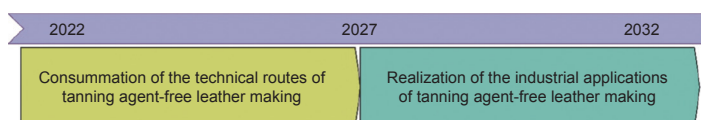


Figure 1.2.7 Roadmap of the engineering research front of “research on the cleaner production technology of tanning agent-free leather making”

Polar organic solvents have the capabilities to provide efficient dehydration role, which are able to be applied in reducing the water content of raw hide effectively. However, the water distribution between organic solvent and raw hide will gradually reach a balance along with the dehydration to proceed, which requires multiple organic solvent changes to achieve deep dehydration performance, thus resulting some problems such as excessive consumption of organic solvents, complicated dehydration process and difficulty in recycling of waste solvents. To this end, the composite dehydration media composed of porous materials and polar organic solvents was developed for realizing the one-step controllable deep dehydration. The porous materials are capable of selectively adsorbing and storing the captured water in the organic solvents, thereby breaking the distribution balance of water between the organic solvent and raw hide so as to keep a constant low water content during the whole dehydration process for realizing continuous dehydration of raw hide. Moreover, the used composite dehydration media were facilely recycled through the solid-liquid separation and reused for tanning agent-free leather making after regeneration. In the future, it is essential to further develop novel composite dehydration media to strengthen the controllable deep dehydration performance of raw hides and consummate the technical routes of tanning agent-free leather making, which in turn lays the foundation for the industrial application of cleaner production technology of tanning agent-free leather making so as to promote the sustainable and green development of the leather industry.

Through the interpretations of core papers on “research on the cleaner production technology of tanning agent-free leather making”, it was found that the citation per paper was relatively low as 5.42 times since this engineering front is still in the early research stage (Table 1.1.1). Table 1.2.9

shows the countries with the greatest output of core papers on this research fronts. Among them, China ranks first with a core paper percentage of 70.83% and a citation of 114 times, which indicates that many Chinese experts and scholars are committed to this front of research. In addition, China also leads other countries and regions in the citations per paper. India ranks second in the two indicators of core paper ratio and citations per paper. In terms of the major output countries or regional cooperation networks (Figure 1.2.8), China and Brazil displayed strong independent research and development capabilities in this field, and many countries also have cooperated extensively.

As shown in Table 1.2.10, the top eight output institutions are all from China, which further indicates that Chinese researchers are highly enthusiastic about this research front. Among them, the top institutions in terms of the percentage of core paper and citation per paper are all Sichuan University, reflecting the leading role of this institution in the engineering front of “research on the cleaner production technology of tanning agent-free leather making”. According to the main inter-agency cooperation network (Figure 1.2.9), most of the institutions have worked in cooperation with other institutions, and a small number of institutions mainly rely on the independent research and development.

As for the ranking of citing papers of this research front, China still occupies a leading position in the world with 54.17% (Table 1.2.11). In addition, the number of citing core papers of Sichuan University and Shaanxi University of Science and Technology leads other scientific research institutions (Table 1.2.12).

Overall, China is not only ahead of other countries in the world, but also has strong independent research and development capabilities in the engineering research front on “research on the cleaner production technology of

Table 1.2.9 Countries with the greatest output of core papers on “research on the cleaner production technology of tanning agent-free leather making”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	17	70.83	114	6.71	2019.6
2	India	4	16.67	15	3.75	2020.0
3	USA	2	8.33	1	0.50	2019.5
4	UK	1	4.17	0	0.00	2021.0
5	Brazil	1	4.17	0	0.00	2021.0
6	Ethiopia	1	4.17	0	0.00	2021.0
7	South Sudan	1	4.17	0	0.00	2021.0

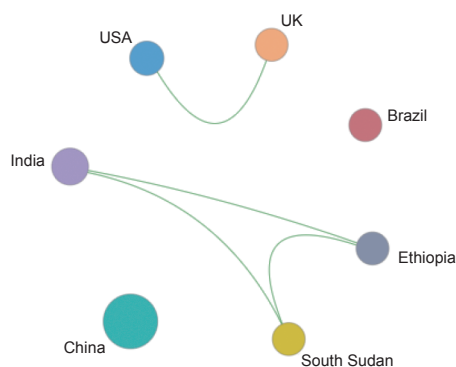


Figure 1.2.8 Collaboration network among major countries or regions in the engineering research front of “research on the cleaner production technology of tanning agent-free leather making”

Table 1.2.10 Institutions with the greatest output of core papers on “research on the cleaner production technology of tanning agent-free leather making”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Sichuan University	10	45.45	79	7.90	2019.4
2	Shaanxi University of Science & Technology	4	18.18	22	5.50	2019.7
3	Southwest Minzu University	2	9.09	12	6.00	2020.0
4	Jiaying University	2	9.09	1	0.50	2019.5
5	Chinese Academy of Sciences	1	4.54	12	12.00	2019.0
6	China National Light Industry Council	1	4.54	6	6.00	2019.0
7	China Leather & Footwear Research Institute Co., Ltd.	1	4.54	2	2.00	2020.0
8	Xi'an Key Laboratory of Green Chemicals and Functional Materials	1	4.54	1	1.00	2021.0

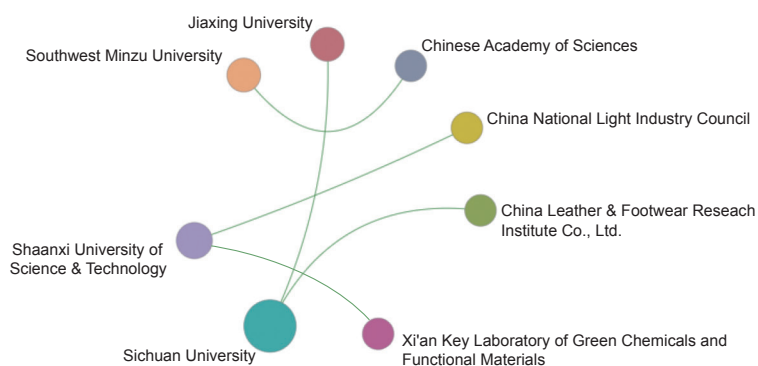


Figure 1.2.9 Collaboration network among major institutions in the engineering research front of “research on the cleaner production technology of tanning agent-free leather making”

Table 1.2.11 Countries with the greatest output of citing papers on “research on the cleaner production technology of tanning agent-free leather making”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	26	54.17	2020.2
2	India	7	14.58	2020.4
3	Italy	4	8.33	2020.2
4	Brazil	2	4.17	2020.0
5	Turkey	2	4.17	2020.0
6	Romania	2	4.17	2019.5
7	Tanzania	1	2.08	2020.0
8	South Africa	1	2.08	2020.0
9	South Korea	1	2.08	2020.0
10	Malaysia	1	2.08	2021.0

Table 1.2.12 Institutions with the greatest output of citing papers on “research on the cleaner production technology of tanning agent-free leather making”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Sichuan University	14	41.18	2020.1
2	Shaanxi University of Science & Technology	7	20.59	2020.4
3	China Leather & Footwear Reseach Institute Co., Ltd.	2	5.88	2020.0
4	Ca' Foscari University of Venice	2	5.88	2020.0
5	Egerton University	2	5.88	2020.0
6	Babasaheb Bhimrao Ambedkar Bihar University	1	2.94	2020.0
7	University of Lucknow	1	2.94	2020.0
8	Huaqiao University	1	2.94	2020.0

tanning agent-free leather making”. It is recommended that the research institutions should continue to carry out in-depth research in related fields so as to maintain the research status of this research front, and promote the technological development of related industries around the world.

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the field of environmental and light textile engineering are summarized in Table 2.1.1. These include the subfields of environmental

science, meteorological science, marine science, food science, textile science, and light industry science. The number of patents related to these individual topics between 2016 and 2021 is presented in Table 2.1.2.

(1) Collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction

The collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction is the key to realize green recycling and low-carbon development. There is an urgent need to: develop green alternative materials, improve the production process, and reduce the output of solid waste sources; research and develop multi-dimensional green, low-carbon and high-value utilization technologies for solid waste in key industries, taking into account the risk prevention and control of carbon emission reduction and

Table 2.1.1 Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	Published patents	Citations	Citation per patent	Mean year
1	Collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction	905	2 163	2.39	2018.4
2	Technologies for collaborative control of multi-medium pollution across surface water/groundwater and soil	844	1 465	1.74	2018.8
3	Technology and equipment for cooperative disposal of soil and groundwater in polluted site of industrial gathering area	121	229	1.89	2019.2
4	Ecological control techniques and devices for water quality in rivers and lakes	840	1 093	1.30	2018.5
5	Development of complex land surface models and their applications in Earth System Modeling	852	2 878	3.38	2018.6
6	Research and development of climate models based on machine learning	994	4 481	4.51	2020.2
7	Microwave remote sensing inversion technology of marine 3D dynamic environment	441	1 065	2.41	2019.7
8	Recyclability and reusability of personal protective equipment	994	712	0.72	2019.8
9	Food safety early warning research based on big data and intelligent identification	982	3 337	3.40	2019.6
10	Environmentally friendly pulp molding technology	847	1 065	1.26	2018.8

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction	137	142	181	203	182	60
2	Technologies for collaborative control of multi-medium pollution across surface water/groundwater and soil	85	116	157	149	188	149
3	Technology and equipment for cooperative disposal of soil and groundwater in polluted site of industrial gathering area	14	7	20	17	31	32
4	Ecological control techniques and devices for water quality in rivers and lakes	101	129	219	131	149	111
5	Development of complex land surface models and their applications in Earth System Modeling	118	130	173	134	128	169
6	Research and development of climate models based on machine learning	3	7	48	131	344	461
7	Microwave remote sensing inversion technology of marine 3D dynamic environment	0	48	53	82	68	190
8	Recyclability and reusability of personal protective equipment	31	50	89	154	247	423
9	Food safety early warning research based on big data and intelligent identification	60	71	120	134	194	403
10	Environmentally friendly pulp molding technology	107	128	152	109	161	190

secondary pollution in the whole life cycle; develop low-energy end treatment process to further reduce carbon emissions. We will focus on the development of cleaner production processes in industrial production, deepen innovation, research and development and application of

green, non-toxic and low-carbon alternative new materials, research and development of clean energy alternative technologies, energy cascade utilization technologies, waste green recycling and high-value utilization technologies, and Research on risk assessment and risk prevention and control

systems of new pollutants, so as to achieve coordinated control of high-quality recycling of solid wastes and pollution and carbon reduction, Effectively support the green, low-carbon and sustainable development of the social economy.

(2) Technologies for collaborative control of multi-medium pollution across surface water/groundwater and soil

The integrated protection and reclamation of mountains, rivers, forests, farmlands, lakes, grasses and sand is an inevitable requirement to improve the quality and stability of the ecosystem, to promote the harmonious compatibility between human and nature, and to forward ecological civilization construction in the new era. The substance exchange among surface water, groundwater and soil is pronounced, and the mutual replenishment between surface water and groundwater plays an important role in maintaining their healthy states. Therefore, it is urgent to develop technologies for collaborative control of multi-medium pollution across surface water/groundwater and soil. This development frontier contains three main technological directions: ① materials/reagents and biological agents for pollution control and remediation, including zero valent metal nanomaterials exemplified by zero valent iron, layered double hydroxides, biochar, biodegradable polymers, remediation plants, bacterial agents, enzymes, etc., ② pollution control methods and processes, including chemical oxidation and advanced oxidation processes, chemical reduction processes, adsorption, thermal desorption and adsorption/condensation treatment, etc., and ③ pollution control and remediation devices and equipment, including high-pressure injection device, permeable reaction barriers, in-situ oil leakage detection and alarm device, vacuum pumping device and equipment for treating volatile organic compounds, extraction/rinsing device, portable integrated equipment for water treatment, etc. The main target pollutants of the collaborative control technologies include petroleum hydrocarbons, halogenated hydrocarbons, and heavy metals.

The top three countries in terms of the number of the core patent applications in this development fronts are China (65.4%), the USA (13.8%) and South Korea (6.1%), demonstrating the great interests of the patent applicants in such countries to develop the collaborative control technologies for multi-medium pollution. However, practical technologies applicable to surface water pollution control or remediation are still in great demand. A promising field of research in the future

is the development of efficient collaborative pollution control technologies based on the multi-medium interaction process and mechanism of composite pollutants across surface water, groundwater, and soil.

(3) Technology and equipment for cooperative disposal of soil and groundwater in polluted site of industrial gathering area

Soil as an important resource, could support the survival and development of human beings, is also the source and sink of large numbers of pollutants. According to the Bulletin of the *National Soil Pollution Survey in 2014*, including 6.3 million square kilometers was under investigation, with a total rate of 16.1 percent exceeding the standard. The main causes of soil pollution are man-made activities such as industry, mining and agriculture. As a typical area with strong human activities, industrial cluster has high urbanization and land utilization rate, always encountering land shortage. There are more than 22 000 industrial zones in China, and 29.4% of the industrial zones have soil exceeding standard. What's more, there are more than 500 000 industrial and mining enterprises retired contaminated sites. As the abundant surface water, shallow underground water level, and sometimes the inshore tidal effect, soil, surface water, and groundwater in industrial cluster always become the sources and sinks of all kinds of pollutants, result in the serious, compound, multi-source, agglomeration shall, and large area pollution, which needs regional coordination control. Most of the existing pollution remediation methods are for a single medium, and are mainly based on a single technology, ecological remediation technology is lacking. It is urgent to study the collaborative treatment technology and equipment of soil and groundwater pollution in industrial clusters, based on the principle of multi-medium process regulation. Integration of pollutant source control scheme to reduce emissions, physicochemical and biochemical methods which strengthen pollutants degradation, purification and catalytic conversion green resource, advanced processing technology such as artificial wetland, creating integration of soil and groundwater remediation equipment, thus to realize the collaborative management and integration of soil water pollution governance mode in industry clusters.

(4) Ecological control techniques and devices for water quality in rivers and lakes

With the development of social economy and the acceleration of urbanization and industrialization, and the sewage

discharged into rivers and lakes indirectly or directly is increasing, which reduces the self-purification capacity of rivers and lakes, and the water environment problems such as water bloom, poor quality, black and smelly water are prominent. In order to solve these problems, improve water quality and protect the ecological functions of water bodies, various purification and treatment technologies and equipment have emerged as required. However, the early technical methods are mainly physical and chemical methods, and less attention is paid to the ecological environment of river and lake basins. In recent years, with the continuous improvement of the understanding of ecological environment protection, especially under the promotion of China's government led water ecological protection policy and pollution control action plan, the research on ecological control of water quality in rivers and lakes has ushered in a breakthrough development opportunity, and the relevant technical equipment has become a research and development hotspot. The ecological treatment of water quality mainly includes technologies such as composite ecological filter bed, biofilm purification, biological oxidation of sediment, and biodiversity regulation. The principle is to introduce domesticated aquatic plants, plankton or microorganisms on artificial wetlands or fixed carriers in water, and use their absorption and degradation of pollutants to achieve the purpose of water quality purification. Generally speaking, the operation and maintenance cost of the relevant technical equipment is low, the energy consumption is low, and the stability is long-term. It can significantly improve the self-purification capacity of rivers and lakes and maintain the balance of river and lake ecosystems.

(5) Development of complex land surface models and their applications in Earth System Modeling

The land surface is an important part of the weather-climate-earth system, and its physical, chemical, and biological processes have a profound impact on the exchange of energy and matter between the land and the atmosphere, and between the land and the ocean. Land surface processes refer to all physical, chemical, and biological processes occurring on the land surface, as well as their interactions with the atmosphere and ocean. Land surface process model is a mathematical and physical model that quantitatively describes these processes and studies the interaction between human activities and the environment. It can be simulated by computer. It is the core component of numerical weather/climate/Earth system models. At present, the

research of land surface process model used in numerical weather/climate/earth system model needs to emphasize the development of multi-temporal and spatial scale and system integration, the combination of global and regional, macro and micro, ecosystem processes, and the combination of multi-source observation and data assimilation; special emphasis is also placed on the close integration of disciplinary research with national needs, sustainable economic and social development, and policy decision-making, so that the research on land surface process models continues to develop in depth and breadth. Realize the coupling of the newly developed land surface process model and the Earth system model to accurately describe and predict the impact of climate change and human activities on land surface physical, biological, and geochemical processes, providing strong scientific support for weather/climate prediction, water resources security, disaster prevention, food security, ecosystem services and other issues.

(6) Research and development of climate models based on machine learning

Traditional climate models are mainly physical models, and physical models (theory-driven) and machine learning (data-driven) are generally considered as two different scientific research paradigms. But in fact, these two approaches are complementary, that is, physical models can in principle be directly interpretable and have predictive and extrapolation capabilities that do not depend on observational data; while machine learning is highly flexible in exploring data, and may find unexpected patterns from the data. The synergy between the two has attracted more and more attention. The National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA) has begun to replace some climate and weather models with machine learning and deep learning models. Traditionally, climate models are largely based on atmospheric and oceanic physicochemical processes, as well as land surface processes. However, they cannot cover the processes that occur on the millimeter or smaller scale in the atmosphere, so these models need to contain some empirical formulations, i.e. parameterizations. Parameterizations can represent complex processes such as clouds and atmospheric convection. An example is strong convection, which occurs on small scales, making it difficult for climate models to accurately represent it. One direction that has attracted attention in recent years is the use of machine learning to more accurately represent

small-scale changes in the atmosphere and ocean. That is, firstly, an expensive high-resolution model is run to solve the corresponding process (such as shallow clouds), then machine learning is used to learn from these simulations, and then the machine learning algorithm is incorporated into the climate model to finally form a faster and more accurate climate model.

(7) Microwave remote sensing inversion technology of marine 3D dynamic environment

Microwave remote sensing inversion technology is a technique to infer the remote sensing image characteristics generated by the microwave signals transmitted or reflected by various geographical ground objects received by the sensor, and to infer the electromagnetic wave condition. In other words, remote sensing data can be transformed into various surface characteristic parameters that people actually need.

The essence of remote sensing is inversion, and from the mathematical source of inversion, the inversion research aims at mathematical model first. Therefore, the basis of remote sensing inversion is to describe the Relational Model between remote sensing signals or remote sensing data and surface applications. The key technology of microwave remote sensing inversion of marine 3D dynamic environment lies in the comprehensive accurate acquisition of remote sensing data and the combined application of various data on the one hand, and the selection and application of inversion model on the other hand.

In the future research work, it is integrating and developing existing remote sensing theories and inversion methods, developing a comprehensive inversion algorithm for multi-instrument observations, carrying out remote sensing quantitative inversion and estimation of key ocean elements, establishing a platform for comprehensive observation and inversion of ocean and surface parameters, establishing remote sensing quantitative inversion products of key surface elements with long time series and high accuracy that will provide more accurate and reliable satellite remote sensing observation data for the study and application of marine 3D dynamic environment system process

(8) Recyclability and reusability of personal protective equipment

Personal protective equipment (PPE) includes protective clothing, helmets, masks, goggles, etc., intended to protect the

wearer from injury or infection. There has been an increase in the global demand for personal protective equipment, such as disposable medical masks and protective clothing, following the outbreak of COVID-19. Disposable medical and health products have caused incalculable environmental pollution. As reported by the Ocean Conservation Organization, approximately 52 billion masks will be manufactured worldwide in 2020, of which at least 1.56 billion will flow into the ocean and will take at least 450 years to degrade. As a result of the degradation process, the ecological environment of the earth will be adversely affected. As an example of estimated damage, taking a mask after wearing it for 4 hours in different environments, there are 1 096 colonies on the outside of the mask on average, and 1 840 colonies inside the mask. Despite the widespread use of disposable masks in our daily lives, there is an increasing amount of waste caused by discarded disposable masks. Therefore, it has become imperative to recycle and reuse personal protective equipment.

(9) Food safety early warning research based on big data and intelligent identification

Big food data and intelligent identification are used throughout the food chain from production, processing, circulation, market to table. The information and data from the supply, production and marketing of food are collected and stored to form a downward traceability from the production source to the consumption terminal and a reverse traceability from the consumption terminal to the production source. The food supply chain information and data system are built to ensure that the entire production and operation activities of food are always under effective monitoring. Meanwhile, the development of characteristic indication mark, alarm and record marking technology will realize the real-time monitoring of dynamic violations in food production, processing and circulation as well as the continuous dynamic recognition and alarm function of the machine generation of human images, so as to build an innovative visualization information service expression method and information data traceability real-time high definition big data visualization supervision system. By collecting and recording big data on ingredient procurement, sterilization records, food additives, waste disposal, food retention samples, and expiration warnings, a food safety warning method based on big data and intelligent identification is proposed to achieve early warning of expiring food or food change information as well

as real-time remote region-wide supervision.

(10) Environmentally friendly pulp molding technology

Petroleum-based plastic products are widely used in product packaging and disposable tableware, while their refractory nature brings potential environmental issues. To address this problem, developing environmentally friendly green degradable materials to replace conventional petroleum-based plastic products is one of the important breakthrough points. Pulp molding technology, a three-dimensional papermaking technique, is capable of enabling pulp to form a pulp wet blank of certain shape and size in a specific mold. The obtained pulp wet blank was subsequently manufactured by cold-pressing dehydration, transferring, hot-pressing drying and other processes to form a molding material. The raw materials of pulp molding technology mainly derived from waste paper in paper industry and non-wood native plant fibers. Therefore, pulp molding products have the advantages of raw materials renewability, products degradability and easy reusability, showing great potentials for the promotable application. Since 2020, the “plastic restriction/plastic ban” policy has been gradually implemented in China, and the pulp molding industry will maintain a high-speed development stage for a long period of time. At present, the molding materials based on the pulp molding technology are mainly utilized in the packaging fields of catering, industrial products, agricultural food and medicine, which also show great development prospects in the future. However, with the improvement of packaging requirements, the shortcomings of pulp molding technology have become increasingly prominent, including the relatively backward supporting equipment, lack of automation level, and low product quality, etc. Especially for the high-quality industrial packaging, the usage effect of pulp molding products is influenced by their packaging cushioning performance, whiteness, moisture-proof performance, corrosion resistance and surface

smoothness, etc., which puts forward higher requirements for the overall process flow of environmentally friendly pulp molding technology. Hence, the important research directions for the promotion of this technology in the future are how to select raw materials, chemical additives and inorganic fillers as well as efficiently design molds.

2.2 Interpretations for three key engineering development fronts

2.2.1 Collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction

How to further improve the resource utilization level of industrial solid waste and effectively prevent the environmental risks in the process of toxic and hazardous chemicals management and solid waste disposal and utilization is an important task to improve the environmental governance system and governance capacity of solid waste and chemicals. The research and development of solid waste disposal technology will be based on the basic principles of reduction, recycling and harmlessness, and will be transformed into the research on the establishment of risk control technology and regulatory system for the whole industry and the whole process. The disposal mode will be transformed from single fight to regional industrial coordination. Green comprehensive utilization, high-value utilization and pollution and carbon reduction coordination will become the key research and development directions in the future. The main development trend forecast in the next 5–10 years is shown in Figure 2.2.1.

First, carry out research on reduction and comprehensive treatment technologies for industrial pollution sources and new pollution sources. Focusing on key industries such as iron and steel, nonferrous metals, building materials, petrochemical, chemical industry and paper making, we will

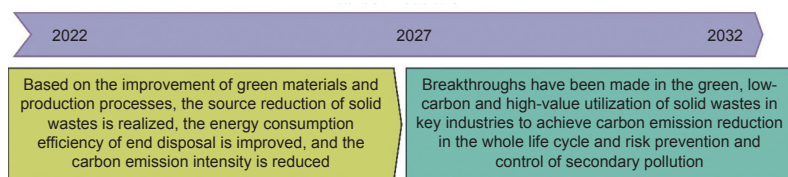


Figure 2.2.1 Roadmap of the engineering development front of “collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction”

carry out research on key technologies for pollution reduction and carbon source control. Research and develop new low toxicity and low pollution green materials, develop energy efficient combustion technology, clean energy substitution technology, high-temperature flue gas, waste heat and waste water and other energy cascade utilization technologies, waste in-situ regeneration and high-value multi-channel green utilization technologies, and help realize the production process of key industrial enterprises and industrial parks under the low-carbon background through the collaborative control of pollution and carbon reduction sources Reduce the source of emerging solid wastes and high-risk hazardous wastes, prevent the transfer of pollutants across media, reduce the environmental and health risks of new pollutants, and relieve the pressure of comprehensive treatment at the end.

Second, research and develop key technologies for collaborative control of pollution and carbon sources in key industries. In view of the problems such as heavy end treatment load, high cost and lack of effective treatment measures for some pollutants, we will focus on key industries such as iron and steel, nonferrous metals, building materials, petrochemical, chemical industry and papermaking, carry out research and development and integration of key materials and major equipment technologies for pollution and carbon reduction source control, develop new low toxicity, low pollution and low energy consumption materials, clean energy substitution and traditional energy efficient combustion

technology, clean production process optimization Key technologies for collaborative control of pollution and carbon reduction sources, such as in-situ regeneration and efficient utilization of wastes in the production process, cascade utilization of energy in the production line such as high-temperature flue gas and waste heat and wastewater, are realized to realize technological innovation of collaborative control of pollution and carbon reduction sources that integrates pollution and carbon reduction, and has multiple objectives such as environmental benefits, economic benefits and climate benefits.

Third, research and development of key technologies for collaborative control of pollution and carbon reduction in industrial parks. Research and develop the key technologies for the efficient recycling of resources in the construction of the ecological industrial chain network of the industrial park; research on the key technologies of green, low-carbon and cascade utilization of energy in industrial parks; research and development of intelligent tracking, identification and optimization control technology for efficient utilization of resources and energy in industrial parks; research on carbon flux monitoring, accounting and carbon Traceability Technology in industrial parks; Research and develop the evaluation technology for the synergy degree of pollution reduction and carbon reduction in the park.

According to Table 2.2.1, the main output countries of core patents in the research direction are China, the USA, Japan and South Korea. Among them, the number of core patents in

Table 2.2.1 Countries with the greatest output of core patents on “collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	754	83.31	1 561	72.17	2.07
2	USA	32	3.54	182	8.41	5.69
3	Japan	27	2.98	92	4.25	3.41
4	South Korea	18	1.99	30	1.39	1.67
5	Germany	10	1.10	34	1.57	3.40
6	France	10	1.10	34	1.57	3.40
7	Belgium	7	0.77	20	0.92	2.86
8	Canada	6	0.66	67	3.10	11.17
9	Russia	6	0.66	17	0.79	2.83
10	Italy	6	0.66	15	0.69	2.50

China ranks first, accounting for 83.31%, exceeding 80% of the global patents. The USA followed, accounting for 3.54%. The cited number of Chinese patents is 72.17%, ranking the first in the world. Countries mainly conduct research independently. There is no cooperation among major countries.

It can be seen from Table 2.2.2 that the institutions with a large number of core patents in this research direction are Central South University, Institute of Process Engineering, Chinese Academy of Sciences, Foshan Sanshui Xiongying Aluminium Surfacing Technology Innovative Centre Company Limited, Jiangsu Province Metallurgical Design Institute Company Limited, Jiangsu University of Technology, and Pangang Group. The number of core patents of these institutions exceeds 6. Institutions mainly conduct research independently. There is no cooperation among major institutions.

According to the above data analysis results, China's core patent output and the number of core patents introduced in the field of Collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction are among the world's leading, and the number of core patents introduced by Chinese research institutions is relatively large.

2.2.2 Development of complex land surface models and their applications in Earth System Modeling

The land-atmosphere and land-sea interfaces are the main places for human activities. With the development of human society, the changes of the earth's land surface caused by human activities have profoundly affected the exchange of matter and energy between land-air and land-sea, and the changes of regional climate and ecological environment. These changes have had a huge impact on nature and humans. Accurately describing the physical, chemical and biological processes of the land surface, accurately calculating the state of the land surface and the material and energy exchange fluxes at the land-atmosphere and land-sea interfaces, is of great scientific and social significance to numerical forecasting of weather/climate, to fully understand the formation mechanism of water security, food security, ecological environment deterioration and other problems caused by global change, and to formulate corresponding countermeasures.

The development of land surface process models has mainly experienced four stages so far, from the relatively simple "bucket model" and the simple energy balance model to the fourth generation of land surface process models containing

Table 2.2.2 Institutions with the greatest output of core patents on "collaborative control technology of high-quality recycling of solid waste and pollution and carbon reduction"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Central South University	27	2.98	84	3.88	3.11
2	Institute of Process Engineering, Chinese Academy of Sciences	9	0.99	33	1.53	3.67
3	Foshan Sanshui Xiongying Aluminium Surfacing Technology Innovative Centre Company Limited	9	0.99	2	0.09	0.22
4	Jiangsu Province Metallurgical Design Institute Company Limited	7	0.77	16	0.74	2.29
5	Jiangsu University of Technology	7	0.77	11	0.51	1.57
6	Pangang Group	7	0.77	6	0.28	0.86
7	Nantong Jiuzhou Environmental Protection Technology Company Limited	6	0.66	3	0.14	0.50
8	Hunan Xinhuoquan Environmental Protection Technology Company Limited	6	0.66	2	0.09	0.33
9	China Petroleum & Chemical Corporation	5	0.55	42	1.94	8.40
10	Changsha Zichen Technology Development Company Limited	5	0.55	16	0.74	3.20

the refined descriptions of land surface physics, chemistry and biology, which has greatly improved our understanding of the land-surface systems. However, the description of the impact of human activities on land surface process disturbances in existing models is relatively lacking or too simple. It is the main goal of future land surface model research and development to include the human activities and ecosystem processes, to realize high-resolution simulation, and to further realize the coupling between the new land surface process model and the earth system model to accurately describe and predict the impact of climate change and human activities on land surface physical, biological and geochemical processes.

The main countries with the greatest output of core patents

on “development of complex land surface models and their applications in Earth System Modeling” are shown in Table 2.2.3. China ranked first in the number of core patent disclosure, the USA ranked second, and France third. However, the average number of citations is lower than that of the USA. This indicates that although China has many core patents in this field, the patents lack of innovation and influence. The technical level of our country in this field still needs to be improved. From the collaboration network between the frontier countries on “development of complex land surface models and their applications in Earth System Modeling” (Figure 2.2.2), it can be seen that the USA, France, Netherland and Canada have collaborations with others, while China has

Table 2.2.3 Countries with the greatest output of core patents on “development of complex land surface models and their applications in Earth System Modeling”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	668	78.40	1 283	44.58	1.92
2	USA	112	13.15	643	22.34	5.74
3	France	19	2.23	87	3.02	4.58
4	Saudi Arabian	19	2.23	73	2.54	3.84
5	South Korea	15	1.76	10	0.35	0.67
6	Netherlands	14	1.64	50	1.74	3.57
7	Canada	13	1.53	37	1.29	2.85
8	Luxembourg	12	1.41	68	2.36	5.67
9	Japan	11	1.29	4	0.14	0.36
10	UK	8	0.94	21	0.73	2.62

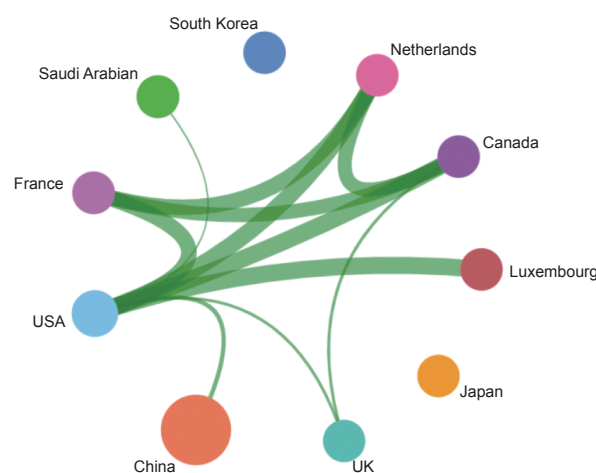


Figure 2.2.2 Collaboration network among major countries in the engineering development front of “development of complex land surface models and their applications in Earth System Modeling”

little collaboration with other countries except the USA.

The main institutions with the greatest output of core patents on “development of complex land surface models and their applications in Earth System Modeling” are shown in Table 2.2.4. The top two cited institutions are SAOC (19) and HESI (19), which are from the Saudi Arabian and the USA institutions. From the perspective of published patents, five of the top ten institutions are from China. Figure 2.2.3 presents the collaboration network among various institutions of the development frontier. As shown in the figure, the collaboration relationship between the development frontier among various institutions or enterprises is very weak and

only Paradigm Sciences Limited and Emerson Paradigm Holding Limited Liability Company has collaborations. This indicates that we should further strengthen exchanges and collaboration with other countries and institutions to further enhance China’s innovation capabilities in this field.

Figure 2.2.4 shows the roadmap of the engineering development front of “development of complex Land surface models and their applications in Earth System Modeling”. It can be seen that there are two key development stages that this development front will experience in the next 5–10 years. The first is to introduce human activities and ecosystem processes into the land surface model. On this basis, the

Table 2.2.4 Institutions with the greatest output of core patents on “development of complex land surface models and their applications in Earth System Modeling”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations	Citations per patent
1	Saudi Arabian Oil Company (SAOC)	19	2.23	73	2.54	3.84
2	Halliburton Energy Services Incorporation (HESI)	19	2.23	60	2.08	3.16
3	China Institute of Water Resources and Hydropower Research	16	1.88	71	2.47	4.44
4	Schlumberger Limited	14	1.64	43	1.49	3.07
5	Paradigm Sciences Limited	11	1.29	82	2.85	7.45
6	Institute of Agricultural Resources and Regional Planning Chinese Academy of Agricultural Sciences	11	1.29	21	0.73	1.91
7	Emerson Paradigm Holding Limited Liability Company	10	1.17	28	0.97	2.80
8	China Petroleum & Chemical Corporation	10	1.17	23	0.80	2.30
9	State Grid Corporation of China	10	1.17	12	0.42	1.20
10	China University of Mining & Technology Beijing	9	1.06	23	0.80	2.56

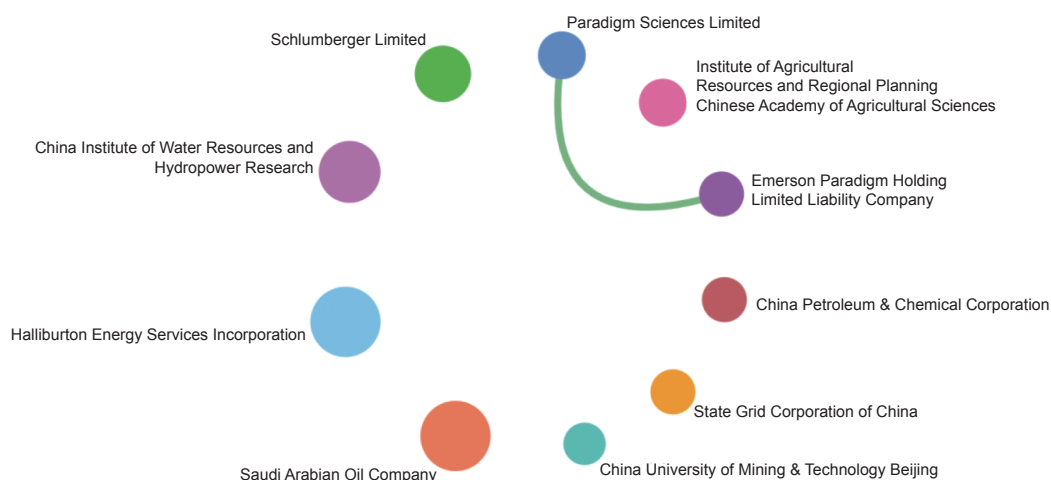


Figure 2.2.3 Collaboration network among major institutions in the engineering development front of “development of complex land surface models and their applications in Earth System Modeling”

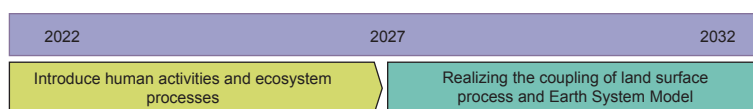


Figure 2.2.4 Roadmap of the engineering development front of “development of complex land surface models and their applications in Earth System Modeling”

second stage goal is to achieve the couple of land surface process models with earth system models.

2.2.3 Recyclability and reusability of personal protective equipment

With the sudden global outbreak of the new crown pneumonia epidemic, it has become necessary to recycle and upgrade discarded personal protective equipment, especially disposable medical masks, in light of the new situation at home and abroad. For example, disposable medical masks typically consist of two layers of spunbond nonwoven material combined with a layer of meltblown nonwoven material as the main body, with ear straps and nose clips attached. Raw material for the main part of the product is polypropylene (PP). It is the primary function of spunbond nonwoven fabrics to provide waterproof and anti-sputtering properties, as well as to provide a certain level of strength to prevent melt-blown nonwovens from becoming weak in the inner layer. The melt-blown non-woven material in the middle layer serves primarily as a filter. The melt-blown nonwoven material has a small fiber diameter, approximately 2 μm , a small pore size, and a large porosity. As a result of electrostatic evaporation, the composite mask is able to effectively absorb dust particles as well as capture bacteria and virus droplets.

Currently, discarded disposable medical masks can be recycled and processed utilizing four different methods: landfilling, incineration, physical recycling, and chemical recycling. In landfills, masks are decomposed by microorganisms, taking a long time to degrade and polluting the soil as a result. Incineration uses the heat generated by combustion to generate power and drive mechanical devices. This process is mature and simple, and it has a wide range of applications, but it is associated with serious environmental pollution, a low capacity for production, and low resource utilization. The discarded disposable medical masks are broken into specified sizes, mixed with other materials evenly, and adhered to form a new product under the influence of heat, pressure,

or a combination of both. Among the characteristics of the process are its relative maturity and its simplicity. There is a low utilization rate of resources; chemical recycling is more effective in repurposing waste disposable medical masks. Through chemical reactions, polymer macromolecules are converted into small molecular compounds for further utilization, or specific groups in waste masks react with chemical reagents to create new ones. In addition to its high added value, this product also protects the environment with green reagents, but some of its reagents pollute the environment, so they can be replaced with green reagents that are environmentally friendly.

Essentially, forming national awareness about the classification and treatment of discarded masks is the basis for developing a new selective green catalyst, degradant, and collaborative detection technologies on the basis of exploring the mechanism of decomposition, reconstruction and re-functionalization of mask-related materials. The formulation of new mask standards, the development of new ideas for utilizing the residual value of existing disposable medical masks, and the development of next generation chemically recyclable mask materials will greatly facilitate the upgrading and reconstruction of discarded disposable medical masks, contributing to society’s sustainable development by transforming waste into treasure.

Figure 2.2.5 illustrates the roadmap of engineering development front of “recyclability and reusability of personal protective equipment”.

In the context of normalized prevention and control needs in the post-epidemic era, it is necessary for my country to improve the prevention and control system for major epidemics in order to compensate for the shortcomings of my country’s medical waste disposal capacity and establish a sound emergency response mechanism which will provide important support for the barrier. Innovative development is necessary in order to recycle medical waste. China has made significant research investments in the development of waste

textile recycling in recent years, and the recycling technology for personal protective equipment is continuously being developed. According to Table 2.2.5, China has disclosed up to 974 patents in recent years, representing 97.99% of all disclosed patents, followed by the USA and South Korea, each with five disclosures. Compared to the USA, Russia, and Japan, China has a much higher number of patents for recycling and reuse of personal protective equipment.

Compared to the USA, Russia, and Japan, Chinese patents have a much lower average citation frequency (Table 2.2.5). There is still a lack of innovation and originality in the

recycling of personal protective equipment. Insufficient and insufficient influence; among the top 10 institutions producing core patents (Table 2.2.6), the top two institutions are Shunchihua (Qingdao) Intelligent Technology Co., Ltd. and Bosi Yingnuo Technology (Beijing) Co., Ltd. There is no R&D cooperation among the major countries and institutions in this development front, and the degree of industrialization is low. There is still a lot of room for industry-academia-research cooperation on recycling technology for personal protective equipment. To further enhance our country's innovation capabilities, we need to strengthen exchanges

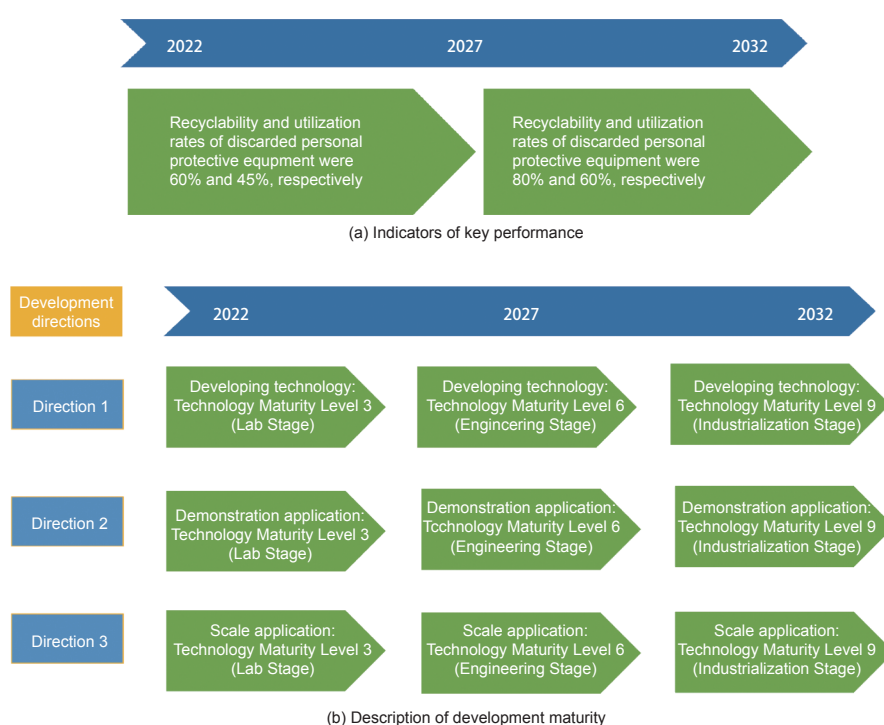


Figure 2.2.5 Roadmap of the engineering development front of “recyclability and reusability of personal protective equipment”

Table 2.2.5 Countries with the greatest output of core patents on “recyclability and reusability of personal protective equipment”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	974	97.99	610	85.67	0.63
2	USA	5	0.50	79	11.10	15.80
3	South Korea	5	0.50	3	0.42	0.60
4	Russia	4	0.40	11	1.54	2.75
5	Japan	3	0.30	8	1.12	2.67
6	Poland	1	0.10	1	0.14	1.00
7	UK	1	0.10	0	0.00	0.00

and cooperation with other countries and institutions. In terms of technology development, the “quantitative alone theory” should also be corrected, and relevant comprehensive assessments of the impact of scientific research output should be increased to encourage scientific research institutions

to pay attention to the quality and impact of research, promote the integration of production, education, and research between university institutions and enterprises, and encourage the rapid development of subject areas.

Table 2.2.6 Institutions with the greatest output of core patents on “recyclability and reusability of personal protective equipment”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Shunchihua (Qingdao) Intelligent Technology Co., Ltd.	6	0.60	0	0.00	0.00
2	Bosi Yingnuo Technology (Beijing) Co., Ltd.	4	0.40	4	0.56	1.00
3	Anhui Kunjian Biotechnology Co., Ltd.	3	0.30	2	0.28	0.67
4	China State Railway Group Co., Ltd.	3	0.30	1	0.14	0.33
5	Shaoxing Xucheng Environmental Protection Equipment Co., Ltd.	3	0.30	1	0.14	0.33
6	Hengyang Wangfa Tin Co., Ltd.	3	0.30	0	0.00	0.00
7	EcoATM Incorporation	2	0.20	76	10.67	38.00
8	China Shipbuilding Industry Corporation	2	0.20	15	2.11	7.50
9	Shenyang Institute of Automation, Chinese Academy of Sciences	2	0.20	11	1.54	5.50
10	Changsha Pengyue Wuyang Information Technology Co., Ltd.	2	0.20	5	0.70	2.50

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VII. Agriculture

1 Engineering research fronts

1.1 Trends in Top 11 engineering research fronts

The Top 11 engineering research fronts in the agriculture field can be classified into three groups: ① research on the molecular biological mechanism on animal and plant production, including “immunosuppression and escape mechanisms of important animal pathogens”, “mechanism of efficient soil carbon sequestration and regulation”, “molecular biological mechanisms of wood formation”, and “interaction network mechanism of breeding environment-livestock and poultry-gut microorganism-nutrient metabolism”; ② molecular breeding as usual, including “polyploid breeding of aquatic animals” and “polygenic breeding of livestock and poultry”; ③ research on improving the production of animal and plant products and green production, including “organ development and quality regulation of horticultural crops”, “green cultivation techniques for crops”, “discovery of resistosome of plant”, “*de novo* domestication and germplasm utilization of wild crops”, and “response of food security to climate change”. The number of core papers of these research fronts

ranges from 7 to 143 with an average of 59, close to 2020 and 2021. The citations per paper ranged from 5.06 to 178.69 with an average of 59.58. Most core papers were published in 2018 and 2019 whereas the core papers of “immunosuppression and escape mechanisms of important animal pathogens” and “*de novo* domestication and germplasm utilization of wild crops” were mostly published in recent years and showed an increasing trend (Tables 1.1.1 and 1.1.2).

(1) *De novo* domestication and germplasm utilization of wild crops

Crop domestication, the process of adapting wild plants into cultivated crops, has played an essential role in the origin of farming civilization and promoted the continuous development of human civilization and the rapid evolution of society. Specifically, domestication is the process of screening beneficial agronomic traits from wild germplasm as the starting material through long-term artificial selection throughout history. The target trait, such as less grain shattering, reduced branching, compact growth, reduced awn, larger seeds, and suitable hand-harvesting. In the view of genetics, domestication is a process of aggregating and retaining ideal genetic variations in the genome. However, this process mostly took a long historical time and the selection

Table 1.1.1 Top 11 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	<i>De novo</i> domestication and germplasm utilization of wild crops	74	2 345	31.69	2019.4
2	Immunosuppression and escape mechanisms of important animal pathogens	45	7 556	167.91	2020.2
3	Mechanism of efficient soil carbon sequestration and regulation	83	14 831	178.69	2018.9
4	Organ development and quality regulation of horticultural crops	61	588	9.64	2018.9
5	Polyploid breeding of aquatic animals	18	91	5.06	2019.2
6	Green cultivation techniques for crops	98	4 868	49.67	2017.6
7	Polygenic breeding of livestock and poultry	50	569	11.38	2019.2
8	Response of food security to climate change	143	11 032	77.15	2017.8
9	Molecular biological mechanisms of wood formation	7	167	23.86	2017.7
10	Discovery of resistosome of plant	34	800	23.53	2020.2
11	Interaction network mechanism of environment-livestock gut microorganism-nutrient metabolism	37	2 842	76.81	2017.3

Table 1.1.2 Annual number of core papers published for the Top 11 engineering research fronts in agriculture

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	<i>De novo</i> domestication and germplasm utilization of wild crops	4	10	6	12	13	29
2	Immunosuppression and escape mechanisms of important animal pathogens	0	0	4	5	15	21
3	Mechanism of efficient soil carbon sequestration and regulation	9	11	7	25	15	16
4	Organ development and quality regulation of horticultural crops	4	10	14	9	7	17
5	Polyploid breeding of aquatic animals	2	2	1	3	5	5
6	Green cultivation techniques for crops	29	17	26	21	5	0
7	Polygenic breeding of livestock and poultry	0	7	11	12	6	14
8	Response of food security to climate change	32	32	34	25	16	4
9	Molecular biological mechanisms of wood formation	2	2	1	0	2	0
10	Discovery of resistosome of plant	0	1	0	6	11	16
11	Interaction network mechanism of environment-livestock gut microorganism-nutrient metabolism	15	6	9	4	3	0

of the targeted traits was random and mindless. Moreover, screening for superior traits also significantly reduced the genetic diversity of the domesticated population. Compared to modern cultivars, wild relatives often have advantages in particular traits, such as greater stress resistance, broader environmental adaptability, and relatively higher biomass. Nowadays, with the development of biotechnology, especially gene editing, *de novo* domestication is starting to be proposed as a promising strategy for crop breeding. That strategy starts from the selection of wild or semi-wild plant species with particularly outstanding traits, then the rapid introduction of the required domestication traits through modern breeding technology, and eventually novel crop species may be achieved in a short time term. This new crop, which repurposes the good wild germplasm that has been lost in the traditional crop domestication or breeding, is of great significance for sustainable agricultural development under the current global trend of environmental change.

(2) Immunosuppression and escape mechanisms of important animal pathogens

China is the world's largest consumer of livestock and poultry and animal-derived food. In recent years, the level of intensive and large-scale animal husbandry has continuously improved. However, infectious diseases, especially some major animal diseases, have always restricted the healthy development of animal husbandry and threaten social public health security. How to effectively prevent and control these important animal pathogens has always been a focus and research hotspot in

the fields of veterinary medicine, medicine and biosafety. One of the main reasons that hinders the prevention and control of epidemic diseases is that these important animal pathogens have developed various strategies to escape and suppress host immunity in the long-term evolution. The body's defense against pathogenic infection mainly relies on host innate and adaptive immune responses. Some important pathogens can evade host surveillance and inhibit key antiviral innate immune responses, resulting in pathogens effectively breaking through the body's immune barriers and establishing productive infections; meanwhile, pathogens can escape host-elicited adaptive responses by generating new variants or strains through mechanisms such as mutation or recombination, which escape neutralizing antibodies or T-cell immunity in the host, thereby preventing them from being cleared by the body and establishing a productive infection. Elaborating the key mechanisms by which pathogens inhibit and evade the body's immunity is the premise for effective prevention and control of important animal pathogens, and it is also a challenging and hot topic in veterinary medicine. The relevant research results will surely provide important guidance and technical support for the prevention and control of major animal diseases.

(3) Mechanism of efficient soil carbon sequestration and regulation

Soil is the largest carbon pool in the terrestrial ecosystem. The global soil organic carbon is 1 500–2 000 Pg, equivalent to 2–3 times of the carbon in the atmosphere. Agricultural

soil carbon sequestration was found to account for 25% of the potential for natural climate solutions. Therefore, promoting agricultural soil carbon sequestration is of great significance for ensuring food security, mitigating climate change and promoting agricultural green development. The core of efficient soil carbon sequestration and regulation is to understand the key processes of turnover and stability of soil organic matter, and to establish a regulatory strategy for efficient carbon sequestration and slowing down its mineralization and decomposition. Soil is an open and complex system in which multiple substances coexist, multiple processes occur simultaneously, and multiple factors influence together. At present, the mechanism of efficient soil carbon sequestration is still unclear. Therefore, in-depth research on carbon sequestration and regulation mechanism needs to be strengthened in the future. For example, accurately distinguishing carbon sources of different organic components, exploring the microbial action mechanism of plant residues to soil organic matter, accelerating research on organic matter stability based on multi-factor coordinated regulation, exploring soil carbon balance mechanism and plant residue input thresholds, etc. Innovate new carbon-based materials with high efficiency of carbon sequestration and nutrient use, improve soil carbon sequestration efficiency, integrate and innovate key technologies for soil carbon sequestration, land conservation and productivity improvement, and promote the application of large-scale agricultural soil carbon sequestration are becoming the frontier in applied research direction in this field.

(4) Organ development and quality regulation of horticultural crops

The products of horticultural crops, such as vegetables, fruit trees, flowers, are diverse, including roots and modified roots, stems and modified stems, leaves and leafy heads, flowers and bolting, fruits and seeds, etc., which are the basis for the production of horticultural crops. The quality of horticultural products includes nutritional quality (such as content of carbohydrates, lipids, proteins, vitamins, minerals, trace elements and other nutrients), sensory quality (including product appearance, texture, palatability, etc., such as size, shape, color, gloss, juice, hardness, defects, freshness, etc.), hygienic quality (including surface cleanliness of fruits and vegetables, heavy metal content in fruit and vegetable tissues, pesticide residues and other restricted substances such as nitrite content, etc.), commercial processing quality (such

as easy to clean, etc.), and other complex characters. With the rapid development of the horticultural industry and the increasing crop yields, close attention has been paid to the changes in product quality traits, the content of healthy ingredients, and the quality and safety of horticultural products. In recent years, my country has carried out some researches on the formation and regulation mechanism of horticultural crops in terms of fruit shape, color, nutritional quality, flavor and bitterness. Mining and analysis of related genes for substance metabolism and their regulatory networks, the molecular mechanism and regulatory network of important agronomic traits such as yield and quality are provided for the further research in theory, but most of the metabolites that determine the organ development and product quality of horticultural crops are still unclear. Therefore, in the future, study the gene expression cascade regulation mechanism and regulatory network analysis should be carried out in terms of transporters, transcriptional regulators, epigenetic modifiers and non-coding RNAs, so as to explore the organ development of horticultural crops, which will provide a scientific basis for the improvement of quality and efficiency of the horticultural industry.

(5) Polyploid breeding of aquatic animals

Polyploid organisms are organisms with three or more complete sets of chromosomes. In plants and animals, polyploidy is widespread. In the long-term evolutionary process, polyploidy is one of the important driving forces for speciation. With the in-depth study of genome and phylogeny, the results of multiple studies support that most species have undergone polyploidy events during their evolution. Once polyploidy occurs, its stability depends on rapid genome recombination and changes in gene expression regulation. The formation of fertile polyploidy not only promotes the exchange of genetic material between species and enriches species diversity, but also lays the foundation for polyploid breeding. Aquatic animal polyploids can be obtained by distant hybridization, physical induction, and chemical induction. Among them, distant hybridization can obtain large-scale polyploid fertile lineages. At present, based on the polyploid breeding technology of aquatic animals, several new germplasms of aquatic animals such as fish, shrimps, crabs, and shellfish have been obtained, and systematic research has been carried out. The study of polyploid breeding of aquatic animals not only has important theoretical significance, but also has important application value.

(6) Green cultivation techniques for crops

Green cultivation is an applied science that studies the mechanisms of crop growth and its relationship with the environmental factors, and to achieves high-yield, high-quality, high-efficiency, ecological safety. The grain yields of rice, wheat and maize per area in China are significantly higher than the world average, and the total grain yield increased continuously for many years, which has made great contributions to ensuring the food security of our country. However, there are still many prominent problems need to be solved in China's crops production, such as inefficient and extensive cultivation practices, imperfect mechanized cultivation techniques, low-integration of engineering technologies, high inputs of water, fertilizer and pesticides, and insufficient integration of green and low-carbon agriculture, intelligence and agricultural machinery. Green cultivation of crops has become a crucial and difficult problem to be solved. The key scientific problems are: ① mechanisms and technologies of synchronizing high-quality, high-yield, high-efficiency, and green crop production; ② synergistic rules of high-quality and high-yield (super-high-yield), and high-efficiency of field crops production and the replicable cultivation mode; ③ green cultivation techniques that is healthy, stress tolerant, carbon sequestered, green house emission reduced, and energy saving for field crops; ④ key technologies of integration of agricultural machinery and intelligent agriculture for field crops; ⑤ the mode and technologies of unmanned green cultivation in the whole process of crops production. Through the innovation of crop cultivation and the cross-integration with frontier science such as physiology, environmental ecology, informatics and mechanical engineering, a new theory of high-quality, high-yield, green and efficient cultivation technology of crops with Chinese characteristics is created, and a unmanned cultivation technology system for agricultural machinery and intelligent agriculture integration for large-scale green production can be established, so as to realize the synergy promotion of yield and quality, production efficiency and production benefit of field crops, to increase comprehensive crop production capacity by 10%–30%, to effectively promote the green high-yielding cultivation level and the modernization of field crop production.

(7) Polygenic breeding of livestock and poultry

Polygenic breeding of livestock and poultry is one of the main

methods of molecular breeding of livestock and poultry, which refers to the aggregation of the excellent genes of excellent individuals scattered in different varieties or lines into the genome of the same individual, so as to obtain new varieties (lines) with specific characteristics. At present, there are two main ways to achieve polygene aggregation. First, on the basis of determining the molecular markers related to the excellent characteristics, the individuals with multiple excellent genes were selected by hybridization, backcrossing and marker-assisted selection. The molecular markers closely linked to the target quantitative trait genes obtained by molecular marker-assisted selection have strong reliability and are not affected by allele dominant-recessive relationships and the environment. The application in animal breeding accelerates the genetic progress and shortens the breeding cycle. However, the aggregated genes in the progeny of individuals selected by this method may reaggregate, resulting in the instability of target trait. In recent years, with the continuous development of transgenic technology and gene editing technology, the realization of multi-gene aggregation through gene modification technology has become the research frontier of multi-gene aggregation breeding of livestock and poultry. However, there are still multiple technical difficulties in realizing multiple gene editing simultaneously in animal genomes. On the one hand, the functional genes related to important traits of livestock and poultry have not been completely analyzed, and the targets of genome manipulation are still unclear. On the other hand, the number of simultaneous gene editing in animal genomes is limited, and it is difficult to edit dozens or hundreds of sites at the same time. China has abundant genetic resources of livestock and poultry. Various phenotypes and genotype databases are constantly enriched, and important functional genes and regulatory sequences related to various traits are continuously excavated. At the same time, with the continuous improvement of the efficiency, accuracy and safety of stem cell breeding technology and gene editing technology, using the characteristics of long-term subculture of stem cells in vitro, multiple gene editing operations can be performed, which is expected to solve the technical difficulties of gene editing aggregation breeding.

(8) Response of food security to climate change

Global climate change refers to a statistically significant change in the average state of the climate on a global scale

or a climate change that lasts for a long period of time. The response of food production to climate change is highly sensitive, and global climate change, characterized by climate warming, and has brought serious impacts on global food security. With global warming, the rise of surface temperature will increase the respiration consumption of crops, affect the progress of photosynthesis and the growth and development of crops. Globally, 18% of the inter-annual variability in maize yields is the result of climate variability, while soybean and wheat are less at risk of simultaneous crop failure, with climate variability accounting for 7% and 6% of their global yield variability, respectively. Research has showed that by 2050, global warming may reduce world food production by 18%. At present, climate change has posed a major threat to the basic survival of human beings and social and economic stability. Elucidating the driving mechanism of climate change and the law of its impact on crop production has become a hot and difficult issue to be solved urgently. And the core scientific issues mainly include: ① identification of the core driving factors of climate change; ② the response mechanism of water flux and productivity of farmland ecosystem to global change; ③ the change mechanism of crop damage under the action of climate change and human activities. With the development of artificial intelligence and big data technology, the core driving factors of climate change can be identified from the global scale, and the law of global crop yield changes can be analyzed from multiple dimensions such as nature, economy, and policy. Also scientific decision-making basis and guarantee will be provided for building a global community with a shared future for mankind.

(9) Molecular biological mechanisms of wood formation

Formation of wood (secondary xylem) is a sequential developmental process that starts from the vascular cambium proliferation, cell expansion and differentiation, secondary cell wall (SCW) deposition and programmed cell death (PCD) to form wood tissue. The main research interests include: ① synthesis mechanism of main components of secondary cell wall; ② regulation of auxin, cytokinin, short peptide and transcription factors on vascular cambium cell genesis, proliferation and xylem cell differentiation; ③ mechanisms of cambium stem cell maintenance, differentiation and co-regulation of xylem development and environmental adaptation; ④ regulation of protein post-translational modification and epigenetic modification in cambium activity and wood development; ⑤ molecular mechanism of tension

wood formation; ⑥ QTL mapping of growth and wood quality traits; ⑦ genome-wide association analysis of important wood properties.

Its development trends mainly include: ① More attention is paid to the application of advanced research methods, technologies and analytical instruments, such as spatio-temporal transcriptome, spatial metabolome, single-molecule imaging, and atomic force microscopy. ② Establish a fine multi-level transcriptional regulation network and feedback regulation mechanisms at different levels. ③ Excavation and identification of important wood quality and properties, and the analysis of hierarchical regulation mechanism. ④ Collect and analyze wood quality information by using new sensor technology. ⑤ Crystal structure analysis of key regulatory proteins and identification of protein interaction surface sites. ⑥ Gene editing technology to create new forest varieties with excellent wood properties. ⑦ Carry out tree molecular design breeding to cultivate new varieties trees with fast growing, high quality and high yield.

(10) Discovery of resistosome of plant

Phytopathogens secrete diverse effectors to interfere with plant immune response. In the resistance plants, there are a set of NB-LRR (nucleotide-binding site, leucine-rich repeat) proteins (R proteins) to directly or indirectly perceive these effectors and to initiate immune response. Based on the “gene for gene” hypothesis proposed by Harold Flor in 1956, hundreds of effectors from various pathogens have been cloned over the years. Correspondingly, many NB-LRR proteins have been cloned, and many of them have been discovered to perceive the cognate effectors. Following these discoveries, several hypotheses have been proposed to explain how the NB-LRR-mediated immunity is initiated in plants, for example the “guard hypothesis” and “bait hypothesis”. In these hypotheses, the NB-LRR activation has been proposed to hydrolyze ATP in the NB domain, leading to the overall allosteric conformational change and the dimerization of N-terminus coil-coil (CC) domain and Toll/IL-1 receptor (TIR) domain that is known to induce hypersensitive response (HR). However, due to lack of resolved protein structures, none of the hypothesis has been experimentally proved, and the NB-LRR-mediated immune activation remains elusive. Until 2019, two Chinese groups resolved the crystal structure of a CC-NB-LRR ZAR1 immune complex for the first time. This immune complex is a wheel-like pentamer, and is activated

by exchanging ADP with ATP upon binding the effector AvrAC from *Xanthomonas campestris* pv. *campestris*. The activated immune complex forms a funnel with five N-terminal helices of the ZAR1 proteins to target the plasma membrane to create a selective calcium channel. The activation of the resistosome triggers apoplastic calcium influx through this channel and induces the accumulation of reactive oxygen species in cytosol, which eventually results in HR-associated cell death, thereby restricting pathogen further infection. Because the ZAR1 immune complex activation resembles the inflammasomes in animal immune system, the complex is then named as plant resistosome. This is a landmark event in plant science, which answers the question for how the NB-LRR-mediated immunity is initiated in the last 30 years since this type of proteins is discovered. Following this discovery, the tetramer immune complex was characterized for TIR-NB-LRR-mediated immunity by a German group and an American group. These groundbreaking discoveries substantially push the move towards fully elucidating the plant disease resistance.

(11) Interaction network mechanism of environment-livestock gut microorganism-nutrient metabolism

The environmental pollution problem of animal husbandry has seriously compressed the development space of animal husbandry, and the new production ecosystem is still in the exploratory stage. According to the investigation of the former State Environmental Protection Administration, the amount of livestock and poultry feces produced in China is about 1.9 billion tons, 2.4 times that of industrial solid waste. The annual discharge of chemical oxygen demand (COD) from animal husbandry in China is more than 12 million tons, accounting for 95.8% of the total agricultural discharge and 41.9% of the total National COD discharge, exceeding industrial pollution. In view of the problems of cost efficiency and environmental pollution, it is necessary to focus on solving major technical bottlenecks such as improving feed quality, improving feed nutritional value and utilization efficiency, reducing processing costs, precision feed preparation and environment-friendly feed production, and realizing automation and intelligent equipment research and development of precision feeding. Develop new in vitro pre digestion technology for efficient utilization of feed nutrients; To study the mechanism of high-efficient utilization and transformation of livestock and poultry feed nutrition, and to develop microbial cell factories according to different feed raw materials by using microbial

culturing omics technology, microbial transformation engineering technology, protein engineering technology and synthetic biology technology, and create in vitro pre digestion additives with high-efficient utilization of feed, anti-nutritional factors and toxin elimination; Based on the process route of bacterial enzyme collaborative fermentation, the key process parameters, safety evaluation and quality control system were established with the aim of acid soluble protein content, anti-nutritional components and toxin degradation rate. Effectively improve the utilization rate of feed nutrients, reduce the addition of feed protein, reduce the anti-nutritional factors and toxic components of feed, promote the digestion and absorption of feed, and effectively reduce environmental pollution.

1.2 Interpretation for three key engineering research fronts

1.2.1 *De novo* domestication of crops and exploitation and utilization of wild germplasm resources

(1) The significance of *de novo* domestication of crops and exploitation and utilization of wild germplasm resources

Crop domestication, the process of adapting wild plants into cultivated crops, has played an essential role in the origin of farming civilization and promoted the continuous development of human civilization and the rapid evolution of society. Specifically, domestication is the process of screening beneficial agronomic traits from wild germplasm as the starting material through long-term artificial selection throughout history. The target trait, such as less grain shattering, reduced branching, compact growth, reduced awn, larger seeds, and suitable hand-harvesting. In the view of genetics, domestication is a process of aggregating and retaining ideal genetic variations in the genome. However, this process mostly took a long historical time and the selection of the targeted traits was random and mindless. Moreover, screening for superior traits also significantly reduced the genetic diversity of the domesticated population. Compared to modern cultivars, wild relatives often have advantages in particular traits, such as greater stress resistance, broader environmental adaptability, and relatively higher biomass. Nowadays, with the development of biotechnology, especially gene editing, *de novo* domestication is starting to be proposed as a promising strategy for crop breeding. That

strategy starts from the selection of wild or semi-wild plant species with particularly outstanding traits, then the rapid introduction of the required domestication traits through modern breeding technology, and eventually novel crop species may be achieved in a short time term. This new crop, which repurposes the good wild germplasm that has been lost in the traditional crop domestication or breeding, is of great significance for sustainable agricultural development under the current global trend of environmental change.

The domesticated crops from wild species enable the adaption to a variety of climatic and soil conditions, as well as the expansion of early cultivation into larger areas. The subsequent crop breeding spawned higher food production, which has been the major contributor to population growth and human civilization. Domestication, similar to the breeding process, aims to select the best combination of genotype and phenotype. Many crops have certain common patterns of trait changes through domestication, including compact growth habits, increased spike size, more seeds, loss of grain shattering, reduced dormancy, changes in flowering time response, changes in seed pigmentation, etcetera. New genotypes arise from new mutations, while different genotypes rely on recombination to achieve the aggregation of different superior traits into a single plant. However, both genotypic mutations and recombination are random processes that cannot be accurately predicted or modulated by our ancestor breeders. In addition, the frequency of genomic spontaneous mutations is extremely low, and the immigration of interspecific fragments during domestication or breeding may also inhibit recombination, leading to fixation of deleterious alleles in these regions and resulting in linkage drag and failure to aggregate superior alleles. A classic example is the introduction of root-knot nematode resistance in tomatoes (controlled by the *Mi-1* gene) and yellow leaf curl virus resistance (controlled by the *Ty-1* gene), and both genes are located within a suppressed recombination region on chromosome 6, and the simultaneous combining of these two resistance traits requires extensive, long-term genetic screening. On the other hand, domestication and the early stage of breeding focused on crop yield improvement, and a large number of ideal variations for other traits were less under selection and thus have been lost, resulting in a “domestication bottleneck”. Meanwhile, the selection of a gene region controlling a specific target trait results in a significant reduction of genetic diversity within that selected

region and also its adjacent regions, resulting in “selective eradication”. The above scenarios result in the relatively narrow genetic diversity in our current breeding population, leading to the lack of breakthrough crop varieties with a synergistic improvement of yield, resistance and nutritional quality.

(2) Current study on *de novo* domestication

Without any underlying biological mechanisms understood, domestication and early stage of breeding were basically done empirically at that time. The recent study of domestication population genetics, especially the rise of the emerging pan-genome sequencing, thoroughly furthers our understanding of the genetic mechanism for crop domestication. Different crops have undergone long-term domestication processes for hundreds or even thousands of years, nevertheless, analysis of more than 200 crops for a set of domestication traits showed that 84% of the crops had only two to five major traits as the main domestication traits. Results of domestication genetics analysis, as exemplified by maize, confirmed that crop domestication is often controlled by a few key genes. Through the in-depth understanding of the genetic basis of crop domestication, combined with the rapidly developing genome editing technology, the era for *de novo* domestication of wild crop relatives or semi-domesticated crops is emerging. In 2008, Research groups from China and Brazil simultaneously reported the *de novo* domestication of wild tomatoes, which maintained the excellent salinity tolerance and disease resistance from wild tomatoes but also achieved new tomato crop showing excellent plant architecture, synergistically improved yield and quality. Shortly after that, scientists in the USA also successfully re-domesticated the semi-domesticated *Physalis pruinosa*, illustrating rapid improvements in yield and overall agronomic traits. A team of Chinese scientists reported the *de novo* domestication of allotetraploid wild rice in 2021, shedding a fresh insight into a novel breeding strategy for the new generation of rice crops with high yields and strong environmental adaptability.

(3) Future research trends and innovation directions.

To further explore wild germplasm resources and expand the application of *de novo* domestication, the technical potential of crop *de novo* domestication needs to be further enhanced in the following directions: ① deepening the analysis of the genetic mechanism of domestication of major crops, mining the interspecifically conserved or species-specific genes

responsible for key domestication traits, providing the genetic and genomic basis for *de novo* domestication; ② collection and genotypic identification of wild germplasm resources, screening wild species or semi-domesticated species with superior agronomic traits, providing germplasm basis for *de novo* domestication; ③ establishment and continuous optimization of efficient genetic transformation system in wild species, breaking the speed-limiting steps that wild species are normally difficult to transform, providing technical prerequisites for *de novo* domestication; ④ establishment and continuous optimization of efficient gene editing system in wild species, achieving precisely modulated gene knockout, single-base editing, prime editing, expression activation or repression editing in wild species; ⑤ high-throughput phenotype identification on domestication traits, achieving

precise and efficient screening of superior traits in large-scale transformation experiments.

In the study of “*de novo* domestication of crops and development and utilization of wild germplasm resources”, the top three countries in terms of the publication of core papers (Table 1.2.1) are China (51.35%), the USA (37.84%), and Germany (13.51%). The citation frequency of these core papers in this research field is distributed from 12.00 to 127.00, of which the citation frequency of Israel and Saudi Arabia exceeds 100. In terms of the distribution of research institutions (Table 1.2.2), Chinese Academy of Sciences (CAS), Chinese Academy of Agricultural Sciences (CAAS), and Huazhong Agricultural University (HZAU) have produced many core papers and cited many times. In terms of cooperation networks among countries (Figure 1.2.1), research cooperation

Table 1.2.1 Countries with the greatest output of core papers on “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	38	51.35	1 189	31.29	2019.8
2	USA	28	37.84	1 486	53.07	2019.2
3	Germany	10	13.51	633	63.30	2019.5
4	Australia	9	12.16	844	93.78	2019.0
5	UK	7	9.46	456	65.14	2019.1
6	France	6	8.11	197	32.83	2018.8
7	Japan	6	8.11	72	12.00	2020.3
8	Brazil	5	6.76	332	66.40	2019.2
9	Israel	3	4.05	381	127.00	2019.0
10	Saudi	3	4.05	309	103.00	2020.3

Table 1.2.2 Institutions with the greatest output of core papers on “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	13	17.57	779	59.92	2019.8
2	Chinese Academy of Agricultural Sciences	8	10.81	197	24.62	2020.8
3	Huazhong Agricultural University	7	9.46	181	25.86	2020.0
4	U.S. Department of Agriculture-Agricultural Research Service	4	5.41	359	89.75	2019.0
5	Zhejiang University	4	5.41	336	84.00	2019.8
6	University of Minnesota System	4	5.41	329	82.25	2018.2
7	University of Sao Paulo	4	5.41	326	81.50	2019.2
8	Federal University of Vicosa	3	4.05	300	100.00	2020.0
9	University of Arizona	3	4.05	198	66.00	2019.7
10	University of Toulouse	3	4.05	143	47.67	2019.7

among countries is more common, and cooperation among China, the USA and Germany is relatively closer. The output is mainly in the cooperation network among agencies (Figure 1.2.2), and there are certain cooperation relations among these agencies. The main output countries of the cited core papers are China, the USA, and Australia, with China accounting for more than 1/3 and the USA accounting for more than 20% (Table 1.2.3). In terms of the main output institutions of the cited core papers (Table 1.2.4), CAAS, CAS, and the Agricultural Research Service of U.S. Department of Agriculture (USDA ARS) ranked among the top three in the number of citing papers. Figure 1.2.3 shows the roadmap of the engineering research front of “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”.

1.2.2 Immunosuppression and escape mechanisms of important animal pathogens

China is a major breeding country and a major consumer of animal-sourced food in the world. Live pigs in China reach an annual output of approximately 700 million heads and account for 50% of the world's total, and China has approximately 14 billion poultry per year. The output of meat and poultry in China ranks first in the world, and the total output value of national animal husbandry exceeds 3.2 trillion. National animal husbandry accounts for nearly 30% of the total agricultural output value and drives the output value of upstream and downstream related industries up to more than 3 trillion RMB. However, the production level of animal husbandry in China is far below the world average level, and the main bottleneck restricting its development is the



Figure 1.2.1 Cooperation network among major countries in the engineering research front of “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

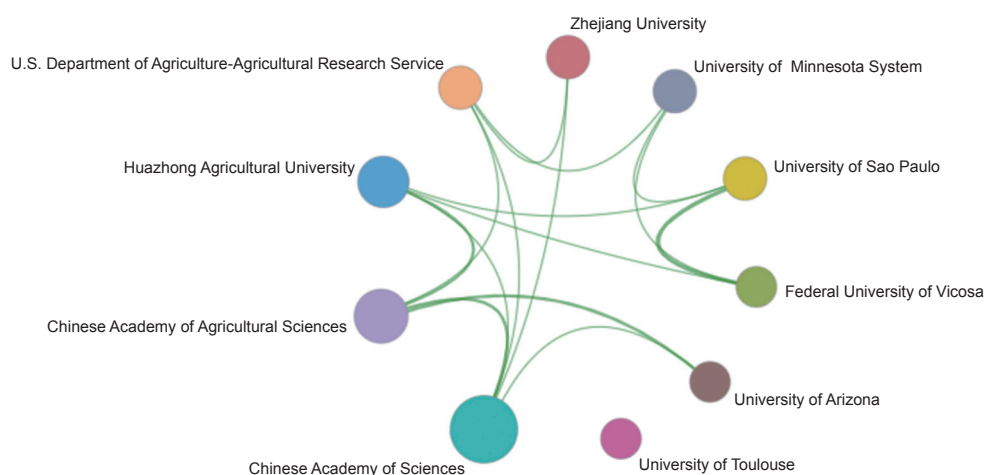


Figure 1.2.2 Cooperation network among major institutions in the engineering research front of “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

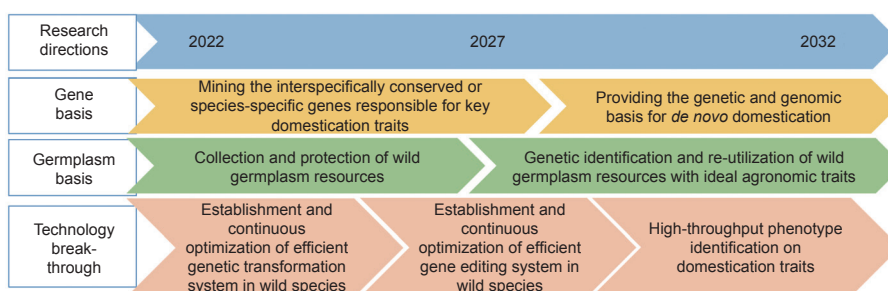


Figure 1.2.3 Roadmap of the engineering research front of “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

Table 1.2.3 Countries with the greatest output of citing papers on “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	863	35.81	2020.4
2	USA	499	20.71	2020.2
3	Australia	164	6.80	2020.2
4	India	160	6.64	2020.2
5	Germany	159	6.60	2020.3
6	UK	142	5.89	2020.1
7	France	119	4.94	2020.0
8	Italy	92	3.82	2020.3
9	Japan	81	3.36	2020.1
10	Spain	66	2.74	2020.2

Table 1.2.4 Institutions with the greatest output of citing papers on “*de novo* domestication of crops and exploitation and utilization of wild germplasm resources”

No.	Institutions	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Agricultural Sciences	207	23.44	2020.5
2	Chinese Academy of Sciences	129	14.61	2020.3
3	U.S. Department of Agriculture-Agricultural Research Service	91	10.31	2020.2
4	Huazhong Agricultural University	83	9.40	2020.6
5	Nanjing Agricultural University	68	7.70	2020.4
6	Zhengzhou University	67	7.59	2020.7
7	China Agricultural University	55	6.23	2020.6
8	Zhejiang University	55	6.23	2020.7
9	University of Western Australia	45	5.10	2020.2
10	The University of Queensland	43	4.87	2019.9

problem of infectious diseases. The continuous occurrence of animal diseases has caused huge economic losses to our country's animal husbandry and seriously affected the output and quality of animal products. For example, in African swine fever (ASF) and peste-des-petits-ruminants, ASF caused devastating damage in 2019, with the number of live pigs falling by 60%, and in some places, it even exceeded 70%. The price of pork soared from 22–24 CNY to more than 60 CNY per kilogram. In addition, the epidemics of zoonotic diseases such as brucellosis, tuberculosis, plague, influenza, rabies, and Ebola pose serious threats to public health security. For example, COVID-19 has caused more than 6 million deaths to date. How to effectively prevent and control the occurrence and prevalence of animal diseases has always been a focus and research hotspot in the fields of veterinary medicine, medicine and biosafety.

However, the key reason for the failure in the prevention and control of animal diseases and zoonotic diseases is the immunosuppression and immune escape of pathogens. The body's defense against pathogenic infections relies primarily on the body's immune system. Immune evasion can lead to pathogens being able to effectively break through the body's immune barrier or vaccine-induced immune responses to establish a productive infection. Immunosuppression can promote pathogenic infection or the establishment of persistent infection. For example, influenza viruses and coronaviruses have the ability to establish infection through a variety of strategies during long-term evolution to escape host immunity and the protection of existing vaccines by constantly producing new mutants. Therefore, revealing the mechanism by which pathogens inhibit the body's immune function and evade host immunity is the premise of effective prevention and control of these important animal pathogens, and it is also a hotspot and challenge in the current scientific research field.

The host immune system, including innate and acquired immunity, is a key force against pathogenic infection. The host initially induces an innate immune response after surveilling pathogen infection through pattern recognition receptors (PRRs). The innate immune response is the first line of host defense against pathogen infection, and many pathogens have acquired the ability to evade or actively suppress host innate immunity during long-term coevolution with their hosts. Pattern recognition receptors (PRRs) are key components of anti-infection immunity that detect

conserved molecular features of viral pathogens and initiate innate immune responses. Therefore, many pathogens have the capacity of immune evasion or suppression, and their molecular mechanisms include: ① sequestering or modifying viral RNA or DNA nucleic acid ligands from the recognition and activation of intracellular PRRs. For example, the nonstructural protein 1 (NS1) of influenza virus and the E3 protein of vaccinia virus prevent viruses from being recognized by the RNA sensor RIG-I by binding to viral dsRNA; ② destabilize or degrade PRRs by manipulating the posttranslational modification of PRR protein. For example, papain-like protease (PLP) of coronavirus and lead protease (Lpro) of foot-and-mouth disease virus (FMDV) can cleave or degrade RLR and MAVS, key proteins in innate immunity, to escape the innate immune response. In addition, many viruses suppress the innate immune response by targeting some of the key downstream molecules shared by the innate immune response, such as TBK1, IRF3, IRF7, and NF- κ B, or by blocking IFN α / β receptor signaling.

In addition to the ability to escape or suppress innate immune responses, some important pathogens escape or suppress acquired immune responses through various mechanisms during long-term evolution. After the pathogen breaks through the body's innate immune barrier to establish infection, the host suppresses and eliminates the pathogen primarily through adaptive immunity. The body's adaptive immune system mainly functions through antibody-mediated (especially neutralizing antibodies) humoral immunity and cytotoxic T-cell-mediated (CTL) cellular immunity. However, pathogens can evade neutralizing antibodies and CTLs by generating new mutant strains through genetic mutation and recombination. Viral genomes, especially RNA viruses, constantly and continually mutate to adapt to host systems under immune selection pressure. For example, influenza viruses and coronaviruses can evade the recognition of T cells and virus-neutralizing antibodies through antigenic drift, weakening the body's acquired immune protection, and some of these mutant strains can even also acquire stronger transmission ability or virulence than the original strain. For example, the transmission ability of the current COVID-19 Omicron variant has increased significantly compared with the original Wuhan strain, the Omicron BA.4/5 R0 has increased from 3.3 to 18.6 of the original Wuhan strain, and the protection of the existing vaccine is greatly decreased due to the spike protein mutation. This is also one of the main

reasons for the repeated COVID-19 epidemic.

In addition to passively evading the body's immunity, some important pathogens can actively attack the host's immune system through a variety of mechanisms to suppress the host's immune response and promote infection. Many pathogens themselves infect important immune organs of the body. For example, porcine reproductive and respiratory syndrome virus (PRRSV) and porcine circovirus can infect the thymus and bone marrow, which are important immune organs responsible for the development of T cells and B cells, respectively, resulting in damage to immune organ function and the suppression of the body's adaptive immunity, thereby establishing persistent infection. In addition, PRRSV and porcine pseudorabies virus can inhibit the induction of adaptive immune responses by interfering with antigen processing and presentation.

The long-term interaction between pathogens and hosts is similar to an endless evolutionary arms race. If humans want to win this arms race, they must know themselves and their enemies, continue to enhance research and invest in related fields, break through traditional models, and develop innovative ideas from the perspective of pathogens and hosts.

① The immune systems of various species are very different. It is necessary to continue to strengthen the basic research on animal and poultry immune systems to reveal some important molecules and signaling pathways that play critical roles in inducing immune responses in the body, as well as the molecular mechanisms of immune protection after infection with important pathogens. ② Construct gene deletion strains by gene editing technology to further identify the key pathogenic genes mediating immune escape or immune

suppression and then develop attenuated vaccine strains on this basis. ③ Development of broad-spectrum vaccines. The development of broad-spectrum vaccines through new technologies is the most effective and economical way to effectively prevent and control the current highly variable important pathogens. Although viruses evolve faster than their hosts, important proteins of viruses are restricted by many functions that affect viral replication, and there are some conserved sites in the pathogen. A large number of studies have confirmed the existence of broad-spectrum neutralizing antibodies and T-cell epitopes in easily mutated viruses. Broad-spectrum neutralizing antibodies and CD8+ T-cell recognition epitopes are identified by using single-cell sequencing technology and high-throughput screening technology, and broad-spectrum mRNA or DNA vaccines containing conserved antigen genes are designed and synthesized through bioinformatics and nucleic acid synthesis technology. These studies can provide important guidance for the development of broad-spectrum vaccines in the future.

Considering the distribution of papers by country, it can be seen that the main contributors of core papers on the "Immune suppression and escape mechanisms of important animal pathogens" were the USA (51%), the UK (31%), and China (18%) (Table 1.2.5). The citations per paper in this field ranged from 240 to 3 616 across the top ten countries, and the citations per paper of the 10 countries all exceeded 100, the citations per paper of the UK exceeded 200, the citations per paper of Thailand and Denmark exceeded 300. The distribution of papers by research institution shows that the number of core papers and the citations were the

Table 1.2.5 Countries with the greatest output of core papers on "immunosuppression and escape mechanisms of important animal pathogens"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	23	51.11	3 063	133.17	2020.0
2	UK	14	31.11	3 616	258.29	2020.4
3	China	8	17.78	1 156	144.50	2019.9
4	Switzerland	4	8.89	554	138.50	2021.0
5	Netherlands	4	8.89	510	127.50	2019.5
6	South Africa	3	6.67	438	146.00	2021.0
7	Thailand	2	4.44	774	387.00	2020.5
8	Denmark	2	4.44	681	340.50	2021.0
9	India	2	4.44	300	150.00	2021.0
10	Singapore	2	4.44	240	120.00	2020.5

highest for University of Oxford, University of Southampton, and University of Cambridge (Table 1.2.6). The collaboration networks among the major countries were common, with the UK and USA sharing the closest collaborative relationship (Figure 1.2.4). From the collaboration network among major institutions (Figure 1.2.5), it can be seen that collaborative relationships existed among all institutions.

The main contributors of core paper citations were USA and China (Table 1.2.7), the number of citing papers in the USA accounts for more than one third, China accounts for more than 10%, and the average citations year of core papers was also relatively recent, which is indicative of the strong developmental momentum of research in this field. From the list of the major core paper citation-contributing institutions (Table 1.2.8), it can be seen that Chinese Academy

of Sciences, University of Harvard and University of Oxford were far ahead of all other institutions, and Chinese Academy of Sciences ranked first. Figure 1.2.6 shows the roadmap of the engineering research front of “immunosuppression and escape mechanisms of important animal pathogens”.

1.2.3 Mechanism of efficient soil carbon sequestration and regulation

(1) The significance of efficient soil carbon sequestration and regulation

Soil organic matter is the core of soil health, maintains soil fertility and crop productivity, and also highly connected to the ecosystem function and the sustainability. In addition, soil is the largest carbon pool in the terrestrial ecosystem.

Table1.2.6 Institutions with the greatest output of core papers on “immunosuppression and escape mechanisms of important animal pathogens”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Oxford	8	17.78	2 202	275.25	2020.5
2	University of Southampton	5	11.11	1 493	298.60	2020.2
3	University of Cambridge	4	8.89	1 183	295.75	2020.2
4	University of Texas Austin	3	6.67	879	293.00	2020.3
5	Harvard University	3	6.67	570	190.00	2021.0
6	University of Edinburgh	2	4.44	1 101	550.50	2021.0
7	University of Glasgow	2	4.44	775	387.50	2021.0
8	Wellcome Sanger Institute	2	4.44	739	369.50	2021.0
9	Imperial College London	2	4.44	681	340.50	2021.0
10	University of Copenhagen	2	4.44	681	340.50	2021.0



Figure 1.2.4 Collaboration network among major countries in the engineering research front of “immunosuppression and escape mechanisms of important animal pathogens”

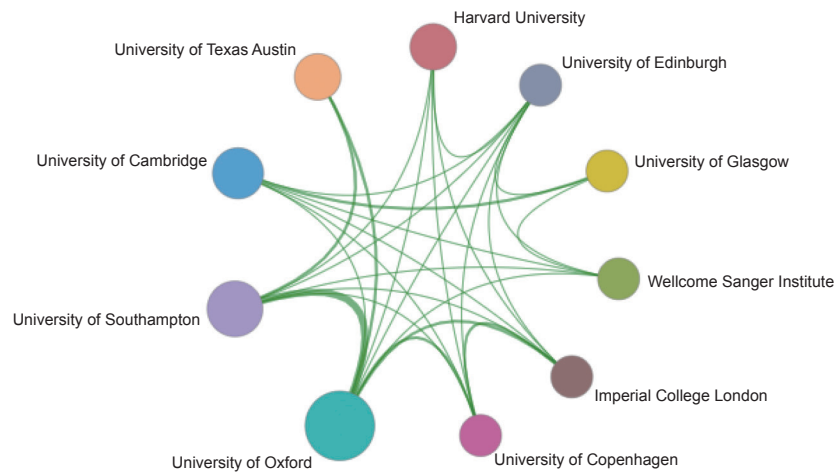


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “immunosuppression and escape mechanisms of important animal pathogens”

Table 1.2.7 Countries with the greatest output of citing papers on “immunosuppression and escape mechanisms of important animal pathogens”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	1 835	31.70	2020.7
2	China	1 050	18.14	2020.7
3	UK	555	9.59	2020.7
4	India	419	7.24	2020.7
5	Germany	404	6.98	2020.8
6	Italy	354	6.12	2020.7
7	France	283	4.89	2020.7
8	Brazil	263	4.54	2020.8
9	Australia	235	4.06	2020.7
10	Canada	218	3.77	2020.7

Table 1.2.8 Institutions with the greatest output of citing papers on “immunosuppression and escape mechanisms of important animal pathogens”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	263	22.87	2020.8
2	Harvard University	147	12.78	2020.8
3	University of Oxford	146	12.70	2020.7
4	University of Washington	100	8.70	2020.7
5	University of Cambridge	77	6.70	2020.8
6	University of Hong Kong	73	6.35	2020.6
7	Fudan University	73	6.35	2020.7
8	Imperial College London	70	6.09	2020.8
9	University of Sao Paulo	68	5.91	2020.8
10	Icahn School of Medicine at Mount Sinai	68	5.91	2020.7

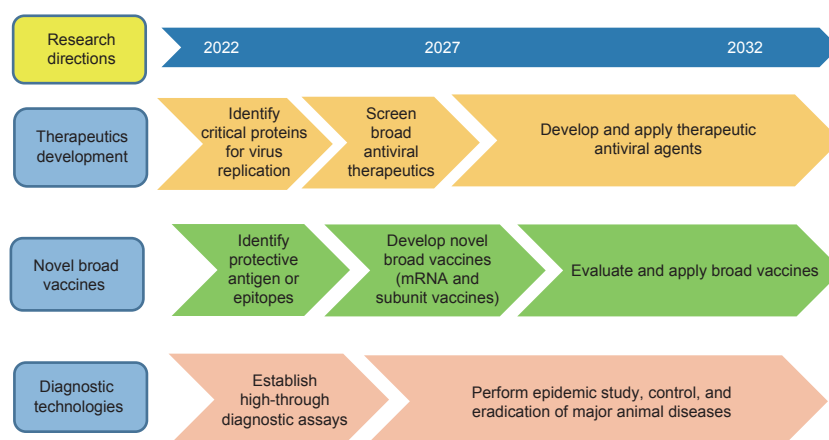


Figure 1.2.6 Roadmap of the engineering research front of “immunosuppression and escape mechanisms of important animal pathogens”

The global soil organic carbon is 1 500–2 000 Pg, equivalent to 2–3 times of the carbon in the atmosphere. Agricultural soil carbon sequestration was found to account for 25% of the potential for natural climate solutions. Therefore, promoting agricultural soil carbon sequestration is of great significance for ensuring food security, mitigating climate change and promoting agricultural green development. The core of efficient soil carbon sequestration and regulation is to understand the key processes of turnover and stability of soil organic matter, and to establish a regulatory strategy for efficient carbon sequestration and slowing down its mineralization and decomposition.

(2) Research status of efficient soil carbon sequestration and regulation

The formation and stabilization of soil organic matter is relatively complex. At present, the formation, occurrence form and stabilization mechanism of soil organic matter are still poorly understood and divergent. The humus defined by the classical humification theory is complex and highly ambiguous, and the current methods are not enough to establish a clear “white box” model for it. Based on the current study in soil organic matter and protection mechanisms in plant residue decomposition, the formation and stability of organic matter is explained as the organic matter continuum model, i.e., the transformation of plant residues into soil organic matter is a step-by-step microbial decomposition process from large plant biopolymers to small molecular compounds, so the existence of soil organic matter is a continuous process from large plant fragments to gradually decomposed into small molecular compounds.

In this model, the volume of exogenous organic materials decreases continuously during the process of microorganism utilization, the thermodynamic gradient gradually decreases, and the polar components, soluble components and ionized components increase accordingly. Moreover, as the molecular complexity gradually decreases, organic compounds are more likely to bind to the mineral surface or enter the interior of the agglomerates to increase their stability. However, there are also studies showed that although soil microorganisms can completely or partially decompose humus, new humus will be produced at the same time to renew organic matter. In a word, both the traditional humification theory and the organic matter continuum model admit that the animal and plant fragments will be broken up by physicochemical action after input into the soil, and then degraded into relatively smaller components by extracellular enzymes, etc. sequestered in the soil.

The process of organic matter formation and stabilization is closely related to the interaction with surrounded soil matrix. Soil aggregates are the main place for the occurrence of soil organic matter, which protect the organic matter through the physical coating, to prevent the decomposition of microorganisms. Therefore, aggregate protective capacity is the physical basis for realization of soil carbon sequestration potential. The chemical protection effect of soil on organic matter mainly refers to the interaction between soil inorganic molecules and organic molecules, which makes organic matter difficult to be utilized by microorganisms. Previous studies have focused on the decomposition of organic carbon by microorganisms. However, more and more studies have

found that microorganisms contribute available soil carbon sources to soil organic matter in the form of metabolites through assimilation, which account for more than 50% of organic carbon in agricultural soils. In addition, it indirectly affects soil organic matter stability through the turnover of aggregates. Therefore, current research believes that the stability of organic matter is the result of the interaction and interdependence of the physical protection of aggregates, the binding of soil minerals, and the metabolic process of microorganisms.

Reasonable management could regulate soil carbon sequestration by affecting the balance between carbon input and output. The input of exogenous carbon is an important source of soil organic matter formation. The metabolic activities of soil microorganisms can convert plant residues into soil organic matter. For example, compared with chemical fertilizers, long-term application of organic fertilizers can significantly increase soil carbon sequestration rates, while improving both organic carbon content and quality. Insufficient supply of organic materials and frequent soil turnover in traditional farming lead to the destruction of soil aggregate structure and the accelerated loss of organic carbon, which limits the growth and metabolism of microorganisms, as well as the accumulation of soil organic matter. In addition, diversified planting and crop rotation changed the quantity and quality of crop residues, significantly affect the structure and activity of soil microbial community, and thus increase the content of soil organic matter.

(3) Future research directions and innovations

Soil is an open and complex system in which multiple substances coexist, multiple processes occur simultaneously, and multiple factors influence together. At present, the mechanism of efficient soil carbon sequestration is still unclear, and it is difficult to improve soil organic matter. Therefore,

in-depth research on carbon sequestration and regulation mechanism needs to be strengthened in the future. For example, accurately distinguishing carbon sources of different organic components, exploring the microbial action mechanism of plant residues to soil organic matter, accelerating research on organic matter stability based on multi-factor coordinated regulation, exploring soil carbon balance mechanism and plant residue input thresholds, etc. Innovate new carbon-based materials with high efficiency of carbon sequestration and nutrient use, improve soil carbon sequestration efficiency, integrate and innovate key technologies for soil carbon sequestration, land conservation and productivity improvement, and promote the application of large-scale agricultural soil carbon sequestration are becoming the frontier in applied research direction in this field (Figure 1.2.7).

In the front of “efficient soil carbon sequestration and regulation mechanism”, the top three countries with the most published core papers are China, the USA, and Germany (Table 1.2.9). The citations per paper of core papers in this front ranges from 94.80 to 297.75. Except for Saudi Arabia, the citation frequency of papers from other countries exceeds 100. In terms of the distribution of research institutions (Table 1.2.10), Lanzhou University, ETH Zurich, University of Sussex, and Tsinghua University produced more core papers and more citations. Countries with the greatest output of citing papers are China, the USA, and Australia (Table 1.2.11). In terms of the main institutions producing citing core papers (Table 1.2.12), University of Chinese Academy of Sciences, Hunan University, and Tsinghua University ranked the top three in terms of the number of citing papers. The cooperation among countries is more common and complex (Figure 1.2.8) where China, the USA, Germany, and the UK cooperate more closely. In terms of the cooperation network among major institutions (Figure 1.2.9), there are certain cooperation relationships

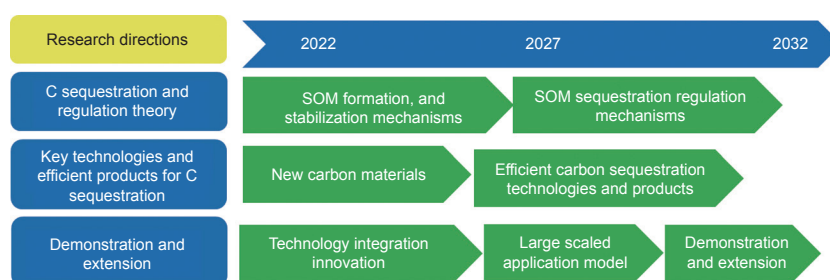


Figure 1.2.7 Roadmap of the engineering research front of “mechanism of efficient soil carbon sequestration and regulation”

Table 1.2.9 Countries with the greatest output of core papers on “mechanism of efficient soil carbon sequestration and regulation”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	51	61.45	9 480	185.88	2019.1
2	USA	32	38.55	5 545	173.28	2018.5
3	Germany	15	18.07	2 954	196.93	2018.3
4	UK	13	15.66	2 702	207.85	2018.5
5	Australia	10	12.05	1 821	182.10	2018.5
6	South Korea	9	10.84	1 267	140.78	2018.6
7	Austrian	5	6.02	1 061	212.20	2018.0
8	Saudi Arabia	5	6.02	474	94.80	2019.6
9	Switzerland	4	4.82	1 191	297.75	2018.5
10	France	4	4.82	1 098	274.50	2019.5

Table 1.2.10 Institutions with the greatest output of core papers on “mechanism of efficient soil carbon sequestration and regulation”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Hunan University	5	6.02	782	156.40	2018.0
2	Korea University	4	4.82	605	151.25	2018.5
3	Chinese Academy of Sciences	4	4.82	480	120.00	2019.5
4	King Saud University	4	4.82	257	64.25	2019.5
5	Lanzhou University	3	3.61	1 227	409.00	2018.3
6	ETH Zurich	3	3.61	1 079	359.67	2018.3
7	University of Sussex	3	3.61	971	323.67	2019.0
8	Tsinghua University	3	3.61	852	284.00	2018.7
9	University of Massachusetts	3	3.61	784	261.33	2016.7
10	Monash University	3	3.61	763	254.33	2019.7

Table 1.2.11 Countries with the greatest output of citing papers on “mechanism of efficient soil carbon sequestration and regulation”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 492	43.90	2019.3
2	USA	522	15.36	2019.1
3	Australia	240	7.06	2019.3
4	UK	236	6.94	2019.4
5	Germany	225	6.62	2019.1
6	South Korea	148	4.35	2019.4
7	Canada	123	3.62	2019.4
8	India	116	3.41	2019.8
9	Spain	115	3.38	2019.1
10	Netherlands	96	2.82	2019.3

Table 1.2.12 Institutions with the greatest output of citing papers on “mechanism of efficient soil carbon sequestration and regulation”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	University of Chinese Academy of Sciences	246	26.59	2019.0
2	Hunan University	160	17.30	2019.0
3	Tsinghua University	123	13.30	2019.3
4	Korea University	62	6.70	2019.5
5	The Hong Kong Polytechnic University	58	6.27	2019.5
6	Lanzhou University	48	5.19	2017.9
7	ETH Zurich	47	5.08	2018.9
8	Sejong University, Korea	47	5.08	2019.4
9	Zhejiang University	47	5.08	2019.1
10	Harbin Institute of Technology	44	4.76	2019.2

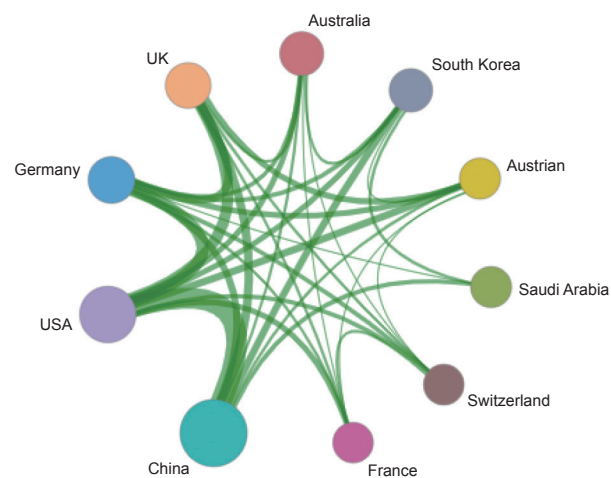


Figure 1.2.8 Collaboration network among major countries in the engineering research front of “mechanism of efficient soil carbon sequestration and regulation”

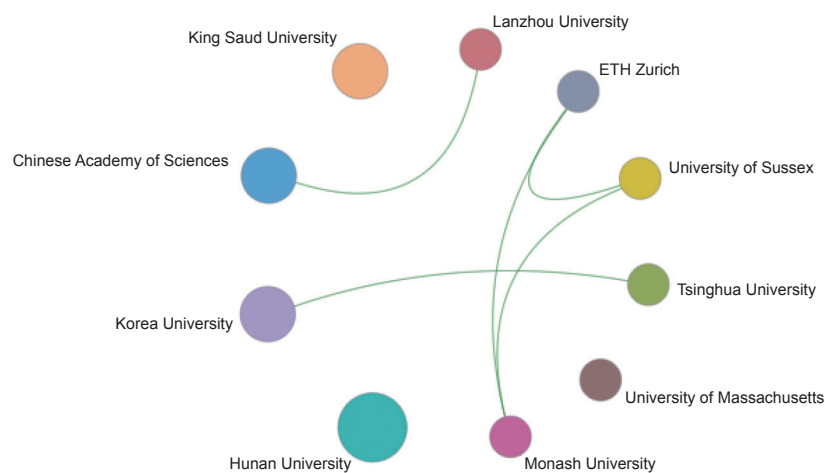


Figure 1.2.9 Collaboration network among major institutions in the engineering research front of “mechanism of efficient soil carbon sequestration and regulation”

between different institutions in the same country and among institutions in different countries. For example, Lanzhou University and Chinese Academy of Sciences, Tsinghua University and Korea University, ETH Zurich, University of Sussex, and Monash University have close cooperations.

2 Engineering development fronts

2.1 Trends in Top 11 engineering development fronts

The Top 11 engineering research fronts in the agricultural field mainly involve biological breeding, smart agriculture, green agriculture, and other directions (Table 2.1.1). Among them, the research fronts related to biological breeding include animal precision gene editing and breeding technology, advanced seed production technology, genome-wide selection in forest tree breeding, and RNAi-based pest control technology. The research fronts related to intelligent agriculture include agricultural autonomous robot, unmanned intelligent cultivation technology for crops, aquaculture technology of ecological intelligent pond. The research fronts related to green agriculture include catalytic degradation processes for organic pollutants, feed antibiotic substitution technology and products. At the same time, the monitoring and early warning for emerging and reemerging animal infectious diseases are also the hot research objects of scientific researchers. The average number of citations of the

advanced seed production technology in the Top 11 research front is as high as 67.69, which indicates that the advanced seed production technology has received extensive attention from scientific researchers in recent years.

The disclosures of core patents involved in various research fronts from 2016 to 2020 are shown in Table 2.1.2. Among them, the number of core patents related to animal precision gene editing and breeding technology is the largest, with 829 in 2021, far higher than other research fronts. The core patents of the genome-wide selection in forest tree breeding are the least, only appeared in 2017 and 2021.

(1) Monitoring and early warning for emerging and reemerging animal infectious diseases

“Emerging and reemerging animal infectious diseases” is defined as a new infection resulting from the evolution or change of an existing pathogen resulting in a change of host range, vector, pathogenicity, or strain; or the occurrence of a previously unrecognized infection or disease. And the re-emerging disease is considered as an already existing disease that either shifts its geographical region or expands its host range or significantly increases its prevalence as altered drug resistance or weakened control measures. In recent years, more than 30 new emerged animal diseases, such as African swine fever, peste des petits ruminants, and bovine lumpy skin disease have been introduced into our country. In particular, African swine fever has swept across the whole country and severely damaged the pork industry. At the same time, many infectious diseases including African horse fever,

Table 2.1.1 Top 11 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Monitoring and early warning for emerging and reemerging animal infectious diseases	454	1 186	2.61	2018.7
2	Animal precise gene editing and breeding technology	4 546	10 294	2.26	2018.2
3	Advanced seed production technology	88	5 957	67.69	2016.7
4	Application of gene editing technology in horticultural crops	50	121	2.42	2019.3
5	Genome-wide selection in forest tree breeding	2	7	3.50	2019.0
6	RNAi-based pest control technology	94	913	9.71	2018.4
7	Agricultural autonomous robot	259	861	3.32	2019.3
8	Catalytic degradation processes for organic pollutants	1 000	2 039	2.04	2018.4
9	Feed antibiotic substitution technology and products	108	140	1.30	2018.4
10	Unmanned intelligent cultivation technology for crops	261	720	2.76	2018.9
11	Aquaculture technology of ecological intelligent pond	103	182	1.77	2019.04

Table 2.1.2 Annual number of core patents published for the Top 11 engineering development fronts in agriculture

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Monitoring and early warning for emerging and reemerging animal infectious diseases	78	62	62	76	68	108
2	Animal precise gene editing and breeding technology	433	654	697	814	685	829
3	Advanced seed production technology	4	9	10	14	9	15
4	Application of gene editing technology in horticultural crops	1	4	11	9	13	12
5	Genome-wide selection in forest tree breeding	0	1	0	0	0	1
6	RNAi-based pest control technology	10	20	19	22	12	11
7	Agricultural autonomous robot	9	28	48	43	56	63
8	Catalytic degradation processes for organic pollutants	68	142	240	191	211	95
9	Feed antibiotic substitution technology and products	16	10	13	11	22	24
10	Unmanned intelligent cultivation technology for crops	22	28	36	47	48	72
11	Aquaculture technology of ecological intelligent pond	3	16	25	8	13	35

Bovine Spongiform Encephalopathy (mad cow disease), etc. are often outbreak and spread in countries and regions along the “Belt and Road”, increasing the risk of cross-border introduction. These economically important animal diseases do not only seriously threaten the safety of meat production, economic safety, and ecological safety, but some of them are also zoonosis. The International Food and Agriculture Organization (FAO) has stated that “the strong international and national animal health control systems are key to preventing animal disease, ensuring food safety and nutrition, and protecting farmers’ interests”. Therefore, monitoring and early warning of emerging and reemerging animal infectious diseases are crucial to safeguarding national biosecurity and preventing and controlling disease outbreaks and epidemics. The core technical requirements of this field mainly include: ① innovation and integration for rapid, accurate, convenient, high-throughput, and differential diagnosis detection technology; ② clarifying the basic characteristics of disease etiology, transmission rules, distribution characteristics, molecular evolution pathway, and co-evolution with the host, disease occurrence and spread models based on pathogen molecular ecology, and prediction indicators of proposing corresponding disease outbreak; ③ establish and improve the information databases of emerging and reemerging animal infectious diseases, early warning, and reporting systems, and improve the accurate assessment of incidence probability and potential hazard. These relevant technological breakthroughs will provide technical support and solutions for the prevention and control of emerging and reemerging animal infectious

diseases and early warning of biosecurity.

(2) Animal precision gene editing and breeding technology

Animal breeding technology has experienced a leap-forward development from the initial phenotypic value breeding technology to the modern genome editing breeding technology. The traditional method of hybrid improvement method is costly, time-consuming and complicated, and defective genes may also be introduced due to gene linkage, while gene editing technology can precisely modify the target gene, through modifying key functional genes and regulatory sequences related to important animal traits, new animal breeds (lines) with characteristic phenotypes can be obtained in one generation, thereby improving the efficiency of animal breeding. Since its introduction, gene editing technology has developed and updated three generations: Zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs) and Clustered regularly interspaced short palindromic repeats-Cas9 (CRISPR-Cas9). Gene editing technology has achieved a major breakthrough in technology from the random targeting and inactivation of the target gene to the accurate replacement of a single base of the gene. In recent years, gene editing technology has become an important method of animal breeding, and has been fully developed and applied in the field of animal breeding. A batch of new materials and new lines with high-yield, high-quality, high-reproduction and disease-resistant breeding have been precisely created through gene editing technology, such as gene edited swines for resistance to porcine reproductive and respiratory syndrome, gene edited beef cattle with myostatin

knockout, and tuberculosis-resistant dairy cows. With the continuous progress of multi-omics sequencing technology, various phenotype and genotype databases are constantly enriched, important functional genes and regulatory sequences related to various traits are continuously mined, and the efficiency, accuracy and safety of gene editing technology are constantly improving. Animal precision gene editing and breeding technology will gradually develop in the direction of engineering and large-scale, and will be widely used in the field of animal breeding in the future, providing important technical support for the cultivation of new animal species.

(3) Advanced seed production technology

The utilization of hybrid vigor in maize, rice and other crop breeding since the middle of the last century was one of the major revolutions in the history of agricultural production. The production of hybrid seeds can be achieved by using male sterile lines or by emasculation of the maternal parent. However, male sterility may be highly affected by environmental factors, and incomplete emasculation is almost inevitable. Consequently, the self-pollination of the maternal parent lines, which would generate a much lower yield than the hybrids, could be adulterated in the hybrids seeds and this has long been the priority issue to be addressed in seed production. Additionally, traditional sterile seed production technology relies on time-consuming introgression for multiple generations and suitable restorer lines. On the other hand, emasculation requires intense labor and experienced skills. Therefore the establishment of a new generation of intelligent seed production technology for hybrids can significantly reduce seed production costs, but also increase the purity and quality of the hybrid seeds as well as the potential yield. Recently, a set of high throughput and high-precision technologies of hybrid seed have been initially established, combining the usage of nuclear sterile lines and selective markers including seed size, transgenic fluorescence, and the pigment of seed coat or seedling. This emerging breakthrough opens more improvement and optimized rooms for integrating multiple sterility genes and different selecting markers, which could be a very promising direction for hybrid seed production technology in China.

(4) Application of gene editing technology in horticultural crops

Gene editing is a technology that changes the original

gene sequence by knocking out several base pairs or a DNA sequence. The three main tool enzymes used are ZFNs, TALENs, and CRISPR-Cas9. Among them, due to the advantages of high editing efficiency, simple operation, and low cost, CRISPR-Cas9 gene editing has become a hot tool for gene editing in recent years and has been widely used in plants. Gene editing technology has been able to achieve precise replacement of a single base of a gene, while it can implement random targeting and inactivation of target genes in the startup phase. A major breakthrough has been achieved in the technology and it has made important contributions to gene function research and crop trait improvement. In 2021, a gamma-aminobutyric acid-rich tomato modified with CRISPR technology has been marketed in Japan. Gene editing technology has been widely used in crops and model plants. Compared with traditional hybrid breeding, gene editing technology has great advantages in crop genetic improvement. Gene editing system has been established in tomato and other horticultural crops. However, many other horticultural crops do not yet have a good gene editing system. It is necessary to establish an efficient gene editing system in different horticultural crops so as to promote the gene editing technology in practice.

(5) Genome-wide selection in forest tree breeding

Genome-wide selection (GS) in forest tree breeding belongs to the discipline of forestry science and is an emerging frontier technology of forest tree breeding. Most of the important traits of forest trees are complex quantitative traits and high genetic heterozygosity. Conventional breeding techniques are difficult to efficiently and rapidly cultivate improved tree varieties. Molecular marker-assisted selection (MAS) is difficult to capture minor-effective loci, and the resolution of genetic mapping is low. The results of MAS are difficult to verify each other and cannot effectively promote the process of forest tree genetic improvement. GS refers to a breeding method that uses high-density genome-wide marker genetic markers to predict complex quantitative traits, which can greatly improve the capture efficiency of polygenic traits compared to MAS. The main technical procedures include: ① establishing a training population, phenotyping and genotyping of all individuals, estimating the effect value of SNPs by a suitable statistical model, and establishing a GS prediction model between phenotype and genotype; ② based on the individual genotype data in the candidate population, calculating the genome estimated breeding value (GEBV) of each individual

using the GS prediction model; ③ screening and selecting individuals at the seedling stage according to the GEBV ranking, inclusion of the phenotypic and genotypic data of selective individuals in the training population to continuously update and optimize the GS model, enhancing the prediction accuracy and efficacy; ④ promoting the integration of forest tree GS with emerging technologies such as early flowering, somatic embryogenesis, gene editing and other technologies, and truly realizing the use of genomic information to guide breeding practices. Genome-wide selection in forest tree breeding is a forest tree breeding strategy with great potential, which can carry out the selection of excellent genotypes at the seedling or even seed stage of forest trees, enhance genetic gain, speed up the breeding process, and promote precise and efficient forest tree breeding.

(6) RNAi-based pest control technology

RNA interference (RNAi) is a great discovery and has won the Nobel Prize in Physiology or Medicine in 2006. RNAi technology has shown great application prospects in many fields, such as medicine and agriculture. By 2022, nearly 20 new RNAi-based pharmaceutical products have entered the clinical research stage. In the field of agriculture, RNAi could be used to silence key genes in the growth, development or important processes of pests, block the normal growth and reproduction, cause death of pests, thereby reducing the damages from pests. RNAi-based pest control technology is called “the third revolution in the pesticide history”. It is an environment-friendly pest management method because of the high target specificity, non-toxicity, and non-residue. In 2017, the U.S. Environmental Protection Agency (EPA) registered the first commercial planting for RNAi-biased genetically modified maize (MON87411, Bayer). This product has obtained the Agricultural GMOs Safety Certificate (2020) from the Ministry of Agriculture and Rural Affairs in China. In addition, a variety of RNAi-based biopesticides have been submitted to EPA such as BioDirect (Bayer), Ledprona GS2 (GreenLight Biosciences), etc. RNAi-based pest control technology has been studied early from last century but the commercial application process is somehow slow, lacking the relevant technical standards, laws and regulations. Besides, several key core issues need to be solved urgently for the commercial R&D process: ① identify the target genes; ② develop industrial synthesis methods for dsRNA; ③ screen the delivery or sustained-release carriers. China need to solve the above problems as soon as possible

so as to promote the commercialization of RNAi-based pest control technology in China, make China highest-ranking in the research on RNAi technology, and seize the international pest control marketplace in the future.

(7) Agricultural autonomous robot

Agricultural autonomous robot is an intelligent agricultural machinery equipment with perception, decision-making, control and execution functions. As the major branch of robotics, Agricultural Autonomous Robot is a cross-integration field of agricultural machinery, artificial intelligence, robot technology and information engineering, and has become an important trend of modern agriculture development. Currently, the agricultural comprehensive mechanization rate in china has exceeded 70%. Agricultural mechanization liberates labor force, improves labor productivity and resource utilization, and promotes farmers' income. However, with the acceleration of urbanization process, a large number of rural labors entering cities. Rural areas faced the problem of seasonal and structural shortage of farm labor. Thus, Agricultural autonomous robot will be an important support to solve the problem of “who will farm land and how to farm”. In view of the unstructured and complex agricultural scenes, agricultural autonomous operating robots focus on breaking through the following key theories and technologies: ① the accurate sensing mechanism and sensing technology of information for operating robots, operating environments and operating objects; ② the scene cognition method based on multi-source perception of heterogeneous information, and the autonomous decision-making, planning and control technology based on job flow and machine learning; ③ design and accurate and efficient operation technology of operating device, terminal actuator and manipulator integrated with advanced agronomics; ④ chassis structure design and line control technology in all terrain, multi-occlusion and dynamic agricultural scenes, and map construction, autonomous planning and obstacle avoidance navigation technology based on multi-sensor fusion; ⑤ key technologies of robot group real-time communication, group autonomous cooperation and man-machine integration. Agricultural autonomous robot represents the most advanced agricultural productivity, which can completely liberate agricultural labor force, greatly improve agricultural productivity, resource utilization and output rate, and realize agricultural intelligent production.

(8) Catalytic degradation processes for organic pollutants

Organic pollutants are a group of compounds with diverse composition and structure, which have environmental mobility, bioaccumulation and ecotoxicity. The occurrence of organic pollutants has become an emerging concern in the field of agricultural environment, which affects the quality of farmland soil, and brings challenges to urban and rural domestic wastewater treatment as well as resource utilization of agricultural organic waste. The development of cost-effective and efficient catalytic degradation processes for organic pollutants is a hotspot in scientific research and application frontier. At present, popular catalytic degradation processes for organic pollutants mainly include photocatalytic degradation, persulfate-based heterogeneous catalytic degradation, catalytic ozonation, and electrocatalytic degradation. Although catalytic degradation processes could achieve high removal efficiency for organic pollutants, the interference of coexisting substances limits specific removal of target organic pollutants in practical applications. In addition, the generation of a series of intermediate products during the catalytic degradation of organic pollutants not only affect the catalytic degradation efficiency, but also may pose a threat to the ecosystem. Therefore, improving the mineralization efficiency of organic pollutants, revealing their catalytic degradation pathways and mechanisms, and developing energy-saving and efficient catalytic degradation new technology and related equipment are the key and difficult points that need to be broken through in technical applications.

(9) Feed antibiotic substitution technology and products

The massive and long-term use of antibiotics has not only caused serious ecological environment pollution, but also made some pathogenic microorganisms produce drug resistance, resulting in the emergence of “super bacteria”, which endangers the health of human beings and animals. China has officially banned the use of feed antibiotics since July 1, 2020. From the perspective of the history of “prohibition and resistance” in Europe, after the comprehensive “prohibition and resistance” of feed, the livestock and poultry incidence rate and mortality will increase, and the breeding cost will increase. Developing high-efficiency, environmental friendly, and non-toxic feed antibiotic substitutes to improve the autoimmune disease resistance of livestock and poultry is conducive to promoting the healthy development of China's

aquaculture industry. The alternatives of feed antibiotics that have been studied more include Acidifiers, antimicrobial peptides and plant essential oils. Probiotics, prebiotics, antimicrobial peptides, plant extracts, Chinese herbal medicines, and enzyme preparations have been proved to have good effects on regulating the intestinal micro ecology of livestock and poultry and improving the intestinal health, and have broad prospects in the development of non-antibiotic breeding. Synthetic biology plays an important role in the creation of these products. At present, the third generation biotechnology with synthetic biology as the core has entered a new stage of rapid technological change and vigorous industrial development. The organization for economic cooperation and development (OECD) predicts that by 2030, 35% of chemicals and other industrial products will come from biological manufacturing, which has laid the core position of biological manufacturing industry as a global strategic emerging industry. Under the guidance of synthetic biology, the development of agricultural biological manufacturing technology based on microorganisms, the design of efficient synthetic routes and artificial organisms for feed bioactive molecules, the breakthrough of the limitations of natural biological synthesis, the reshaping of biological feed production mode, the creation of new feed resources and feed additives and the realization of industrialization can effectively solve the problems of shortage of feed raw materials, excessive addition of antibiotics and safety of animal husbandry products in China, It will produce extensive social and economic benefits.

(10) Unmanned intelligent cultivation technology for crops

With the rapid development of modern science and technology as well as the upgrading transformation of agricultural management mode, the unmanned and intelligent crop production will become the main research area of crop production in the future. Countries around the world once relied on investment in economy and science and technology have shifted to investments in the unmanned intelligent crop production. The crop unmanned intelligent cultivation aims at the green, high-quality, high-yield and efficient production of crops, which integrates the modern crop cultivation technologies and new generation of information technologies such as satellite navigation, internet of things, big data, artificial intelligence and so on. In the crop unmanned intelligent cultivation, intelligent machines (equipment) could accurately monitor and diagnose crop

growth, and exactly and variably apply of water, fertilizer and drugs, and resulted in the unmanned cultivation and steady growth of crops in whole crop growth. Thus, the unmanned and intelligent crop cultivation will be a major innovation in the crop production with the features of precision, intelligence, automation, high efficiency, safety, reliability and versatility et al. The crop unmanned intelligent cultivation, which is a system engineering technology with deep integration of multi-disciplinary such as crop cultivation, mechanical engineering and information science, focusing on the following core scientific problems: ① the effective approaches and mechanisms of crop unmanned intelligent cultivation that can realize of green, high-quality, high-yield and efficient cooperative production; ② the development and screening of the products suitable for unmanned intelligent cultivation system such as seeds, fertilizers and pesticides; ③ the manufacturing and selection of agricultural machines which can integrated with information technologies and applied to unmanned intelligent cultivation; ④ the research and application of the green, high-quality, high-yield and efficient integrated “cultivation-machinery-information” cultivation technologies. For example, in a rice-wheat rotation system, the green, high-quality, high-yield and efficient synergetic cultivation technologies were integrated with the simplest unmanned intelligency in the whole processes of crop production. The unmanned and intelligent rate of rice-wheat rotation reaches more than 85%, the annual average yield of rice-wheat has stabilized to more than 1 300 kg/667 m², and the unmanned and intelligent crop cultivation technology achieves large-scale promotion and application, it will promote the unmanned intelligent cultivation in rice-wheat rotation to reach leading level internationally.

(11) Aquaculture technology of ecological intelligent pond

At present, the aquaculture area in China is about 7 036 thousand hectares, of which freshwater aquaculture accounts for 5 041 thousand hectares (71.6%). In the freshwater aquaculture area, pond aquaculture is the main type of freshwater aquaculture (accounting for 74%). Pond aquaculture occupies a pivotal position and is the basis for stabilizing the supply of aquatic products. The healthy and sustainable development of pond aquaculture involves national food security and urgently requires continuous and steady development. The key problems faced by pond culture include lack of high-quality fry, old ponds for aquaculture and backward supporting technologies. In response to these

problems, domestic and foreign researchers have provided high-quality fry for aquaculture, improved the intelligence and precise control technology for water quality, developed efficient purification equipment and emission reduction systems, established full-process information aquaculture management and control system based on the Internet of Things (IoT) to evaluate the intelligence and precise control level for pond aquaculture. The establishment of the ecological, intelligent and industrialized modern pond aquaculture model has promoted the healthy and sustainable development of modern pond aquaculture.

2.2 Interpretations for three key engineering development fronts

2.2.1 Animal precision gene editing and breeding technology

Animal breeding technology has experienced a leap-forward development from the initial phenotypic value breeding technology to the modern genome editing breeding technology. The traditional method of hybrid improvement method is costly, time-consuming and complicated, and defective genes may also be introduced due to gene linkage, while gene editing technology can precisely modify the target gene, through modifying key functional genes and regulatory sequences related to important animal traits, new animal breeds (lines) with characteristic phenotypes can be obtained in one generation, thereby improving the efficiency of animal breeding. Since its introduction, gene editing technology has developed and updated three generations: zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs) and Clustered regularly interspaced short palindromic repeats-Cas9 (CRISPR-Cas9). Gene editing technology has achieved a major breakthrough in technology from the random targeting and inactivation of the target gene to the accurate replacement of a single base of the gene. In recent years, gene editing technology has become an important method of animal breeding, and has been fully developed and applied in the field of animal breeding. A batch of new materials and new lines with high-yield, high-quality, high-reproduction and disease-resistant breeding have been precisely created through gene editing technology, such as gene edited swines for resistance to porcine reproductive and respiratory syndrome, gene edited beef cattle with myostatin

knockout, and tuberculosis-resistant dairy cows. With the continuous progress of multi-omics sequencing technology, various phenotype and genotype databases are constantly enriched, important functional genes and regulatory sequences related to various traits are continuously mined, and the efficiency, accuracy and safety of gene editing technology are constantly improving. Animal precision gene editing and breeding technology will gradually develop in the direction of engineering and large-scale, and will be widely used in the field of animal breeding in the future, providing important technical support for the cultivation of new animal species.

Animal Precision gene editing and breeding technology refers to a method that uses CRISPR-Cas9 and other genome editing tools to precisely modify the functional genes and regulatory sequences related to important animal traits, and directionally breed new animal breeds (lines) with specific phenotypes. Since its introduction, gene editing technology has developed and updated three generations: ZFNs, TALENs, and CRISPR-Cas9. From the first introduction of mutations in the target gene by shearing and breaking, to now, the precise replacement of a single base of the gene, as well as the precise insertion or replacement of large fragments, can be realized, which has achieved a major breakthrough in technology. With the continuous progress of multi-omics sequencing technology, various phenotype and genotype databases are constantly enriched, important functional genes and regulatory sequences related to various traits are continuously mined, and the efficiency, accuracy and safety of gene editing technology are constantly improving. Animal precision gene editing and breeding technology will gradually develop in the direction of engineering and large-scale, and will be widely used in the field of animal breeding in the future, providing important technical support for the cultivation of new animal species.

Gene editing technology has become an important method of animal breeding, and has been fully developed and applied in the field of animal breeding. A batch of new materials and new lines with high-yield, high-quality, high-reproduction and disease-resistant breeding have been precisely created through gene editing technology, such as gene edited swines for resistance to porcine reproductive and respiratory syndrome, gene edited beef cattle with myostatin knockout, and tuberculosis-resistant dairy cows. The improvement of livestock meat yield and quality, fluff yield and quality

and other production traits is crucial to the efficient and sustainable development of animal husbandry. The precise modification of key genes through gene editing technology has become an effective tool for improving important economic traits of livestock. Using gene editing technology to mutate *BMP15* and *GDF9* genes has significantly improved the reproductive efficiency of cattle and sheep, and created breeding materials for high-breeding animals. By precisely modifying the key gene *MSTN*, which regulates muscle production, the gene-edited swines, beef cattle and sheep obtained showed a double-muscle phenotype, and the meat production rate was significantly improved. The exogenous *Fat1* gene was successfully inserted into the swine genome by gene editing technology, which significantly increased the content of n-3 polyunsaturated fatty acids in pork and improved the flavor of pork. Precise mutation of the *FGF5* gene improves wool quality in Alpine Merino sheep. New breeding materials for specific pathogen resistance can be developed through precise modification of the receptor gene of pathogen entry into cells or precise insertion of resistance gene into the safety locus of animal genome. Swines with resistance to African swine fever were generated using ZFNs. CSFV-resistant pigs were obtained by gene editing technology. CRISPR-Cas9 knockout of the CD163 receptor to produce PRRS-resistant swines. Aiming at the pathogens that cause diseases such as porcine pseudorabies, porcine reproductive and respiratory syndrome, and multisystem wasting syndrome of weaned piglets, the CRISPR-Cas9 system was used to modify a number of key genes in the host, and the corresponding disease-resistant pig breeds were bred. By precisely integrating the *Ipr1* and *NRAMP1* genes, a tuberculosis-resistant dairy cow was created. The chicken subtype B leukemia-resistant chicken cell line was established by editing the chicken subtype B tumor virus gene (TVB) using CRISPR-Cas9 technology. The above studies show that animal precision gene editing and breeding technology has important application value in the field of new animal breed breeding.

Gene editing technology solves the problem of long animal breeding cycle, accelerates the breeding process and reduces breeding costs. The precise gene editing technology based on CRISPR-Cas9 and other systems can be applied to the gene editing in various organisms and cells, and the targeted modification is more accurate, the action time is shorter, and the operation is simpler. The modified genes can also achieve

germline inheritance, showing great potential and advantages in the field of animal production. However, the current gene editing technology is still in the initial stage of research and application, and key issues need to be solved, such as its high off-target efficiency and the need for further improvement of editing efficiency. In the future development, the continuously improved and mature gene editing technology in practice will surely become a powerful auxiliary tool in the field of animal husbandry research and production, and ultimately promote the high-quality development of animal husbandry.

The countries and institutions with the greatest output of

core patents on “animal precision gene editing breeding technology” are shown in Tables 2.2.1 and 2.2.2, respectively. China has the most core patents, with 3 860 patents, accounting for 84.91%; the second is the USA, with 187 patents, accounting for 4.11%; the third is South Korea, with 168 patents, accounting for 3.7%. The percentage of citations of China is 56.63%, far exceeding the second-ranked USA, but the citations per patent is only 1.51, far behind France, Canada, and the USA. In terms of cooperation between countries in this front, there is cooperation between the USA, the UK, the Netherlands, Canada, and Australia; there is no cooperation among

Table 2.2.1 Countries with the greatest output of core patents on “animal precision gene editing breeding technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	3 860	84.91	5 830	56.63	1.51
2	USA	187	4.11	2 854	27.72	15.26
3	South Korea	168	3.70	155	1.51	0.92
4	Russia	88	1.94	55	0.53	0.62
5	Japan	69	1.52	190	1.85	2.75
6	France	20	0.44	664	6.45	33.20
7	UK	20	0.44	480	4.66	24.00
8	Australia	18	0.40	98	0.95	5.44
9	Canada	13	0.29	382	3.71	29.38
10	Netherlands	12	0.26	52	0.51	4.33

Table 2.2.2 Institutions with the greatest output of core patents on “animal precision gene editing breeding technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Chinese Academy of Agricultural Sciences	237	5.21	336	3.26	1.42
2	China Agricultural University	146	3.21	448	4.35	3.07
3	Northwest A&F University	124	2.73	197	1.91	1.59
4	South China Agricultural University	123	2.71	222	2.16	1.80
5	Yangzhou University	96	2.11	114	1.11	1.19
6	Huazhong Agricultural University	51	1.12	98	0.95	1.92
7	Shandong Agricultural University	45	0.99	72	0.70	1.60
8	Sichuan Agricultural University	43	0.95	94	0.91	2.19
9	Guizhou University	36	0.79	37	0.36	1.03
10	Nanjing Agricultural University	33	0.73	54	0.52	1.64

other countries (Figure 2.2.1). The institution that produced the most core patent was the Chinese Academy of Agricultural Sciences, with a total of 237 patents, followed by China Agricultural University, and Northwest Agriculture and Forestry University. The top three institutions in terms of citation ratio are China Agricultural University (4.35%), Chinese Academy of Agricultural Sciences (3.26%), and South China Agricultural University (2.16%). The institution with the highest citations on average is China Agricultural University with 3.07 times. There is no cooperation between the different institutions. Figure 2.2.2 shows the roadmap of this front.

2.2.2 Application of gene editing technology in horticultural crops

The gene editing technology of horticultural crops changes the original gene sequence by knocking out a few base pairs or a DNA sequence. It has been developed and updated for

three generations since its inception: ZFNs editing technology, TALENs editing technology and CRISPR-Cas9 editing technology. Among them, the CRISPR-Cas9 editing system has become the current horticultural crop due to its high editing efficiency, simple operation and low cost. Gene editing technology now can achieve precise replacement of a single base of a gene, as well as precise insertion or replacement of large fragments. A major breakthrough has been achieved in genome analysis of important horticultural crops such as tomato, watermelon, cucumber, Chinese cabbage, citrus, apple, kiwi, Chinese rose, and Chinese lotus. Some important achievements have been made in gene mining of important traits such as development, stress resistance, yield and quality. With the continuous improvement of the efficiency, accuracy and safety of gene editing technology, the gene editing technology of horticultural crops will gradually develop towards engineering and scale, and will be widely used in the field of horticultural crop production in the future.



Figure 2.2.1 Cooperation network among major countries in the engineering development front of “animal precision gene editing breeding technology”

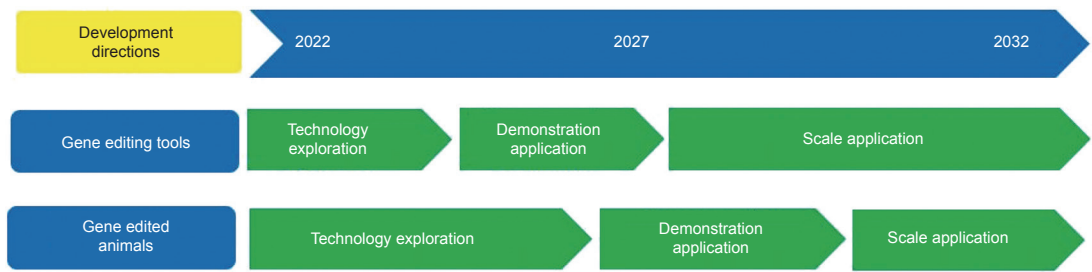


Figure 2.2.2 Roadmap of the engineering development front of “animal precision gene editing breeding technology”

Gene editing technology has become an important method for the study of important gene functions of horticultural crops, and has been greatly developed and applied in the field of horticultural crop research. The CRISPR-Cas9 system was first applied in tomato in 2014, researchers successfully knocked out the *Argonaute7* gene to produce a *wiry* phenotype in tomato leaves. With the development of CRISPR-Cas9 technology, it has been applied in more and more horticultural crops, including cucumbers, strawberries, bananas, grapes, apples, watermelons and kiwifruit, in the study of plant growth and development, product quality, biotic and abiotic stresses, and crop domestication. For example, using CRISPR-Cas9 technology to knock out *ARF8* (*Auxin Response Factor 8*) in strawberry produces plants with faster growth of seedlings; tomato *SICLV3* promoter mutation results in more locules and larger fruit; tomato yellow leaf curl virus resistance more stronger than wild-type tomato; it has become possible to accelerate the domestication process of various wild plants by using the known agronomic traits of the model plants. In addition, the availability and purpose of gene editing, regenerated genetic material without exogenous DNA and the opening of regulatory regulations for genetically improved crops are promoting the research and application of gene editing in horticultural crops.

Horticultural crop gene editing technology not only plays a great role in promoting scientific research, but also in commercial applications. In 2021, a tomato enriched γ -aminobutyric acid, five times more than ordinary tomatoes, with CRISPR technology has been for sale in Japan, which is a very important milestone for CRISPR technology to be used in horticultural crop breeding. However, most horticultural

crops have not yet established a successful CRISPR gene editing system, the transformation rate is low, or gene editing plants cannot be obtained. Therefore, it is still a challenge to break through the CRISPR gene editing system of different horticultural crops.

The countries and institutions with the greatest output of core patents on “application of gene editing technology in horticultural crops” are shown in Tables 2.2.3 and 2.2.4, respectively. In terms of quantity, the number is generally low. China has the most disclosed core patents, with 38 patents, accounting for 76.00%; the second is South Korea, with 4 patents, accounting for 8.00%; the third is Japan, with 3 patents, accounting for 6.00%. China patents were cited 117 times, accounting for 96.69%, far exceeding the second-ranked South Korea. There is no cooperation between countries. The institution with the most core patent output is Jiangsu Academy of Agricultural Sciences, with a total of 6. Beijing Academy of Agricultural and Forestry Sciences and Institute of Horticulture Corp Xinjiang Academy of Agricultural Sciences ranked second and third respectively. The top three institutions in terms of citation ratio are Jiangsu Academy of Agricultural Sciences (29.75%), Zhejiang Academy of Agricultural Sciences (19.01%), and Institute of Horticulture Corp Xinjiang Academy of Agricultural Sciences (14.05%). The institution with the highest average number of citations is Shanghai Institutes for Biological Sciences, CAS, whose citations per patent is 14. There is no cooperation between the different agencies. Figure 2.2.3 Shows the roadmap of this front.

Table 2.2.3 Countries with the greatest output of core patents on “application of gene editing technology in horticultural crops”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	38	76.00	117	96.69	3.08
2	South Korea	4	8.00	0	0.00	0.00
3	Japan	3	6.00	1	0.83	0.33
4	Germany	1	2.00	2	1.65	2.00
5	USA	1	2.00	1	0.83	1.00
6	Switzerland	1	2.00	0	0.00	0.00
7	Netherlands	1	2.00	0	0.00	0.00
8	Russia	1	2.00	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “application of gene editing technology in horticultural crops”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Jiangsu Academy of Agricultural Sciences	6	12.00	36	29.75	6.00
2	Beijing Academy of Agricultural and Forestry Sciences	4	8.00	2	1.65	0.50
3	Institute of Horticulture Corp Xinjiang Academy of Agricultural Sciences	3	6.00	17	14.05	5.67
4	Zhejiang Academy of Agricultural Sciences	2	4.00	23	19.01	11.50
5	Northwest A&F University	2	4.00	6	4.96	3.00
6	Zhejiang University	2	4.00	2	1.65	1.00
7	Chinese Academy of Agricultural Sciences	2	4.00	1	0.83	0.50
8	Nanjing Agricultural University	2	4.00	0	0.00	0.00
9	Shanghai Institutes for Biological Sciences, CAS	1	2.00	14	11.57	14.00
10	South China Agricultural University	1	2.00	6	4.96	6.00

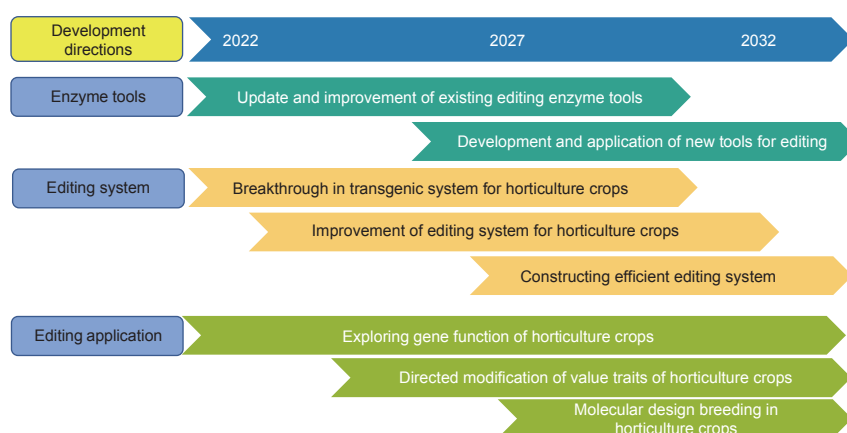


Figure 2.2.3 Roadmap of the engineering development front of “application of gene editing technology in horticultural crops”

2.2.3 Genome-wide selection in forest tree breeding

Most of the important traits of forest trees are complex quantitative traits and high genetic heterozygosity. Conventional breeding techniques are difficult to efficiently and rapidly cultivate improved tree varieties. Molecular marker-assisted selection cannot capture micro-effective loci, the resolution of genetic mapping is low, and the results of quantitative trait genetic mapping cannot be mutually verified, resulting in slow progress in forest tree breeding, and the growth and production efficiency of artificial forests are

far from meeting economic and ecological needs. In view of the shortcomings of phenotypic selection and MAS breeding strategies, Meuwissen et al. proposed genome selection (GS), also known as genome-wide selection. GS is a genome-wide marker-assisted selection method, which mainly uses the high-density genetic marker information covering the whole genome to estimate the individual GEBV, and selects excellent genotypes based on GEBV ranking. GS is an early selection technology established by combining the research results of functional genomics and single nucleotide polymorphism

(SNP) chip technology. Based on the genotype of tree seeds or seedlings, it can predict the forest tree phenotypic traits, identify and screen individuals with excellent genes accurately. In order to the final establishment of an intelligent-design-breeding-system for forest trees with GS as technical core, we should: investigate the realization path of GS technology in tree parent selection, hybrid combination prediction and early breeding of excellent progeny; accurately select new forest trees with polygenes and excellent phenotypes, and scientifically control the breeding process; promote the cross-integration of multi-technology and disciplines including tree GS, gene editing, quantitative trait locus (QTL), genome wide association study (GWAS) and phenomics, accelerate the mining of key genes for complex tree traits.

The advantages of GS mainly include the following aspects.

① Breeding speed is faster. Compared with phenotypic selection, early individual selection based on GEBV can effectively reduce the generation interval. ② The intensity of selection is greater. The cost of high-throughput genotyping is lower than that of phenotyping, and more candidates can be evaluated based on genotypes. Increasing the size of the breeding population is particularly important for plant breeding with large progeny populations. ③ The prediction accuracy is higher. Molecular marker-based GEBV is more accurate than EBV estimation based solely on phenotype and pedigree, and can greatly improve the capture efficiency of minor-effective loci, thereby improving the accuracy and genetic standard deviation of complex quantitative trait prediction. ④ It is more conducive to maintaining genetic diversity. By effectively integrating the genetic populations of different hybridized combinations and breeding programs, conducting genetic evaluation and selection in large-scale population is conducive to the preservation of abundant genetic resources. ⑤ It saves time and labor costs. The asexual propagation and progeny test can be directly performed on preselected individuals instead of all individuals. Overall, GS is a tree breeding strategy with great potential and can significantly improve the genetic improvement accuracy of target traits and reduce operating costs. GS is especially suitable for tree species with long breeding cycle, complex genetic target traits, and difficult phenotype measurement with high cost.

GS is a key technology and research hotspot in animal and crop genetics and breeding, and important progress has been made in the genetic improvement of some animals

and plants. However, forest tree GS breeding is relatively backward and is still in its infancy. Since 2010, nearly 80 studies in the field of forest GS have been published, most of which focus on eucalyptus, spruce, loblolly pine, Douglas fir and other timber species. The scope of these studies involves GS prediction models that are mainly built for traits such as tree growth, wood properties, and resistance to pests and diseases, and its influencing factors exploration, including the size and composition of the training population, the heritability of traits, the density and number of markers, and the comparison and optimization of model algorithm. The application examples of GS breeding in forest trees and across multiple generations are rarely reported. The reasons for the lag of forest trees GS breeding include: the genetic resources collection of most tree species and the evaluation of germplasm are not in-depth, and there is a lack of established test plantation for rapidly establishing large-scale training populations; weak genetic research foundation, backward high-throughput phenotyping technology, and lack of standardized low-cost genotyping technology; lack of genotype $\times$ age/environment interaction model and analysis tools for tree characteristics. The low quality of tree reference genome and molecular markers that can reduce the prediction accuracy of the GS model.

In order to overcome the difficulties and promote the development of forest tree GS breeding, we should carry out research in the following directions. ① Establish a unified genotype and phenotype acquisition platforms. Collect genotype data in a high-throughput, low-cost, and standardized manner by using high-density SNP chips and other technologies. Obtain non-destructive, large-scale, multidimensional phenotype data by using high-throughput phenotype determination platform. ② Optimize and develop forest tree GS model algorithm. According to the characteristics of forest trees, combine with multi-omics, -environment and -year data, develop genotype $\times$ environment/age interaction models by using machine learning and deep learning to realize the optimization and improvement of GS algorithm, and continuously expand and update the training population, to improve the universality and long-term efficacy of the GS model of forest trees in unknown climate environment. ③ Integrate and analyze the large-scale data of thousands samples spanning multiple populations, obtain stable and reliable molecular markers by integrating GS and meta-QTL, and develop SNP chip products

for specific trait breeding. ④ Use programming languages, such as C++, Julia, and R to develop analysis tools for the characteristics of forest trees (perennial, outcrossing, and large sample size). It is necessary to develop analysis software that can quickly process massive molecular marker data (>100 k) for the low analysis speed of the most commonly used R software. ⑤ Carry out tree pan-genome research and establish high-quality reference genomes for conifers and polyploid species which difficult to obtain high-quality genomes to improve the GS model prediction accuracy. In addition, the demand of population sample and cost for forest tree GS is large and high, the collaboration and sharing of data and population materials between research institutions and breeding companies is important, to ensure long-term stable investment and research.

The front of “genome-wide selection in forest tree breeding” includes two core patents (Tables 2.2.5 and 2.2.6), which have been cited seven times, all of which are Chinese patents and

both from South China Agricultural University. The inventor is a forest tree genetics and breeding research team led by LIN Yuanzhen. The patent “a method based on genome selection of traits is forest breeding for multiple traits polymerization”, combining GS technology and multi-trait polymeric breeding technology, establishes a new method system of multi-trait polymeric breeding of forest trees, realizes multi-trait oriented and precise breeding, and significantly shortens the breeding cycle of forest trees. The patent “forest genome selection method based on individual genetic competition and environment space analysis and application” fully considering the differences in genetic material and planting environment background. The method markedly improves the accuracy of the forest tree GS by constructing the genomic relationship matrix by using SNP markers, fitting individual genetic competition effect by the US structure, and fitting environment space effect by AR1 structure. Figure 2.2.4 Shows the roadmap of this front.

Table 2.2.5 Countries with the greatest output of core patents in the engineering development front on “genome-wide selection in forest tree breeding”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	2	100.00	7	100.00	3.50

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front on “genome-wide selection in forest tree breeding”

No.	Institution	Published patents	Percentage of Published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	South China Agricultural University	2	100.00	7	100.00	3.50

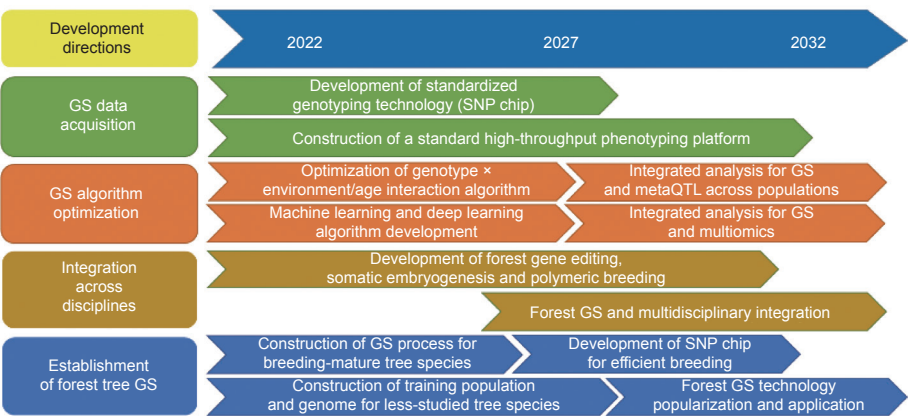


Figure 2.2.4 Roadmap of the engineering development front of “genome-wide selection in forest tree breeding”

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VIII. Medicine and Health

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of medicine and health include basic medicine, clinical medicine, medical informatics and biomedical engineering, and traditional Chinese medicine (Table 1.1.1). These 10 fronts also involve “immune heterogeneity and intervention strategies of solid tumors”, “mechanisms in tumor heterogeneity and evolutionary dynamics”, “stem cell aging”, “design and precise prediction of protein folding structure”, “artificial intelligence in drug design”, “biomacromolecular phase separation and phase transition”, “mechanisms of genome regulation”, “mechanism of neoantigen generation and its role in tumor immunity” “3D printing and organ regeneration”, and “AI-assisted disease diagnosis and treatment system”. All core papers on these fronts published between 2016 and 2021 are listed in Table 1.1.2.

(1) Immune heterogeneity and intervention strategies of solid tumors

The heterogeneity of the immune microenvironment is prevalent in solid tumors, and changes during tumor

progression and upon therapeutic intervention in a spatial or temporal manner. This immune heterogeneity is closely related to disease progression and treatment responsiveness. A comprehensive understanding of immune heterogeneity and the development of corresponding intervention strategies are crucial for the appropriate assessment of immune heterogeneity in clinical practice and promoting the development of effective personalized management. By using multi-site biopsy sampling, multi-omics sequencing, single-cell sequencing, and longitudinal liquid biopsy methods, several studies have shown the complexity of tumor immune heterogeneity and its potential value in guiding clinical diagnosis and treatment strategies. Current research mainly focused on establishing and improving of the diagnostic techniques for immune heterogeneity, developing new tools for the research of immune heterogeneity, and developing therapeutic strategies that target immune heterogeneity.

The immune heterogeneity of solid tumors is an important frontier research field in tumor immunology and immunotherapy, and many countries have large research investment and extensive cooperation. China is currently in a trend of following the similar studies abroad. Intensive effort should take advantage of China’s quantitatively clinical sample resources. Institutions should establish a research platform for investigating immune heterogeneity of solid tumors and a

Table 1.1.1 Top 10 engineering research fronts in medicine and health

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Immune heterogeneity and intervention strategies of solid tumors	945	144 130	152.52	2017.9
2	Mechanisms in tumor heterogeneity and evolutionary dynamics	474	47 136	99.44	2018.3
3	Stem cell aging	610	63 316	103.80	2017.5
4	Design and precise prediction of protein folding structure	491	41 898	85.33	2018.2
5	Artificial intelligence in drug design	453	49 852	110.05	2018.1
6	Bio-macromolecular phase separation and phase transition	858	79 732	92.93	2017.6
7	Mechanisms of genome regulation	280	37 959	135.57	2017.3
8	Mechanism of neoantigen generation and its role in tumor immunity	211	56 200	266.35	2017.7
9	3D printing and organ regeneration	700	79 548	113.64	2017.8
10	AI-assisted disease diagnosis and treatment system	975	202 804	208.00	2019.2

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in medicine and health

No.	Engineering research frontis	2016	2017	2018	2019	2020	2021
1	Immune heterogeneity and intervention strategies of solid tumors	201	208	211	188	114	23
2	Mechanisms in tumor heterogeneity and evolutionary dynamics	81	101	89	73	62	68
3	Stem cell aging	169	155	140	95	43	8
4	Design and precise prediction of protein folding structure	107	104	73	72	47	88
5	Artificial intelligence in drug design	79	81	109	96	74	14
6	Bio-macromolecular phase separation and phase transition	265	165	203	134	80	11
7	Mechanisms of genome regulation	93	70	63	32	16	3
8	Mechanism of neoantigen generation and its role in tumor immunity	51	50	53	37	16	4
9	3D printing and organ regeneration	143	172	159	136	55	35
10	AI-assisted disease diagnosis and treatment system	51	104	155	198	214	253

systematic tumor sample bioresource library and information database, enhance the application of spatial omics technology in decoding immune heterogeneity, active carry out clinical trials and encourage multimodal combination therapy, and strengthen international cooperation to promote data sharing.

(2) Mechanisms in tumor heterogeneity and evolutionary dynamics

Tumorigenesis and progression are dynamic evolution processes. Somatic mutations, chromosomal rearrangements, copy number variations, and other alterations occur in healthy tissues, leading to genomic instability, tumor suppressor gene loss, and proto-oncogene activation and resulting in malignant characteristics. Early driving ancestor mutations gradually extended into multi-branch mutations, forming different subclones. Under the pressure of microenvironment and therapy, dominant clones continue to be selected, with progression, metastasis, and resistance. These molecular events are involved in every cancer stage. The understanding of the dynamic evolution mechanisms of tumor has long been limited to the genome itself, but with the advancement of technology and the deepening of research, mechanisms such as epigenetic aberrations and microenvironment interaction networks have promoted evolution. Cell identity can be epigenetically encoded during development similar to that in tumors. Epigenetic regulation such as DNA methylation, chromatin plasticity, and histone modifications determine

the “on” or “off” of genes, induce transient changes in gene expression, and ultimately act on tumor evolution. The tumor microenvironment, including blood vessels, immune cells, fibroblasts, and extracellular matrix, exerts direct selection pressure on tumor cells, and adaptive changes made by tumor cells shape the microenvironment. Research on the dynamic evolution mechanisms of tumor is gradually moving towards systematization, integration, and deepening, in which the rapid development of high-throughput and single-cell sequencing has played a great add-on role. Understanding the dynamic evolution mechanisms of tumor is critical to cancer prevention, diagnosis, prognosis stratification, drug resistance identification, and the development of novel therapeutic strategies.

(3) Stem cell aging

Stem cells, a class of cells capable of self-renewal and differentiation, play a critical role in maintaining the structure and function of tissues and organs, and coping with damage repair. However, during aging, the number, function, or regenerative capacity of stem cells is undermined, leading to a faster degeneration than the regeneration in tissue dynamics. Eventually, the exhaustion of stem cells results in the loss of tissue homeostasis and the occurrence of a series of aging-related diseases, including neurodegeneration, hematopoietic and immune dysfunction, declined reproductive capacity, decreased muscle mass, rarefaction of bone, and pulmonary

fibrosis. Therefore, unveiling the molecular mechanisms of stem cell aging and deciphering the critical intrinsic and extrinsic regulatory factors of stem cells will facilitate the development of new methods enhancing stem cell homeostasis and function, thus providing novel strategies to alleviate aging-related diseases and extend healthspan.

Over the past decades, a series of breakthroughs have been achieved in the field of stem cell research, including the identification of different types of adult stem cells, the elucidation of the molecular mechanisms of functional regulation, and the maintenance of certain stem cell states via small molecule-based strategies. However, many challenges remain in the field of stem cell aging research. For instance, researchers have yet to determine how to develop novel models of stem cell aging, how to systematically investigate the mechanisms of stem cell aging, and how to establish novel stem cell-based strategies for the interventions against aging and aging-related diseases. Adult stem cells in different tissues are heterogeneous with regard to molecular characteristics, regulatory networks, and microenvironments. Therefore, new models and technologies are demanded for stem cell aging research. In addition, the use of multidisciplinary approaches to systematically investigate the mechanisms of stem cell aging at multiple dimensions could facilitate the regenerative strategies for the reactivation of senescent stem cells and thus the reconstruction of the homeostasis and function of aged tissues and organs. These advancements can also provide a basis for the development of interventions for stem cell rejuvenation and treatments for aging-related diseases.

(4) Design and precise prediction of protein folding structure

The design and precise prediction of protein folding structure are based on artificial intelligence (AI) methods for predicting the 3D structure and designing skeleton and sequence of protein based on multiple sequence alignment and deep learning for a specific biological function. Protein plays a key role in life and its function is determined by the 3D structure based on the paradigm of sequence-structure-function. Researchers have used X-ray to measure the 3D structure of protein in the 1950s. Until now, X-ray, Nuclear magnetic resonance (NMR), and cryo electron microscopy (cryoEM) remain as the main technologies for protein structure analysis. Protein Data Bank collected these 3D structures and constructed an integrate database, including

approximately 194 000 released experimental protein 3D structures. However, a huge gap exists between released 3D protein structure and sequence. To improve this issue, scientists have constructed different types of computer models to predict the folding of protein in the 1970s. In 1994, John Moult began to organize the Critical Assessment of Protein Structure Prediction for once every 2 years. However, the GDT score of protein structure is less than 60 in the beginning. Until 2020, AlphaFold2 has a break for this competition, in which the average GDT score is higher than 92, and it can solve the protein folding for the 50-year-old grand challenge in biology. The rapid development of protein folding structure prediction also promotes the iterative optimization of protein design. The skeleton design based on hallucination and inpainting and the automatic generation of sequence have improved the precision of protein design. Currently, the main challenge of protein folding structure prediction and design lays in how to effectively improve the prediction precise for disordered regions, because the pLGDT score of AlphaFold2 is approximately 50 for these regions with low confidence. Therefore, AI combined with the simulation of precise force field might be used to improve the prediction precise and realize end-to-end information return. Moreover, researchers have yet to determine how to improve the performance of prediction for protein folding structure with less homologous sequences. Furthermore, the prediction of protein complex needs to be improved. For the protein design, dynamic conformation should be included the skeleton design of protein, because the dynamics conformation has strong relationship with the function. Finally, the coverage of sequence space should be increased for the automatic generation for sequence. Accordingly, iterative optimization can be used for the precise prediction and design of protein folding structure by using more effective AI architecture combined with sequence and structure big data with greater computational power. In recent years, many practitioners in China have already played instrumental roles in the field of protein structure prediction and design, especially in the area of the methodology for protein design. Nevertheless, most commonly used research platforms and solutions of protein structure prediction still follow the previous works. In these frontier fields of signal transduction, disease diagnosis, and virtual drug screening, the application of protein folding structure prediction and design for China remains at the

initial stage.

(5) Artificial intelligence in drug design

Artificial intelligence (AI) has become one of the strategic frontiers in the field of pharmaceutical science and technology, and as an emerging technology, it has also been gradually applied to drug discovery and design. At present, AI-assisted drug design is still in its infancy, and many bottlenecks are encountered as follows:

1) The sources and types of drug research and development (R&D) data urgently need to be broadened, and the quality needs to be improved. AI-based drug design is based on data, from which trends are discovered, emphasizing the need for high-quality labeled data. Open access data of drug development are limited at this stage, and most of them involve *in vitro* test data of compounds in the drug discovery stage. Drug R&D data involves enterprise confidentiality and subject privacy with low degree of sharing and no standardization. In small-molecule targeted drug design, the amount of biological activity data for a given target is small, especially negative and novel target data, while the quality of artificial experimental data varies greatly.

2) AI models should fully consider the intracorporal process of drugs and the biological characteristics of their targets. Most of the existing AI models that are used in drug design only start from the perspective of compound structure, and they do not fully consider the metabolism and transformation of drugs in the body and the biological characteristics of the targets, including three-dimensional or stereoscopic characteristics of the drug-target interaction, induced fit effect, physiological environment, and off-target effect. The accuracy of model prediction is not ideal enough.

3) Molecular generative models lack standardized evaluation methods, and many aspects need to be improved in molecular collaborative optimization. Technically, the molecular generative model based on AI expands the chemical space of the designed molecule, considers the synthesizability of the molecule, and realizes collaborative optimization. However, most of the small molecules designed by existing AI models only target one or two properties of the molecule. The molecules designed to consider the biological activity, synthesizability, structural diversity, and druggability often have problems such as difficult synthesis, great toxicity, and poor druggability. The operability of the prediction results is poor, and the experimental verification is difficult. Therefore

theoretical research and practice have no closed loop.

4) Solving several key scientific problems in the field of drug design is also key to the successful application of AI. At present, considering the limitation of model accuracy, AI-aided design of molecules has several possibilities, which require further prediction and screening by traditional computer-aided drug design techniques. Therefore, the prediction of protein-ligand interaction patterns and affinity is still the key point.

Technical advice on the above key scientific issues or difficulties are as follows. ① Strengthen the mining and modeling of data in the clinical research stage of drugs, realize the utilization and model sharing of confidential data of enterprises through federated learning (“data available and invisible”), and make full use of limited data through data enhancement, thereby establishing an AI model that predicts the multidimensional nature of drugs (including the fate of clinical research). ② Develop computational methods to characterize the biological characteristics of drug targets (e.g., three-dimensional stereoscopic and induced fit), study the fusion with compound structure information, and provide data-based AI models physical and biological significance. ③ Develop the evaluation system of molecular generative models, quantitatively compare the efficiency and performance of different models, select the optimal molecular generation framework or model, carry out molecular design by using high-precision activity/property prediction model as a scoring function, closely combine with organic synthesis and biological activity evaluation to achieve a closed loop between theory and practice, and improve model performance through experimental data feedback. ④ Develop the scoring function of high-precision protein-ligand affinity, improve the speed of combined free energy calculation, achieve a balance between precision and speed, and solve key scientific problems in the field of traditional drug design. Thus, new AI technologies and platforms specifically applied to drug design should be developed to improve the efficiency of new drug R&D.

(6) Bio-macromolecular phase separation and phase transition

Interactions between multivalent binding partners, where each partner has multiple binding sites of its counterpart, have intrinsic propensities to undergo liquid-liquid phase separation (LLPS), resulting in a dilute solution phase and a macromolecule-enriched condensed phase. The biological significance of LLPS is exemplified by the numerous

membrane-less organelles in cells. The connection between LLPS and membrane-less organelles was revealed in seven seminal studies approximately 10 years ago. In 2009, Tony Hyman and coworkers from Max Planck Institute studied the physical state of P-granules, a class of membrane-less organelles in *Caenorhabditis elegans* embryos, and reported that P-granules were assembled via LLPS. In 2012, Michael Rosen and Steve McKnight from the University of Texas Southwestern Medical Center separately reconstituted condensates derived from phase separation by using simple biochemical systems. The Rosen study explicitly revealed that multivalent interactions drive LLPS, and the McKnight study mainly dealt with a special type of condensates, hydrogels, which are often solidified from liquid condensates through a liquid-solid phase transition process. In the subsequent years, scientists worldwide have employed the concept of phase separation/transition to rationalize numerous biochemical phenomena.

As a newly appreciated organization principle in cells, phase separation actually plays essential roles in various biological processes and aggregate-associated diseases. Consequently, biomolecular condensates become a frontier biomedical research area. LLPS is a major driving force for the assembly of membrane-less organelles in cells, and this process is involved in important biological processes, such as gene expression regulation, signal transduction, maintenance of cellular structures, cellular homeostasis, stress-response, cell-fate determination, and cell proliferation. Notably, phase separation is an integral aspect of cellular functions. The relationships between aberrant phase separation and diseases are a cutting-edge question in the field of biomolecular phase separation. Generally, aberrant phase separation may play essential roles in neurodegenerative diseases and many types of cancers. Hence, phase separation provides a new angle that provides a better understanding of pathological mechanism and novel therapies. For instance, the field is actively engaged in screening for small molecule drugs that can reverse aberrant phase separation and evaluating their therapeutical potentials. In parallel, new LLPS-based techniques are actively being devised for biomedical research.

Nowadays, the concept of phase separation enhances various biomedical research fields. Chinese scientists have been a series of breakthroughs in the field, and many are highly recognized worldwide. However, while scientists are enthusiastic in studying phase separation, many research

efforts are limited to simply categorize more phase separation phenomena or employ phase separation to explain some unexplained biochemical phenomena. Studies have not fully determined the underlying mechanisms, such as the mechanism in which cells precisely control the assembly and disassembly of biomolecular condensates, how multiple types of membrane-less organelles maintain their independent identity while fulfilling functional cooperativity, the mechanism in which membrane-bound membrane organelles and membrane-less organelles interact and the specific biological functions that the two kinds of organelles jointly control, to the method to carry out phase separation studies *in vivo*, and whether small molecule drugs precisely and specifically control (aberrant) phase separation. While studying bio-macromolecular phase separation is challenging, it offers opportunities in advancing many biomedical research fields. The improved understanding of phase separation in biology will allow its full utilization in substantiating both basic research and translational studies and enabling novel modalities in precise medicine.

(7) Mechanisms of genome regulation

The fine-tuned spatiotemporal regulation of gene expression forms the molecular basis of cellular structural and functional diversity. With the rapid development of genome sequencing technology, the focus of genomics research has shifted from the analysis of the linear sequence of DNA to the study of genome structure, function, and regulatory mechanism. The mechanistic research on genome regulation, which focuses on the non-coding genomic DNA, studies the composition and structure of gene regulatory elements from the perspectives of epigenetic modifications, chromosome state and three-dimensional conformation, and non-coding RNA, analyzes their dynamics in three-dimensional nuclear space, constructs the regulatory network between regulatory elements and genes, and dissects the mechanisms of gene regulatory elements on cell-specific gene expression. The current strategies used in genome regulation research include the construction of chromatin epigenetic modification and three-dimensional structure map through multi-omics methods under different physiological and pathological conditions, the use of multi-omics data and computational biology to predict cell type-specific gene regulatory elements and their targets genes, and the use of gene editing technologies such as CRISPR to verify the function of gene regulatory elements in cells and model organisms. The mechanistic study of genome

regulation is the foundation for understanding the complexity of cell diversity and phenotype, and it is mainly used to interpret the pathogenesis of non-coding variants of human diseases from the perspective of gene expression regulation.

Several critical scientific questions need to be addressed in future as follows: ① cell-type-specific gene regulation mechanisms and models, which could be mainly addressed using single-cell multi-omics and spatial-omics to establish the cellular holographic atlas of chromatin epigenomes, transcriptomes, and cellular phenotype information, and identify gene regulatory elements and network prediction models by integrating multi-omics data; ② functional annotation of genomic regulatory elements, which could be mainly addressed by developing high-throughput, multi-scale new technologies and systems to determine the functions of gene regulatory elements, and systematically building a functional database with spatiotemporal and cell-type information; ③ the key regulatory mechanism of the genome, which could be mainly addressed using genetic perturbation, high-resolution live-cell imaging, and phase separation to analyze the interactions between non-coding regulatory elements and genes, analyze the regulatory factors and complexes involved in the interaction, and establish several general models of genome regulation; ④ the pathogenic mechanism of non-coding variants, which could be mainly addressed by integrating GWAS and other population genetic data and the above-mentioned gene regulation databases to establish disease-type-specific non-coding biomarkers and reveal the initiation and development mechanisms of complex diseases.

In recent years, many large international cooperative organizations, such as DNA Elements Encyclopedia (ENCODE) and 4D Nucleome, have achieved substantial groundbreaking work in the study of genome regulation mechanisms by systematically producing massive multi-omics data and developing new technologies and data analysis pipelines. Chinese scientists have also made many important achievements in the field of genome regulation research, especially in analyzing the dynamics of the genome regulation process in early mammalian embryonic development and establishing large-scale disease biobanks and databases. In the future, Chinese scientists need more effort to develop original and cutting-edge genomics technologies and systems, establish cooperative and multi-institutional platforms and organizations, and build large-scale genomic databases and

standards for the Chinese population.

(8) Mechanism of neoantigen generation and its role in tumor immunity

Neoantigens originate from somatic mutations in tumor cells, which, if occurring in the protein encoding region, will cause the protein to undergo corresponding amino acid mutations. If the mutated amino acid is located on a peptide fragment that can be presented by MHC, it will be presented to the cell surface, and then recognized as “non-self” by T cells, triggering T cells to attack. It is the natural target for T cells to recognize tumor cells. Neoantigens are different from tumor-associated antigens. The amino acid sequence of tumor-associated antigens is not mutated, but the expression level is increased. They are not considered “non-self” by immune cells for the principle of central immune tolerance, and they do not produce an immune response. Considering that somatic mutations occur randomly, neoantigens have individual characteristics, and neoantigens are difficult to analyze with the use of previous experimental techniques at the individual level. Until the cost of gene sequencing has been greatly reduced, humans have the opportunity to perform comparative gene sequencing on cells from different sources of individuals, analyze the somatic mutations of tumor cells at the omic level, and determine corresponding neoantigens. In 2010, Nature first reported the whole genome comparative sequencing results of individual tumor tissues and control tissues of patients. The detected somatic mutations were more than 20 000 for lung cancer cells and more than 30 000 for melanoma cells. In 2017, Nature took the lead in reporting the first individualized cancer vaccine, which was designed from the profile of neoantigens analyzed from the somatic mutation detected from a melanoma patient. Specific immune response and actual efficacy were observed, resulting in a new research field.

Tens of thousands of sequencing results are available in the international tumor gene sequencing databases, such as The Cancer Genome Atlas (TCGA) and ICGC. Statistics show that the vast majority of somatic mutations are individual characteristics. Besides, only a few tumor-driven mutations, such as Kras G12V, BRAF V600E, IDH1 R132H, and PIK3CA H1047R, have a certain distribution in patients. Different individuals have different tumor somatic mutation profiles and different tumor neoantigen profiles. Therefore, therapeutic drugs need to be customized for each patient. This kind of precision medical technology, which is specially

designed to customize a drug for a patient, has begun to take shape.

The somatic mutations of tumor cells can be detected using genomic analysis software and the gene sequencing results of the patient's tumor tissue and self-control sample. The mutation of amino acid in the corresponding protein can be analyzed according to the Central Dogma of Biology. This part of bioinformatics technology is relatively easy, and the analysis software is quite mature. Whether the mutated peptide will be presented by the MHC is the key to determining whether the somatic mutation has a corresponding neoantigen. Many MHC gene polymorphisms occur in the general population, causing individuals to have different MHC genotypes, which will present different peptides. Only those mutant peptides resulted from somatic mutations have sufficient affinity with their own MHC molecules can become a neoantigen. Furthermore, whether the neoantigen can activate T cell immunity and cause enough tumor cell killing effect results in the difficulty in further designing neoantigen vaccine. The establishment and maturity of prediction technology not only depends on the accumulation of a large number of experimental data, but also requires the progress of artificial intelligence technology, especially the understanding of the interaction of MHC, neoantigens and TCR in the spatial structure. Considering that neoantigens important for tumor treatment and participate in the occurrence and development of refractory diseases such as diabetes, atherosclerosis, and Alzheimer's disease, the AI prediction of neoantigens has become a new race track for researchers at home and abroad. Bioinformatics and artificial intelligence technology have shown unprecedented importance in medicine.

Chinese researchers and foreign scholars only have a little gap in this field. In particular, it has many advantages in AI analysis technology in China. Many achievements have been obtained in transformation research, and the neoantigen-loaded T cell therapy technology and DC vaccine have been approved by the national CDE for clinical trials. Neoantigen peptide vaccine, neoantigen mRNA vaccine, and neoantigen DNA vaccine are all under rapid research. It can be expected that neoantigens will change the passive situation of tumor and other refractory diseases.

(9) 3D printing and organ regeneration

The reconstruction of artificial organs with normal physiological functions *in vitro*, which is the cutting-edge

technology in the biological manufacturing field, is critically important for the repair or transplantation of diseased organs. Biological 3D printing technologies are developed to control the three-dimensional controllable assembly of cells in space and time to construct multicellular functional bodies with biological activities. During this process, a diverse of biological ink containing cells and biological materials as the basic building units has been developed as the printing raw material. Thus, biological 3D printing is a new discipline that emerged from the cross-interaction of many fields, such as life science, materials science, engineering, and informatics, which can provide new technical means and opportunities for the development of regenerative medicine, advanced medical devices, and other biotechnological industries in the 21st century.

Human artificial organs have multi-type cell composition in multi-scale and multi-dimension assembly, and the complex interactions among inter-cells and between cells and the extracellular matrix microenvironment finally endow the artificial organs with certain physiological functions. How to simulate the three-dimensional spatial composition of cells and the complex multicellular interactions is the key to determine whether artificial organs can be accurately constructed. This research gap poses of the following challenges to bio-3D printing: ① diverse type of cells are available; ② bio-inks with excellent biocompatibility, printability, cultivability, and matching the physicochemical properties of extracellular matrix need to be synthesized; ③ it must have the ability to print multiple types of cells with high precision at high survival rate and accurately control their spatial distribution at both macro and micro scales; ④ the nutrient supply and metabolism circulation of organs need to be ensured at different scales for long-term culture; ⑤ the printed artificial organs must be able to produce part or all of the functions of real human organs under external induction or spontaneous action.

Currently, many advances have been made in 3D printing of artificial tissues and organs. For some tissues with simple composition, including skin, cartilage, and bones, their manufacture and clinical translation applications have been achieved. For complex organs such as heart, liver, and kidney, although artificial organs can be printed with similar shapes, their functions are still far from those of real human organs because of the limited cell types, low printing accuracy, and mismatched macro and microstructures. The artificial organ

printing in the future will focus on the transformation from hypotaxis (shape-like) to parataxis (function-like). Specifically, 3D printing technology will be developed from low precision to high precision and even to the single-cell precision of biological composition. The composition and function of organs will vary from a single cell with a single function to multi-cells with a multi-functional synergy. The organ scale will range from micro-sized and shaped-like organs to macro-sized organs with real physiological function.

Many domestic universities and research institutions have begun the research on bio-3D printing and artificial organ manufacturing for a long time. Some achievements are in the forefront of the world, but a big gap remains from the world's advanced level. Core bio-3D printing technologies and equipment mainly mimic those of US and Europe counterparts. Artificial organs are mainly based on follow-up research. The advanced level of bio-3D printing technology as a key factor determines the functionality of the manufactured artificial organs. Thus, to catch up with the world's advanced levels, institutions should focus on the R&D of advanced biological 3D printing technology and functional printing materials, study the structure and function of organs, encourage the cross-cooperation of clinical, basic, and engineering sciences. The fabrication a few of the important artificial organs should be focused on to promote the development of organ printing and regeneration in China.

(10) AI-assisted disease diagnosis and treatment system

The AI-assisted disease diagnosis and treatment system often uses novel AI technologies such as deep learning to mine high-dimensional quantitative information from medical big data such as medical images, pathologic images, and multi-omics data. The extracted information could reflect changes at the molecular and cellular levels of diseases and could thus be used for disease screening, diagnosis, and prediction of treatment response. The common AI-assisted disease diagnosis and treatment methods include feature engineering-based radiomics and end-to-end deep learning. Radiomics extracts many handcrafted features from multimodal medical imaging data, selects key features related to clinical tasks, and builds a machine learning model to assist in the diagnosis and treatment. Deep learning uses deep neural networks for feature extraction, model construction, and prediction in an end-to-end manner. Its representative methods include convolutional neural network and transformer. Methods that

integrate radiomics and deep learning have also received attention.

Many review papers published in the top medical journals *CA: A Cancer Journal for Clinicians* and *Nature Medicine* show that AI has formed some typical clinical application cases in assisting with disease diagnosis and treatment. In some clinical tasks, the performance of AI can reach or even exceed the judgment of clinicians. Some AI technologies have also been adopted into domestic and foreign clinical guidelines. AI is mainly applied in tumors, cardiovascular and cerebrovascular diseases, and other diseases. In terms of tumors, a series of studies have used AI technology to mine high-dimensional quantitative features in tumor macroscopic images, correlate microscopic pathological and genetic information, and then assist in tasks such as early screening, classification and staging, and prediction of treatment response. AI has achieved remarkable results in lung nodule screening, prediction of EGFR mutation in lung cancer, prediction of occult peritoneal metastasis in gastric cancer, diagnosis of microvascular invasion in liver cancer, pathological classification of brain tumor, and evaluation of immunotherapy response in lung cancer. In addition, the combination of medical image and pathological image has been applied to predict the treatment response of neoadjuvant chemotherapy in colorectal cancer and the outcome of radio-chemotherapy in nasopharyngeal cancer. In terms of cardiovascular and cerebrovascular diseases, researchers focus on the vascular plaque, such as the diagnosis of coronary plaque composition, prediction of fractional flow reserve, and judgment of carotid artery stenosis. AI has also been applied in liver fibrosis staging, prediction of bone age in children, first-trimester screening for trisomy 21, and diagnosis of COVID-19. The above-mentioned applications show that AI could provide an effective auxiliary means for reducing the workload of clinicians and improving the efficiency and effectiveness of disease diagnosis and treatment.

The development of AI-assisted disease diagnosis and treatment products has received great attention. The USA, the European Union, and other countries and regions have approved several AI-based medical products. In 2022, the Medical Device Technology Evaluation Center of the China National Medical Products Administration (NMPA) issued the *Guidelines for the Registration and Review of Artificial Intelligence Medical Devices* and actively promoted the approval of AI medical products. As of August 2022, nearly 50

AI medical products have been issued Class III registration certificates in China, promoting the clinical applications of AI.

In summary, AI-assisted disease diagnosis and treatment systems have shown a flourishing development trend in the world and have received extensive clinical attention. In the future, the AI-assisted disease diagnosis and treatment system will be developed in the direction of standardization. By overcoming the influence of different equipment and acquisition parameters, the accuracy and generalization of AI systems will be greatly improved, and AI will ultimately benefit patients.

1.2 Interpretations for three key engineering research fronts

1.2.1 Immune heterogeneity and intervention strategies of solid tumors

Tumor immunotherapy has marked a major milestone in the history of cancer clinical treatment, but its efficacy remains considerably limited because of various factors. For instance, the tumor immune heterogeneity (TIH) has received the most attention of scientists. In TIH, in the process of tumorigenesis, with the continuous progression, evolution, and selection of tumor cells, the anti-tumor immunity develops from immune clearance and balance to immune escape, which is manifested as the heterogeneity of the constitution, phenotype, and function of immune cell subsets involved in anti-tumor immunity. In the process of tumor metastasis, considering the metastatic selectivity of the tumor cells (such as epithelial-mesenchymal cells and tumor stem cells) and their tendency to metastasize to organs, as well as the immune heterogeneity (IH) of the metastatic organs, the IH of primary tumor and its metastases and even different metastatic organs is formed. During tumor treatment, considering the selective killing of tumor cells, the effect of therapeutic agents on immune cells, and the remodeling of tumor microenvironment, IH manifests as temporal heterogeneity. Thus, IH is not only manifested in different tumor types, different populations of the same tumor type, and patients with different molecular typing, but also in different metastases of the same patient and different regions within the same tumor and different stages of tumor progression and treatment processes. Therefore, the temporal and spatial heterogeneity of tumor immunity should be fully determined for the development of new immunotherapeutic

strategies, the discovery of novel biomarkers, the realization of precision immunotherapy, and the development of strategies to overcome immunotherapy resistance.

TIH originates mainly from genetic instability, differences in epigenetic modifications, fitness of the microenvironmental perturbations, and response to antitumoral therapies. Under the influence of these factors, tumor immunity exhibits two dimensions of heterogeneity, namely, spatial heterogeneity (SH) and temporal heterogeneity (TH). Both SH and TH are primarily determined by tumor cells and tumor microenvironment. Spatial and temporal differences in their localization, abundance, or activity, including the expression of immune checkpoints, secretion of immunosuppressive and proinflammatory cytokines, infiltration of immunosuppressive or effector cells, state of the vasculature, and distribution of metabolic nutrients, collectively determine TIH, thus influencing the clinical prognosis and treatment response of patients.

IH remarkably affect the diagnosis and treatment of cancer. In terms of its effect on biomarkers for tumor immunotherapy, the expression level of PD-1L has been widely used as a clinical indicator for the prediction of treatment response to the immune checkpoint inhibitors (ICIs) in various types of solid tumors. However, PD-1L expression displays distinct heterogeneity at intra- and intertumoral levels in both spatial and temporal dimensions, resulting in limited efficacy of PD-1L as a biomarker to predict the effectiveness of immunotherapy. Tumor mutation burden (TMB), a reasonable approximate substitute for neoantigen burden, has been used to identify populations with potential benefit from ICIs immunotherapy in various solid tumors. Nevertheless, the response of patients with high TMB to ICI immunotherapy is highly heterogeneous, and a large proportion of patients with low TMB levels can benefit from ICI immunotherapy and vice versa. In terms of cancer treatment effect, different metastatic sites of the same tumor have different responses to immunotherapy. Bone and liver metastases are resistant, while lymph node metastases are sensitive to immunotherapy. On the other hand, different conventional cancer treatment approaches can cause dynamic changes in the tumor immune microenvironment (TIME), leading to favorable or unfavorable effects on tumor therapy. Hence, TIH is a key bottleneck for the development of immunotherapeutic biomarkers and the realization of precision immunotherapy.

At present, the diagnosis and treatment strategies for IH are mainly established from the following aspects:

1) Establishment and improvement of the diagnostic techniques for IH. Currently, non-invasive diagnostic techniques such as liquid biopsy can be used to dynamically assess TIH, including the detection of circulating tumor cells (CTCs), circulating tumor DNA (ctDNA), and interstitial fluid and the evaluation of tumor progression and ICI efficacy. Considering the spatiotemporal characteristics of IH, the application of existing technologies such as single-cell sequencing and spatial transcriptome sequencing will obtain huge data. These data need to be combined with the advantages of artificial intelligence machine learning, data computing, and image recognition to rapidly and systematically evaluate the TIME of patients and assist in pre-clinical research and clinical treatment.

2) Development of new models for IH research. Given that the IH of solid tumors is mainly exhibited as TH and SH, its research model selection is important. At present, the research is mainly carried out in mice with high homology to humans, and the changes of TIME in humans can be analogized by studying the TIME of mouse models, including transgenic mice, drug-induced tumor model, and cell line-derived xenograft. The use of organoid model has been able to screen drugs that are sensitive to tumor cells and achieve individualized treatment to a certain extent. However, the maintenance of IME *in vivo* on organoids still faces challenges caused by the close connection between the whole body and the cells/molecules of TIME. The dilemma of using humanized animal models to study TIH can be attributed in the donor immune system and the immune rejection of the transplanted tumor, which largely limit the use of this model in TIME study. In the future, *in vitro* organoid models, which can reflect the TIME *in vivo*, need to be developed.

3) Exploration of therapeutic strategies targeting immune heterogeneity. ① Development of adoptive cell therapy targeting neoantigens. Under the guidance of precision medicine concept, the discovery of individualized tumor neoantigens and design of corresponding antigen-specific T cells for adoptive therapy are among the practical solutions for targeting TIH. The discovery of neoantigens relies on the clinical application and individualized analysis of transcriptomics, proteomics, and metabolomics. Considering the discovery of specific neoantigens of individual patient and

the high-cost and long-cycle of the autologous neoantigen-specific T cell preparation, the adoptive T cell therapy (ACT), which is established using neoantigens, is still in a case-by-case stage. Alternately, ACT targeting shared neoantigens have been tested in clinical trials, but the adoptive T cell depletion remains unsolved. In the future, clinical trials of ACT with multiple antigen targets and individualized neoantigen-specific ACT will be carried out. ② Enhancement of immunogenicity by the induction of epitope spreading and antigenic drift. TIH occurs, because the immune surveillance of the body eliminates the tumor cells with dominant antigenic epitopes, while the tumor cells with cryptic epitopes survive and progress. Cytotoxic agents, photodynamic therapy, irradiation, thermal ablation or freezing, and oncolytic viruses can be used to induce the immunogenic death of tumor cells, promote epitope spreading, especially the cryptic epitopes, and increase antigenic drift for strengthening the immune response against tumors for the moment and years ahead. ③ Overcoming IH by use of combination therapy. The application of ICIs is a breakthrough in cancer treatment. Although some patients can benefit from the therapy for their survival, the emergence of drug resistance promotes the occurrence of IH to a certain extent. Immunotherapy combined with strategies targeting other causes of IH, as a multi-pronged approach, is helpful to overcome IH. Numerous clinical trials of combination therapy are being carried out, including conventional treatment such as combined chemotherapy, radiotherapy, and targeted therapy. The combination of metabolic target drugs, costimulatory molecular agonists, tumor vaccines, ACT, and dual ICIs can also be used. In the future, breakthroughs will be made in the integration of multi-target therapeutic agents, such as immune checkpoint antibody-drug conjugates, bispecific T cell engagers (BiTEs), and immunotherapy combined with intestinal microbiota transplantation.

The analysis of the formation mechanism of TIH and development of strategies for cancer diagnosis and treatment are the challenges existed in pre-clinical research and clinical treatment on tumor immunity. The precise treatment of cancer coincides with the specific characteristic of immunology, and the design of individualized immunotherapy regimens for patients based on TIH features may become a reality. This research depends on the development of new technologies. First, the technology for the rapid and systematic monitoring of TIME variations needs to be further improved to help in the

early monitoring of the efficacy of basic research and clinical trials. Second, design concepts for new therapeutic agents also need to be updated, such as the design of prodrugs of immunotoxic molecules and development of dual-target antibodies and cells by applying the characteristics of IH. Lastly, the identification and application of individualized tumor neoantigens and cell populations and the use of novel individualized tumor vaccines and oncolytic drugs are expected to improve the efficacy of immunotherapy.

Currently, in the front of “immune heterogeneity and intervention strategies of solid tumors”, the top three countries with core papers published are the USA, the UK, and China. Among them, China accounts for 14.50% of the published papers, making it one of the major countries in

research of this front (Table 1.2.1). From the perspective of the cooperation network among main countries (Figure 1.2.1), the Top 10 countries have highly close cooperation relations.

The Top 10 institutions with core papers published in “immune heterogeneity and intervention strategies of solid tumors” were from the USA, France, and China. The top three institutions, including Harvard University, Dana-Farber Cancer Institute, and University of Texas MD Anderson Cancer Center (Table 1.2.2), were from the USA, while Chinese Academy of Sciences ranks ninth. According to the cooperation network among the main institutions (Figure 1.2.2), scientific research institutions in the USA have strong cooperation, and some cooperation is perceived among other institutions.

Table 1.2.1 Countries with the greatest output of core papers on “immune heterogeneity and intervention strategies of solid tumors”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	489	51.75	84 966	173.75	2017.8
2	UK	142	15.03	23 480	165.35	2018.0
3	China	137	14.50	17 443	127.32	2018.6
4	Germany	99	10.48	19 621	198.19	2017.8
5	France	90	9.52	17 400	193.33	2018.0
6	Italy	89	9.42	16 431	184.62	2017.8
7	Spain	57	6.03	13 972	245.12	2017.7
8	Netherlands	51	5.40	10 578	207.41	2017.9
9	Canada	49	5.19	9 487	193.61	2017.7
10	Australia	44	4.66	8 867	201.52	2017.7

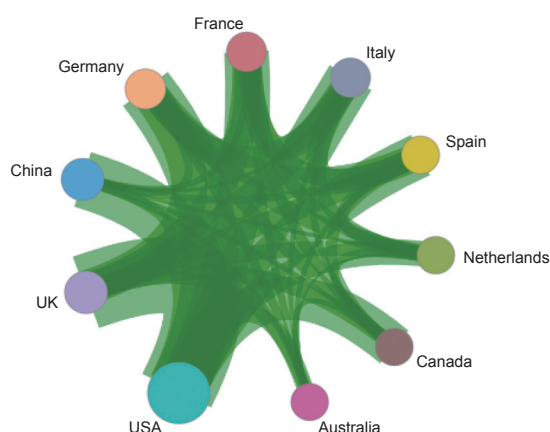


Figure 1.2.1 Collaboration network among major countries in the engineering research front of “immune heterogeneity and intervention strategies of solid tumors”

Table 1.2.2 Institutions with the greatest output of core papers on “immune heterogeneity and intervention strategies of solid tumors”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	83	8.78	18 002	216.89	2017.6
2	Dana-Farber Cancer Institute	51	5.40	11 641	228.25	2017.6
3	University of Texas MD Anderson Cancer Center	48	5.08	11 923	248.40	2018.1
4	Memorial Sloan Kettering Cancer Center	48	5.08	10 668	222.25	2017.4
5	Johns Hopkins University	31	3.28	7 090	228.71	2018.1
6	Stanford University	28	2.96	6 144	219.43	2018.1
7	Brigham and Womens Hospital	27	2.86	5 425	200.93	2017.1
8	Institut National de la Santé et de la Recherche Médicale	24	2.54	5 876	244.83	2017.3
9	Chinese Academy of Sciences	22	2.33	2 487	113.05	2018.6
10	Weill Cornell Medical College	21	2.22	5 998	285.62	2017.7

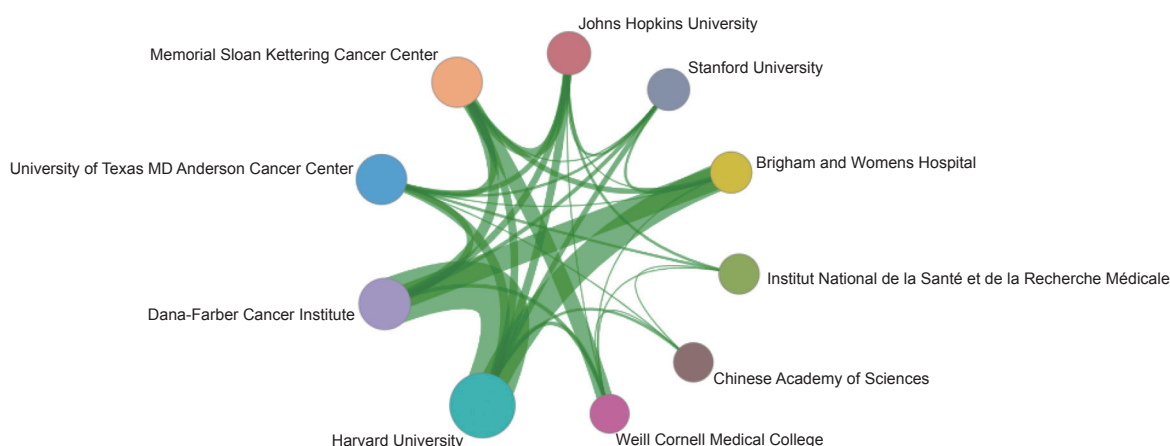


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “immune heterogeneity and intervention strategies of solid tumors”

The immunological heterogeneity is universally presented spatially or varies temporally along with tumor evolution or therapeutic intervention across almost all solid tumors. The heterogeneity of anti-tumor immunity shows a profound association with the progression of disease and responsiveness to treatment, particularly in the realm of immunotherapy. Therefore, an accurate understanding of tumor immunological heterogeneity is essential for the development of effective therapies. Facilitated by multi-regional and -omics sequencing, single cell sequencing, longitudinal liquid biopsy and organoid technologies, recent studies have demonstrated the potential to investigate the complexity of immunological heterogeneity of the tumors and its clinical relevance in immunotherapy. Single-cell omics profiling has been transformative for the

fields of immunology and immuno-oncology. The single-cell sequencing technologies have progressed with rapid development. With both technological advances and cellular throughput increasing exponentially, multiple layers of information including epigenomic, genomic, transcriptomic, and proteomic characteristics of individual cells and their combinations can be obtained at unprecedented resolution. Such high resolution is ideally suited to studying the properties of immune cells, which are well-known for their diverse developmental lineages, antigen specificities, phenotypic plasticity, and adaptability to various microenvironments. Organoids provide a new and reliable model system for the interaction of the immune system with tumor cells. Organoids currently provide the most accurate in vitro system for the

culture of human epithelial cells of almost any organ and show great promise for both fundamental and translational research in the future. New technologies have been developed to explore mechanisms of tumor immune heterogeneity and facilitate the development of more effective personalized therapies. For details see the development roadmap (Figure 1.2.3).

Based on the above statistical analysis results, for the research front of “immune heterogeneity and intervention strategies of solid tumors”, China is follows the trend of similar studies abroad. Some suggestions are proposed for this frontier field as follows:

- 1) By using China’s quantitative advantage in clinical sample resources, a research platform for investigating TIME heterogeneity of solid tumors and a systematic tumor sample bioresource library and information database can be established. These platforms can be helpful for the analysis of the constitutive characteristics and evolution rules of TIME in human solid tumors, which further assist in establishing effective clinical intervention strategies, providing essential support for improving the treatment prognosis of patients with solid tumors, and promoting the sustainable development of society and economy.
- 2) The application of spatial omics technology in decoding TIH can be enhanced. Emerging technologies including spatial transcriptome, spatial proteome, spatial metabolome, spatial epigenome, and spatial multi-omics should be developed to explore the temporal-spatial heterogeneity of immunity, upon which, the composition of immune environment can be depicted at multiple levels, and the transcriptional regulation and intercellular communication in tumors may be analyzed. In addition, the development of computational strategies for

the data mining of novel spatial omics help in determining SH at the intratumoral and intertumoral levels and even between individuals. By using dynamic biopsy tissue samples, the dynamic evolution mechanism of the immune spatial environment could be explored. Moreover, the analysis of the relationship between the TIME function and the formation of heterogeneity and related regulatory mechanism is important. Based on this, intervention targets that overcome IH may be discovered. Accordingly, new therapeutic strategies, novel clinically relevant biomarkers, and immunotherapy regimens may be developed, ultimately facilitating the immune spatial atlas to become a key resource for impelling the intervention strategies development.

- 3) Research on new models and technologies of IH ought to be deepened. The full combination of gene editing, library screening, organoid culture, and radiation-induced mutation and the development of *in vitro* and *in vivo* models that mimic the establishment, composition, and evolution of IH can guide the discovery of key molecules and characteristics associated with IH.
- 4) Actively carrying out clinical trials and encouraging multimodal combination therapy are recommended. By focusing on the critical molecules, cells, and signaling pathways occurred in the composition and evolution of TIH, the original principle and technology can be transformed into one or more stages of clinical intervention strategies. By conducting prospective clinical trials, promoting potential clinical application, and proving its effectiveness, clinical benefits, and risks, new technologies for clinical diagnosis and treatment may generate.
- 5) International cooperation should be strengthened to promote data sharing. Currently, international research

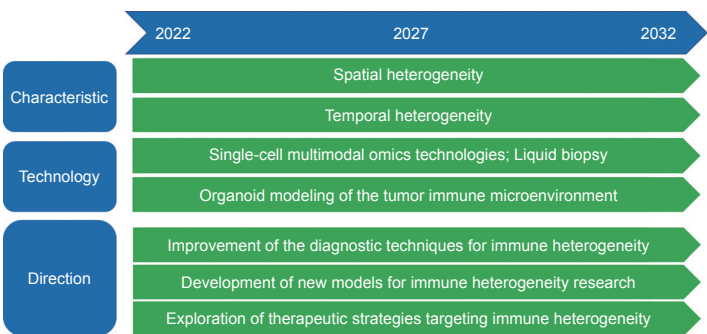


Figure 1.2.3 Roadmap of the engineering research front of “immune heterogeneity and intervention strategies of solid tumors”

institutions have certain advantages in TIH research theory, omics data production and accumulation, bioinformatics analysis methods, and clinical data integrity and systematization. Exchanges and cooperation with leading academic institutions should be further strengthened to facilitate the establishment of an effective sharing mechanism for clinical and genetic data and promote the development of related research fields.

1.2.2 Mechanisms in tumor heterogeneity and evolutionary dynamics

In 1859, Charles Darwin first proposed the theory of evolution under natural selection in *The Origin of Species*, and in 1976, the American pathologist Peter Nowell introduced the theory of evolution into the field of cancer. Cancers evolve according to Darwinian rules, that is, mutation and selection of beneficial new mutations drive the expansion of subclones, and between and within selected clones, the cellular populations experience neutral evolution. From an evolutionary biology perspective, tumor is considered to be an evolving ecosystem.

For more than a decade, scientists have conducted research to reproduce the cellular structure, functional properties, and evolution in various cancer types. Tumors have complex ecosystems, in which they form and evolve under strong selective pressures from the microenvironment, including components such as nutrition, metabolism, immunity, and therapy. These pressures promote spatiotemporal diversity of malignant and non-malignant (i.e., endothelial, stromal, and immune) components in tumor niches, resulting in a specific degree of intra-tumoral heterogeneity (ITH) that can advance disease progression and confer resistance to therapy.

Multi-region genome-sequencing studies have revealed considerable variations in the genetic makeup of malignant cells across distinct anatomical locations and disease stages, as well as in distinct regions of the same tumor, and this process is known as spatial ITH. Longitudinal studies have also demonstrated that genetic features of the same lesion can substantially vary over time, which is known as temporal ITH. Importantly, ITH does not manifest exclusively at the genetic level, but it encompasses epigenetic, transcriptional, phenotypic, metabolic, and secretory components. Such components can vary independently from each other (e.g., genetically stable tumors with high

epigenetic variability) or in a tightly interconnected manner (e.g., genetical and epigenetic alterations cooperating at defining transcriptomic and phenotypic profiles). Thus, the abundance, localization, and functional orientation of each cellular component of the TME evolves over space and time to dictate ITH. This spatiotemporal evolution is determined by the dynamic nature of its sources, including cancer-cell-intrinsic processes such as genetic instability and features of the TME. Mechanisms of clonal selection, cooperation, and competition operate in the context of multidirectional interactions between malignant cells and the other cellular compartments of the TME. However, the crucial features that define ITH and its spatiotemporal evolution are still largely uncharted.

The mechanisms of tumor dynamic heterogeneity are as follows:

- 1) Genetic heterogeneity. Genetic heterogeneity is crucial for cancer cell proliferation, invasion, and resistance to therapy, because it confers plasticity to evolving tumors. Thus, clonal diversity offers a fertile soil for tumor evolution, ultimately shaping genomic features such as oncogenic makeup and immunogenicity, and the tumor mutational burden (TMB) and karyotypic profile of the tumor.
- 2) Epigenetic heterogeneity. Cancer cells harness epigenetic aberrations to transition easily between cell states. Although these epigenetic changes generally reversible, they can be acquired by the cell progeny, thus influencing the clonal landscape of the tumor and its evolution.
- 3) Behavioral and immunological heterogeneity. Genetic and epigenetic processes determine the behavioral and immunological heterogeneity of cancer cells. Behavioral ITH influences rather ‘canonical’ processes involved in disease progression, such as proliferative properties and invasiveness, whereas immunological ITH revolves around antigenicity, adjuvanticity, and immuno-evasion.
- 4) Immune–stromal heterogeneity. As a multicellular ecosystem with complex cell composition, tumors such as immune and interstitial cells show considerable differences in species, number, state, and spatial distribution, which are important sources of tumor heterogeneity.

The key scientific issues that need to be addressed urgently in the research of tumor dynamic evolution mechanisms include: ① how to perform a more holistic analysis of

tumors across time and space from isolated points to a complete timeline and overall picture; ② the role of epigenetics, transcriptomes, proteomes, metabolomes, and microenvironment in tumor evolution aside from genomics; the effect of tumor evolution on the tumor microenvironment and corresponding treatment; and the presence of other synergistic mechanisms; ③ differentiation methods for functional and nonfunctional ITH among the numerous variants detected; ④ identification method for different patterns and positive or negative selection events of the tumor evolution process; ⑤ optimization method for the sequencing and algorithm analysis and increasing the resolution and higher dimension data by using multi-omics technology; ⑥ classification technique for driver genes based on an in-depth understanding of evolutionary mechanisms; ⑦ the use of dynamic evolutionary mechanisms to serve the clinic, such as exploring more resistance mechanisms and novel treatment strategies; ⑧ how to improve the sensitivity of liquid biopsy for its application in the study of tumor dynamic evolution mechanisms, and to explore efficient body fluid biomarkers for different cancer types.

The development of high-throughput and single-cell sequencing technology has greatly promoted the study of tumor dynamic evolution mechanisms, and its main applications include:

- 1) Inferring clonal architecture. The integration of read depth and variant allele frequencies of somatic mutations in whole-genome sequencing data can be used to infer tumor purity, ploidy, and local copy number for each mutation and thus determine the cancer cell fractions (CCFs) that harbor the mutations and clonal architecture.
- 2) Depicting lineage landscape. Multi-sampling can define the dynamic evolutionary process of tumor clones. Considering the coordinated patterns of CCF fluctuations over time, multi-sampling at different time points can provide higher-resolution data. Analogous to temporal sampling, multiregional sampling in tumor helps in the evaluation of the spatial composition of clones within tumor and refining clonal relationships to improve clinical stratification.
- 3) Tracing genetic history in single cells. Despite the additional resolution that multi-sampling provides to the clonal deconstruction of cancer evolution, phylogeny needs to be resolved at single-cell resolution to derive the precise clonal

dynamics and evolutionary history of a tumor.

4) Revealing the heterogeneity of cell states. Cell state plasticity, transcriptional state heterogeneity, and epigenetic plasticity can act as a mediator for cancer evolution and drive clonal evolution of tumors, and single-cell transcriptome and epigenetic sequencing as transformative technologies have an important applications in this field.

5) Defining the spatial dynamics of the tumor ecosystem. The spatial location of cancer cells and the resulting differential microenvironment interaction represent another dimension related to fitness. Spatial single-cell omics research has unique advantages in defining the spatial dynamics of tumor ecosystems and has become a rapidly developing frontier field.

Regarding the engineering research front related to “mechanisms in tumor heterogeneity and evolutionary dynamics”, the USA has the highest number of core papers, followed by China and the UK with average citations per paper ranging from 41.28 to 237.77 (Table 1.2.3). The citations per paper of China is 41.28, indicating a great room for improvement. Based on the cooperation network among main countries, close cooperation relationships are present between the Top 10 countries in terms of the number of core papers (Figure 1.2.4), indicating that “mechanisms in tumor heterogeneity and evolutionary dynamics” is the frontier direction of common concern in various countries.

The Top 10 institutions with the most published core papers on “mechanisms in tumor heterogeneity and evolutionary dynamics” are mainly from USA, China, and the UK. The institutions from the USA include Harvard University, Dana-Farber Cancer Institute, Memorial Sloan Kettering Cancer Center, Stanford University, and University of Texas MD Anderson Cancer Center. The institutions from China include Chinese Academy of Sciences and Peking University. The institutions from the UK include the University of Cambridge, Francis Crick Institute, and University College London (Table 1.2.4). According to the cooperation network among main institutions, a strong cooperation is present among scientific research institutions in the USA, and some cooperation is perceived among other institutions (Figure 1.2.5).

Tumor evolution encompasses a complex interplay of genetic, cell state, epigenetic, spatial and microenvironmental factors. Within the last decade, single-cell analysis has revolutionized our understanding of cellular processes and heterogeneity

Table 1.2.3 Countries with the greatest output of core papers on “mechanisms in tumor heterogeneity and evolutionary dynamics”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	261	55.06	37 421	143.38	2018.0
2	China	148	31.22	6 109	41.28	2018.9
3	UK	78	16.46	15 234	195.31	2018.3
4	Germany	49	10.34	11 469	234.06	2018.1
5	France	42	8.86	3 228	76.86	2018.0
6	Italy	39	8.23	9 273	237.77	2017.6
7	Australia	39	8.23	5 685	145.77	2018.6
8	Canada	28	5.91	5 448	194.57	2018.3
9	Spain	25	5.27	4 468	178.72	2017.7
10	Netherlands	25	5.27	2 953	118.12	2018.5

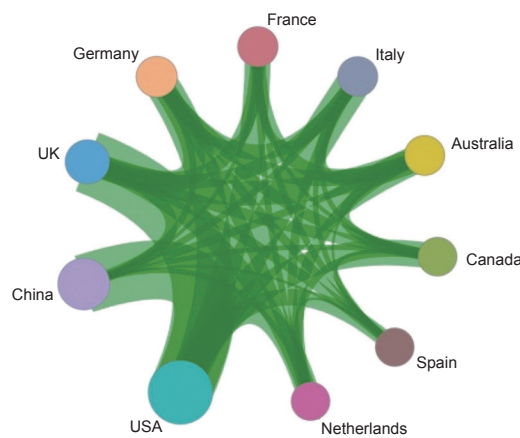


Figure 1.2.4 Collaboration network among major countries in the engineering research front of “mechanisms in tumor heterogeneity and evolutionary dynamics”

Table 1.2.4 Institutions with the greatest output of core papers on “mechanisms in tumor heterogeneity and evolutionary dynamics”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	54	11.39	11 583	214.50	2017.8
2	Chinese Academy of Sciences	45	9.49	1 629	36.20	2019.0
3	Dana-Farber Cancer Institute	33	6.96	8 063	244.33	2017.6
4	Memorial Sloan Kettering Cancer Center	29	6.12	10 341	356.59	2018.2
5	University of Cambridge	25	5.27	5 391	215.64	2019.0
6	Stanford University	21	4.43	3 474	165.43	2018.1
7	Peking University	21	4.43	1 500	71.43	2018.8
8	Francis Crick Institute	20	4.22	6 462	323.10	2018.5
9	University of Texas MD Anderson Cancer Center	18	3.80	6 101	338.94	2018.2
10	University College London	18	3.80	5 494	305.22	2018.6

across all disciplines of life science. Single-cell multimodal omics methods have greatly expanded our toolkit for delineating the complex molecular and cellular networks operating in diverse biological systems. High-throughput sequencing and novel multi-omics technologies have begun to integrate across these genetic and non-genetic determinants of tumor evolution at the critical resolution of the single cell—the fundamental evolutionary unit. These methods pave the way to address central questions on tumor evolutionary dynamics through the study of human tissue (Figure 1.2.6).

Based on the above statistical analysis results, for the research frontier on “mechanisms in tumor heterogeneity and evolutionary dynamics”, China follows the trend of similar studies abroad. Tumor evolution includes the complex interaction of genetic, cellular state, epigenetic, spatial, and microenvironmental factors. Considering the great individual differences in the population, the origin and evolutionary dynamics of tumors should be studied in a larger sample size

cohort, and the corresponding theoretical and molecular mechanisms of tumor dynamic evolution need to be determined.

1.2.3 Stem cell aging

Aging is a complex biological process accompanied by systemic functional decline. Stem cell aging is a hallmark of organ degeneration and thus stem cell aging study is a basis for resolving aging and aging-related diseases, as well as a key starting point for developing aging-related interventions. Stem cells include totipotent stem cells (TSCs), pluripotent stem cells (PSCs), and adult stem cells (ASCs). ASCs, such as hematopoietic, skin, muscle, neural, and intestinal stem cells, are found in multiple tissues and have unidirectional or multidirectional differentiative potentials, playing indispensable roles in the homeostatic maintenance and functional restoration of given organs. These stem cells are

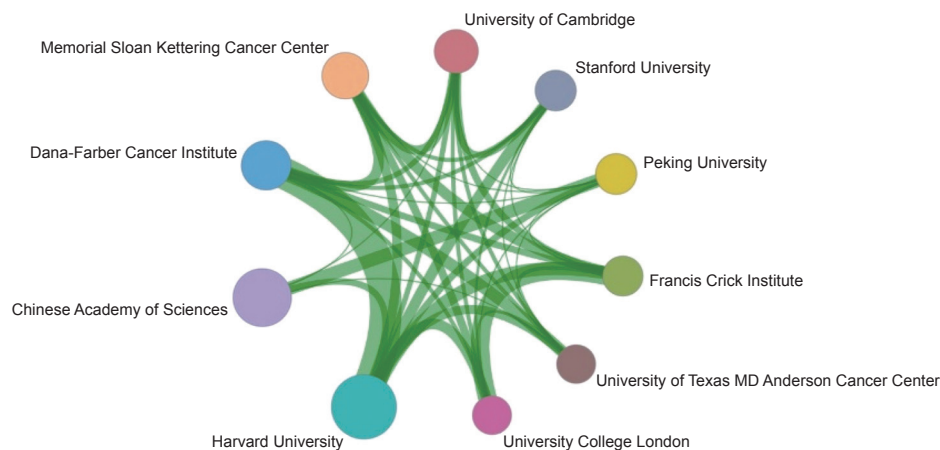


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “mechanisms in tumor heterogeneity and evolutionary dynamics”

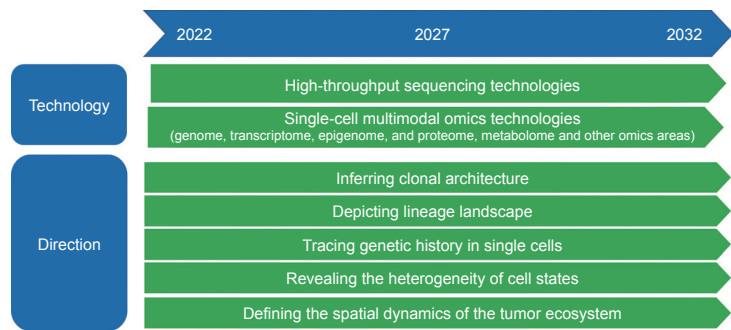


Figure 1.2.6 Roadmap of the engineering research front of “mechanisms in tumor heterogeneity and evolutionary dynamics”

tissue-specific and have profound interactions with immune, vascular and neural microenvironments, being vital to the maintenance of tissue regenerative ability and organ function.

Usually, various damages are accumulated in stem cells during the aging process, including genomic DNA damage, epigenetic changes, cell cycle abnormalities, excessive reactive oxygen species, mitochondrial dysfunction, proteostasis imbalance, altered microenvironment and metabolic dysregulation. In addition, systemic inflammation can also contribute to stem cell exhaustion. These intrinsic and extrinsic factors jointly lead to the gradual age-associated decline in the function and regenerative ability of stem cells. As aforementioned, stem cell aging is one of the most important drivers of organismal aging, leading to decreased tissue regenerative ability, impaired organ function and aging-related diseases. Therefore, it is imperative to systematically study the mechanisms of stem cell aging and develop intervention strategies for stem cell aging, thus improving the regenerative ability of tissues and organs in aging and aging-related diseases.

Currently, there are mainly two lines of stem cell-based interventional strategies, which are the activation of the regenerative activity of *in situ* stem cells and stem cell transplantation. To activate the regenerative activity of endogenous stem cells, we can use small molecules or gene intervention targeting stem cells to improve their self-renewal and differentiative capacities, or refine the microenvironment to increase the viability of stem cells and enhance their functions. For stem cell transplantation, adult stem cells can be expanded *in vitro* and re-introduced into the body, which can effectively replenish the reservoirs of stem cells in the tissue. It would further improve tissue homeostasis and function when combined with genetically enhanced stem cells with improved genetic characteristics. To date, stem cell-based therapies have shown great potentials for treating various types of diseases, including aging frailty, spinal cord injuries, type I diabetes, Parkinson's disease, amyotrophic lateral sclerosis, Alzheimer's disease, myocardial infarction, and osteoarthritis. In addition, the rapid progress in various cross-cutting fields has further advanced the mechanistic studies of stem cell aging, providing potential targets for the development of new intervention strategies. For example, organoid technology helps in building a research system for human organ aging and is being applied to observe the interactions between stem cells and their microenvironment *in vitro*. Gene editing and lineage tracing will help explore

the effects of different genes on stem cell homeostasis and cellular senescence. Partial reprogramming technology helps in understanding the epigenetic landscape of stem cell aging and exploring to reset the epigenetic aging clock. Single-cell and spatial multi-omics have facilitated the discovery of the relationship between tissue spatiotemporal heterogeneity and the regulation of stem cell aging. Accordingly, the effective integration of the existing interdisciplinary technologies, the development of new perspectives and technologies, the exploration of novel mechanisms and potential targets in stem cell aging research will be critical for the development of new intervention strategies against aging and aging-related diseases so as to actively cope with population aging.

There are a few key scientific issues to be addressed in stem cell aging research as listed below.

- 1) Develop novel models of stem cell aging. Stem cell aging is a complex biological process accompanied with a high degree of heterogeneity and asynchronicity in different species and tissues. Thus, it is urgent to build up a multi-species model-based novel paradigm, along with various *in vitro* models of human stem cells, their derivatives, and organoids mimicking multiple diseases, to provide a prerequisite for the exploration of stem cell aging mechanisms.
- 2) Systematically investigate the mechanisms of stem cell aging. The exploration of the drivers for stem cell aging is the most advanced and active branch in the field of aging. However, the mechanism by which epigenetics, metabolism, immunity, inflammation, and rhythms under different circumstances influence stem cell aging lacks systematic investigations. Thus, the spatiotemporal, dynamic, and multi-dimensional landscape should be profiled, the common and specific mechanisms underlying stem cell aging await determination, complex issues such as the heterogeneity and spatiotemporal specificity during stem cell aging process ought to be solved, and the potential targets need to be explored using multi-dimensional technologies, such as single-cell multi-omics, spatial multi-omics, and high-resolution dynamic imaging combined with interdisciplinary research systems, including new materials, artificial intelligence, synthetic biology, regenerative medicine, optogenetics, biosensing, and gene editing. These studies will facilitate not only the mechanistic studies of stem cell aging but will also take the stem cell aging research from bench to bedside.
- 3) Establish novel stem cell-based strategies for the

interventions against aging and aging-related diseases. As stem cell aging is one of the most important driving forces of organ aging, the exploration of stem cell aging based on new models and technologies will help in establishing novel intervention strategies against aging and aging-related diseases. Especially based on the in-depth understanding of stem cell aging, it is possible to confer stem cells with improved adaptability to the microenvironment of aging lesions and increased resistance to malignant transformation. High-throughput screening platforms can be used to explore rejuvenation factors that delay stem cell aging and promote stem cell regeneration. Targeted gene editing technologies such as CRISPR-Cas9 and efficient gene delivery systems can be used to facilitate the development of novel gene therapies to enhance stem cell performance. Bioengineering technologies, such as special biomimetic materials and nanorobots, can be employed to enhance stem cell homeostasis and resilience. By exploring the regulatory mechanisms of active and healthy lifestyles, such as exercise, diet control, and keeping regular schedules, to discover intervention targets of stem cell aging, which can be used to enhance stem cell activity and maintain organ homeostasis.

Highlights for future research:

1) Construct and utilize multi-species models, combined with multi-lineage human stem cells, their derivatives and organoids for aging and disease-mimicking, to generate a new paradigm for the systematic study of human stem cell aging.

2) Develop and optimize cross-hierarchical, multi-dimensional and high-resolution techniques to identify the specificity and heterogeneity for stem cell aging with spatiotemporal resolution.

3) Investigate the precise logic underlying the spatiotemporal regulation of cell-cell and cell-microenvironment crosslinks during stem cell aging, especially the interactions between stem cells and the immune, hematopoietic, metabolic, and neuroendocrine microenvironments.

4) Build up novel high-throughput screening platforms based on aging stem cells to identify novel small-molecule compounds and rejuvenation factors that can enhance the activity of stem cells.

5) Establish new strategies for cell transplantation using genetically enhanced stem cells and their derivatives, and evaluation of the long-term safety and efficacy in animal models and/or clinical trial systems.

6) Discover new drugs, vaccines or immune cell therapies specifically targeting senescent stem cell antigens to achieve safe and efficient removal of senescent stem cells.

7) Evaluate the effectiveness, safety and key regulatory mechanisms of healthy lifestyles, such as diet control, exercise, and rhythm regulation in delaying stem cell aging.

The roadmap of the engineering research front of “stem cell aging” is shown in Figure 1.2.7.

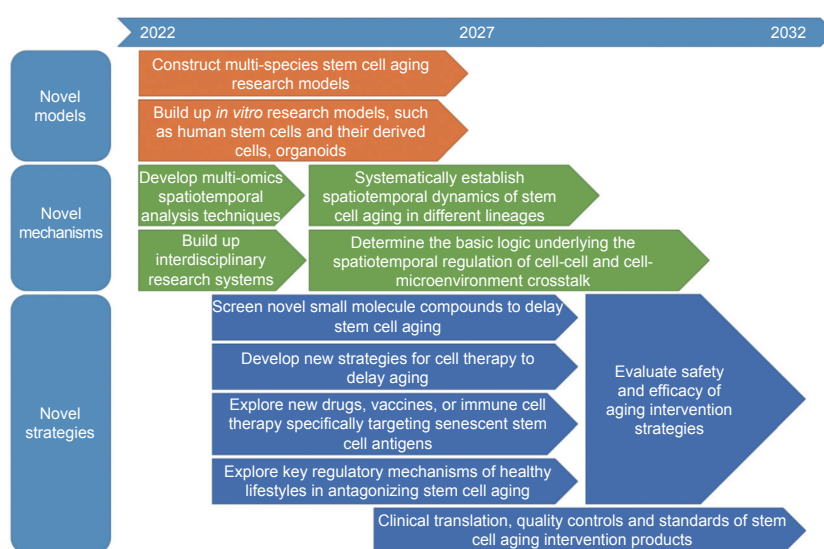


Figure 1.2.7 Roadmap of the engineering research front of “stem cell aging”

In the engineering research front of “stem cell aging”, the USA is leading in terms of the output of core papers, followed by China and the UK (Table 1.2.5). The citations per paper of China is 86.64. In terms of cooperation network among the main countries, the Top 10 countries have cooperative relationships, especially the Top 4 countries (the USA, China, the UK, and Germany), which have close cooperation in this field (Figure 1.2.8).

The Top 10 institutions with the most published core papers on “stem cell aging” are mainly from the USA, China, and the UK. The institutions from the USA include Harvard University, Stanford University, Mayo Clinic, Johns Hopkins University, University of California, Los Angeles (UCLA), University of California, San Francisco (UCSF), and Buck Institute for

Research on Aging. The institution from China is Chinese Academy of Sciences. The institutions from the UK include University of Cambridge and University College London (Table 1.2.6). The cooperation network among the main institutions in this front is shown in Figure 1.2.9, and some institutions have cooperative relations.

According to the statistical analysis above, in the frontier study of “stem cell aging”, China currently keeps pace with the rest of the world. As such, the following suggestions are put forward.

1) Establish basic and translational innovation centers for stem cell aging research, and encourage the establishment of human stem cell resource banks, stem cell function

Table 1.2.5 Countries with the greatest output of core papers on “stem cell aging”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	314	51.31	37 629	119.84	2017.6
2	China	100	16.34	8 664	86.64	2017.7
3	UK	85	13.89	9 725	114.41	2017.7
4	Germany	55	8.99	6 226	113.20	2017.4
5	Italy	44	7.19	4 888	111.09	2017.6
6	Spain	33	5.39	3 647	110.52	2017.6
7	Canada	31	5.07	3 801	122.61	2017.4
8	France	29	4.74	3 159	108.93	2017.7
9	Netherlands	28	4.58	3 788	135.29	2017.5
10	Japan	24	3.92	3 942	164.25	2017.8

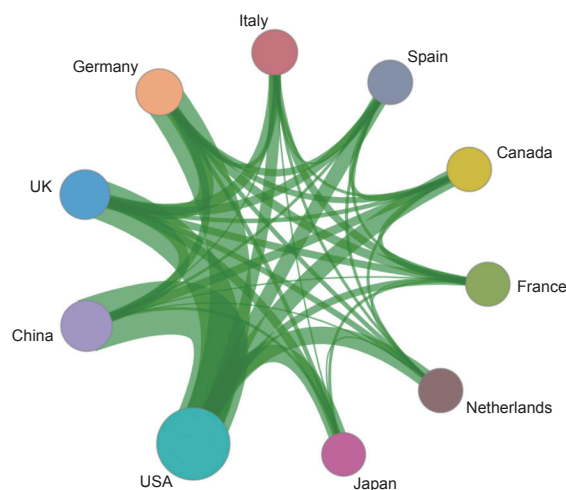


Figure 1.2.8 Collaboration network among major countries in the engineering research front of “stem cell aging”

Table 1.2.6 Institutions with the greatest output of core papers on “stem cell aging”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	30	4.90	3 951	131.70	2017.9
2	Stanford University	27	4.41	2 558	94.74	2017.9
3	Chinese Academy of Sciences	25	4.08	3 220	128.80	2017.9
4	Mayo Clinic	23	3.76	3 741	162.65	2018.2
5	Johns Hopkins University	20	3.27	3 196	159.80	2017.7
6	University of Cambridge	17	2.78	1 590	93.53	2018.2
7	University of California, Los Angeles	16	2.61	2 508	156.75	2017.8
8	University of California, San Francisco	15	2.45	1 552	103.47	2018.0
9	Buck Institute for Research on Aging	14	2.29	2 916	208.29	2017.5
10	University College London	13	2.12	1 927	148.23	2016.8

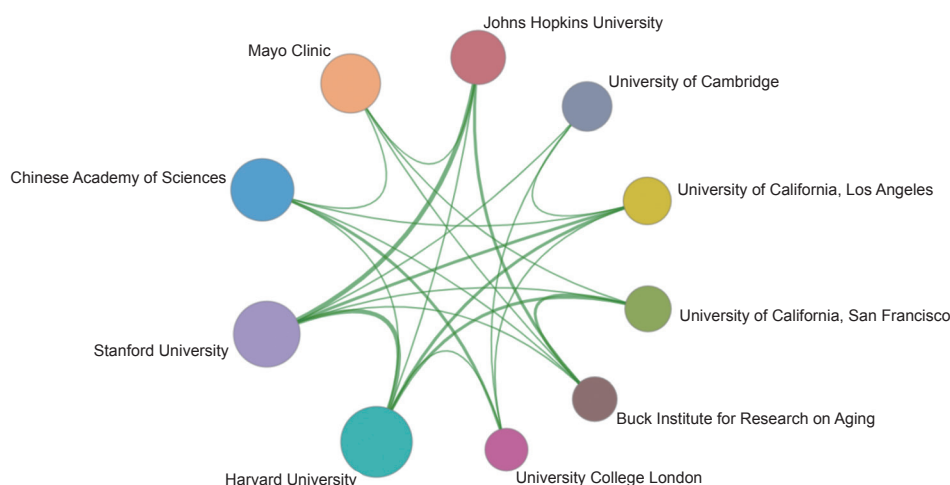


Figure 1.2.9 Collaboration network among major institutions in the engineering research front of “stem cell aging”

evaluation systems, and drug development systems for stem cell rejuvenation; facilitate the transition from research to the commercial promotion of stem cell therapeutic products against aging and aging-related diseases.

2) Accelerate the development of ethical standards, evaluation systems, and standards of stem cell aging research; strengthen the protection of intellectual property, and promote the commercialization of scientific and technological findings.

3) Launch and expand the national stem cell aging research programs and stem cell aging clinical translational research funds to increase the financial support for basic and translational studies as well as policy research in the field of stem cell aging.

4) Gather and cultivate the creative talents and world first-class research teams in the stem cell aging field; build up a scientific environment focusing on talents based on local research institutions of science and technology, innovative talent training center, medical establishments, and biomedical enterprises.

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

This section of the review describes the Top 10 engineering

development fronts in the field of medicine and health, including the fields of basic medicine, clinical medicine, pharmacy, traditional Chinese medicine, medical informatics, and biomedical engineering. The emerging fronts are “*in vivo* gene editing technology”, “development and application of base editors in biomedicine”, “Proteolytic targeting chimera degrader”, and “lineage-traceable multiplexed single-cell sequencing technology”. Traditional research has focused on “organoid-based drug screening”, “AI + surgical robotics”, “a technical system for the efficient discovery of pharmacodynamic substances in traditional Chinese medicine”, “invasive brain–machine interface technology”, and “Stem cell expansion system and intelligent tumor risk

assessment based on multimodal biomedical big data” (Table 2.1.1). All patents related to these 10 fronts published between 2016 and 2021 are listed in Table 2.1.2.

(1) Organoid-based drug screening

Organoids are established using human tissue stem cells or patient tumor tissues and are crucial *in vitro* models with stable phenotypic and genetic characteristics enabling long-term and stable subculture. Since the first mouse intestinal organoids was developed in 2009, organoid technology has sprung up as a powerful tool in precision medicine, regenerative medicine, drug screening, and disease modeling over the past 10 years and still enjoys limitless development

Table 2.1.1 Top 10 engineering development fronts in medicine and health

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Organoid-based drug screening	185	473	2.56	2019.7
2	<i>In vivo</i> gene editing technology	726	5 668	7.81	2019.1
3	Development and application of base editors in biomedicine	246	850	3.46	2019.9
4	AI + surgical robotics	1 103	3 363	3.05	2019.8
5	Proteolytic targeting chimera degrader	344	774	2.25	2018.5
6	Lineage-traceable multiplexed single-cell sequencing technology	24	80	3.33	2019.2
7	A technical system for the efficient discovery of pharmacodynamic substances in traditional Chinese medicine	2 225	2 136	0.96	2019.0
8	Invasive brain–machine interface technology	179	1 492	8.34	2019.6
9	Stem cell expansion system	969	1 394	1.44	2018.9
10	Intelligent tumor risk assessment based on multimodal biomedical big data	200	917	4.58	2019.8

Table 2.1.2 Annual number of patents published for the Top 10 engineering development fronts in medicine and health

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Organoid-based drug screening	6	13	21	29	42	74
2	<i>In vivo</i> gene editing technology	39	101	116	154	136	180
3	Development and application of base editors in biomedicine	1	3	23	51	77	91
4	AI + surgical robotics	44	45	73	195	281	465
5	Proteolytic targeting chimera degrader	61	55	79	31	48	70
6	Lineage-traceable multiplexed single-cell sequencing technology	1	3	4	5	4	7
7	A technical system for the efficient discovery of pharmacodynamic substances in traditional Chinese medicine	217	317	310	367	424	590
8	Invasive brain–machine interface technology	7	13	21	24	46	68
9	Stem cell expansion system	141	120	115	164	176	253
10	Intelligent tumor risk assessment based on multimodal biomedical big data	6	9	23	28	42	92

potential worldwide.

However, the following issues remain to be addressed for organoid-based drug screening: construction of various organoid and disease models, construction of complex organoid models, commercial production of organoid culture medium and basement membrane matrix, standardization and automation of organoid culture and drug screening, development of multi-dimensional analytical methods for organoids, high-content imaging and analysis techniques for organoids, tracking, supervision, and management specifications of human-derived organoids, and societal acceptance and ethical review system of organoids.

Several popular areas have undergone major progress, including the establishment of diversified organoid and disease models, the construction of vascularized, immune, and systematic organoid models, the optimization and industrialization of organoid culture systems, and the development of organoid high-content imaging systems and analytical methods. Organoid models are important for drug screening and drug R&D, and have been widely recognized and enthusiastically supported by regulatory authorities, organizations, and pharmaceutical companies globally.

China, is now the top owner of published core patents, followed by the USA and the Republic of Korea, in terms of organoid-based drug screening, accounting for 30.81% of the overall published patents (Table 2.2.1). Cross-border collaboration between research institutions is rarely seen. As a late starter in this field, China still manages to catch up with the advanced level by virtue of its prior knowledge of scientific research and policy and regulatory support. As the organoid industry enjoys high-speed development and broad prospects, accelerating the product transformation and clinical application of organoids in China will introduce breakthroughs in drug R&D and precision medicine.

(2) *In vivo* gene editing technology

The extensive development and optimization of CRISPR-Cas technologies have yielded robust tools for gene editing, including programmable nucleases, base editors, and prime editors. These gene editors have been widely used in various animal disease models to explore the efficacy and safety of gene editing. In recent years, several human clinical trials have demonstrated the potential of gene editing technologies represented by CRISPR. In comparison with the rapid development of gene editing tools, delivery remains a

bottleneck for therapy development. Therefore, the efficient delivery of precision gene editing agents into tissues in mammals continue to play a critical role in advancing the field. Researchers have identified and engineered several classes of delivery vehicles that can overcome these complex molecular obstacles to intracellular delivery. Current state-of-the-art delivery systems, including viral vectors, LNPs, and VLPs, can satisfy these key criteria for efficient *in vivo* delivery vehicles, making them well-suited for the *in vivo* delivery of gene editing agents. In June 2021, the *New England Journal of Medicine* reported the first clinical research data that support the safety and efficacy of CRISPR gene editing *in vivo*. This is the first clinical result of CRISPR gene editing therapy *in vivo*, proving that the direct injection of CRISPR components can perform efficient gene editing *in vivo*, which further expands the application scope of CRISPR gene editing therapy and opens up new avenues for the treatment of many human diseases. *In vivo* gene-editing therapies are rapidly making their way to the clinic.

(3) Development and application of base editors in biomedicine

Base editor is a new generation of gene editing tool developed by combining the CRISPR-Cas system with an individual deaminase. Considering the capacity of base editors to achieve site-specific single-base substitution at in genomic DNA without introducing double-stranded DNA breaks, they offer more precise and secure genome editing effects than conventional artificial nuclease system such as CRISPR-Cas9. Thus, base editors are emerging as a research hotspot in precise gene editing and have been successfully applied in basic and applied research on various animals, plants, and microorganisms. In the field of biomedicine, base editors have demonstrated important applications in gene function investigation, directed protein evolution, genetic lineage tracing, disease modeling, and gene therapy. Since the two main base editors, namely, cytosine base editors (CBEs), which converts a C–G base pair into a T–A base pair, and adenine base editors (ABEs), which converts an A–T base pair into a G–C base pair, were developed, scientists have developed more than 100 optimized base editors with improved editing efficiency, precision, specificity, targeting scope, and capacity to be delivered *in vivo* to data. Subsequently, they have enriched the arsenal of base editors and expand their application potential in biomedicine. Currently, base editors have been successfully applied to therapeutic gene editing for

the prevention or treatment of human diseases by correcting pathogenic mutations or introducing additional single nucleotide variants in genome *in vitro* or *in vivo*.

(4) AI + surgical robotics

AI + surgical robotics (AI + SR) is an intelligent diagnosis and treatment technology that studies the advanced learning algorithm of artificial intelligence for surgery and empowering the surgical robot. It allows the surgical robot to autonomously perceive the internal cavity environment of the patient, conduct real-time surgery decision-making, autonomously perform the surgical tasks without the operator's intervention, and perform the surgery with increased precision, safety, automation and efficiency. The large-scale practical application of AI + SR in clinical practice can be realized by addressing the following key technical issues: ① intelligent instrument segmentation, motion tracking, and reliable perception of intracavitary surgical tools with environment; ② learning from the demonstration, recognition, and execution of complicated surgical operation tasks; ③ multifunctional and lightweight dexterous surgical robot hardware and intelligent human-machine interaction control systems. With the development and maturation of AI and surgical robotics, especially the breakthroughs in surgery-specific learning data sets and training models, new robot configuration design, and human-robot interaction technologies, the laboratory prototypes of AI + SR will realize actual clinical applications. They are also expected to be widely used in many fields such as general surgery, urology, cardiovascular surgery, thoracic surgery, gynecology, orthopedics, neurosurgery, and dentistry. Considering its broad prospects in the field of human health care, China and developed countries such as Europe, America, and Japan have prioritized the investment in AI and surgical robotics research, targeting "AI + SR" solutions for major diseases and key clinical technologies. Moreover, an "industry-academia-research-medical-inspection-application" collaborative innovation mechanism has been established. In recent years, a series of technology startups has emerged in China and continues to achieve breakthroughs in unit technology and launch some new products. China's AI technology-based intelligent diagnosis and treatment equipment and surgical robot products have formed a certain scale, and its market size continues to grow at a high rate. The development of real-time intraoperative guidance in dynamic intracavity environment, multimodal data fusion and perception, human-

robot intelligent interaction control in complicated surgical environment, multi-degree-of-freedom dexterous surgical robot configuration and drive technology, and limited surgical training data sets labeling and model training technology will be the key to promote AI + SR technology breakthrough. AI + SR is a high-end medical technology that integrates medicine, artificial intelligence, robotics, mechanics, control science, biomechanics, and computer science. The deep integration of multiple disciplines will aid in the diagnosis and treatment of many major and difficult diseases and generate huge social and economic benefits in the field of people's health.

(5) Proteolytic targeting chimera degrader

Proteolytic targeting chimera (PROTAC) is a newly emerging technology, which draws target protein and E3 ligase close by heterobifunctional small molecules in cells, and induces the selective degradation of target protein through ubiquitin-protease system. PROTAC molecule is composed of three parts, namely, a target protein ligand, an E3 ligase ligand, and a linker that connects both ligands. By recruiting ligands at both ends, a ternary complex of "target protein-PROTAC-E3 ligase" is formed to induce the subsequent degradation of the target protein. PROTAC-induced degradation regulates the function of target protein in a catalytic manner. The quick and efficient discovery and optimization of PROTAC molecules is the key issue of this new technology. ① Ligand discovery of PROTAC molecules. The quick and effective screening of target protein ligands and the discovery of suitable E3 ubiquitin ligases and corresponding ligands that can be used in PROTAC technology are important scientific problems that restricts the design and development of PROTAC molecules, and they are limited by the lack of target protein ligands and E3 ligase ligands. The optimization of linkers between both ligands is also an important issue in PROTAC development. ② Selectivity and degradation activity. No rules have been set to improve the selectivity and degradation activity of PROTACs, and concise theoretical guidance is needed. The usual "hook effect" of PROTAC molecules will also affect the evaluation of degradation selectivity and activity. ③ Optimization of PROTAC druggability. Considering the unique mode of mechanism of PROTAC, the optimization of its drug-like properties also needs extensive exploration, and the optimization experiences learned from small molecule drugs cannot be simply copied. ④ Evaluation system for preclinical studies. Traditional methods cannot accurately evaluate the pharmacokinetics, pharmacodynamics, and

toxicity of PROTAC molecules, and a mature preclinical evaluation system for PROTAC molecules has not been established. Therefore, how to rationally develop PROTAC drugs remains an urgent and unsolved problem. PROTAC can target the disease-related proteins that cannot be addressed by small molecule inhibitors or antibody technology, such as undruggable targets, drug-resistant targets to small molecule inhibitors, and proteins with scaffold functions. Therefore, PROTAC technology represents an innovative strategy for the development of new drug modality. In addition, PROTAC, as a novel chemical knock-down method, plays an important role in biomedical research. Currently, PROTAC technology has become a new frontier of drug discovery. More than 130 targets, including kinases, transcription factors, and receptors, can be degraded using the PROTAC technology. Several start-up and public biotech companies in Europe and America have focused on PROTAC drug development, and most international pharmaceutical giants have joined the PROTAC field. At present, more than 20 pharmaceutical companies in China have participated in the development of PROTAC pipelines. Currently, more than 10 PROTAC drugs have entered the clinical stage. Overall, PROTAC drug pipelines are still in the early stages of development. Among these tested drugs in clinical studies, most are used for the treatment of different types of cancer, and the first PROTAC drug has been advanced to clinical phase 2. In future, indications for treatment of PROTAC molecules will not only cover oncology, but also be expanded to other disease fields such as inflammation, immunology, neurodegeneration, stimulating immune response to fight cancer, and anti-virus. At the same time, new types of PROTAC molecules, molecular glues, and other innovative degradation technologies with similar mechanisms are constantly emerging. Targeted protein degradation agent is expected to become the fourth main drug modality independent of traditional small molecule inhibitor, antibody, and cell therapy. Considering that the PROTAC technology presents a great opportunity for China to realize cornering overtaking in the competition of drug discovery, China needs to accelerate the development of PROTAC drugs.

(6) Lineage-traceable multiplexed single-cell sequencing technology

Lineage-traceable multiplexed single-cell sequencing (SC-seq) technology integrates cutting-edge SC-seq technologies and computational analyses to re-construct the cell lineages in normal and disease tissues. It involves multiplexed cellular

barcoding, multi-modal single-cell omics, and CRISPR-based cloning analysis, which enable the establishment of dynamic cell atlases at tissue-, organ- and organism-levels, and the underlying gene regulatory networks. With the increasing application of SC-seq technologies in life sciences and medicine, lineage-traceable multiplexed SC-seq technology has been used extensively to study the composition and developmental history of normal tissues and the etiology and transformation process of diseases. The inference of tumor clone evolution has promoted our understanding of the tumor progression and relapse after therapy, revealing useful biomarkers for precision oncology. Currently, laboratories around the world have come together to build the Human Cell Atlas and Tumor Cell Atlas. Lineage-traceable multiplexed SC-seq technology is among the most recent technological advancements of these projects that could revolutionize the study of human diseases. In the future, its maturation and further development will benefit from high-throughput long-read sequencing (DNA or RNA), custom-design of cellular and molecular barcoding for multiplexed sequencing, effective processing of clinical samples for SC-seq studies, and computational tools for multi-modal single-cell datasets. Lineage-traceable multiplexed SC-seq technology is expected to play a key role in studying the mechanism of recurrent and relapsed cancers by revealing the primary and secondary tumor clones between treatments. This line of investigation could serve as the foundation of precision medicine. It will reveal useful biomarkers for the diagnosis and prognosis of relapsed patients and provide important clues for the development of therapeutic strategy for the treatment of relapsed cancers.

(7) A technical system for the efficient discovery of pharmacodynamic substances in traditional Chinese medicine

The pharmacodynamic substances of traditional Chinese medicine (TCM), which are extracted and isolated from Chinese medicinal materials, Chinese decoction pieces, Chinese patent medicines, or prescriptions, are chemical substances with specific pharmacological activities for the treatment or prevention of diseases or regulation of the physiological functions of the body. It includes both the original components of traditional Chinese medicine and the newly generated metabolites of traditional Chinese medicine. The determination of effective substances from the complex material system of TCM remains one of the core scientific and technological challenges in TCM modernization. The

development of modern analysis and separation technologies has encouraged the gradual employment of new technical means such as chromatography-mass spectrometry analysis, chromatographic separation, NMR structure identification, and multi-omics analysis for the exploration of TCM pharmacodynamic substances. This provides technical support for promoting the study of the material basis of TCM and the discovery of active lead compounds and innovative drugs based on TCM and natural medicine resources. Relevant technologies are also being constantly updated. For example, direct infusion-tandem mass spectrometry (DI-MS/MSALL), which performs analysis at high speed and can simultaneously detect chemical components with different polarities, has replaced liquid chromatography mass spectrometry (LC-MS). A precision single-cell microfluidic technology platform has been developed. With the combination of advanced analytical techniques such as high-content imaging and mass spectrometry, the active components of TCM can be directly screened from complex systems without pre-separation of the components. Cell membrane chromatography in bio-chromatography has become a hot spot in the field of traditional Chinese medicine in recent years. It is used for the separation and identification of medicinal components based on whether the components in the extract have specific affinity with active cells. *In vitro* cell membrane chromatography can quickly and effectively screen the effective parts and active components of traditional Chinese medicine compounds, thus allowing the high-throughput screening of traditional Chinese medicines.

In recent years, the identification technology of *in vivo* metabolites of TCM based on “omics” has garnered much attention. The robust applications of transcriptomics, proteomics, and metabolomics can be found in TCM pharmacodynamic research through the comparison of miRNA expression, gene expression, protein expression or metabolites before and after intervention with TCM. It further clarifies the mechanism of action of TCM pharmacodynamic substances and offers the potential to systematically evaluate the efficacy of the active ingredients or components. The rapid development of omics provides a new means for the integration of traditional Chinese medicine with modern technology and systems biology. High-throughput and high-content screening by using innovative platforms substantially increases the efficiency for activity evaluation and the screening rate of active compounds. High-throughput

screening enables the large-scale activity screening of components, while high-content screening simultaneously increases the dimensions of the screening. This may be a significant boost for the rapid discovery of pharmacodynamic substances in the complexities of TCM and allows the analysis of gene, protein, and metabolite spectra of biological systems and the large-scale study of the biological functions. Network pharmacology based on computer simulation is widely used in the research of the pharmacodynamics of TCM. By computing a complex biological network of “disease phenotype-gene target-drug ingredients”, the target spectrum of TCM ingredients is elucidated, pharmacologically active ingredients and mechanisms are predicted, and prescription compatibility rules are discovered.

As the human perception of complex diseases gradually expands, the traditional reductionist way of thinking (from molecules to genes then to cells) is slowly being replaced by the application of systems theory in methods such as systems biology and network biology. Multi-modal and cross-scale observation of the effects of TCM on cell phenotype, tissue/organ structure, and body function will uncover the effects of various constituents/components on multiple subsystems of the body and their synergistic effects, which may open new channels in the exploration of pharmacodynamic substances of TCM. Driven by big data, by using model construction and biological information technology, and considering the multi-component and multi-target characteristics of TCM in treating diseases, an in-depth analysis of the multi-component, multi-target, and multi-disease relationship of TCM can be carried out through AI, and an interaction network of drug component, component target, and disease gene can be constructed. The results will help predict the active ingredients, potential efficacy, clinical indications, and mechanism of action of TCM compounds, which may plot an untraveled course for the R&D of new TCM drugs.

(8) Invasive brain-machine interface technology

Brain-machine interface (BMI) creates a direct information route between the brain and external devices. It is an important tool for the cutting-edge neuroscience research and clinical diagnosis and treatment of major brain diseases. The key challenge of the development of useful BMIs is how to achieve a balance between minimizing brain damage and maximizing brain utilization, which highly depends on the specific application. In comparison with their non-invasive

counterparts, invasive BMIs are in close contact with neurons and therefore have intrinsic advantages in key performance, such as the quality of neural signals and the accuracy of neural modulation. However, the brain trauma caused by implantation surgery and the long-term *in vivo* safety of implanted devices are the current bottlenecks.

BMI is a highly sophisticated system, which involves many key components such as electrodes (more contacts, thinner, and more flexible), chips (lower power consumption), algorithms (more robust), and implantation tools (faster, less brain damage and more automatic). In terms of scientific research, BMIs can promote the sustainable progress of fundamental neuroscience by mapping the brain validity connection network and analyzing new neural circuits through high-throughput neural data recording in multiple brain regions. In the diagnosis and treatment of brain diseases, BMIs can build the connection between human brain and neural prosthesis by extracting and decoding neural activities of the brain spatially and temporally to restore and/or replace the motor function of limbs. It can also simulate and transmit corresponding signals to the target position and provide nerve stimulation for nerve repair. In military applications, by using high-performance BMI technology, the information communication between the brain and the electronic system is optimized in the form of direct information interaction to improve the efficiency of information analysis and execution. It allows human beings to effectively participate in decision-making and keep up with the pace of ever-evolving machines.

At present, more than 200 companies provide BMI-related products and services around the world, mainly in the USA (more than 50% of the global market), the European countries (Germany, UK, and Switzerland), and China. The global BMI market is expected to grow at a compound annual growth rate of 13.8% from 2020 to 2027, and the industry scale will grow to more than 3 billion US dollars by 2027. Clinical validation for major disease treatment will be the key arena for BMI technologies. However, insufficient recording channels, large implantation trauma, and lack of close-loop control (i.e., record and stimulate) are key challenges that need to be solved. High-throughput, minimally invasive implantable closed-loop BMI technology has gained widespread attention and is gradually becoming the key research direction worldwide at present and in the next 5–10 years.

In the field of invasive BMIs, China still lacks original core

technology and many key performances of BMI for real-world applications, such as the bandwidth, accuracy, and *in vivo* stability, and the technology still lags behind that of the USA. In recent years, increasing domestic units have begun to turn to the research of invasive BMI technology. In 2021, the Shanghai Institute of Microsystems and Information Technology, Chinese Academy of Sciences developed the “a minimally invasive implantable high-throughput flexible BMI” technology, which has over 1 000 recording channels and can be implanted in the brain with a surgical opening of less than 1 mm. The technology has been verified in rodent and non-human primate animal models. At present, various key components (e.g., electrodes, chips, wireless communication and powering units) need to be synergistically integrated to achieve a high-performance BMI system with an appropriate implantation strategy. The technology needs to enter the clinical trial stage legally immediately to accelerate the verification of key technologies and the optimization of the overall system.

(9) Stem cell expansion system

Stem cells are a kind of pluripotent cells that can self-renewing and differentiate into various functional cells under specific conditions. They are essential for the study of tissue and embryo development, regenerative medicine, and the development of novel drugs. Stem cell expansion system (SCES) is a sterile culture technology and equipment that is used to increase the number and maintain the characteristics of stem cells after isolation, purification, and identification through morphological and molecular biological approaches. This technology precisely regulates the cell-cell, cell-cytokine and cell-extracellular matrix interactions by bioinspired design the stem cell niche *in vivo* (including physical, chemical and biological signal parameters). It aims to promote stem cell self-replication on a large scale, reduce cell damage, senescence, and stemness loss, and maintain cell homeostasis and differentiation potential for improving the quantity, function, and safety of stem cells. At the same time, the individualized stem cell expansion process and quality control standards should be established in line with the application demands to improve the stem cell expansion efficiency and reduce the production cost. SCES is rapidly developing towards diversification, standardization, and large-scale use, and it has become one of the main technology platforms for stem-cell-based biomedical basic research and translational medicine. The effective SCES of human induced pluripotent

stem cells strongly supports the construction of human organs and intelligent human multi-organ chip systems, showing its promising applications in the areas of human physiological and pathological simulation and new drug development. A variety of SCES of adult stem cells has gradually entered the clinical transformation of stem-cell-based regenerative medicine to overcome the limitations of traditional medical treatment, including hematopoietic stem cells (HSCs) that are used for the treatment of leukemia, mesenchymal stem cells (MSCs) that have been used for immune regulation and tissue repairs of uterus, skin, and cartilage, and human neural stem cells (NSCs) that have been used to repair various nervous system injuries. Considering the wide application prospects of SCES in the field of biomedical basic research and clinical translational, the development of SCES has attached huge investment in China and developed nations such as Europe, the USA, Japan, and South Korea.

With the opening of national policies in recent years, many technology start-up companies have been established at home and abroad. These companies have developed and optimized a series of new reagents and automated equipment that can realize the safe application of stem cells to clinical and drug screening, such as a complete kit of cell culture reagents with safe and identified components, fully enclosed culture equipment that reduces artificial error and contamination risk, and cell-free treatment programs by producing engineered exosomes. These technologies and products have formed a certain scale, and their market will increase with as the stem cell research continues to advance quickly. The key breakthroughs in SCES include the development of large-scale manufacture processes of stem cell expansion, empowerment, separation, and related reagents to perfect a comprehensive and accurate quality control standard system, further innovate the bioactive stem cell carrier materials, and the fully enclosed automatic cell production equipment that monitors cell status in real-time and regulates the cell microenvironment. A new era of visualization, quantification, and controllable biologically active drugs based on stem cells will usher because of the deep integration of SCES with material engineering, imaging technology, and numerical control technology.

(10) Intelligent tumor risk assessment based on multimodal biomedical big data

The cancer-risk intelligent assessment is developed based on

massive multi-source (heterogeneous) multimodal biomedical data under macroscopic and microscopic scales by using high-performance computing systems, bioinformatics technology, machine/deep learning methods, and other “IT+BT” technologies. The cancer-risk intelligent assessment system mainly aims to boost the prevention, diagnosis, and treatment of malignant tumors by dynamically providing a full-process, interpretable, high-precision, and interactive risk assessment/decision-making guidance. The intelligent cancer-risk assessment system requires the establishment of scalable, high-quality standardized datasets, intelligent hospital resource planning systems, daily health monitoring/follow-up systems, cancer imaging/omics/pathological detection methods, trusted biocomputing, and multi-scale software and hardware platforms such as data visualization/analysis tools (i.e., deconvolution algorithms for tumor cells and their microenvironment), natural language retrieval systems, and professional knowledge base/databases. The construction of new tools for cancer-risk assessment can be accelerated by providing theories, technologies, and platforms to facilitate the collection, storage, sharing, fusion, deep mining, model/marker validation, and clinical applications of cross-scale multimodal biomedical big data. The intelligent cancer-risk assessment system is valuable for the dynamic monitoring, real-time warning, and early screening of various malignant tumors, which is the basis of individualized treatment and early intervention for disease progression. It can provide different disease risk reports for healthy people and patients from real-world clinical practice/clinical trial. Currently, the commercial products of AI-assisted diagnosis (e.g., medical imaging) and high-throughput multi-omics detection have been widely promoted and applied in China and other countries. These commercial products provide substantial case and data resources for the precision diagnosis and development of novel targeted therapies such as small molecule therapeutics/cellular immunotherapy. With the population aging trend and the increasing incidence of cancers, the demand for intelligent health diagnosis products will continue to increase. The economic benefits are expected to grow from tens of billions to hundreds of billions of dollars in the next few years. Big scientific projects represented by TCGA, the Cancer Cell Line Encyclopedia, the UK Biobank, the Human Proteome Project (HPP), and the International HPP (IHPP) have provided unprecedented opportunities for the early prevention and precise diagnosis and treatment of

cancer. In the future, additional advancements will be crucial for the products of intelligent tumor risk assessment, such as the construction of the sharing platform for all cancer/data types, the integrated analysis of large-scale electronic health record systems, and the development of dynamic modeling methods for multimodal data and millions of healthy people/disease cohorts. In addition, omics-based molecular diagnosis (i.e., single-cell/single-molecule detection), AI-based drug virtual screening technologies, and other cloud computing and information technologies are still iterating. These emerging technologies and the establishment of intelligent cancer-risk assessment systems will substantially promote the understanding of tumor susceptibility mechanisms, the discovery of targeted agents and their sensitive patients, and the design of clinical trials. It will become one of the indispensable aspects for reducing the economic burden of tumor-susceptible populations/patients and improving patients' long-term survival and quality of life.

2.2 Interpretations for three key engineering development fronts

2.2.1 Organoid-based drug screening

Organoids are tissue analogs with a certain spatial structure formed by *in vitro* three-dimensional (3D) culture of human tissue stem cells or patient tumor tissues. These analogs have stable phenotypic and genetic characteristics, thus enabling long-term and stable subculture. In comparison with traditional two-dimensional culture models, organoids effectively simulate the physiological functions of source organs or tissues in structure and function. Moreover, compared with animal models, the construction of organoids is less expensive and simpler in terms of operation, and faster in culture with a higher rate of success, making it suitable for disease pathology research and high-throughput drug screening. These advantages also justify the widespread use of organoids in precision medicine, regenerative medicine, drug screening, and disease modeling. Since the first mouse intestinal organoid is developed in 2009, numerous organoids with some key physiological structures and functions and the corresponding tumor tissue organoids have been cultured and established, including the kidney, liver, lung, intestine, brain, prostate, and pancreas. Guiding clinical medication and precision treatment is an important goal of organoid

technology. Organoids have been listed in *Science's* top 10 breakthroughs of 2013 and chosen as the Method of the Year 2017 by *Nature Methods* in 2018. As of September 2020, 63 clinical trials with the use of organoids were filed in the Food and Drug Administration (FDA). Since 2017, 20 clinical studies that involve organoids and cover eight cancer types have been registered and approved by ethics committees in China. Organoids enjoy considerable development potential worldwide.

The following critical issues remain to be addressed for organoid-based drug screening: construction of various organoid and disease models, construction of complex organoid models, such as organoids that recapitulate the tumor microenvironment, development of standardized, inter-batch consistent, and cost-effective organoid culture medium ingredients and basement membrane matrix, standardization and automation of organoid culture and drug screening procedures, development of multi-dimensional analytical methods for organoids, establishment of high-content imaging and analysis techniques for organoids, tracking, supervision, and management specifications of human-derived organoids, and societal acceptance and ethical review system of organoids. The key areas with critical implications for organoid-based drug screening include:

- 1) Establishment of diversified organoid and disease models. Organoids (including tumor organoids) derived from the heart, brain, lung, liver, intestine, stomach, kidney, breast, ovary, bladder, tongue, pancreas, prostate, thyroid gland, thymus, and retina have been used for drug screening. For example, MCLA-158, a bispecific antibody from Merus, was identified from the screening of patient-derived colorectal cancer organoids and is now under phase 1/2 clinical studies. The latest data show that all seven patients enrolled with head and neck squamous cell carcinoma had tumor reduction. Another typical example is a cystic fibrosis model constructed via single CFTR mutation in an intestinal organoid. Vertex's blockbuster cystic fibrosis drug, ORKAMBI, was approved in the Netherlands based entirely on the results obtained from this type of organ models. However, less than one-third of all 78 organs in the human body have been constructed as organoids. Non-tumor disease models based on organoids are even more limited. The establishment of diversified organoid and disease models that cover the spectrum of human diseases is the premise of drug screening and development and thus exhibits various possibilities.

2) Construction of vascularized, immune, and systematic organoid models. Various tumor organoids, which are constructed to screen the majority of cytotoxic and targeted drugs, are not applicable to angiogenesis inhibitors and immunotherapy that are now under the spotlight, because they lack tumor microenvironment details, such as blood vessels, immune cells, and stromal cells and thus cannot realize the effects of angiogenesis inhibitors and immunotherapy in full. Tumor organoids with vascular structures have been constructed, and anti-tumor immune cells have been produced by co-culturing immune cells with tumor organoids. “Assembloids” that are composed of multiple organ cell types, which are spatially organized to precisely simulate human tissues or organs, have also been reported in studies over the past few years. Although these models enhanced the complexity of tumor organoid microenvironment, they cannot be compared to the one *in vivo*, and they are rarely used for drug screening. Systematic organoid models require the connection of multiple types of organoids to mimic the circulation of materials, energy, and body fluids involving their counterparts *in vivo*, enabling a thorough evaluation of the efficacy and toxicity of drugs. For example, heart, liver, kidney, and intestine organoids are enriched in a chip, in which a culture medium is perfused to simulate the circulatory system. Candidate drugs can then be analyzed for toxicities to several important organs at one time. The construction of vascularized, immune, and systematic organoid models further improves the accuracy of organoid simulation of *in vivo* situations and is expected to provide more comprehensive pharmacodynamics and toxicity information for drug screening.

3) Optimization of an organoid culture system for drug screening. Drug screening requires large-scale and stable production of organoids, and its major constraints are organoid culture medium and basement membrane matrix with complex ingredients. Organoid culture medium usually contains miscellaneous critical growth factors, such as EGF, FGF2, R-Spondin 1, Noggin, and Wnt3a. These growth factors have been commercialized but are often exorbitant, with varying quality between batches. Moreover, their manufacturers may apply different specifications. The downside partially limits the large-scale application of organoids for drug screening. The basement membrane matrix has even more constraints than the organoid culture medium. The most commonly used basement membrane

matrix, Matrigel, provides essential three-dimensional support and some growth factors for organoid growth. However, the product, which is derived from extracts of Engelbreth-Holm-Swarm (EHS) mouse sarcoma tumors, is characterized by complex ingredients, large batch-to-batch differences, and the potential rejection of some human-derived organoids. Some researchers and companies have developed purely chemically synthesized substitutes for the basement membrane matrix and performed several organoid culture studies. However, these novel substitutes have not been fully proven to be functionally equivalent to Matrigel and are not readily accessible. Most growth factors can now be produced in China, but this is not the case for basement membrane matrix, because virtually all GMP-grade products need to be imported. In addition, the development and application of 3D bioprinting technology in organoid design and construction provide possible solutions for the large-scale, standardized, and precise production of complex organoids.

4) Development of multi-dimensional analytical methods for organoids and standardized evaluation of drug screening. Conventional methods include cell imaging, pathological detection, and gene sequencing. However, a series of analytical methods that are further applicable to large-scale drug screening should be developed to produce and evaluate organoids in a multi-dimensional and standardized manner. For example, ordinary microscopes hardly obtains a photograph of organoids in three-dimensional space. Meanwhile, a high-content imaging system provides abundant physiological or pathological phenotype information about organoids, although some commercial high-content imaging systems are expensive and limited by the slow running speed and unstable operation. In addition, researchers usually cannot obtain all the information from high-content images on organoids through only visual observation or simple software analysis. For high-throughput drug screening, a standardized evaluation system needs to be established. By using image recognition and AI, standardized analysis algorithms can be developed to evaluate parameters, such as organoid activity, size, composition, and spatial structure, and drug effects and safety.

Cell and animal models are an important foundation for disease modeling and drug development. A large number of rare diseases for which drug development is not possible due to lack of relevant animal models. Traditional cell models are quite different from actual physiological conditions, while

animal models face issues of long duration of modeling, high cost, and difficulty in automatic culture. Therefore, drug R&D is challenged by immense cost, long duration, and high probability of failure. Organoids hold promise for more efficient and precise drug screening and R&D. Since 2015, Pfizer, Johnson & Johnson, Sanofi, AstraZeneca, and other leading global drug companies have increased their presence in organoids through services procurement, collaboration and licensing, and investment. In 2022, the FDA approved the world's first new drug for a clinical trial (NCT04658472) with preclinical data based on an "organ chip". The approval represents the FDA's acceptance of organoid studies and provides a new option for drug studies targeting diseases that lack appropriate animal models. As a late starter in this field, China still manages to catch up with the advanced level by virtue of its prior knowledge of scientific research and policy and regulatory support. From 2009 to 2019, only 8% of the published papers associated with organoids came from Chinese teams. In 2020, this figure rose to 14%, second only to the USA. In January 2021, China's Ministry of Science and Technology issued the notice on soliciting opinions for the guidelines of application in 2021 for six key specialized projects of the 14th Five-Year Plan's National Key R&D Program including "mathematics and applied research". As stated in this Notice, "stem cell-based human major refractory disease models" are one of the first key projects in the 14th Five-Year Plan. In December 2021, the NMPA issued the "Technical Guidelines for Non-Clinical Research and Evaluation of Gene Therapy Products (Interim)", which first included organoids

in the validation guidelines for gene therapy and cell therapy. In July 2022, the first expert consensus on organoids to guide precision oncology was established in China. Considering that the organoid industry enjoys high-speed development and broad prospects, the product transformation and clinical application of organoids need to be accelerated in China.

As of 2021, 198 core patents have been published in the front of "organoid-based drug screening", and the top three countries with the greatest output of core patents are China, the USA, and South Korea (Table 2.2.1). Up to 30.81% of such patents are filed by Chinese applicants, making China one of the frontrunners in this field (Table 2.2.2). However, collaboration is absent between the top core patent-owning countries. The top core patent-owning institutions include the Yonsei University, Royal Netherlands Academy of Arts and Sciences, Swiss Federal Institute of Technology in Lausanne, and Keio University (Table 2.2.2). Among these institutions, collaboration is only present between Keio University and Osaka University in Japan (Figure 2.2.1).

So far, organoid technology has been widely used in many fields, including disease modeling, drug development and drug screening. Under 3D culture conditions, many kinds of organs such as lung, stomach, intestine, liver, kidney and other organoids have been successfully cultivated. Guiding clinical medication and precision treatment is an important goal of organoid technology. Engineered organoids, a combination of bioengineering techniques is used to standardize and automate the production, control and

Table 2.2.1 Countries with the greatest output of core patents on "organoid-based drug screening"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	China	57	30.81	74	15.64	1.30
2	USA	48	25.95	158	33.40	3.29
3	South Korea	32	17.30	8	1.69	0.25
4	Japan	15	8.11	43	9.09	2.87
5	Netherlands	6	3.24	77	16.28	12.83
6	Switzerland	5	2.70	54	11.42	10.80
7	UK	5	2.70	40	8.46	8.00
8	Australia	5	2.70	3	0.63	0.60
9	Germany	3	1.62	5	1.06	1.67
10	Sweden	2	1.08	3	0.63	1.50

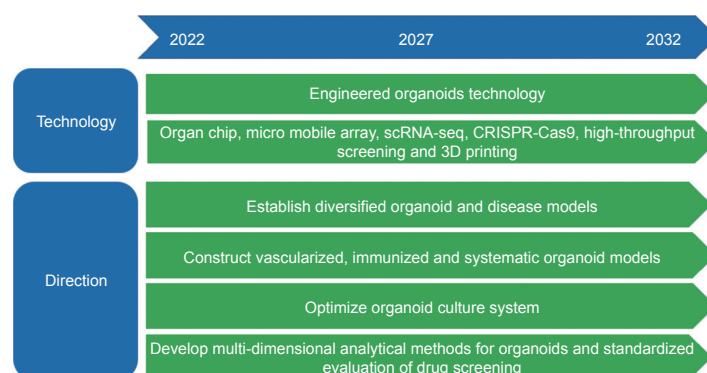


Figure 2.2.2 Roadmap of the engineering development front of “organoid-based drug screening”

2.2.2 *In vivo* gene editing technology

Approximately 70 years since the discovery of the DNA double helix, the techniques for determining, analyzing, and altering genome sequences and gene expression patterns in cells and organisms have been developed. These molecular tools are the foundation of molecular biology, thus improving the biomedical industry by increasing the understanding of the genetics of normal and disease traits. The ability to diagnose genetic diseases has grown rapidly as the cost of genome sequencing has decreased, the comparative analysis of human genome sequences has increased, and the application of high-throughput genomic screening has increased. Preliminary research suggests that genome editing tools can be used to inactivate or correct disease-causing genes in patients, leading to novel, life-saving treatments for people with genetic disorders.

The commonly used tools for gene-editing technology include Zinc Finger Endonuclease (ZFN), Transcription Activator Like Effector Nuclease (TALEN), and CRISPR-Cas (Clustered Regularly Interspaced Short Palindromic Repeats-associated) system. CRISPR-Cas9 was first discovered in bacteria and archaea. It is an adaptive immune defense mechanism formed during the long-term evolution of bacteria to fight invading viruses and foreign DNA. Scientists have used the CRISPR-Cas9 gene-editing technology to make specific DNA modifications to target genes and have made significant progress in applications involving gene therapy, such as blood diseases, tumors, and other genetic diseases. By using the Cas9 enzyme to discover, cut, and replace specific sequences of DNA, CRISPR-Cas9 gene editing can make permanent and precise changes to a patient's chromosomes, repair potential genetic mutations, and cure diseases with genetic origins. Therefore,

it is considered as a “game changer” in biology.

Recent advances include the development of robust tools for gene editing in mammalian cells, including programmable nucleases, base editors, and prime editors. These gene-editing agents have been widely applied for the treatment of numerous disorders with a genetic component across various animal models.

At present, product development by using CRISPR gene-editing technology as a gene therapy method covers the fields of blood diseases, solid tumors, rare diseases, and regenerative medicine. Therapeutic gene editing has greatly facilitated the applications of gene-editing therapies into clinical practice.

Jennifer Doudna, who won the Nobel Laureate in Chemistry, pointed out in the 2020 *Nature* review that “Delivery remains perhaps the biggest bottleneck to somatic-cell genome editing.” According to whether the gene-editing process occurs *in vivo* or *in vitro*, CRISPR can be divided into *in vitro* gene editing and *in vivo* gene editing. Most current gene-editing clinical trials are limited to *in vitro* gene editing, and the process is quite complex, including the isolation of cells from patients, *in vitro* editing, and reinfusion to patients. At present, this kind of research has made important progress in blood diseases and has been applied for the treatment of solid tumors. However, most diseases are not suitable for *ex vivo* manipulation. *In vivo* gene editing involves the use of vectors to directly deliver CRISPR to human diseased organs and tissues and directly modify diseased genes in the human body.

The *in vivo* gene-editing process is simple and oriented to a wide range of indications, and the cost is only about one-

tenth of the *in vitro* gene-editing treatment, providing the greatest hope for the development of many drugs for genetic diseases that patients can afford. However, the key to making therapeutic *in vivo* gene editing a reality is the safe and effective delivery of gene-editing agents to relevant organs and tissues in the body.

To overcome the off-target risk and immune response risk of *in vivo* gene editing, the ideal *in vivo* delivery of gene editing should be transient and cell-targeted. The delivery technologies currently used to achieve *in vivo* gene editing contain adeno-associated virus (AAV) delivery, lipid nanoparticle (LNP) delivery, and virus-like particle (VLP) delivery. These delivery technologies have been validated in mice, non-human primates (NHPs), and other animals, and are entering the stage of clinical validation.

1) Virus Delivery. Viruses naturally evolved to overcome barriers to *in vivo* delivery and can natively deliver nucleic acid cargos to many cell types. Considering these favorable characteristics, viruses are promising vehicles for delivering gene-editing agents. Many viral vectors have been developed for *in vivo* gene therapy applications. Most *in vivo* gene editing applications use adeno-associated viruses (AAVs), and a few pre-clinical studies have used lentiviruses or adenoviruses. To date, viral vectors offer some of the highest gene-editing efficiencies observed in many organs because of their inherent ability to efficiently transduce different types of cells and deliver their nucleic acid vectors *in vivo*. However, the progress of AAV-CRISPR therapy also faces a series of obstacles that are prevalent in the development of AAV gene therapy. Future improvements to viral vectors will require careful efforts to overcome the challenges outlined above, including the immunogenicity of the vector, prolonged expression of the gene editing agent, off-target gene editing, potential for genomic integration, manufacturing cost, and dose-limiting toxicity. Vector engineering approaches to improve the potency and specificity could reduce the required dose and the cost of manufacturing of viral delivery platforms. Methods to durably silence cargo expression after on-target editing will also substantially improve the safety profile of viral delivery.

2) Lipid nanoparticle (LNP) Delivery. LNPs have grown increasingly popular as non-viral vehicles for delivering gene-editing agents *in vivo*. For decades, LNPs have been used to deliver nucleic acid cargos, including siRNAs and therapeutic mRNAs. Their encapsulated payloads are delivered into target

cells by first entering cells through endocytosis, and then escaping endosomes by disrupting endosomal membranes after endosome acidification, and subsequently gaining access to the target cell cytosol. Following extensive development and optimization, LNPs have been approved for use in humans by the US FDA, including the intravenous administration to deliver therapeutic siRNAs to hepatocytes, for the treatment of transthyretin amyloidosis (ATTR). However, most nucleic acids delivered by LNP are degraded through the endosomal pathway and still face endosomal escape. The further development of LNPs needs to overcome the challenges of extrahepatic tissue delivery.

3) Virus-like particle (VLP) Delivery. VLPs have emerged as potentially promising vehicles for delivering gene-editing agents. VLPs are non-infectious assemblies of viral proteins that package desired cargo mRNAs, proteins, or RNPs in addition to or instead of viral genetic material. Considering that VLPs are derived from existing viral scaffolds, they exploit natural properties of viruses that enable efficient intracellular delivery, including their ability to encapsulate cargos, escape endosomes, and achieve efficient intracellular delivery. VLPs can be specifically delivered to different types of cells through reprogramming on the particle surface. However, unlike viruses, VLPs transiently deliver gene-editing agents as mRNA or protein instead of as DNA, which substantially reduces the risks of off-target gene editing and viral genome integration. Given that more than 50% of the human population has a pre-existing immune response against Cas9, the characteristics of VLP transient delivery can effectively reduce the risk of gene-edited cells being cleared by the human immune system. Therefore, VLPs are attractive vehicles for delivering gene editing agents, because they can offer key benefits of both viral and non-viral delivery.

In June 2021, the *New England Journal of Medicine* reported the first clinical research data supporting the safety and efficacy of CRISPR gene editing *in vivo*. The indication for this study is transthyretin amyloidosis (ATTR), a rare autosomal dominant disorder, which is a life-threatening disease characterized by the progressive accumulation of misfolded transthyretin (TTR) protein in tissues, predominantly the nerves and heart. NTLA-2001 is an *in vivo* gene-editing therapeutic agent that is designed to deliver liposome-encapsulated CRISPR-Cas9 complexes by intravenous infusion, reducing the concentration of TTR in serum. The research has opened up new avenues for the treatment of human diseases

and has been hailed as “opening a new era of medicine”. In addition, Editas Medicine has conducted a clinical study of Leber’s congenital amaurosis type 10 based on AAV delivery of CRISPR (EDIT-101). In China, BDgene Therapeutics Co., Ltd. has carried out clinical research on CRISPR antiviral treatment of viral keratitis based on VLP delivery.

New techniques of *in vivo* gene editing are also emerging. In June 2022, Precision BioSciences announced that it had reached an exclusive worldwide collaboration and licensing agreement with Novartis for *in vivo* gene editing R&D. Precision will develop a custom ARCUS nuclease based on a naturally occurring genome-editing enzyme, I-Crel, which has evolved from *C. reinhardtii* to perform highly specific cleavage in cellular DNA. Precision scientists reengineered I-Crel to form the ARCUS nuclease to edit new DNA sequences for the insertion, removal, or repair of DNA in living cells and organisms. The approach holds promise for the treatment of certain hemoglobin disorders, such as sickle cell disease and beta-thalassemia.

The clinical application of gene editing has a double standard of safety and efficacy. Viral vectors have uncertainties in safety because of the long-term expression of gene editing enzymes, while nanomaterials face efficiency challenges. An ideal gene-editing delivery tool needs to be both transient and efficient to ensure the safety and efficacy of the treatment. Therefore, the CRISPR gene-editing technology needs to be carefully evaluated. Notably, the “God’s knife” of CRISPR gene editing must also resolve ethical and moral conflicts.

The era of therapeutic gene editing in humans has arrived. Extensive development and optimization of CRISPR-Cas technology has yielded powerful gene-editing tools, including nuclease, base, and guide editing. The combination of these gene editing tools with effective *in vivo* delivery methods (viral vectors, LNPs, and VLPs) for the treatment of disease has been applied from proof-of-concept in animal models to clinical treatment in humans. With the development of *in vivo* gene editing therapies and future advances in gene delivery technology, it will provide a reliable approach and a solid foundation for the clinical treatment of genetic diseases in different organs.

The countries with the largest number of core patents are the USA, China, and Switzerland (Table 2.2.3). As shown in the cooperation network among main countries, the USA, Switzerland, China, the UK, Germany, Netherlands, and Japan have cooperation (Figure 2.2.3). The top institutions in terms of core patents output are Harvard University, The Broad Institute Incorporation, and University of California (Table 2.2.4). A cooperative relationship was observed between The Broad Institute Incorporation, Massachusetts Institute of Technology (MIT), Harvard University, and Brigham and Women’s Hospital. Partnership was also present between CRISPR Therapeutics and Vertex Pharmaceuticals Incorporated (Figure 2.2.4).

According to statistical analysis results, China is currently in a situation of running parallel with similar foreign countries for the development of “*in vivo* gene editing technology”.

Table 2.2.3 Countries with the greatest output of core patents on “*in vivo* gene editing technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	USA	493	67.91	4 594	81.05	9.32
2	China	103	14.19	209	3.69	2.03
3	Switzerland	51	7.02	538	9.49	10.55
4	South Korea	16	2.20	32	0.56	2.00
5	UK	15	2.07	55	0.97	3.67
6	France	14	1.93	106	1.87	7.57
7	Germany	12	1.65	28	0.49	2.33
8	Netherlands	7	0.96	118	2.08	16.86
9	Canada	7	0.96	22	0.39	3.14
10	Japan	5	0.69	88	1.55	17.60

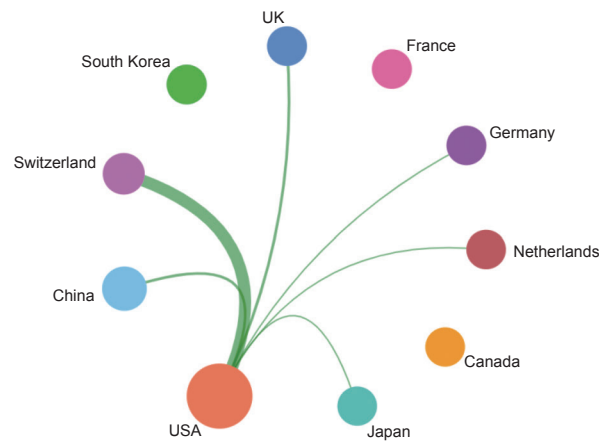


Figure 2.2.3 Collaboration network among major countries in the engineering development front of “*in vivo* gene editing technology”

Table 2.2.4 Institutions with the greatest output of core patents on “*in vivo* gene editing technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Harvard University	61	8.40	1 229	21.68	20.15
2	The Broad Institute Incorporation	54	7.44	644	11.36	11.93
3	University of California	48	6.61	469	8.27	9.77
4	CRISPR Therapeutics	37	5.10	301	5.31	8.14
5	Massachusetts Institute of Technology	31	4.27	614	10.83	19.81
6	Dana-Farber Cancer Institute	19	2.62	85	1.50	4.47
7	Brigham and Women's Hospital	18	2.48	98	1.73	5.44
8	Beam Therapeutics	17	2.34	70	1.24	4.12
9	Stanford University	14	1.93	77	1.36	5.50
10	Vertex Pharmaceuticals Incorporated	11	1.52	112	1.98	10.18

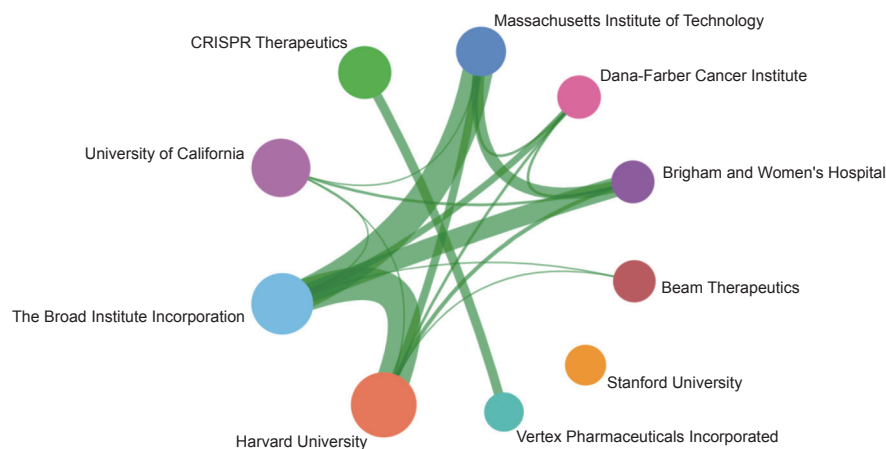


Figure 2.2.4 Collaboration network among institutions in the engineering development front of “*in vivo* gene editing technology”

Considering that the CRISPR gene-editing technology has great advantages and prospects in the fields of disease treatment, disease detection, and genetic breeding, the commercial application of CRISPR gene-editing technology has broad prospects. The original gene therapy vector independently developed by Chinese scholars reflects China's scientific and technological progress in the field of gene therapy.

In vivo gene editing has more diversity and flexibility in the selection of adaptation disease, which can cover almost all diseases. *In vivo* gene editing has higher requirements on vector technology. In particular, vector technology needs to be safety and effective. In order to improve the safety of gene editing therapy *in vivo*, one is to develop more precise gene-editing enzymes, the second is to realize efficient gene editing enzyme delivery system. At present, VLP and LNP can achieve mRNA delivery *in vivo*, which has been clinically verified and is an ideal delivery vector for gene editing therapy *in vivo*. In the future, the tissue targeting of vectors needs to be further solved. Future directions will focus on the optimization of nuclease-mediated gene editing technology, the development of novel base editing therapies, and the realization of tissue-specific gene editing enzyme and instantaneous delivery technology. At present, the R&D of *in vivo* gene editing technology mainly focus on rare diseases, ocular diseases, and the development of neurological diseases is still in a very early stage. In the long run, gene editing *in vivo* has made it possible to cure HBV, HPV, HIV, HSV, and other viral infections. In addition, the possibility of clinical breakthroughs in the treatment

of metabolic diseases and neurological diseases by gene editing *in vivo* is promising. Huntington's disease that have no substantial breakthroughs for a long time may be cured by gene editing *in vivo* (Figure 2.2.5).

2.2.3 Development and application of single base editors in biomedicine

Base editor (BE) is a new genome-editing tool developed by combining the CRISPR-Cas system with different deaminases. With the guidance of CRISPR-Cas system, the fused deaminase is directed to bind the target locus and catalyze the site-specific deamination within editing window. It stimulates cellular base excision repair (BER) and DNA replication of that strand to achieve precise base substitution. In 2016, the first base editor (BE), namely, the cytosine base editor (CBE), which is a derivative of the CRISPR-Cas system, efficiently and precisely converted the C–G base pair to a T–A base pair without inducing DNA double-stranded breaks (DSBs) and without participate of DNA templates. CBE has become a milestone as it rapidly brought genome-editing technology into the era of single-base resolution. The following year, another BE, namely, adenine base editors (ABEs), induced a A–T base pair to a G–C base pair substitution efficiently, further booming development of base editor tools. In recent years, researchers have worked on the development and optimization of BEs and have generated many new BEs with richer variants, improved functions, and expanded application scenarios. In term of functions, in addition to CBEs and ABEs, researchers have developed glycosidase base editors (CGBEs) that enable substitution from C–G base pair to G–C base pair

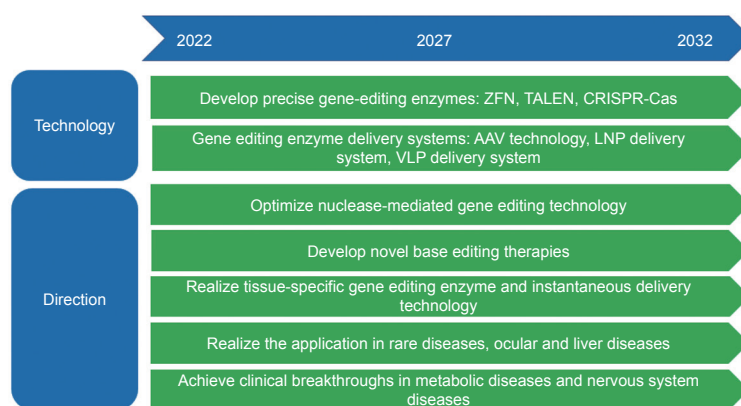


Figure 2.2.5 Roadmap of the engineering development front of "*in vivo* gene editing technology"

and from C–G base pair to A–T base pair substitution and dual-base editors that enable concurrent adenine and cytosine editing, such as STEME, ACBE, and AGBE. According to editing substrates, the aforementioned BEs are nuclear DNA base editors, and RNA base editors (e.g., REPAIR and RESCUE) and mitochondrial DNA base editors (e.g., DdCBE and TALEd) have been developed. Theoretically, the BEs reported currently can correct approximately 2/3 of pathogenic single nucleotide variants, but they cannot introduce all six possible base pair conversions. To break through this limitation, David R. Liu and colleagues have developed the prime editors (PEs) that can mediate all 12 possible base-to-base conversion without requiring DSBs, which substantially expands the scope of genome editing at single-base resolution. Based on the existing data, PE applications are limited by low editing efficiency, keeping it from being a core tool in the field of base editing.

DNA base editors enable the permanent and irreversible conversion of one target DNA base into another in genome, while RNA base editors merely modify RNA sequences and do not change the genome sequences, thus requiring continuous administration. Both tools have their advantages and disadvantages, and the optimal choice of BEs depends on the intended application.

As a new genome-editing tool, BEs have the advantages of high efficiency, precision, safety, and non-cell cycle dependence over conventional artificial nuclease system. However, some key technical hurdles were found in the practical applications of BEs, mainly including the low product purity caused by random base repair, variable editing efficiency affected by sequence context, genome targeting scope limited by PAM compatibilities, bystander editing with enlarged editing windows, Cas-dependent predictable off-target editing caused by non-specific binding of guide RNA (gRNA), random genome- and transcriptome-wide off-target editing induced by deaminases, *in vivo* delivery difficulty caused by large size of base editing components, and inability to control tissue- or organ-specific targeting. Many researchers have made remarkable progress in the optimization of existing base editing tools or development of new ones with enhanced editing performance by improving editing window, editing efficiency, precision, DNA specificity, PAM compatibility, and delivery vehicle. These advances are crucial for applications with more stringent requirements for the safety and efficacy, such as gene therapy, in which

technical barriers have been cleared up, thus promoting the translation of BEs from laboratory research to clinical practice.

The emergence of BE has met the demands for precise gene editing in the field of life science and brings gene function study to the single-base resolution. Since BEs are developed, they have been applied in animals, plants, and microorganisms successfully. BEs have also exhibited broad application prospects in biomedicine field.

To date, the hotspots of BE applications in the field of biomedicine include the following:

1) Generation of disease animal models. Among known human pathogenic mutation, single nucleotide variants account for approximately 58%, and more than 60% of them are C–G to T–A or A–T to G–C mutations. Therefore, BEs could act in generating animal models for human genetic diseases, which mimic the clinical features of patients in both genotype and phenotype. Based on BEs, many genetic disease animal models such as zebrafish, mice, rabbits, dogs, pigs, monkeys, and human cell models have been established via embryo microinjection or somatic cell nuclear transfer approaches, contributing to the investigation of mechanisms of diseases and development of novel therapeutics.

2) Gene therapy. The vast majority of human somatic cells are non-dividing and cannot be efficiently edited through conventional homology-directed repair. Given that BEs perform base conversions through cellular mismatch repair machinery, a process that does not depend on the cell cycle, they can create efficient nucleotide mutation in non-dividing cells. Accordingly, BEs are considered as an important technical tool for precision genome editing. By delivering base editing components to cells *ex vivo* or directly to the patient *in vivo*, the disease-causing mutations can be directly corrected, restoring normal function for therapeutic purposes.

3) Directed protein evolution and genomic diversification. BEs can be used to induce the mutagenesis of coding sequence of specific functional domain of protein. By using a specific screening strategy, the key amino acid sites associated with protein function can be identified, especially for those caused by point mutations related to drug resistance. A similar approach can be used to generate mutant libraries of human disease-related genes to discover key loci that determine the function of the target genes.

4) Genetic lineage tracing. Lineage tracing by using cellular marker technologies is an important tool for tracking cellular origins and fate transitions during development, disease, and regeneration. By combining the DNA barcode with single-cell sequencing technology, the information of single-cell transcriptome and associated cell lineage can be captured simultaneously, thus enabling single-cell resolution lineage tracing. Substitution mutations created by BEs can record abundant mutations per barcode. In comparison with the common CRISPR barcode strategy, BEs can accumulate more mutation information, because they do not generate indels, which is useful to reduce the consumption of barcodes. Thus, lineage tracing with BEs is effective for the reconstruction of the developmental process of tissues and organs in complex multicellular organisms.

Considering the applications mentioned above, as a new gene-editing tool, BEs have realized the treatment of many diseases, such as genetic mutation, cancer, and viral infections. In 2018, the National Institutes of Health launched the Somatic Cell Genome Editing program to accelerate the development of safer and more effective genome-editing therapeutics by editing the genomes of disease-relevant somatic cells in patients, which will enormously promote the clinical translation of genome-editing tools, including BEs.

Before formal clinical trials, BEs have been used in gene therapy research in animal models with two strategies, namely, *ex vivo* cell base editing followed by transplantation and direct *in vivo* delivery of base editing elements for disease treatment. ABEs have been used for the treatment of type I hereditary tyrosinemia by *ex vivo* editing of mouse liver precursor cells followed by transplantation for the treatment of sickle cell disease caused by the *ex vivo* editing of mouse hematopoietic stem cells followed by transfusion. In terms of *in vivo* delivery of vectors, ABEs have been used for the treatment of Hutchinson-Gilford progeria syndrome or hereditary retinal disease and Duchenne muscular dystrophy mice, to reduce cholesterol levels by editing monkey PCSK9 gene. CBEs has also been used for the treatment of amyotrophic lateral sclerosis mice. RNA base editor has been used for the treatment of genetically deaf mice.

These experimental advances in animals have laid a solid preliminary foundation for BEs to enter clinical trials. In July

2022, Verve Therapeutics in New Zealand announced that the first patient has been administrated with VERVE-101, a first-in-class base-editing medicine designed for the treatment of heterozygous familial hypercholesterolemia. This study involves the first *in vivo* base-editing clinical trial in the world and is considered as a new milestone and a crucial step in the translation of base-editing therapies from bench to bedside. Subsequent clinical trials by using BEs for sickle cell disease, β -thalassemia, and CAR-T cell editing, are also forthcoming. Notably, BEs hold an extensive application prospect in biomedicine. The use of BEs to conduct precise and efficient editing at the DNA or RNA level will be the future trend of precise gene therapy.

The market potential for gene therapy is huge, making it a popular track for capital investment. The global gene therapy market size is expected to reach 30.54 billion dollars by 2025, and China market alone will be 2.59 billion dollars. At present, the frontier of “development and application of single base editors in biomedicine” has more than 240 patents. The USA, China, and South Korea have a high number of patents, among which 36.18% of the patents are filed by Chinese authors, which shows that China has made remarkable achievements in this frontier field (Table 2.2.5). However, in terms of the proportion of citation frequency and average citation frequency of patents, that of China is significantly lower than that of USA. From the perspective of the cooperation network among the countries with core patents, the USA has cooperation with Switzerland, China, and the UK (Figure 2.2.6). The TOP institutions in terms of core patent outputs are Harvard University and Harvard-MIT Broad Institute and Beam Therapeutics (Table 2.2.6). Collaborations are present between Harvard-MIT Broad Institute and Harvard University, MIT, Brigham and Women’s Hospital, Massachusetts General Hospital, and Beam Therapeutics (Figure 2.2.7). China is closely following the world frontier in the development and application of BEs with fruitful achievements, but lack of original innovation of the root technology. Thus, China still faces challenging to step up from “following player” and “paralleling player” to “leading player”

The rapid advancement of genome editing agents over the past decade has yielded many new therapeutic possibilities to treat genetic diseases that were once considered incurable. Base editing is one of the most recent advances in the field of genome editing, which has attracted much attention since

Table 2.2.5 Countries with the greatest output of core patents on “development and application of single base editors in biomedicine”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	138	56.10	650	76.47	4.71
2	China	89	36.18	142	16.71	1.60
3	South Korea	5	2.03	21	2.47	4.20
4	Switzerland	4	1.63	21	2.47	5.25
5	UK	3	1.22	15	1.76	5.00
6	France	3	1.22	3	0.35	1.00
7	Germany	2	0.81	0	0.00	0.00
8	Italy	1	0.41	4	0.47	4.00
9	Lithuania	1	0.41	4	0.47	4.00
10	Canada	1	0.41	1	0.12	1.00

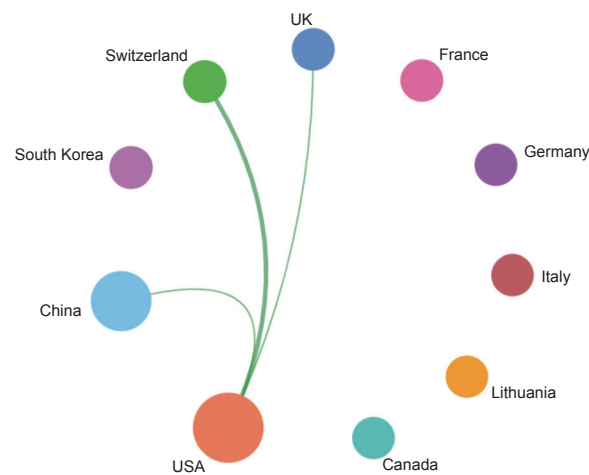


Figure 2.2.6 Collaboration network among major countries in the engineering development front of “development and application of single base editors in biomedicine”

Table 2.2.6 Institutions with the greatest output of core patents on “development and application of single base editors in biomedicine”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Harvard University	26	10.57	373	43.88	14.35
2	Harvard-MIT Broad Institute	26	10.57	122	14.35	4.69
3	Beam Therapeutics	24	9.76	77	9.06	3.21
4	Shanghai university of science & technology	20	8.13	91	10.71	4.55
5	Massachusetts General Hospital	18	7.32	70	8.24	3.89
6	MIT	14	5.69	60	7.06	4.29
7	Arbor Biotechnology Inc	8	3.25	36	4.24	4.50
8	Sun-Yat-Sen University	8	3.25	24	2.82	3.00
9	Brigham and Women’s Hospital	7	2.85	8	0.94	1.14
10	University of California	5	2.03	25	2.94	5.00

its publication in 2016. Up to now, scientists have developed more than 100 optimized base editors with improved editing efficiency, precision, specificity, targeting scope, and capacity to be delivered *in vivo* to data. Recent advances in the DNA and RNA base editors are revealing exciting therapeutic opportunities for these technologies. Together, improving and

expanding base editor technologies as well as establishing various systems suitable for human *in vivo* delivery of base editors will collectively represent the next step forward in the field of precision medicine. The roadmap of the engineering development front of “development and application of base editors in biomedicine” is shown in Figure 2.2.8.

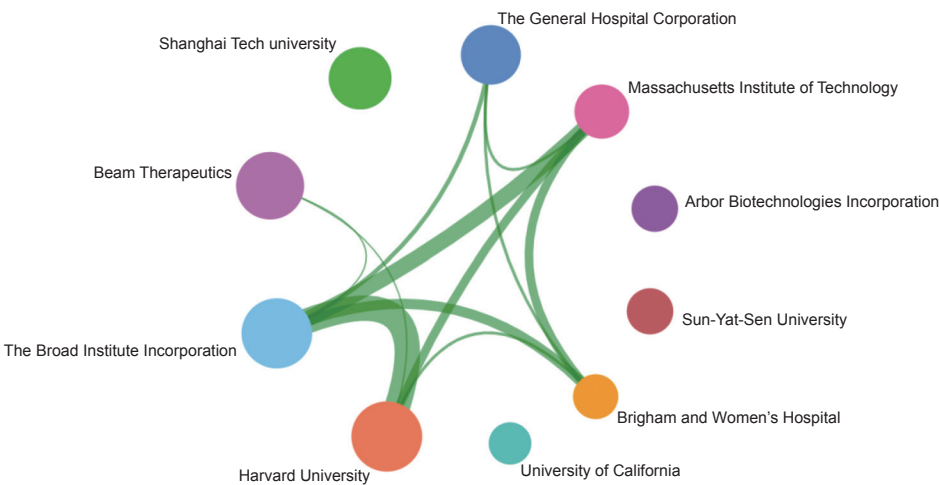


Figure 2.2.7 Collaboration network among major institutions in the engineering development front of “development and application of single base editors in biomedicine”

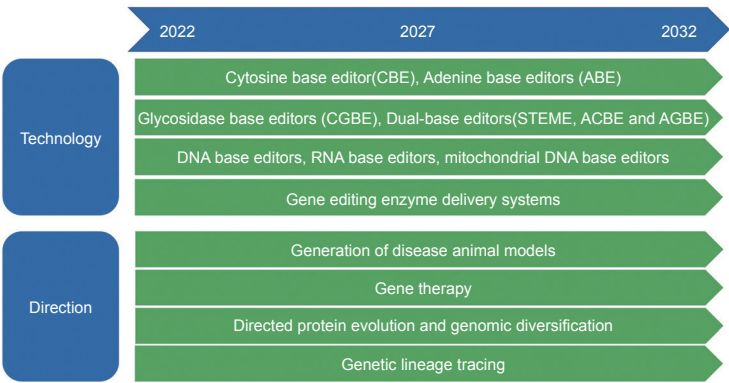


Figure 2.2.8 Roadmap of the engineering research front of “development and application of single base editors in biomedicine”

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IX. Engineering Management

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

In the field of engineering management, the global Top 10 engineering research frontiers this year are “research on industrial digital transformation empowered by industrial internet platform”, “research on global supply chain security risk management in the digital age”, “research on big data governance methods in artificial intelligence scenarios”, “research on the theory and method of accurate construction and evolution of digital twin model”, “research on sustainable transportation system under carbon peaking and carbon neutrality strategy”, “formation mechanism, evolutionary law and governance policy of global public health crisis”, “medium- and long-term sustainable supply paths and policies for basic and typical strategic resources”, “group consensus mechanism under social network”, “big data-

based financial risk assessment”, and “research on intelligent operation and maintenance management of infrastructures from the perspective of socio-technical system theory”. The core papers published are listed in Table 1.1.1 and Table 1.1.2. Among them, “research on industrial digital transformation empowered by industrial internet platform”, “research on global supply chain security risk management in the digital age”, “research on big data governance methods in artificial intelligence scenarios”, and “research on the theory and method of accurate construction and evolution of digital twin model” are the key fronts for interpretation, and their current development trends and future trends will be explained in detail later.

(1) Research on industrial digital transformation empowered by industrial internet platform

The industrial Internet platform is the carrier of scenario-driven deep integration of new generation information technology and manufacturing industry and is the key infrastructure for digital technology and data elements to collaboratively drive the digitalized, networked and

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on industrial digital transformation empowered by industrial internet platform	115	10 561	91.83	2018.3
2	Research on global supply chain security risk management in the digital age	12	710	59.17	2017.9
3	Research on big data governance methods in artificial intelligence scenarios	33	2 789	84.52	2018.3
4	Research on the theory and method of accurate construction and evolution of digital twin model	199	17 231	86.59	2019.2
5	Research on sustainable transportation system under carbon peaking and carbon neutrality strategy	96	7 830	81.56	2017.9
6	Formation mechanism, evolutionary law and governance policy of global public health crisis	6	668	111.33	2017.3
7	Medium- and long-term sustainable supply paths and policies for basic and typical strategic resources	14	1 039	74.21	2018.3
8	Group consensus mechanism under social network	14	1 835	131.07	2017.8
9	Big data-based financial risk assessment	238	18 885	79.35	2018.4
10	Research on intelligent operation and maintenance management of infrastructures from the perspective of socio-technical system theory	29	713	24.59	2018.0

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in engineering management

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Research on industrial digital transformation empowered by industrial internet platform	13	20	26	27	22	5
2	Research on global supply chain security risk management in the digital age	3	2	3	2	1	1
3	Research on big data governance methods in artificial intelligence scenarios	5	5	8	6	9	0
4	Research on the theory and method of accurate construction and evolution of digital twin model	10	20	19	56	56	38
5	Research on sustainable transportation system under carbon peaking and carbon neutrality strategy	21	21	21	14	18	1
6	Formation mechanism, evolutionary law and governance policy of global public health crisis	1	3	1	1	0	0
7	Medium- and long-term sustainable supply paths and policies for basic and typical strategic resources	2	1	6	1	4	0
8	Group consensus mechanism under social network	2	5	3	2	2	0
9	Big data-based financial risk assessment	37	35	36	48	55	21
10	Research on intelligent operation and maintenance management of infrastructures from the perspective of socio-technical system theory	5	3	8	4	5	2

intelligent transformation and upgrading of the industry. As the digital economy and a new round of technological revolution are evolving in depth on a global scale, industrial Internet platforms such as Amazon AWS, GE Predix, Siemens MindSphere, Haier COSMOPlat, Ali supET, Sany ROOTCLOUD, yonyou ERP, Huawei FusionPlant, etc. have become the key engines, important ways and new carriers dynamic capability and accelerating the digital transformation of industry. The industrial Internet platform, through a comprehensive digital empowerment platform, realizes the comprehensive interconnection of humans, machines, and things and the comprehensive linkage of the whole industrial chain, the whole value chain, the whole innovation chain, and the whole staff and the whole elements, and promotes the deep integration of the digital economy and the real economy. It can meet the complex comprehensive and personalized demands of multiple industrial scenarios with higher efficiency, lower cost, and dynamism, and promote the formation of a new industrial manufacturing and digital and intelligent service system. The research on industrial digital transformation empowered by industrial internet platform mainly focuses on the technical architecture of industrial Internet platform, the process mechanism of empowering industrial digital transformation, the dynamic capability of industrial digitalization, the ecological construction of integration and

innovation of large, medium and small enterprises, and the governance of industrial Internet platform. The development of new generation digital technologies, such as satellite internet, federal learning, privacy-enhanced computing, Web 3.0, and Metaverse, and the demand trend of green and low carbon development make industry cloud-native platform, industrial Metaverse, scenario-driven innovation and so on become the future trend of the research on industrial digital transformation empowered by industrial internet platform.

(2) Research on global supply chain security risk management in the digital age

In the new round of technological revolution and industrial transformation, digital technology is driving great changes in the global supply chain industry, and the supply chain has ushered in a digital, networked, and intelligent “digital change”. Although digital technology innovation is gradually pushing the expectation of global industrial services to its peak, the ensuing global supply chain security issue has also become increasingly prominent. On the one hand, in the critical period of intensifying international trade friction, increasing uncertainties, and high-quality transformation of industries, the supply chain risk problems brought by weak key technologies are gradually exposed. From the root, the problem of key technology “bottleneck” comes from

the imperfect layout of the key industrial chain. Especially under the current trend of reverse globalization and active decoupling of supply chains in developed countries, how to ensure the supply chain security of global high-tech industries has become an increasingly urgent issue. On the other hand, although the emergence of the digital economy has effectively promoted the development of supply chain transparency and wisdom, the information leakage problem brought by data integration has been frequent, the digital divide between countries has been expanding, and the struggle for digital sovereignty has entered into a white heat, which has affected the rapid development of global smart supply chain. In recent academic research, the key research directions are the industrial chain layout method of key technologies in the supply chain, supply chain security issues in high-tech industries under the intensified economic competition of reverse globalization, and supply chain data leakage and information security threats caused by data integration.

(3) Research on big data governance methods in artificial intelligence scenarios

Big data governance is a set of management behaviors involving the use of big data in an organization. It contains two definitions, one is “governance of big data”, that is, to use a certain method or form for continuous governance of big data itself, such as data source import, cleaning, and processing, data normalization, data storage, data computing, data service application and so on to improve the quality and value of data, which is conducive to the subsequent use of big data. The other is “relying on big data for governance”, that is, to use big data, cloud computing, artificial intelligence (AI), and other advanced technologies to achieve intelligence of process regulation, efficiency improvement, and social governance means. Firstly, the key technologies of big data governance under artificial intelligence scenarios mainly include structured data processing, data quality assessment and data cleaning, data normalization, data fusion and extraction, data organization, and data sharing, and other whole process service links. Secondly, by constructing big data mapping knowledge domain, it realizes understanding data, explaining phenomena and knowledge reasoning, discovering deep relationships, and realizing intelligent search and intelligent interaction. Thirdly, big data governance under the AI scenario faces the problem of security controllability. There is a need to solve data security and algorithm security problems such as privacy leakage, data rights validation, algorithm bias, and

technology abuse, to promote social wisdom governance and intelligent industrial transformation. Finally, the typical AI application scenarios of big data governance are applied to more complex and high-value scenarios such as finance, healthcare, urban management, public opinion monitoring and so on for solving management needs such as business decision-making, resource allocation, process optimization, operation and maintenance assurance, and risk prevention and control.

(4) Research on the theory and method of accurate construction and evolution of digital twin model

Digital twin models are digital representations of real-world entities or systems that can be used to understand, predict, optimize, and control physical-world entities or systems. Therefore, the construction of the digital twin model is the basis for model-driven implementation. The construction of the digital twin model is the digital modeling of the properties, methods, and behaviors of physical entities and processes in digital space. The model construction can be multidimensional in “geometry-physics-behavior-rules”, or multi-domain in mechanical, electrical, hydraulic, and other fields. The digital twin model should cover multi-dimensional and multi-domain models to achieve a comprehensive and realistic characterization and description of physical objects. For building models of relatively complex objects, it is necessary to solve the problem of how to assemble and fuse simple models to form complex models. To ensure the correctness and validity of the digital twin model, the model needs to be validated and evolved to ensure that the model describes and characterizes the state or characteristics of the physical object correctly, i.e., to ensure the virtual-real consistency of the model. Therefore, the main research direction can focus on the six stages of the digital twin model, i.e., “construction-assembly-fusion-validation-correction-management”, for carrying out the accurate construction of the multi-dimensional/multi-domain digital twin model, the assembly and fusion of all-elements/multi-scale twin digital model, the validation and correction of virtual-real consistency of digital twin model, and the interactive iteration and dynamic evolution of digital twin model. The digital twin must accurately represent the physical system in its current state, which requires the digital twin model to reflect the changes and updates of the physical system through fast and reliable accuracy. In the future, the construction and evolution of digital twin models will definitely develop in the direction

of improving modeling efficiency and accuracy.

(5) Research on sustainable transportation system under carbon peaking and carbon neutrality strategy

The process of promoting sustainable transportation systems is a search for more scientific energy structures and energy use mechanisms, lower emissions, and easier ways and technologies for system emissions management or self-absorption and solidification, including the development and implementation of policies, standards and laws, and regulations.

In 1992, China became one of the first parties to sign the *United Nations Framework Convention on Climate Change*, and in 2002, the Chinese government ratified the *Kyoto Protocol*. With active promotion by China, the world reached the *Paris Agreement* to address climate change in 2015. In 2016, China took the lead in signing the Agreement. In September 2020, President Xi Jinping announced at the 75th UN General Assembly that China strives to peak its CO₂ emissions by 2030 and work towards carbon neutrality by 2060. This carbon peaking and carbon neutrality strategy proposes a new direction for the research and advancement of sustainable transportation systems.

Concerning sustainable transportation systems, research at the environmental level has focused on three main areas, including the reduction of pollution emissions, the shifting of emissions, and the management of emissions. From the perspective of emission reduction, from land transportation to aviation, to water transportation, cleaner energy is promoted and how to overcome technical or cost constraints is studied, allowing cleaner energy more widely available than traditional energy. Another path to emission reduction is to continuously optimize the use of vehicles and equipment, the construction, maintenance, and use of facilities, and the allocation of time, space, and related resources. Thirdly, reduce energy consumption through technological upgrading. In the context of the carbon peaking and carbon neutrality strategy, the research has gradually shifted from regional air quality issues to global climate change issues, and the focus is increasingly put on carbon emissions. From the perspective of shifting emissions, both the promotion of new energy vehicles and the setting up of marine pollution emission control zones fall within the scope of the research. The research in this field often does not start with reducing carbon emissions but focuses on reducing the emission of harmful gases in

high-density population areas. At present, the research on pollutant management mainly covers harmful gases, and the research on carbon neutrality is still emerging.

(6) Formation mechanism, evolutionary law and governance policy of global public health crisis

A global public health crisis is an event induced by a public health emergency, which brings a serious impact (or even causes a shutdown) on the normal operation of social systems in most countries around the world, and has a serious impact on international economic and trade exchanges, national security, etc. The main research directions include:

- 1) Research on the mechanism of formation and evolution of global public health crises. This direction focuses on the evolutionary mechanism of local health events into global public health crises, the mechanism of the coupling of complex systems such as economy, transportation, and information on the evolutionary process, and the failure mechanism of existing monitoring and warning and risk governance systems, and the vulnerability analysis of different populations in crises.
- 2) Research on the governance strategy of global public health crises. This direction focuses on scarcity management, capacity expansion, supply chain failure, and other optimized resource allocation and institutional mechanism design issues of catastrophic peak demand scenarios, international participation, and international cooperation and coordination mechanisms in the governance of global public health crisis, the laws, and mechanisms of research and decision making of multiple subjects in typical scenarios, and the analysis of the impact of the implementation of typical policy tools on the interventions with the mentality and behavior of multiple subjects.
- 3) Research on learning, change, and resilience enhancement after the global public health crisis. This direction can focus on the recovery and learning mechanisms of public and private organizations, institutions, and societies after crises, the impact mechanisms of the combination of fiscal and taxation policy tools on the recovery of individuals, enterprises, and industrial chains, the laws of change and adaptation of multiple subjects after crises, the top-level design, and model reconstruction of the response system, and the strategies of resilient governance enhancement.

The probability of global public health crises is low, and

governments and other subjects lack long-term attention to system building and capacity reserve. How to use the COVID-19 epidemic crisis as an opportunity to promote research, system building and capacity reserve will be a topic worthy of attention in the future.

(7) Medium- and long-term sustainable supply paths and policies for basic and typical strategic resources

Basic and typical strategic resources generally refer to resources that are related to global livelihoods and dominate the resource system, and their sustainable supply depends on factors such as resource endowment, supply and demand, economic development, reserve effectiveness, and international material availability. Traditionally, resources such as energy, minerals, water, and land are the most typical basic and strategic resources. However, with the progress of science and technology and global economic development, data resources, highly skilled professional labor, and carbon emission rights are also included in the category of basic and typical strategic resources. At present, systematic research has been conducted on the medium- and long-term sustainable supply paths and policies for basic and typical strategic resources, and an analysis framework of sustainable supply paths and policies has been constructed from both production and consumption sides, focusing on the life cycle measurement and management of basic and typical strategic resources, improvement of resource utilization efficiency, environmental health and waste recycling, supply chain security risk assessment, government regulation and optimal allocation of resources, and sustainable supply performance evaluation. Based on technical methods such as systems thinking and artificial intelligence, exploring a set of thinking paradigms, practice paradigms, and research paradigms for sustainable supply and management policies of basic and typical strategic resources from a medium- and long-term perspective will become the focus of future research breakthroughs. Key scientific issues such as the lifecycle benefits and cost optimization of basic and typical strategic resources, sustainable supply chain modeling and governance paths, green technology innovation and circular economy, global climate change mitigation and sustainable resource supply, optimal allocation of resources from a blockchain perspective, resource security and policy simulation analysis, artificial intelligence and sustainable management decision system are frontier research hotspots at the intersection of multiple disciplines.

(8) Group consensus mechanism under social network

Group consensus seeks to reconcile the conflicting views of decision makers and to find a group decision solution that unifies the majority opinion. Traditional group consensus models assume that decision-makers are independent of each other, but in fact, decision-makers are in a social network, and their mutual relationship with each other and the structural characteristics of the corresponding network are important factors that affect group consensus.

In recent years, the widespread popularity of social media has accelerated the interaction and information transfer among decision-making individuals, and group consensus is facing more and more conflicts and challenges, such as the expansion of decision-making group size, diversity of interest groups, differences in individual preferences, and complexity of decision problems. Social networks are used to accurately characterize the interrelationships among decision makers (interest relations, trust relations, conflict relations, emotional relations, etc.), providing a new research perspective for the development of group consensus mechanisms. In the context of big data, the introduction of social network analysis methods into group decision-making scenarios can be widely used in scenarios such as emergency decision-making of major public opinion events and automatic discovery of social hotspots and exceptional events.

Currently, the main research directions of group consensus mechanisms under social networks include the research on group consensus models in dynamic social network environments, consensus compensation and non-cooperative behaviors in social network environments, and malicious manipulation behaviors in social network environments. In addition, with the development of artificial intelligence and Metaverse technologies, there are social robots as well as online virtual humans in addition to real humans on social networks. How these new social relationships (e.g., human-machine interaction and machine-machine interaction) affect the group consensus process urgently needs to be studied in depth.

(9) Big data-based financial risk assessment

Data are numerical characteristics or information obtained through observation. With the development of digital technology and its wide application in the financial field, financial data with diverse types, massive heterogeneity, complex relationships, low-value density, high noise, and

non-normal characteristics continue to emerge at a high speed, forming a wave of financial big data. In this context, the research and application of financial technology in financial risk monitoring, assessment, and early warning are becoming more and more in-depth, which enables and enhances efficiency and also leads to the emergence of new and potentially harmful financial risk problems. Financial risks are characterized by complexity, concealment, cross-domain, transmission, and dynamics, which make them difficult to characterize, cognize, identify, track, model, reason, and evaluate. The current monitoring, evaluation, and early warning of financial risks are based on the analysis and processing of massive financial data, and the identification and prediction of risks by establishing algorithmic models. The research mainly focuses on the security protection, safe storage, safe transmission, real-time processing and analysis and sharing circulation of massive financial data, the rapid identification methods of financial risks based on graph data, text data, stream data and other non-structural data, research on the prevention and early warning of systemic financial risks using graphical models and statistical models, research on the use of data science for financial credit risk assessment, etc. Future research trends include the research on financial data sharing and traceability methods under the division of management system, research on autonomous and controlled financial data intelligent twin and sensitive feature masking technology, research on financial twin data privacy risk and data quality assessment technology, research on financial data twin security environment construction and data deposition technology, research on financial data twin-based approximate query processing and next-generation financial database test benchmark building technology, research on financial risk behavior characterization, cognition and financial network risk transmission, modeling and evaluation, research on big data-driven technology for rapid risk identification and analysis of fintech products, construction of a large-scale financial risk awareness mapping system through financial big data, etc.

(10) Research on intelligent operation and maintenance management of infrastructures from the perspective of socio-technical system theory

Modern infrastructure systems, with engineering facilities as carriers, rely on complex technologies and equipment to perform their functions and provide important support for social production and residents' lives. On the other hand,

its operation and maintenance management involves many aspects such as operation, maintenance, and consumer services, and is influenced by the decisions and behaviors of various stakeholders such as technicians, management teams, and end users, as well as the constraints of external conditions such as economic, social and environmental conditions. Therefore, infrastructure has typical socio-technical system characteristics. With the continuous development of infrastructure, the interactive coupling between its social and technical components becomes more and more frequent and complex, which has an increasingly critical impact on the effectiveness and safety of infrastructure. In recent years, domestic and foreign scholars have made significant progress in such hot research directions as socio-technical system modeling and simulation of infrastructure, operation and maintenance scenario construction and derivation of infrastructure and stakeholder interaction, infrastructure operation and maintenance optimization based on human factors engineering and behavioral decision theory, infrastructure security and resilience management based on information-physical-social convergence system, the pathways and management strategies for the role of infrastructure in socio-economic development and security, and policies and institutional mechanisms for green and low-carbon infrastructure development. In the context of the rapid development of information technology such as the Internet of Things, cloud computing, and artificial intelligence, how to further promote the paradigm, methods, and technological innovation of infrastructure operation and maintenance management based on the multi-dimensional integration of physical-social-information, optimize the interaction mode and efficiency of the technical components and social components of infrastructure, and realize the transformation of intelligent and low-carbon infrastructure and the continuous improvement of efficiency and security level, is expected to become an important research hotspot in the future.

1.2 Interpretations for four key engineering research fronts

1.2.1 Research on industrial digital transformation empowered by industrial internet platform

The focus of the industrial digital transformation empowered by the industrial Internet platform is to study how the

industrial Internet platform can accelerate the process mechanism of industrial digitalization, networking, and intelligent transformation and the ecological construction of integration and innovation of large and medium-sized enterprises and their effective governance by creating a comprehensive service platform of digital technology, data elements and intelligent manufacturing with deep collaboration, targeting the needs of multiple industrial application scenarios. After GE proposed the concept of the Industrial Internet in 2012, domestic and foreign policies and academic fields gradually reached a consensus that the Industrial Internet is the key new engine to drive the transformation of the manufacturing industry from the supply-side perspective after the consumer Internet. Since then, GE, together with IBM, Cisco, Intel, and other leading international enterprises, has established the Industrial Internet Consortium (IIC), and the industrial Internet platform has shown a global trend of spurt. In China, based on “Made in China 2025”, more and more attention has been paid to the traction role of the industrial Internet in further promoting the integration of informatization and industrialization and the digital transformation of industry. In 2021, the national industrial Internet platform exceeded 600, with more than 100 with certain industry and regional influence. In 2021 and 2022, China’s Ministry of Industry and Information Technology issued *The 14th Five-Year Plan for Deeply Integrated Development of Informatization and Industrialization* and *Industrial Internet Innovation and Development Action Plan (2021–2023)*, both of which focus on the industrial Internet platform as a key direction. Especially under the trend that the risk of blockage and breakage in the global industrial chain and supply chain intensifies and the digital transformation of the manufacturing industry enters deep water, the industrial digital transformation and upgrading empowered by the industrial Internet platform become a more important and urgent issue.

In recent years, scholars at home and abroad have focused on topics such as the technical architecture of industrial Internet platforms, the process mechanism of empowering industrial digital transformation, the dynamic capability of industrial digitalization, the ecological construction of integration and innovation of large, medium and small enterprises, and the governance of industrial Internet platform. Among them, the research on the technical architecture of industrial Internet platforms focuses on different technical architectures such

as IaaS, PaaS, SaaS, and the emerging AaaS, breakthroughs in key common digital core technologies, localization of platform software and its differentiated business model to empower industrial digitalization. The research on the process mechanism of empowering industrial digital transformation focuses on the mechanism of organic integration of digital technologies, data elements, and platform modules and the application of multiple industrial scenarios. The research on the dynamic capability of industrial digitalization focuses on how the leading enterprises can realize their transformation and empower the all-around transformation of the industrial chain and value chain through the construction of a digital technology capability system, digital management capability system, and digital scenario application capability system. The research on the ecological construction of integration and innovation of large, medium, and small enterprises focuses on how to support small and medium enterprises lacking data elements and key digital technologies to participate in the ecological construction of industrial Internet platforms and accelerate digital transformation, to ensure the safe and resilient development of the industrial chain and supply chain. The research on the governance of industrial Internet platforms focuses on data privacy, platform monopoly, platform interconnection, and governance standard system.

Looking ahead, with the emergence of a new generation of digital technologies and the acceleration of the co-evolution of industrial Internet platforms and industrial digital transformation, industry cloud-native platforms, industrial Metaverse, and scenario-driven innovation become research directions worthy of attention and forward-looking layout.

(1) Industry cloud-native platform

Industry cloud-native is an emerging concept in the field of cloud computing and industrial Internet, a new thinking and innovative model for industrial Internet platform construction and service application, and a key infrastructure for platform services. It can realize agile application development, iterative efficiency improvement, and delivery speed of industrial Internet platform for industry personalized needs. Industry cloud-native platform is still in the rapid emergence and exploration stage, and further attention needs to be paid to the as-a-service delivery model, continuous software-defined delivery, distributed enterprises based on industry cloud-native platform, and the construction of standardized and

highly automated cloud services and intelligent decision-making systems.

(2) Industrial Metaverse

Industrial Metaverse is the application of Metaverse-related technology and software in the industrial field led by a new generation of artificial intelligence technology. It can realize the virtual-real mapping of physical space, virtual space, and cyberspace in the industrial field as well as the interactive integration, thus realizing the new digital industrial economic system of industrial whole industrial chain, whole value chain, whole element wisdom collaboration based open interconnection and scenario integration characterized by virtual promoting real and virtual enhancing real. Industrial Metaverse is one of the typical forms of intelligent manufacturing in the future, which is the advancement and ascension of the digital twin. The current research on industrial Metaverse is in the stage of proof of concept, infrastructure construction, and model exploration, and is in urgent need of a further breakthrough.

(3) Scenario-driven innovation

Scenario-driven innovation is not only the process of applying existing digital technologies and industrial Internet platform services to specific scenarios to create greater value, but also the process of driving the integration and co-integration of innovation elements and contextual elements such as strategy, technology, platform, and market demand based on future trends and vision needs, breaking through the technical bottlenecks of existing industrial Internet platforms,

developing new technologies, new products, new channels, new business models, and even opening up new markets and fields. The scenario-driven innovation provides a breakthrough direction for the industrial digital transformation empowered by the industrial Internet platform. In the future, there should be more focus on the opportunities and mechanisms for carbon peaking, carbon neutrality, common prosperity, military, and civilian integration, and rural revitalization empowered by industrial Internet platforms.

The top three countries in the quantity of core papers in the engineering research front of “research on industrial digital transformation empowered by industrial internet platform” are China, the USA, and the UK (Table 1.2.1). The main output organizations of core papers are Aalto University, South China University of Technology, Beihang University, etc. (Table 1.2.2). From the perspective of the cooperation network among main countries (Figure 1.2.1), there is more cooperation among the USA, China, and other countries. From the perspective of the cooperation network among main institutions (Figure 1.2.2), there is more cooperation among South China University of Technology, King Saud University, and University of Messina.

The quantity of citing papers in China ranks first, as shown in Table 1.2.3. The top-ranked institutions are the Chinese Academy of Sciences, Beijing University of Posts and Telecommunications, and Beihang University, as shown in Table 1.2.4.

Figure 1.2.3 shows the roadmap of the engineering research

Table 1.2.1 Countries with the greatest output of core papers on “research on industrial digital transformation empowered by industrial internet platform”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	32	27.83	2 553	79.78	2018.6
2	USA	24	20.87	2 360	98.33	2017.9
3	UK	16	13.91	1 794	112.12	2018.3
4	Germany	10	8.70	577	57.70	2018.0
5	Canada	9	7.83	1 269	141.00	2018.8
6	Finland	9	7.83	866	96.22	2018.7
7	India	8	6.96	606	75.75	2018.8
8	Spain	8	6.96	471	58.88	2018.1
9	South Korea	7	6.09	785	112.14	2017.3
10	Italy	7	6.09	429	61.29	2018.9

Table 1.2.2 Institutions with the greatest output of core papers on “research on industrial digital transformation empowered by industrial internet platform”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Aalto University	5	4.35	446	89.20	2019.6
2	South China University of Technology	5	4.35	404	80.80	2018.4
3	Beihang University	4	3.48	445	111.25	2019.0
4	University of Vaasa	4	3.48	420	105.00	2017.5
5	The University of Auckland	3	2.61	565	188.33	2017.7
6	King Saud University	3	2.61	232	77.33	2018.7
7	University of Messina	3	2.61	214	71.33	2018.7
8	KTH Royal Institute of Technology	3	2.61	207	69.00	2017.0
9	Arts et Metiers Institute of Technology	2	1.74	466	233.00	2019.0
10	Polytech Montreal	2	1.74	466	233.00	2019.0



Figure 1.2.1 Collaboration network among major countries in the engineering research front of “research on industrial digital transformation empowered by industrial internet platform”

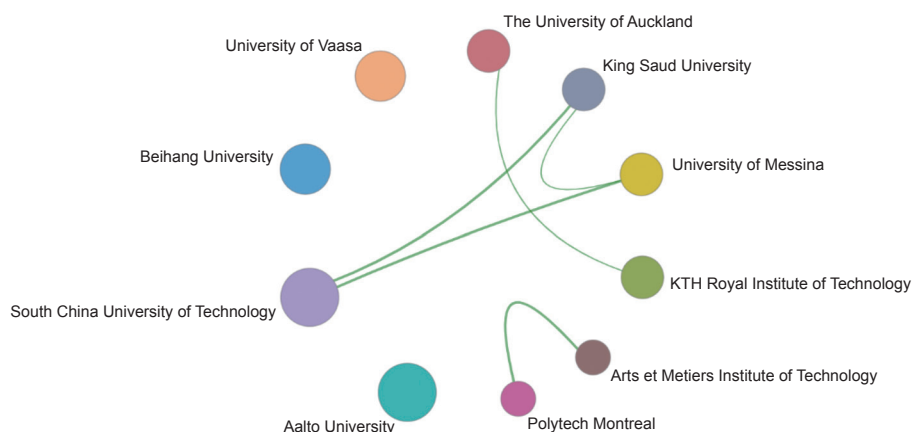


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “research on industrial digital transformation empowered by industrial internet platform”

Table 1.2.3 Countries with the greatest output of citing papers on “research on industrial digital transformation empowered by industrial internet platform”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 705	31.44	2020.2
2	USA	1 091	12.68	2020.0
3	India	942	10.95	2020.2
4	UK	777	9.03	2020.1
5	Italy	624	7.25	2020.1
6	South Korea	460	5.35	2020.1
7	Germany	430	5.00	2020.1
8	Canada	419	4.87	2020.1
9	Spain	402	4.67	2020.0
10	Australia	401	4.66	2020.1

Table 1.2.4 Institutions with the greatest output of citing papers on “research on industrial digital transformation empowered by industrial internet platform”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	126	12.32	2020.2
2	Beijing University of Posts and Telecommunications	120	11.73	2020.1
3	Beihang University	113	11.05	2019.6
4	Shanghai Jiao Tong University	108	10.56	2019.7
5	Nanyang Technological University	93	9.09	2020.1
6	The Hong Kong Polytechnic University	93	9.09	2020.2
7	King Saud University	92	8.99	2020.2
8	Tsinghua University	74	7.23	2020.1
9	Zhejiang University	73	7.14	2020.4
10	Huazhong University of Science and Technology	66	6.45	2019.9

front of “research on industrial digital transformation empowered by industrial internet platform”.

1.2.2 Research on global supply chain security risk management in digital age

The supply chain management refers to business flow, logistics and information flow, including production, transportation, warehousing and many other processes, and any problems in any process can affect supply chain security and cause supply chain risk. In the digital era, digital analysis methods and tools provide the technical guarantee to resist supply chain risks. However, the technology itself

is vulnerable to external complex systems, especially under the trend of reverse globalization and active disconnection of supply chains in developed countries. How to ensure supply chain security in global high-tech industries has become an increasingly urgent issue.

Currently, scholars from various countries around the world have provided a quantity of solutions to deal with the global supply chain risks in the digital era. In terms of the main output countries of core papers, the top three countries are the UK, China, and Canada (Table 1.2.5). The main output institutions of core papers are University of British Columbia, University of Guelph, and the Ohio State

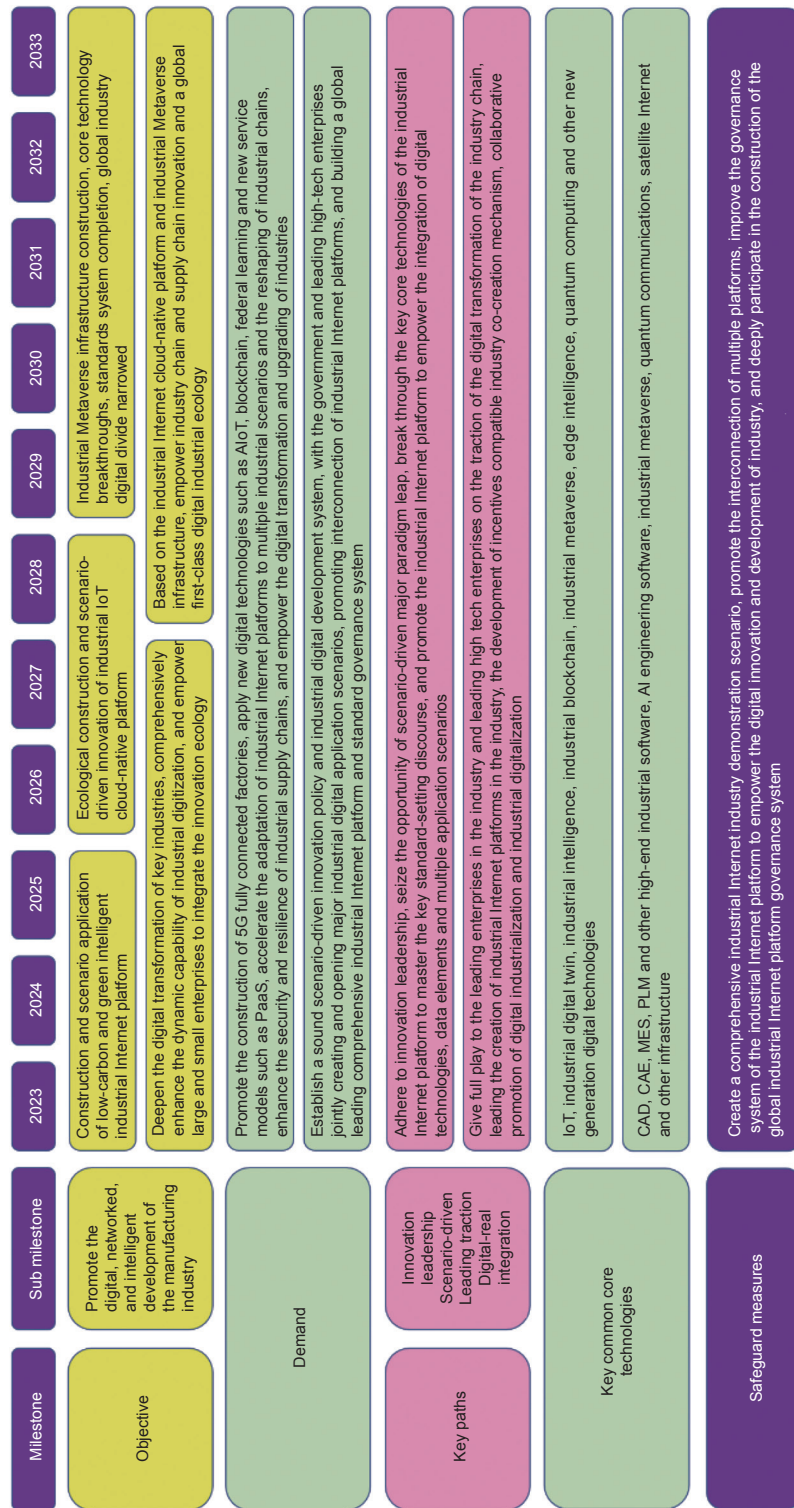


Figure 1.2.3 Roadmap of the engineering research front of "research on industrial digital transformation empowered by industrial internet platform"

University (Table 1.2.6), with these three institutions having more than 90 citations.

In terms of the cooperation network among main countries (Figure 1.2.4), there is cooperation between France and Germany, China and Belgium, and the UK and Iran. In terms of the cooperation network among main institutions (Figure 1.2.5), only University of East Anglia and the Ohio State University have not collaborated with other organizations. It can be seen from Table 1.2.7 that the top three countries in terms of the quantity of the citing papers are China, the UK, and the USA, with more than 100 citing core papers each. In particular, the percentage of citing papers in China is as high as more than 20%. Meanwhile, according to Table 1.2.8, the

top organizations are Hamad Bin Khalifa University, University of Bordeaux, and Chinese Academy of Sciences.

Based on the review of the existing literature, a more in-depth analysis on how to identify, assess and prevent the risks of global supply chain in the digital era is conducted, and insights are provided on the future development trend. The specific research trends are as follows.

(1) Risk identification method of global supply chain based on digital technology in complex situations

In the identification of supply chain risks, the more intuitive representation of the digital technology is the big data algorithm, which analyzes the risk characteristics of the supply

Table 1.2.5 Countries with the greatest output of core papers on “research on global supply chain security risk management in digital age”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	UK	4	33.33	213	53.25	2017.5
2	China	2	16.67	82	41.00	2019.0
3	Canada	1	8.33	99	99.00	2019.0
4	USA	1	8.33	98	98.00	2020.0
5	Spain	1	8.33	70	70.00	2017.0
6	France	1	8.33	60	60.00	2016.0
7	Germany	1	8.33	60	60.00	2016.0
8	Poland	1	8.33	48	48.00	2016.0
9	Iran	1	8.33	41	41.00	2016.0
10	Belgium	1	8.33	40	40.00	2021.0

Table 1.2.6 Institutions with the greatest output of core papers on “research on global supply chain security risk management in digital age”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of British Columbia	1	8.33	99	99.00	2019.0
2	University of Guelph	1	8.33	99	99.00	2019.0
3	The Ohio State University	1	8.33	98	98.00	2020.0
4	University of East Anglia	1	8.33	73	73.00	2018.0
5	IE University	1	8.33	70	70.00	2017.0
6	Zaragoza Logistics Center	1	8.33	70	70.00	2017.0
7	Queen’s University Belfast	1	8.33	60	60.00	2018.0
8	Youngs Seafood	1	8.33	60	60.00	2018.0
9	The French National Centre for Scientific Research	1	8.33	60	60.00	2016.0
10	Universitat Augsburg	1	8.33	60	60.00	2016.0

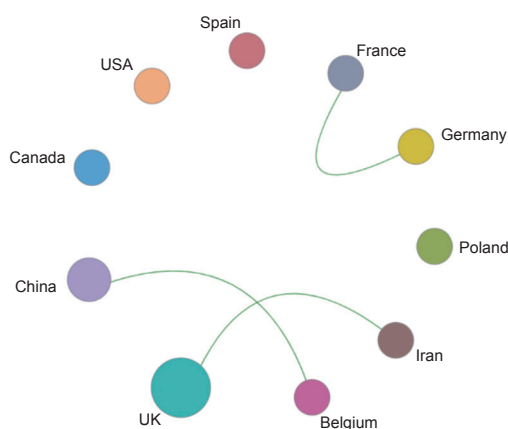


Figure 1.2.4 Collaboration network among major countries in the engineering research front of “research on global supply chain security risk management in digital age”

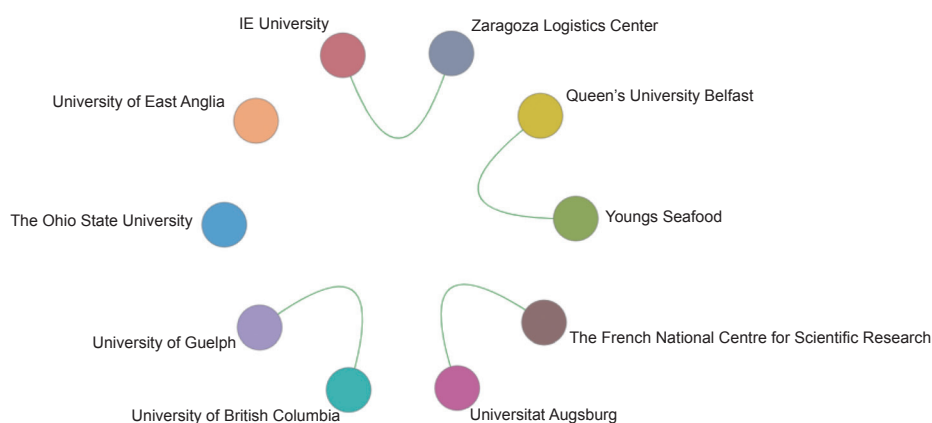


Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “research on global supply chain security risk management in digital age”

Table 1.2.7 Countries with the greatest output of citing papers on “research on global supply chain security risk management in digital age”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	144	20.20	2020.3
2	UK	107	15.01	2019.9
3	USA	106	14.87	2020.2
4	India	56	7.85	2020.2
5	Germany	56	7.85	2019.8
6	Australia	46	6.45	2020.2
7	France	45	6.31	2019.7
8	Italy	45	6.31	2020.4
9	Poland	42	5.89	2019.7
10	Canada	39	5.47	2020.3

Table 1.2.8 Institutions with the greatest output of citing papers on “research on global supply chain security risk management in digital age”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Hamad Bin Khalifa University	17	12.14	2020.5
2	University of Bordeaux	16	11.43	2019.4
3	Chinese Academy of Sciences	16	11.43	2019.8
4	University of Waterloo	13	9.29	2019.2
5	Shahid Beheshti University	13	9.29	2020.1
6	Polish Academy of Sciences	13	9.29	2019.5
7	Technical University of Berlin	13	9.29	2019.5
8	Cranfield University	10	7.14	2020.1
9	The French National Centre for Scientific Research	10	7.14	2019.6
10	Ghent University	10	7.14	2020.1

chain based on the collection of information flow in the supply chain network, establishes a risk prediction system, and predetermines whether there is a security risk in the supply chain. The commonly used supply chain risk identification algorithms include fuzzy comprehensive evaluation method, neural network, etc. The field of application tends to be credit risk, liquidity risk identification and enterprise operation risk prediction in supply chain finance. In the context of the current COVID-19 pandemic, the mainstream of research is to use multiple methods and technologies to identify the risks of manufacturing capacity, production level and other aspects of the supply chain, and to optimize different methods and compare the results.

(2) Risk impact assessment of global supply chain based on digital technology

Digital technology can be adopted to virtualize and visualize the whole process of the supply chain, and evaluate all potential risks in the supply chain through big data, simulation and other technologies. Recently, the digital technology for assessing the impact of supply chain risks has become more systematic, such as the application of smart devices such as RFID and sensors to collect real-time data. In combination with historical maintenance data and derived data, the above digital technology simulates the operation process of the supply chain in real time and comprehensively evaluates the unknown risks and impacts in the supply chain. The evaluation of supply chain risk through decision support system, tracking system and digital twin technology has

become a research hotspot. How to assess the supply chain security risks of global high-tech industries in the current critical period of intensified international trade friction, increased uncertainty and high-quality transformation of various industries has become an increasingly urgent issue under the current trend of reverse globalization and active decoupling of supply chains in developed countries, which deserves further research.

(3) Interruption and security prevention of global supply chain under digital background

The application of digital technology has led to data co-construction and sharing, promoted multi-chain cooperation, and improved the integrated decision-making ability of the supply chain, which is crucial to risk prevention of supply chain. During the spread of COVID-19, 3D printing, cloud logistics, and contactless distribution technologies and equipment such as automated guided vehicles (AGV) and radio frequency identification (RFID) provide important support for preventing supply chain disruptions. Research hotspots in this field focus on methods to prevent supply chain disruption, and to design and practice supply chain architecture based on blockchain, cloud platform and other technologies. Therefore, the key research directions in academic research recently are layout methods of key technology industrial chain and supply chain, supply chain security problem of high-tech industry under the intensification of reverse globalization economic competition, and supply chain data leakage and information security threat caused by data integration.

(4) Global supply chain risk impact law and control mechanism driven by data

As an important tool for identifying, evaluating and preventing supply chain risks, the digital technology has been widely studied by scholars for managing supply chain risks, but there remain some aspects to be considered. From the micro level, there are still loopholes in digital technology, with data leakage and information security threats. From the macro level, the impact and the solution mechanism of smart supply chain innovation and government industrial layout on global supply chain risks remain unclear, and it is necessary to prepare a supply chain risk management standard suitable for the digital age. Future research driven by data should focus on solving the problems of weak digital key technologies, specifically, the basic theory and method of supply chain resilience in the digital age, the impact law and Simulation of Sino-US trade friction on global supply chain, the supply chain security assessment and early warning mechanism of key industries in China, the risk of global supply chain disruption, system prediction and security governance system, etc. For the above problems, further study is deserved.

To further improve the global supply chain risk security management in the digital age, this paper further plans the development path of applying digital technology to deal with supply chain risks in the future (Figure 1.2.6).

1.2.3 Research on big data governance methods in artificial intelligence scenarios

By reviewing the existing literature and analyzing the current development situation and future trends, the research on big data governance methods in artificial intelligence scenarios focuses on the following aspects.

(1) Key technologies for big data governance in artificial intelligence scenarios

The whole process data service includes structured data processing, data quality assessment and data cleaning, data normalization, data storage, and data sharing. Structured data processing starts with parsing multi-source heterogeneous data sources, extracting the required information using information extraction techniques, and further converting them into structured data. The key technology for data quality assessment is data visualization technology. The user defines some data cleaning rules to deal with the quality problems

in the data in batches and improve the efficiency of data cleaning. In the field of database research, there are also studies to improve the efficiency of data cleaning with the help of crowdsourcing ideas. In the process of data cleaning, multiple rounds of human-computer interaction are required, and the interaction interface and interaction mode of the system is particularly important for the effectiveness of data cleaning algorithms. The data normalization processing determines the data granularity and expression according to the demand characteristics of the application. It is necessary to consider the balance of big data preservation time and storage space and identify the data elements that have a critical impact on business. It is also desirable to establish a data governance standard system to solve the institutional and technical problems that make data difficult to share.

(2) Construction of big data mapping knowledge domain in artificial intelligence scenarios

By constructing big data mapping knowledge domain, it realizes understanding data, explaining phenomena and knowledge reasoning, discovering deep relationships, and realizing intelligent search and intelligent interaction. Firstly, based on metadata information such as enterprise and social, algorithms such as natural language processing, machine learning, pattern recognition, and business rule filtering are used to improve processing efficiency and enhance the accuracy of knowledge extraction. Secondly, knowledge is represented and stored in the form of ontology and automatically constructed into mapping knowledge domains.

Finally, through mapping knowledge domain relations, knowledge discovery, knowledge reasoning, and mining are carried out through mapping computing, and intelligent search and correlation query means are used to provide more accurate data to end users.

(3) Big data security controllability issues in artificial intelligence scenarios

There is a need to solve data security and algorithm security problems such as privacy leakage, data rights validation, algorithm bias, and technology abuse. Firstly, cryptography technology, smart contracts, and privacy computing are the key technologies for achieving data security. Encryption of data using technologies such as public key cryptography can define the identity of data subjects and effectively support data rights validation. Privacy computing technologies, such as multi-party security computing, can realize the exploitation

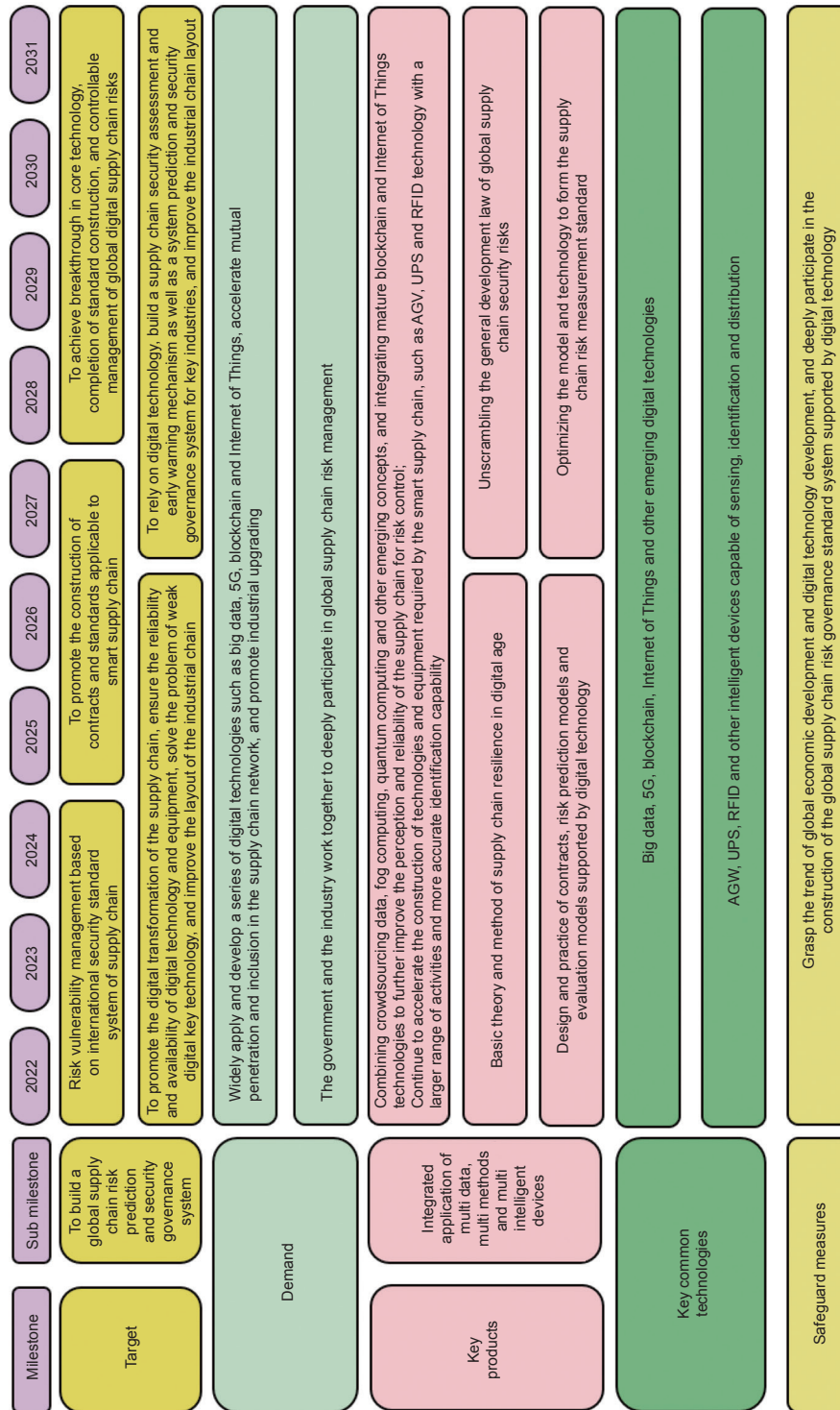


Figure 1.2.6 Roadmap of the engineering research front of "research on global supply chain security risk management in digital age"

of data without transferring the original data and promote the separation of data ownership and use rights. By integrating privacy computing and trustworthy privacy computing technologies, it can effectively solve the problem of re-identification of personal information after anonymization, and realize the “computable but not identifiable”. Using contract theory and incentive mechanism, it can balance security protection and benefit sharing to realize “data available but not visible”. Secondly, algorithmic models are difficult to explain, difficult to control, and difficult to account for, leading to discrimination, vulnerability, exploitation, information cocoon, and other security risks. By using the four elements including knowledge, data, algorithms, and computing capabilities, it can establish new interpretable and robust AI theories and methods to further develop safe, trustworthy, reliable, and scalable AI technologies.

(4) Typical artificial intelligence application scenarios of big data governance

Big data governance has been applied in more complex and high-value artificial intelligence scenarios such as finance, healthcare, retail, urban management, public opinion monitoring and so on for solving management needs such as business decision-making, resource allocation, process optimization, operation and maintenance assurance, and risk prevention and control. In the field of business decision-making, big data visualization technology is applied to realize the effective transmission of complex analysis processes and analysis elements. In the field of resource allocation, the

dynamic management of resource allocation is realized by relying on big data collection and computing capabilities. In the field of process optimization, bottlenecks in business processes are discovered to improve operational efficiency and customer experience. In the field of operation and maintenance, instant monitoring of operation is realized based on stream data processing technology. In the field of risk prevention and control, risk clues are identified through visualization technology to enhance risk warning capability.

In the above typical AI application scenarios of big data governance, on the one hand, a systematic big data governance framework has not yet been formed, and key technologies such as open sharing, security and privacy protection, quality assessment, and value prediction are far from mature. On the other hand, there are problems including monopoly regulation of Internet companies, regulation of financial digital business, regulation and guidance of online public opinion, data security and privacy protection, and other AI application problems.

The top three countries in the engineering research front of “research on big data governance methods in artificial intelligence scenarios” regarding the quantity of core papers are the USA, the UK, and China (Table 1.2.9), and the top three countries in terms of citations per paper are France, South Korea, and Sweden. Among the main output countries, the USA, the UK, the Netherlands, Australia, and other countries have more collaborations (Figure 1.2.7). The top organizations in terms of the quantity of core papers are Zhejiang University,

Table 1.2.9 Countries with the greatest output of core papers on “research on big data governance methods in artificial intelligence scenarios”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	13	39.39	1 178	90.62	2018.7
2	UK	10	30.30	685	68.50	2017.9
3	China	8	24.24	561	70.12	2019.0
4	Netherlands	7	21.21	380	54.29	2018.6
5	France	5	15.15	542	108.40	2017.0
6	Australia	5	15.15	326	65.20	2018.2
7	South Korea	3	9.09	302	100.67	2018.7
8	Germany	3	9.09	178	59.33	2018.0
9	Austria	3	9.09	177	59.00	2018.3
10	Sweden	2	6.06	187	93.50	2018.5

Imperial College London, and the London School of Hygiene & Tropical Medicine (Table 1.2.10). Among the main output institutions, Imperial College London and the London School of Hygiene & Tropical Medicine have very close collaborations with other organizations, while University of North Carolina and University of California, San Francisco also have many collaborations (Figure 1.2.8). As can be seen from Table 1.2.11, the USA ranked first in the quantity of citing core papers. As can be seen from Table 1.2.12, the top-ranked institutions are Chinese Academy of Sciences, Harvard University, and the University of Melbourne. Figure 1.2.9 shows the roadmap of the engineering research front of “research on big data governance methods in artificial intelligence scenarios”

1.2.4 Research on the theory and method of accurate construction and evolution of digital twin model

The digital twin is driven by multi-dimensional models and fused data to achieve monitoring, simulation, prediction, optimization, and other services and application requirements, where the construction of the digital twin model is a prerequisite for achieving digital twin practice and landing application. The digital twin model can evolve in real-time by receiving data from physical objects, thus maintaining consistency with physical objects throughout their lifecycle. Based on the digital twin model, analysis, prediction, diagnosis, training and so on can be performed and the simulation results can be fed back to the physical object, thus helping to optimize and



Figure 1.2.7 Collaboration network among major countries in the engineering research front of “research on big data governance methods in artificial intelligence scenarios”

Table 1.2.10 Institutions with the greatest output of core papers on “research on big data governance methods in artificial intelligence scenarios”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Zhejiang University	3	9.09	288	96.00	2019.0
2	Imperial College London	3	9.09	258	86.00	2018.7
3	The London School of Hygiene & Tropical Medicine	3	9.09	210	70.00	2017.0
4	University of Amsterdam	3	9.09	164	54.67	2018.7
5	University of Oxford	2	6.06	136	68.00	2017.5
6	University College London	2	6.06	131	65.50	2018.0
7	University of Michigan	2	6.06	116	58.00	2019.0
8	University of California, San Francisco	2	6.06	111	55.50	2017.5
9	University of North Carolina	2	6.06	111	55.50	2017.5
10	Zhengzhou University	2	6.06	110	55.00	2019.0



Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “research on big data governance methods in artificial intelligence scenarios”

Table 1.2.11 Countries with the greatest output of citing papers on “research on big data governance methods in artificial intelligence scenarios”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	686	22.96	2020.1
2	China	595	19.91	2020.4
3	UK	361	12.08	2020.0
4	Italy	237	7.93	2020.0
5	Australia	219	7.33	2020.3
6	Germany	174	5.82	2020.0
7	India	171	5.72	2020.4
8	Canada	163	5.46	2020.2
9	France	141	4.72	2019.7
10	Spain	124	4.15	2020.0

Table 1.2.12 Institutions with the greatest output of citing papers on “research on big data governance methods in artificial intelligence scenarios”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	49	11.32	2020.4
2	Harvard University	47	10.85	2019.9
3	The University of Melbourne	45	10.39	2020.1
4	University College London	44	10.16	2019.8
5	The University of Sydney	44	10.16	2020.1
6	Sorbonne University	39	9.01	2019.3
7	Imperial College London	39	9.01	2020.1
8	Huazhong University of Science and Technology	36	8.31	2019.9
9	Johns Hopkins University	31	7.16	2019.6
10	University of Oxford	30	6.93	2019.4

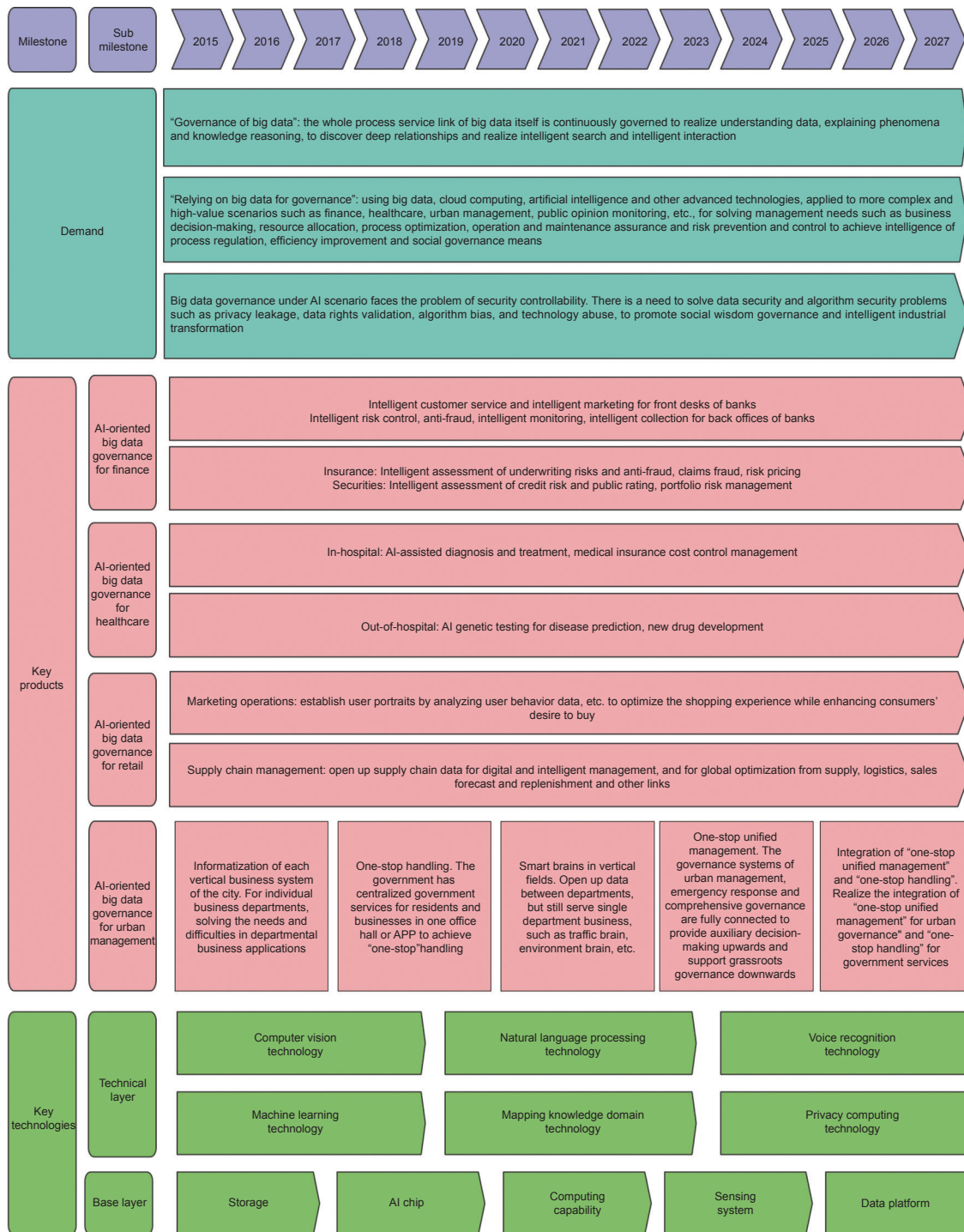


Figure 1.2.9 Roadmap of the engineering research front of "research on big data governance methods in artificial intelligence scenarios"

make decisions on the physical object. Models are the core foundation of the digital twin, but modeling technology has emerged since the 1950s and has developed over the decades into more than a dozen new modeling models, technologies,

and industries, such as model engineering, data-driven modeling, high-performance modeling, and complex system modeling. The emergence of the digital twin has further promoted the development of modeling technology.

The purpose of digital twin modeling is to eliminate the uncertainty of various physical entities, especially complex systems.

The construction of the digital twin model is the digital modeling of the properties, methods, and behaviors of physical entities and processes in digital space. The model construction can be multidimensional in “geometry-physics-behavior-rules”, or multi-domain in mechanical, electrical, hydraulic, and other fields. The modeling of complex entities is often cross-domain, cross-type, and cross-scale, involving multiple dimensions, and the effect of modeling through a single dimension is not good. It is also necessary to achieve the construction of more complex object models through model assembly and fusion at multiple levels and granularities to achieve a comprehensive characterization of the characteristics of each domain of complex physical objects. To ensure the correctness and validity of the digital twin model, the constructed and assembled or fused models should be validated to check whether the model describes and characterizes the state or features of the physical object correctly. If the model validation results do not meet the requirements, model correction is needed to make the model closer to the actual operation or use of the physical object to ensure the accuracy of the model. Therefore, the main research direction can focus on the six stages of the digital twin model, i.e., “construction-assembly-fusion-validation-correction-management”, for carrying out the accurate construction of the multi-dimensional/multi-domain digital twin model, the assembly and fusion of all-elements/multi-scale twin digital model, the validation and correction of virtual-real consistency of digital twin model, and the interactive iteration and dynamic evolution of digital twin model.

Building digital twin models is not the final purpose, but a means to improve the performance and operational efficiency of their corresponding real objects through the analysis of digital twin models. Important future development directions include multidimensional deep fusion modeling of complex entities, continuous improvement of modeling efficiency and accuracy, interoperability and interactive evolution of models, mutual iteration and dynamic evolution of models and physical entities, and unified model semantics and syntax. The digital twin is in the rising stage of development, the technical system is improving, the industrial integration continues to accelerate, and the industry application is accelerating penetration. Application scenarios include various fields such as aerospace, intelligent manufacturing, health care, smart cities, energy and power, and integrated transportation.

The top three countries for the quantity of core papers in the engineering research front of “research on the theory and method of accurate construction and evolution of digital twin model” are China, the USA, and Germany (Table 1.2.13), and the main output institutions of core papers are Guangdong University of Technology, Beihang University, and the University of Auckland (Table 1.2.14). From the cooperation network of the main countries (Figure 1.2.10), there is very close cooperation between China and other countries, and from the main institutions, Guangdong University of Technology and City University of Hong Kong, National University of Singapore and Beihang University cooperate more closely (Figure 1.2.11). As can be seen from Table 1.2.15, China ranks first in the quantity of citing core papers. As can be seen from Table 1.2.16, the top three institutions are Northwestern Polytechnic University, Beihang University,

Table 1.2.13 Countries with the greatest output of core papers on “research on the theory and method of accurate construction and evolution of digital twin model”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	72	36.18	6 501	90.29	2019.8
2	USA	33	16.58	2 526	76.55	2019.0
3	Germany	25	12.56	3 209	128.36	2018.1
4	UK	19	9.55	1 699	89.42	2019.0
5	Sweden	13	6.53	980	75.38	2019.4
6	Singapore	10	5.03	1 359	135.90	2020.0
7	Australia	10	5.03	1 262	126.20	2019.9
8	Italy	9	4.52	448	49.78	2018.9
9	France	8	4.02	1 178	147.25	2019.5
10	South Korea	8	4.02	358	44.75	2018.9

and Shanghai Jiao Tong University. Figure 1.2.12 shows the roadmap of the engineering research front of “research on the

theory and method of accurate construction and evolution of digital twin model”

Table 1.2.14 Institutions with the greatest output of core papers on “research on the theory and method of accurate construction and evolution of digital twin model”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Guangdong University of Technology	10	5.03	1 041	104.10	2019.5
2	Beihang University	9	4.52	2 094	232.67	2019.4
3	The University of Auckland	7	3.52	743	106.14	2019.7
4	National University of Singapore	6	3.02	1 077	179.50	2020.2
5	City University of Hong Kong	6	3.02	475	79.17	2020.0
6	Berlin School of Economics and Law	5	2.51	1 097	219.40	2020.2
7	The Hong Kong Polytechnic University	5	2.51	363	72.60	2019.6
8	University of Patras	5	2.51	270	54.00	2019.2
9	The University of Hong Kong	5	2.51	230	46.00	2020.4
10	University of Michigan	5	2.51	221	44.20	2020.2



Figure 1.2.10 Collaboration network among major countries in the engineering research front of “research on the theory and method of accurate construction and evolution of digital twin model”

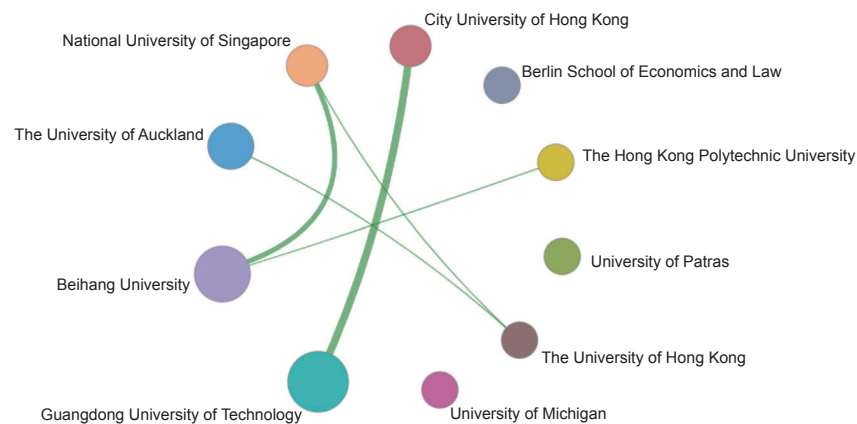


Figure 1.2.11 Collaboration network among major institutions in the engineering research front of “research on the theory and method of accurate construction and evolution of digital twin model”

Table 1.2.15 Countries with the greatest output of citing papers on “research on the theory and method of accurate construction and evolution of digital twin model”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 720	32.12	2020.5
2	USA	1 281	15.13	2020.3
3	Germany	900	10.63	2020.2
4	UK	811	9.58	2020.4
5	Italy	550	6.50	2020.4
6	India	481	5.68	2020.4
7	France	411	4.85	2020.3
8	Australia	384	4.53	2020.4
9	Spain	336	3.97	2020.3
10	South Korea	307	3.63	2020.4

Table 1.2.16 Institutions with the greatest output of citing papers on “research on the theory and method of accurate construction and evolution of digital twin model”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Northwestern Polytechnic University	115	11.09	2020.3
2	Beihang University	113	10.90	2020.1
3	Shanghai Jiao Tong University	111	10.70	2020.5
4	Chinese Academy of Sciences	104	10.03	2020.5
5	The Hong Kong Polytechnic University	97	9.35	2020.4
6	Polytechnic University of Milan	95	9.16	2020.3
7	Tsinghua University	87	8.39	2020.4
8	The University of Hong Kong	87	8.39	2020.4
9	Huazhong University of Science and Technology	80	7.71	2020.6
10	RWTH Aachen University	76	7.33	2020.4

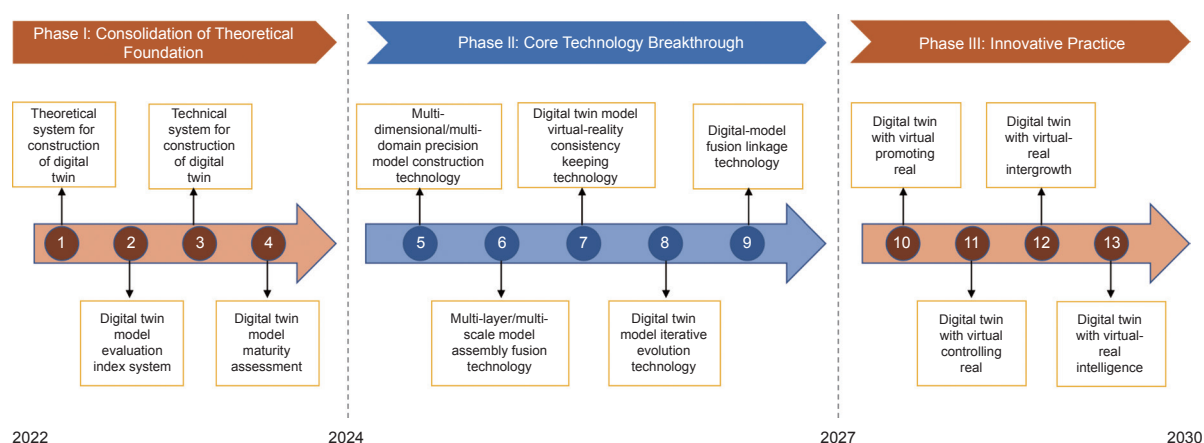


Figure 1.2.12 Roadmap of the engineering research front of “research on the theory and method of accurate construction and evolution of digital twin model”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

In the field of engineering management, the top 10 global engineering development frontiers this year are “product and service recommendation system based on the mapping knowledge domain”, “construction of autonomous transportation system of ‘mobility as a service’”, “network security situation awareness technology in high threat environment”, “development of human-machine co-driving system with self-evolution and self-learning”, “medical-networking management and control system for major contagious diseases”, “research and development of human-cyber-physical system in healthy building environment”, “factory early warning system based on digital twin”, “industrial internet production management system based on cloud platform”, “immersive building environment modeling and intelligent evaluation system”, and “smart contract for specific application and automatic generation method”. The core patents are listed in Tables 2.1.1 and 2.1.2. Besides, the Top 10 engineering development fronts include many disciplines

such as medicine, architecture, transportation, and computer. Among them, “product and service recommendation system based on the mapping knowledge domain”, “construction of autonomous transportation system of ‘mobility as a service’”, “network security situation awareness technology in high threat environment”, and “development of human-machine co-driving system with self-evolution and self-learning” are the key fronts for interpretation, and their current development trends and future trends will be explained in detail later.

(1) Product and service recommendation system based on the mapping knowledge domain

Mapping knowledge domains can organize and represent complex semantic associations accurately. The “product and service recommendation system based on the mapping knowledge domain” is an intelligent system that uses mapping knowledge domains to establish complex knowledge associations among users, products, and services, understand the personalized preferences and needs of users, and help users filter out interesting products and services. It collects multi-source heterogeneous data and extracts and fuses the knowledge of users, products, and services and their associations to build a mapping knowledge domain. Through the analysis of the mapping knowledge domain, it

Table 2.1.1 Top 10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Product and service recommendation system based on the mapping knowledge domain	56	239	4.27	2020.3
2	Construction of autonomous transportation system of “mobility as a service”	40	527	13.18	2019.7
3	Network security situation awareness technology in high threat environment	158	2 162	13.68	2019.2
4	Development of human-machine co-driving system with self-evolution and self-learning	68	434	6.38	2019.8
5	Medical-networking management and control system for major contagious diseases	39	176	4.51	2018.9
6	Research and development of human-cyber-physical system in healthy building environment	37	191	5.16	2019.0
7	Factory early warning system based on digital twin	120	302	2.52	2019.6
8	Industrial internet production management system based on cloud platform	134	1 332	9.94	2020.0
9	Immersive building environment modeling and intelligent evaluation system	139	1 672	12.03	2019.0
10	Smart contract for specific application and automatic generation method	119	892	7.50	2019.8

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in engineering management

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Product and service recommendation system based on the mapping knowledge domain	1	1	1	5	20	28
2	Construction of autonomous transportation system of “mobility as a service”	2	4	3	4	11	16
3	Network security situation awareness technology in high threat environment	8	11	28	37	40	34
4	Development of human-machine co-driving system with self-evolution and self-learning	0	0	6	16	33	13
5	Medical-networking management and control system for major contagious diseases	5	5	7	5	7	10
6	Research and development of human-cyber-physical system in healthy building environment	1	5	11	6	5	9
7	Factory early warning system based on digital twin	2	7	16	23	41	31
8	Industrial internet production management system based on cloud platform	3	6	11	22	26	66
9	Immersive building environment modeling and intelligent evaluation system	7	21	25	30	26	30
10	Smart contract for specific application and automatic generation method	7	7	9	9	12	11

accurately recommends personalized products and services for users and improves the accuracy and interpretability of recommendations. The “product and service recommendation system based on the mapping knowledge domain” faces problems such as heterogeneous data from multiple sources, sparse value density, difficult user security and privacy protection, and complex application scenarios, which make the system development face many challenges. Therefore, the innovation and optimization of multi-source data acquisition and integration, cross-domain recommendation with data migration and interaction, text information understanding and processing, intelligent data analysis of mapping knowledge domain, dynamic recommendation technology, multi-task learning model development, user information acquisition and processing mediated by smart devices, and user privacy security and protection are important directions for future development.

(2) Construction of autonomous transportation system of “mobility as a service”

In recent years, with the acceleration of global urbanization, travel services have gradually presented significant features such as decentralization, refinement, lightweight, and heterogeneity. “Mobility as a service” (MaaS) is a user-centered intelligent travel management and distribution system that integrates multiple travel services and provides them to end users through a data interface, enabling them to seamlessly plan their trips and make payments. Autonomous

transportation system (ATS) is based on the business logic of autonomous perception, learning, decision-making, and response, and accomplishes transportation through self-organized operation and autonomous services to achieve the goals of safety, efficiency, convenience, green, and economy. Compared with the existing transportation system, the MaaS ATS system is designed with the functions of one-stop travel, reservation-based travel, autonomous decision-making, autonomous service, instant demand response, dynamic matching of supply and demand, etc. It integrates various transportation modes through the information service platform, encourages green, low-carbon, and slow-moving travel modes, and quickly and accurately matches travel demand and transportation supply. It reduces the human passive intervention of the transportation system, improves the autonomy of the transportation system, eases the contradiction between the scattered travel demand for the traditional transportation system and intensive transportation supply, and the contradiction between flexible travel demand and planned transportation service, and improves the effect of the intelligent travel experience of users, which is of great significance to realize the intelligent transformation of transportation. Two major research hotspots have emerged in MaaS ATS system construction technology, including the optimized design of demand-oriented “individual-specific” personalized travel solutions in the multi-dimensional decision-making variable environment of individual travel, based on the heterogeneous user profile, and the

independent construction of dynamic supply and demand matching and collaboration system for reservation-based travel in the mobile Internet environment, based on the user reservation-based travel information, real-time transportation network situation judgment, vehicle supply status and other multi-source transportation information, relying on real-time dynamic simulation technology and mathematical optimization algorithms.

(3) Network security situation awareness technology in high threat environment

Under the background of increasingly fierce global cyberspace games and interweaving of real conflicts and network conflicts, the network security is facing a high threat environment with the coexistence of multi-level attack actors from hacker groups to national advanced persistent threat (APT) organizations. Network security situation awareness is an ability to master the security risks dynamically. Through continuous monitoring of network system status and security events, combined with threat intelligence, international relations, geopolitics and other information, the technology can understand the threat attack intent and evaluate the impact scope, so as to make forecast and early warning for follow-up actions and impacts, and assist the decision-making and action. Besides, the network security situation awareness mainly includes the collection of security data, security data processing, analysis of security data and visualization technology. The collection of security data is to obtain massive basic data closely related to security, such as traffic, logs, vulnerabilities, samples, etc.; security data processing is to carry out operations such as cleaning, classification and standardization for the collected massive security data; the analysis of security data is to extract network threat characteristics and indicators and comprehensively evaluate network security risks through technologies such as data mining, intelligent analysis and so on; the visualization technology is to visually display the security risks. Due to the limitation of factors such as data source, processing capacity and deployment environment, the ability of traditional network security situation awareness for situation awareness and prediction is insufficient. Furthermore, with relaying on the data collection and acquisition, massive data storage and calculation platform, evaluation and prediction of intelligent situation, the network security situation awareness in high threat environment establishes the system architecture. Regarding technical methods, it is provided with methods of

combination of the active discovery and passive collection, static analysis and dynamic analysis, distributed deployment and centralized processing, with taking into account both the macro and meso levels. It also combines the collection of real-time monitoring data with the accumulation of intelligence, experience and knowledge, so as to realize automatic and intelligent action response and strategy adjustment.

(4) Development of human-machine co-driving system with self-evolution and self-learning

In a narrow sense, human-machine co-driving means that both the driver and the intelligent drive system have partial or total control of the vehicle and jointly determine the movement of the vehicle through an appropriate coordination mechanism. Besides, broadly speaking, human-machine co-driving also means that vehicles only driven by human beings, vehicles of human-machine co-driving in a narrow sense and vehicles only driven by intelligent systems drive together on the road.

It is widely expected that the rapid development of technologies such as new generation artificial intelligence, vehicle wireless communication and vehicle infrastructure cooperation can accelerate the realization of human-machine co-driving and reduce the physiological/psychological burden of drivers. The traditional driver assistant systems only help drivers simplify the actions of exercising specific control, namely, control enhancement. However, since the advanced driver assistant systems (ADAS) is proposed by researchers, intelligent vehicles have begun to be provided with development in aspects including the awareness enhancement, assistance of decision-making, specific function replacement, even complete replacement of human driving, etc. Unlike pure unmanned driving, the main target of human-machine co-driving is to integrate the advantages of drivers and the machines under the current condition of indispensable human driving, so as to achieve the hybrid enhancement of human-machine intelligence and the driving effect of “1+1>2”.

Considering that many drivers hope to keep the full-time or part-time self-driving, and the current development of artificial intelligence is still difficult to achieve complete unmanned driving in complex traffic environment, besides, since related laws and regulations are still in the process of further development and improvement, the human-machine co-driving in the narrow and broad sense will become the

main operation mode of ground vehicles such as private cars, taxis and logistics trucks in the future. Therefore, the related research has important scientific value and application prospects.

(5) Medical-networking management and control system for major contagious diseases

The medical-networking management and control system for major contagious diseases refers to an intelligent management system for epidemic which is distributed in space including different medical and healthcare institutions, communities and families and based on elements including personnel, finance, objects and information related to “prevention-control-treatment” of major contagious diseases, implementing accurate risk evaluation, monitoring & alarming, coordinated deployment of supplies and collaborative optimization of prevention, control and treatment for the outbreak of major contagious diseases.

Scholars involved blend medical-networking, a brand new academic concept, into management and control system for major contagious diseases. Thus, facing with the prevention and control of major contagious diseases, the technological direction including a multi-agent data-based approach to governance for outbreak control, cross-regional treatment collaboration and prevention and control regulation during the entire process is gradually formed, which facilitates the transformation of management and control mode for major contagious diseases. For instance, in 2020, at the beginning of the outbreak of COVID-19 epidemic, Hefei University of Technology together with relevant enterprises set up the Wuhan Big Data Governance Platform for Epidemic Prevention and Control, which helped to rapidly complete the data analysis and data access for 70 hospitals including Huoshenshan Hospital and Leishenshan Hospital, public security bureau and civil affair bureau, markedly improving the management and control efficiency of epidemic.

As the medical-networking management and control system for major contagious diseases gradually progresses, the “high-coverage, high-response, and high-collaboration” medical service system will be established step by step in the future; the prevention-control ability of management and control system will be constantly enhanced in terms of intelligent and accurate non-contact monitoring technology and up-down-collaboration prevention-control system of contagious diseases; the medical service system will be transformed

from “human adapt to systems” into “systems serve human”; the information barrier of hospitals of various levels will be broken; the medical and healthcare resources of all levels can be effectively mobilized and shared; the normalized management and control of medical networking for major contagious diseases featured by “sentinel alarm at grass-roots level, driven by monitoring data and full-spectrum joint prevention and control” will come into being.

(6) Research and development of human-cyber-physical system in healthy building environment

Building is the micro-environment which is established to meet the requirements generated from life and production process, including the safety and health of residents. As science and technology develop and progress, people begin to positively renovate the architectural environment that is subject to control by means of devices. Currently, the architectural environment mainly refers to the indoor physical environment, namely the physical factors which act and influence on human’s physiology through sensory organs of human, including indoor thermal and humid environment, air quality, airflow environment, light environment and acoustic environment, etc. Human interact and interplay with indoor physical environment mainly through information technologies. The subject of information technologies include sensing technologies, communication technologies, computer technologies and control technologies. Among others, the sensing technologies obtain information, enabling Building to function as sensory organs; communication technologies convey information, enabling Building to function as nervous system; computer technologies process information, enabling Building to function as organs of thought; control technologies apply information, enabling Building to function as effector organs and generate actual effectiveness. Consequently, human-cyber-physical system in healthy building environment is an intellectualized system for building with health as its goal, with intelligent technologies as approaches, possessing comprehensive intelligent ability integrated sensory, inferential, judging and decision-making abilities and coordinating human and indoor physical environment. The fundamental theories include the building environment theory, control theory, information theory and system theory, etc. The iteration of computer networking technology facilitates the development from human-cyber-physical system in healthy building environment to control

network and information network integration technology, so as to realize the intelligentized system monitoring, information sharing and intensive management. In addition, the Internet of Things-based intelligent grid is greatly influencing the application and development of human-cyber-physical system.

(7) Factory early warning system based on digital twin

Factory hazards include the possibility of damage to people and the environment from equipment and sound, light, fire, electricity, and poison, as well as the possibility of damage to materials, equipment, and production from people. Unlike traditional methods that rely on the feelings and experiences of people in the field, the factory early warning system based on digital twin enables remote, accurate, and fast factory early warning of hazards through a five-dimensional model of physical entities, virtual entities, early warning services, twin data, and connectivity. The current main research includes but is not limited to ① remote diagnosis of workshop equipment based on digital twin, ② rapid construction of modular factory digital twin low-code platform, ③ health monitoring and management of factory building environment based on BIM technology, ④ intelligent identification and early warning of uncertain objects in the factory environment, ⑤ identification and early warning of multiple disaster-inducing digital twin sensing, ⑥ data-driven life prediction and health management of critical parts, ⑦ design and rehearsal of digital twin-based evacuation plan, ⑧ cloud platform for factory operation and maintenance monitoring and simulation, ⑨ early warning and control of human-machine interaction safety, and ⑩ simulation and dynamic real-time scheduling of factory logistics. With the construction of globalized smart factories, the demand for “factory early warning system based on digital twin” has surged. It is an inevitable development trend to reflect hazards more comprehensively, predict them more quickly and accurately, and design hazard plans more scientifically based on digital twin technology.

To achieve this, there is an urgent need to absorb the achievements in the fields of sensing technology, perception technology, communication technology, artificial intelligence technology, simulation technology, and big data technology to provide support for early warning of smart factory hazards based on enhanced cognition of various industrial production laws.

(8) Industrial internet production management system based on cloud platform

Industrial Internet refers to the connection and fusion between global industrial systems and advanced computing, analysis, sensing technologies as well as internet. The nature of industrial internet is to closely link and fuse the equipment, production lines, factories, suppliers, products and clients through open and global industry-class network platforms, effectively sharing various elements and resources of industrial economy. Cloud platforms are highly-shared platforms in which the resources are manufactured based on cloud computing information technologies, linking different the tremendous manufacturing resources through industrial internet; the open collaboration of manufacturing resources and services can be achieved, with highly-shared social resources. The production management system specializes in comprehensive management integrating production plans, organization, coordination and control, achieving estimated production goals by means of reasonably organizing the production process, effectively utilizing production resources and economically and reasonably conducting production activities

Currently, most of production management systems manage closed and static domains based on expertise and heuristic rules, which is difficult to adapt to complicated and changeable custom-tailed manufacturing tasks and lacks the effective application of potential knowledge of big data of manufacturing resources. The new generation information technologies featured by cloud computing, big data and artificial intelligence integrate with manufacturing industry; for industrial internet, based on the interconnection of various underlying industrial systems and upper cloud manufacturing platforms, the originally closed manufacturing system become open and interconnected, so the open and sharing manufacturing resources of the entire industry chain and the production management of the entire process are obtained, which provides supporting technologies for production management which requires high collaboration, including the manufacture of high-end equipment. As the core of industrial internet cloud platforms, the production management system is the core support engine for intelligent configuration of large-scale distributed manufacturing resources and cost reduction and efficiency improvement of enterprises under the open environment of industrial internet, so as to achieve the adaption to dynamic changes in different domains and the

scalability to complicated constraints; from the perspective of new technologies in which data and artificial intelligence develop in a coordinated way, core issues including high timeliness, high complexity and high dynamics in the face of modern manufacturing scheduling can be comprehensively and effectively addressed.

The development tendency indicates the researches on effective, transferable and self-adaption production management system based on manufacturing big data and driven by artificial intelligence, including edge & cloud computing-collaboration distributed artificial intelligence processing framework to realize the intelligent dynamic cooperative scheduling which balances the cloud manufacturing and manufacturing resources of isomerism on the side of edge, seamless integration of application among collaboration organizations and management through sharing business data and collaboration, so as to further achieve cross-organization business process collaboration and realize effective, low-cost, quality modeling approaches combined with multiple requirements based on deep reinforcement learning for the entire cross-organization work, as well as man-machine coordination production management technologies blending internal scheduling models of enterprises, data of production factors and manual production scheduling experience.

(9) Immersive building environment modeling and intelligent evaluation system

“Immersive” is based on virtual reality (VR) technology, so that the user’s visual and other sensory channels are immersed in the computer-generated content and can interact with it, thus creating a sensory experience of being in a virtual world. Compared with the presentation of 2D drawings or desktop computers, VR enables project stakeholders to experience and evaluate architectural design solutions on a real spatial scale before the design is implemented, thus better meeting users’ functional, aesthetic, and comfort requirements for buildings and promoting the improvement of design management.

For immersive architectural review, it is desirable to solve three levels of technical problems including modeling, interaction, and knowledge extraction. Firstly, it is needed to complete the rapid construction of 3D models of buildings and environments, and realize the data interoperability between mainstream modeling software and virtual reality-

related software. Secondly, it is required to solve the problem of natural interaction between people and the virtual building environment in the immersive environment. Through various external interactive devices, it is possible to observe the size, layout, material, and other attributes of the building and components from the first-person perspective, and to interact naturally with the building model and other users based on signals such as movement and voice. Finally, in the process of immersive experience, a large amount of data will be generated during the interaction between users and the building, environment, and other users. Storing, integrating, expressing, and reusing these interaction data and forming design knowledge will support the research of intelligent review algorithms and systems.

With the continuous development of virtual reality technology, the portability, comfort, and fluency of VR devices will be further improved in the future, and the immersive design experience system will become more popular, forming a powerful supplement to the existing engineering design work methods. The immersive workspace provided by VR technology will also make distributed multi-party collaborative design more convenient.

(10) Smart contract for specific application and automatic generation method

Smart contract refers to a program with status, which operates on blockchain platform and driven by events. The data assets on blockchain ledger may be stored and processed by smart contract, and smart contract is widely used in engineering management, medical treatment, finance and other fields. The smart contract on blockchain has many characteristics such as decentralization, de-trust, programmable and tamper-resistant, which enable the realization of efficient information exchange, value transfer and asset management. In terms of technology, the smart contracts on different blockchain platform vary in used programming language. For example, bitcoin is developed by using special bitcoin script, Ethereum is developed by using Solidity and Hyperledger is developed by using multiple programming languages to develop smart contract. The automatic generation of smart contract can greatly reduce the difficulty of developing smart contract code to a large extent and improve the friendliness of smart contract programming. However, smart contract has many development languages and the smart contract in different fields greatly varies in

application design, which makes it very difficult to generate smart contract automatically and is not conducive to the standardized design in large-scale engineering projects and the collaborative use of multiple blockchain platforms. For the automatic generation of smart contract, smart contract can be classified on the basis of domain characteristics. For the data in different contract classification, big data and artificial intelligence analysis can be carried out. At the same time, the special programming language can be selected according to analysis results to generate the unified and domain specific smart contract template. In application field, smart contract is widely used in engineering management, medical treatment, finance and other fields, which enables possible to develop the smart contract with special functions for specific application scenarios. For example, compared with traditional financial field, smart contract can realize lower legal and transaction expenses and meanwhile, reduce the threshold for users to use. While in the application field of large-scale engineering construction, engineering developer can solve the accident accountability and anti-corruption during engineering supervision by using smart contract. In the future development, there are mainly two problems: privacy supervision and performance for smart contract. Generally, the data processed by smart contract is fully open and transparent. Everyone can acquire account balance, transaction information and contract contents through public query. These open operations and data may result in user data leakage and the de-anonymous attacks from attackers to blockchain or smart contract in some specific application scenarios. In addition to privacy security, currently in terms of performance, the majority of blockchain has low throughput on the infrastructure. But the design of smart contract can be optimized according to specific application scenarios to reduce contract execution cost and improve system efficiency.

2.2 Interpretations for four key engineering development fronts

2.2.1 Product and service recommendation system based on the mapping knowledge domain

The product and service recommendation system based on the mapping knowledge domain is a knowledge-driven recommendation platform, which makes product and service recommendations more intelligent, accurate, personalized,

and interpretable by deeply mining the value of data. From the patent analysis, the main research areas are as follows.

(1) Intelligent Q&A and data analysis technology based on the mapping knowledge domain

The intelligent Q&A technology based on the mapping knowledge domain gets user requirements through natural interaction, retrieves facts stored in the mapping knowledge domain, and gets answers to questions. The data analysis technology based on the mapping knowledge domain connects data silos to provide a complete view of data analysis, gain data insight, improve decision-making, and improve recommendation quality. Existing technologies include database storage, data mining, and heterogeneous data processing. Therefore, the development of massive mapping knowledge domain storage, multi-source heterogeneous data collection, and processing analysis technologies become the focus.

(2) Intelligent recommendation technology for products and services based on the mapping knowledge domain

Intelligent recommendation for products and services based on the mapping knowledge domain finds potential connections between users and products and services by analyzing the massive knowledge associations in the mapping knowledge domain and provides users with high-quality recommendations. The development hotspots cover key technologies such as big data, cloud computing, machine learning, and deep learning.

(3) Development of product and service recommendation system for different business scenarios

System development is mainly distributed in the fields of intelligent medical care, e-commerce, and smart life. Although the development in the field of intelligent medical care covers medical information provision, medical material distribution, disease prediction, and medical assistance, there is less technology development for user privacy and security protection. The field of e-commerce is more complete in terms of intelligent customer service and recommendation systems but is constrained by static recommendations and the influence of complex user environments. Emphasis should be placed on the development of voice, video, image, emotional information acquisition and processing technology, and dynamic update technology of mapping knowledge domain for media

devices. The technology development in the field of smart life involves the recommendation of household items, which is mostly complemented by intelligent robots and electronic devices. How to collect information through media devices, analyze user needs, accurately recommend products and services, and terminal server development have become the focus of development.

In terms of the quantity of published patents, the top country is China (Table 2.2.1). The country with the highest citations per patent is the USA (Table 2.2.1). The top three institutions in terms of the quantity of published patents are China Ping'an Property Insurance Co., Ltd., Tencent Technology (Shenzhen) Co., Ltd., and Peking University (Table 2.2.2). There is no cooperation relationship among all countries and institutions.

China focuses on the mapping knowledge domain, big data, and medical integration and development of smart medical care, such as medical and health service recommendation methods, systems, electronic devices and storage media R&D, clinical test results analysis methods, and systems based on medical mapping knowledge domain, etc. Korea

focuses on smart home and smart tourism product and service recommendation systems, such as decoration, TV, pet, social, AI Reminder for food and health and other products and service system, personalized recommendation and service in various aspects such as transportation, accommodation, scenic spots, etc. The USA is more concerned about applications related to smart devices and e-commerce, such as systems and methods used to integrate third-party services with digital assistants, automated assistance systems for computing devices, precision marketing for e-shopping recommendations, etc.

Figure 2.2.1 further maps out the future development path of the "product and service recommendation system based on the mapping knowledge domain".

2.2.2 Construction of autonomous transportation system of "mobility as a service"

The technology for the construction of autonomous transportation system of "mobility as a service" (MaaS) aims to meet the public requirements for intelligent, comfortable,

Table 2.2.1 Countries with the greatest output of core patents on "product and service recommendation system based on the mapping knowledge domain"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	52	92.86	75	31.38	1.44
2	South Korea	3	5.36	2	0.84	0.67
3	USA	1	1.79	162	67.78	162.00

Table 2.2.2 Institutions with the greatest output of core patents on "product and service recommendation system based on the mapping knowledge domain"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Ping'an Property Insurance Co., Ltd.	4	7.14	3	1.26	0.75
2	Tencent Technology (Shenzhen) Co., Ltd.	4	7.14	3	1.26	0.75
3	Peking University	3	5.36	1	0.42	0.33
4	Gree Electric Appliances Incorporation of Zhuhai	2	3.57	0	0.00	0.00
5	Viasat Incorporation	1	1.79	162	67.78	162.00
6	Guilin University of Electronic Technology	1	1.79	13	5.44	13.00
7	Shaanxi Normal University	1	1.79	13	5.44	13.00
8	Nanjing Silicon Intelligence Technology	1	1.79	8	3.35	8.00
9	Shandong Shunnet Media Co., Ltd.	1	1.79	6	2.51	6.00
10	Alibaba Group Holding Limited	1	1.79	5	2.09	5.00

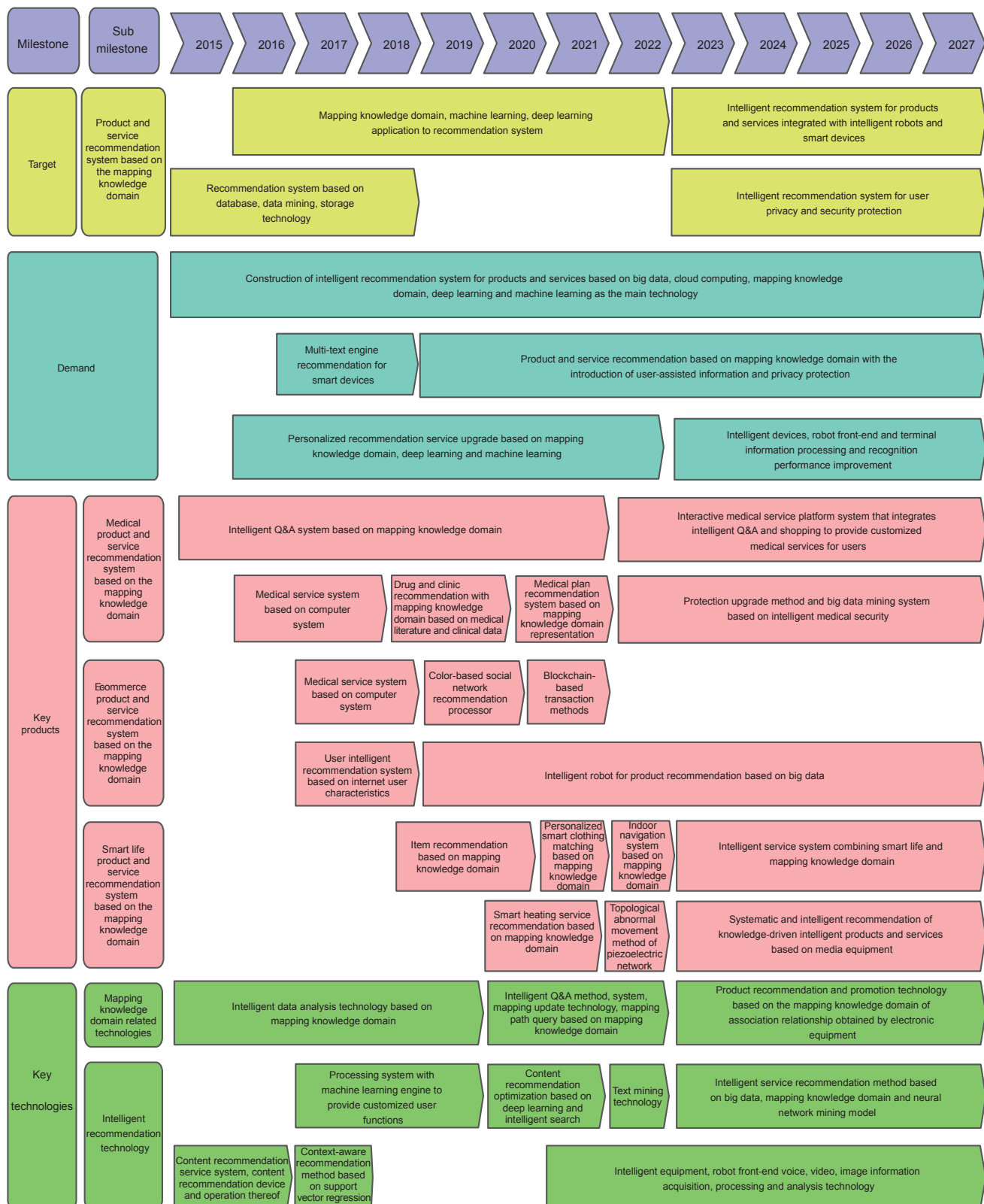


Figure 2.2.1 Roadmap of the engineering development front of “product and service recommendation system based on the mapping knowledge domain”

personalized, and 3D travel is characterized by multi-modal, full-chain, and reservation-based travel services, guiding individual intensive travel, regulating multi-modal travel and optimizing service supply through economic incentives such as joint ticketing packages, to achieve sustainable urban transportation. On the management side, a fast optimization decision model is established for multi-modal and multi-objective combined travel optimization. On the supply side, the optimal allocation of travel resources in time and space is studied. On the user side, real-time information and personalization are improved to meet personalized travel needs. The following is a more in-depth analysis from three perspectives, including the collaborative optimization of multi-modal supply resources for MaaS, personalized and integrated intelligent travel services, and multi-resolution simulation of the ATS system.

(1) Collaborative optimization of multi-modal supply resources for MaaS

An important feature of MaaS is the integration of various transportation modes and service systems with efficiently operated public transportation as the backbone. Unlike traditional transportation networks, the multi-layer composite network can realize the separation of the physical layer (road network, rail network, etc.) and mode layer (mini car, bus, subway). Collaborative optimization of cross-modal supply resources is based on comprehensive travel cost measurement of mode chains to resolve the mode transfer mechanism, estimate the transfer matrix, reconfigure the traffic flow distribution model by integrating the composite network, and optimize the supply resource allocation based on the spatial and temporal distribution of network traffic flows. In recent years, with the increasing popularity of shared travel, the research concept has changed from a static single mode of transportation space-time resource allocation to a shared resource allocation based on reservation and real-time response.

(2) Personalized and integrated intelligent travel services

Based on the real-time perception information of the transportation network, it can accurately control the matching relationship between travel demand and multi-modal transportation supply and realize online iteration and update of the dynamic supply and demand matching optimization algorithm. It can also analyze the impact of the supply-demand matching optimization scheme on the travel time, waiting time, transfer times, and vehicle congestion of each

travel mode, the impact on other related travel modes, and the impact on road conditions.

It can further establish a prediction model for travel mode selection by travelers, develop a dynamic demand prediction technology for urban multi-modal transportation based on big data, deduce the flow distribution of all passengers, and evaluate the operation service level and global optimization effect of each travel mode based on this, thus realizing personalized and integrated intelligent travel services based on real-time transportation information in the mobile Internet environment.

(3) Multi-resolution simulation of ATS system

The digital twin city is currently being used to promote the construction of smart cities, providing a multi-resolution digital twin platform with high fidelity for ATS systems, from the multi-source data access layer, to the computational simulation layer, to the decision-making application layer. Based on the holographic perception of static and dynamic data, it realizes the reproduction of scenarios based on twin data, derives and generalizes twin scenarios, accelerates the realization of shared autonomous driving technology, and helps the construction of ATS systems. Using the macro, meso, and micro multi-resolution simulation system driven by digital twin technology, and with the help of high-efficiency simulation optimization technology, it can optimize the design of a one-stop and reservation-based service capacity organization and operation plan.

The top three countries in the quantity of published patents are the USA, South Korea, and Japan (Table 2.2.3). For the quantity of organizational patents, the top three are Mobileye Vision Technologies Limited, Sony Group Corporation, and Toyota Motor Company (Table 2.2.4). Seen from the cooperation network among main countries (Figure 2.2.2), cooperation only exists between the UK and Japan, while there has been no cooperation between individual institutions.

Looking ahead, the construction of the MaaS autonomous traffic system will be significant technical changes in the innovative mobile Internet environment. In particular, with the rapid development of mobile sensors, communication networks, artificial intelligence, big data analysis, cloud computing, deep learning, reinforcement learning, and other

Table 2.2.3 Countries with the greatest output of core patents on “construction of autonomous transportation system of ‘mobility as a service’”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	20	50.00	75	14.23	3.75
2	South Korea	6	15.00	3	0.57	0.50
3	Japan	5	12.50	1	0.19	0.20
4	Germany	4	10.00	115	21.82	28.75
5	China	3	7.50	301	57.12	100.33
6	Cyprus	1	2.50	32	6.07	32.00
7	UK	1	2.50	0	0.00	0.00
8	Israel	1	2.50	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “construction of autonomous transportation system of ‘mobility as a service’”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Mobileye Vision Technologies Limited	7	17.50	4	0.76	0.57
2	Sony Group Corporation	4	10.00	1	0.19	0.25
3	Toyota Motor Company	4	10.00	0	0.00	0.00
4	LG Electronics Incorporation	3	7.50	2	0.38	0.67
5	Didi Chuxing Technology Company	2	5.00	58	11.01	29.00
6	Google Incorporation	2	5.00	43	8.16	21.50
7	Xerox Corporation	2	5.00	14	2.66	7.00
8	Uber Technologies Incorporation Limited	2	5.00	9	1.71	4.50
9	Shanghai Zhaoxin Semiconductor Co., Ltd.	1	2.50	243	46.11	243.00
10	Siemens Corporation	1	2.50	112	21.25	112.00

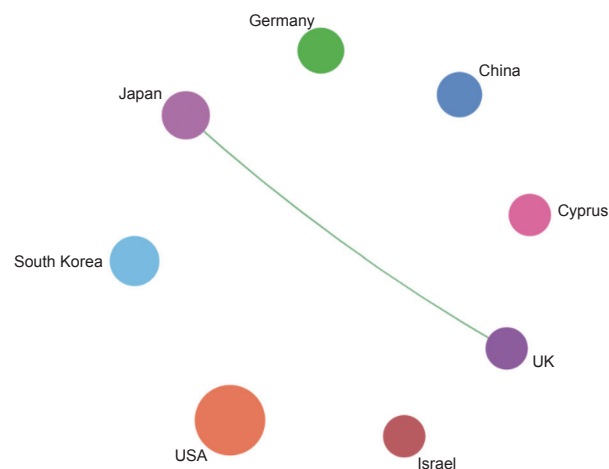


Figure 2.2.2 Collaboration network among major countries in the engineering development front of “construction of autonomous transportation system of ‘mobility as a service’”

technologies, the ability to accurately obtain and intelligently analyze dynamic travel information has been greatly improved. Based on these emerging technologies, digital and intelligent supervision of MaaS autonomous transportation systems, personalized travel demand management, and platform online decision optimization will be realized, which will effectively promote one-stop smart travel services for future urban transportation. In order to form a MaaS system for future autonomous transportation systems, it is necessary to research the one-stop travel and reservation-based traffic travel optimization methods driven by big data and artificial intelligence, and to establish adaptive sensing multi-task dynamic learning methods and decentralized multi-intelligence. On the other hand, it needs to propose a variety of strategic dynamic optimization methods such as efficient matching, optimal scheduling, mode combination, and dynamic pricing of smart travel service platforms, and build a personalized travel demand management and online decision-making optimization platform. Figure 2.2.3 shows the roadmap of the engineering development front of “construction of autonomous transportation system of ‘mobility as a service’”.

2.2.3 Network security situation awareness technology in high threat environment

Secretary General Xi Jinping pointed out that it is necessary to “perceive the network security situation in an all-weather and all-round way and enhance the network security defense and deterrence capabilities”. Network security situation awareness is an important condition for realizing network security guarantee by acquiring, understanding, displaying the elements that cause the change of network security status and predicting the development trend to assist decision-making and action. In the high threat environment where multi-level attack actors coexist, there are many challenges in perceiving threats and preventing and controlling risks, and forward-looking technical exploration and engineering practice are required.

Network security situation awareness in high threat environment focuses on data collection, threat detection, comprehensive assessment, prediction and early warning, intelligent response and other technologies in specific scenarios. Relatively mature solutions include network threat analysis/network detection response, endpoint

detection response, extended detection and response, security orchestration and automatic response, APT detection based on techniques, tactics and procedures, etc. Typical data collection includes deep flow inspection, deep packet inspection, honeypot/honeyfarm/honeynet, internet asset detection, etc. Massive security information and event management are carried out based on big data technology, intelligent analysis and other technologies are used to realize comprehensive assessment and early warning with threat intelligence as the support, and the situation awareness capability of threat detection, security analysis and sharing and cooperation is formed.

From the perspective of patent analysis, network security situation awareness involves data acquisition and processing, situation assessment and prediction, and network security situation awareness of specific industries.

(1) Data acquisition and processing

The network and system status information and equipment log information are received, and the big data platform is used for preprocessing, aggregation and association analysis to realize the extraction of situation awareness elements, and provide a data basis for situation assessment and prediction.

(2) Situation assessment and prediction

The assessment and prediction of the security situation are realized by constructing the analysis model, which mainly includes: methods based on neural network, such as back propagation (BP) neural network, radial basis function (RBF) neural network, etc.; methods based on expert knowledge, such as mapping knowledge domain and game theory; methods based on pattern recognition, such as grey correlation method and rough set theory.

(3) Network security situational awareness of specific industries

With the power industry as an example, there are the security situation awareness and assessment methods such as electric power communication network, power supervisory system network, Internet of things in power systems, power wireless private network and power mobile terminal network.

In terms of the quantity of patents (Table 2.2.5), the top countries are China and the USA. China is mainly involved in the network security situation assessment and prediction model, and the USA is mainly involved in the situation

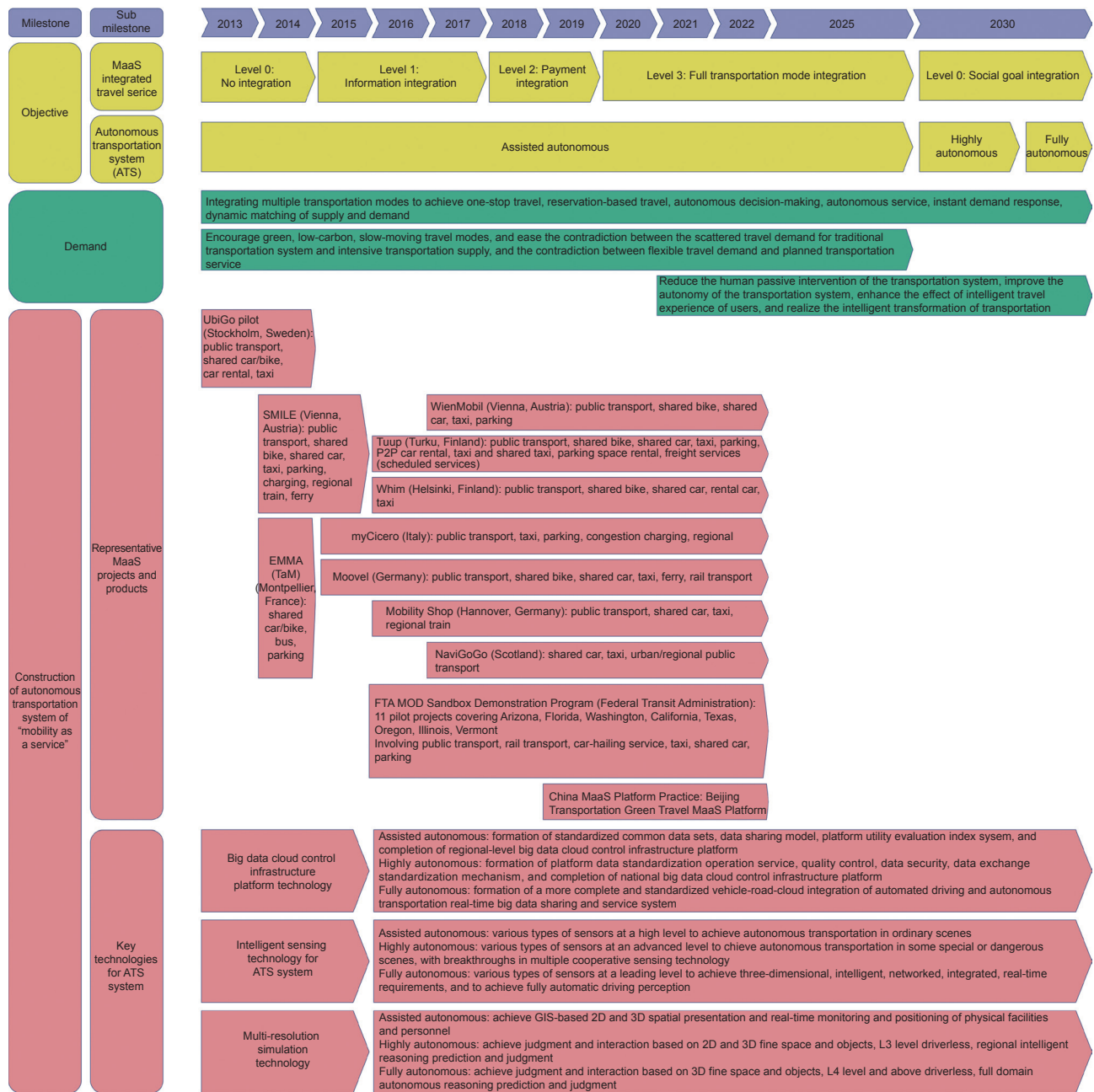


Figure 2.2.3 Roadmap of the engineering development front of "construction of autonomous transportation system of 'mobility as a service'"

awareness system architecture and implementation. In terms of patent output, there has been no relevant cooperation among countries. The top institutions in the quantity of patents (Table 2.2.6) are State Grid E-commerce Co., Ltd. and Guangxi Power Grid Co., Ltd. In terms of cooperation network among main institutions (Figure 2.2.4), State Grid E-commerce Co., Ltd. of China, Beijing University of Posts

and Telecommunications, and North China Electric Power University are closely connected.

Looking forward to the future, the network security situation awareness platform in the high threat environment covers such as data acquisition, massive data storage and calculation platform, intelligent situation assessment and prediction in

Table 2.2.5 Countries with the greatest output of core patents on “network security situation awareness technology in high threat environment”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	130	82.28	738	34.14	5.68
2	USA	22	13.92	1 301	60.18	59.14
3	UK	2	1.27	100	4.63	50.00
4	Israel	1	0.63	13	0.60	13.00
5	Ireland	1	0.63	7	0.32	7.00
6	Switzerland	1	0.63	3	0.14	3.00
7	Poland	1	0.63	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “network security situation awareness technology in high threat environment”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	State Grid E-commerce Co., Ltd.	12	7.59	121	5.60	10.08
2	Guangxi Power Grid Co., Ltd.	8	5.06	46	2.13	5.75
3	Hubei Yangzhong Jushi Information Technology Co., Ltd.	4	2.53	36	1.67	9.00
4	Beijing Institute of Technology	4	2.53	19	0.88	4.75
5	Splunk Incorporation	3	1.90	76	3.52	25.33
6	Beijing University of Posts and Telecommunications	3	1.90	29	1.34	9.67
7	Civil Aviation University of China	3	1.90	15	0.69	5.00
8	Hangzhou DBAPP Security Co., Ltd.	3	1.90	12	0.56	4.00
9	University of California	3	1.90	8	0.37	2.67
10	North China Electric Power University	3	1.90	5	0.23	1.67

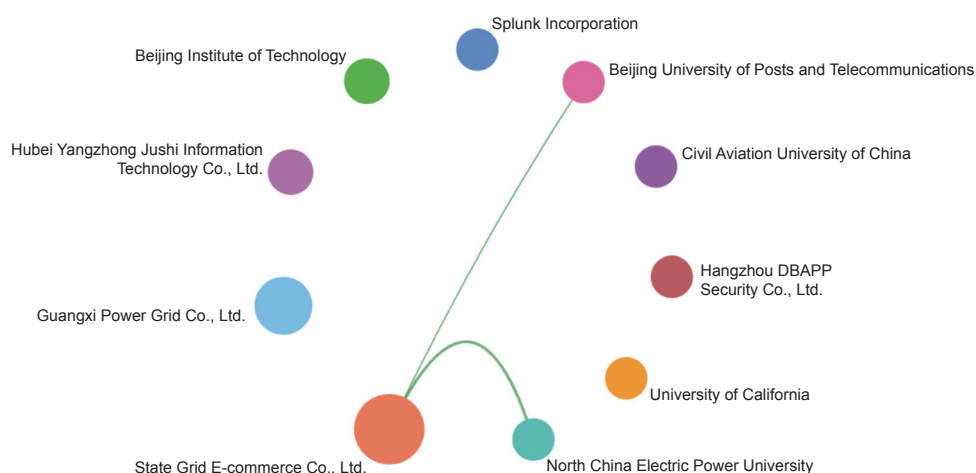


Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “network security situation awareness technology in high threat environment”

structure (Figure 2.2.5). The combination of active discovery and passive acquisition, static analysis and dynamic analysis, distributed deployment and centralized processing will be comprehensively adopted to explore the application of artificial intelligence, edge computing, privacy computing and other technologies in technology and methods. Taking both macro and medium perspectives into account, it combines real-time data with intelligence, experience and knowledge accumulation to support automatic and intelligent action response and strategy adjustment, and form full coverage of the Internet and the Internet of things.

2.2.4 Development of human-machine co-driving system with self-evolution and self-learning

(1) Human-machine co-driving and the autonomy classification of intelligent vehicles of the narrow sense

Society of Automotive Engineers (SAE) released the six-level

classification principle of intelligent vehicle autonomy in 2016. In 2022, China's Ministry of Industry and Information Technology also issued a recommended national standard of *Taxonomy of Driving Automation for Vehicles* with division of six levels, among which Level 0 is emergency assistance; Level 1 is part of the driving assistance and the driving automation system can continuously control the lateral or longitudinal motion of the vehicle under its designed operating conditions; Level 2 is combined driving assistance. Besides the above functions, it is equipped with functions such as detection and response to some targets and events. In automatic driving of Level 0 to Level 2, the task of monitoring road conditions and responding is completed by the driver and the system. It is needed to take over the dynamic driving task for the driver. Level 3 is conditional automatic driving. The driving automation system continuously performs all dynamic driving tasks under its designed operating conditions so that users can take over the dynamic driving tasks in an appropriate way. Level 4 is

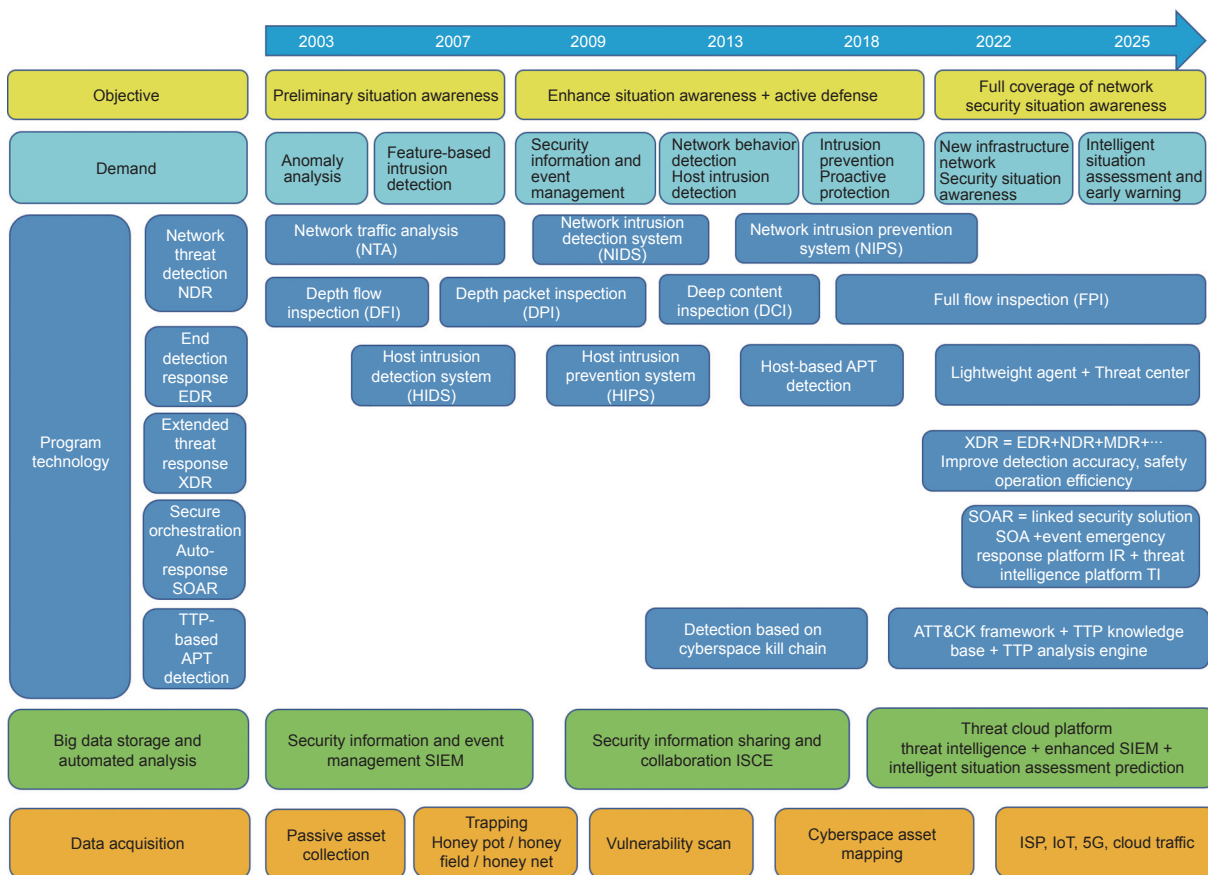


Figure 2.2.5 Roadmap of the engineering development front of “network security situation awareness technology in high threat environment”

highly automatic driving where the system can continuously perform and take over all dynamic driving tasks under its designed operating conditions. When the system sends a takeover request, the system is able to reach the minimum risk state automatically if the passengers do not respond. Level 5 is fully automatic driving. In automatic driving of Level 4 and Level 5, the driver completely changes into the role of passenger without steering wheel and pedal brake in vehicles. Human-machine co-driving research of narrow sense mainly focuses on the above-mentioned intelligent driving in Level 2 to Level 4 (some scholars believe that intelligent driving in level 4 is no longer man-machine co-driving of narrow sense). Because human driving behavior is easily influenced by psychological and physiological state, the research focus of human-machine co-driving in Level 2 is to take over the vehicle in an emergency by combining the characteristics of intelligent system such as no distraction, standardized decision-making and precise control, so as to realize the complementary advantages of human intelligence and machine intelligence to reduce man-made traffic accidents. Therefore, it is also called standby human-machine co-driving. With the improvement of intelligent system, the human-machine co-driving research in Level 3 focuses on the switching of human-machine dominance. Under reasonable conditions, intelligent systems can take over some driving tasks and reduce the driving burden of human beings. Therefore, it is also called human-machine driving based on division of labor. With the further improvement of intelligent system, the human-machine co-driving research in Level 4 focus on realizing the scene perception and decision-making ability beyond human driving through various technologies such as vehicle wireless communication and vehicle-road coordination. In most cases, long-term replacement of human driving vehicles significantly improves the safety, comfort and other performance of automobiles. Therefore, it is also called human-machine co-driving with time-share.

(2) State monitoring and intention understanding for human drivers

The driving behavior of human driver is determined by his physiological condition and psychological activity with the corresponding vehicle driving behavior produced at the same time.

Early research focuses on real-time monitoring and intelligent

evaluation of human driver's driving behavior and state to find possible operational errors as soon as possible and avoid traffic accidents. With difficulty in observing directly and describing quantitatively the driver's driving behavior, the related research mainly focuses on a simple longitudinal driving behavior analysis to evaluate whether the driver keeps a safe and reasonable driving distance. The driver's turning characteristics shall be monitored to avoid the lateral driving behavior analysis of rushing out of the lane; It is needed to detect physiological and psychological state whether the driver is tired driving, drunk driving, and distracted while driving (such as dialing/receiving a mobile phone while driving).

With the development of artificial intelligence technology, researchers deeply analyze the psychophysiological cognitive process of human drivers' perception in the surrounding driving environment and rational driving behavior in complex road condition. The major smart car manufacturers and research institutes have collected a large quantity of real driving data of human drivers for analysis and study, hoping that smart cars can "learn" more driving skills and experience in judging and making decisions on driving situations from the driving behaviors of human drivers. The correct driving intention understanding model obtained by this imitation learning is worth application greatly not only for human-machine co-driving, but also for completely unmanned driving.

With the complicated scenes and tasks of autonomous driving, most of the human-machine co-driving systems combine regular setting with data-driven learning currently to improve the human-machine co-driving ability gradually by constantly testing the system in new scenes and tasks. However, closed-loop self-evolutionary learning, exploring new scenes and tasks independently and improving itself, is successful in the field of human-machine driving and unmanned driving with breakthrough in many other fields.

(3) Human-machine switching and mutual-trust

Human-machine co-driving also involves the "research on man-machine trust and cooperation mechanism in man-machine collaborative decision-making" mentioned in the Top 10 engineering research frontiers in engineering management field selected by Chinese Academy of Engineering in 2021. Judging from the accident data of man-machine co-driving vehicles in mass production at present, many human drivers

cannot take over the control of vehicles in time of crisis with trust in the intelligence and autonomy level of vehicles, resulting in accidents. With the continuous popularization and application of artificial intelligence system in production and life, the over-trust in automation system will be one of the research focuses in the future.

The top three countries in terms of the quantity of published patents in the engineering development front of “development of human-machine co-driving system with self-evolution and self-learning” are South Korea, the USA, and China (Table 2.2.7). In terms of the quantity of organizational patents, the top three are StradVision Incorporation, Baidu Online Network Technology (Beijing) Co., Ltd., and Toyota Motor Company (Table 2.2.8). There was no relevant cooperation among

various countries. In terms of institutions, only Hyundai Motor Company and Kia Motor Company have ever cooperated (Figure 2.2.6).

According to the literature and survey of patents, the current research of human-machine co-driving focuses on the following four points: correct understanding of driving scenarios and driving tasks, which is also a difficulty in the research of fully-unmanned autonomous driving; driver’s state detection and intention understanding, requiring timely detection of abnormal driver’s state for intervention and rapid identification of changeable driving intentions for assistance in driving; research on handover timing and mechanism of dominance in driving, which reduces cognitive conflicts and mental/psychological burdens of

Table 2.2.7 Countries with the greatest output of core patents on “development of human-machine co-driving system with self-evolution and self-learning”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	South Korea	23	33.82	73	16.82	3.17
2	USA	19	27.94	271	62.44	14.26
3	China	11	16.18	49	11.29	4.45
4	Japan	11	16.18	32	7.37	2.91
5	Germany	2	2.94	7	1.61	3.50
6	Israel	2	2.94	2	0.46	1.00

Table 2.2.8 Institutions with the greatest output of core patents on “development of human-machine co-driving system with self-evolution and self-learning”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	StradVision Incorporation	12	17.65	45	10.37	3.75
2	Baidu Online Network Technology (Beijing) Co., Ltd.	7	10.29	72	16.59	10.29
3	Toyota Motor Company	5	7.35	14	3.23	2.80
4	Hyundai Motor Company	4	5.88	9	2.07	2.25
5	Kia Motor Company	4	5.88	9	2.07	2.25
6	Mobileye Vision Technologies Limited	3	4.41	9	2.07	3.00
7	NVIDIA Corporation	2	2.94	102	23.50	51.00
8	Mazda Motor Corporation	2	2.94	11	2.53	5.50
9	Nissan Motor Company	2	2.94	11	2.53	5.50
10	Huawei Technologies Co., Ltd.	2	2.94	7	1.61	3.50

human drivers in emergency; and trust issues in human-machine co-driving for figuring out how to make human drivers aware of when they should manipulate their

vehicles by themselves. Figure 2.2.7 shows the roadmap of this front.

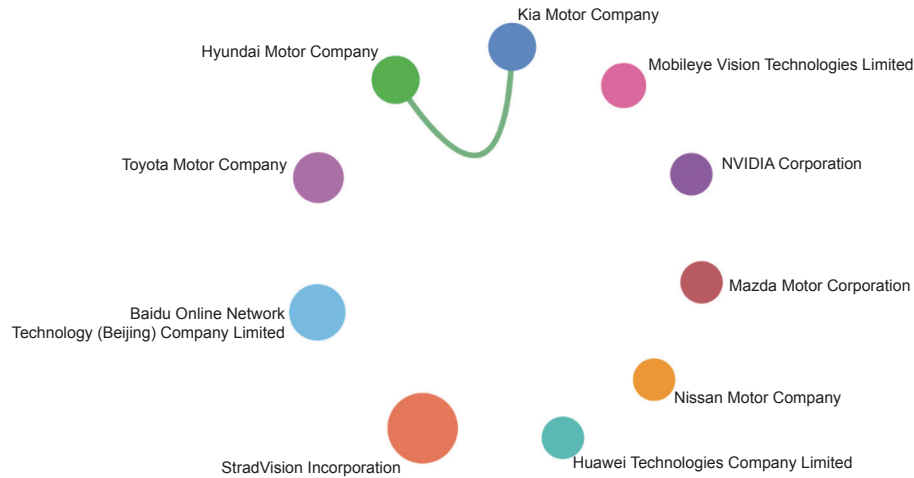


Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “development of human-machine co-driving system with self-evolution and self-learning”

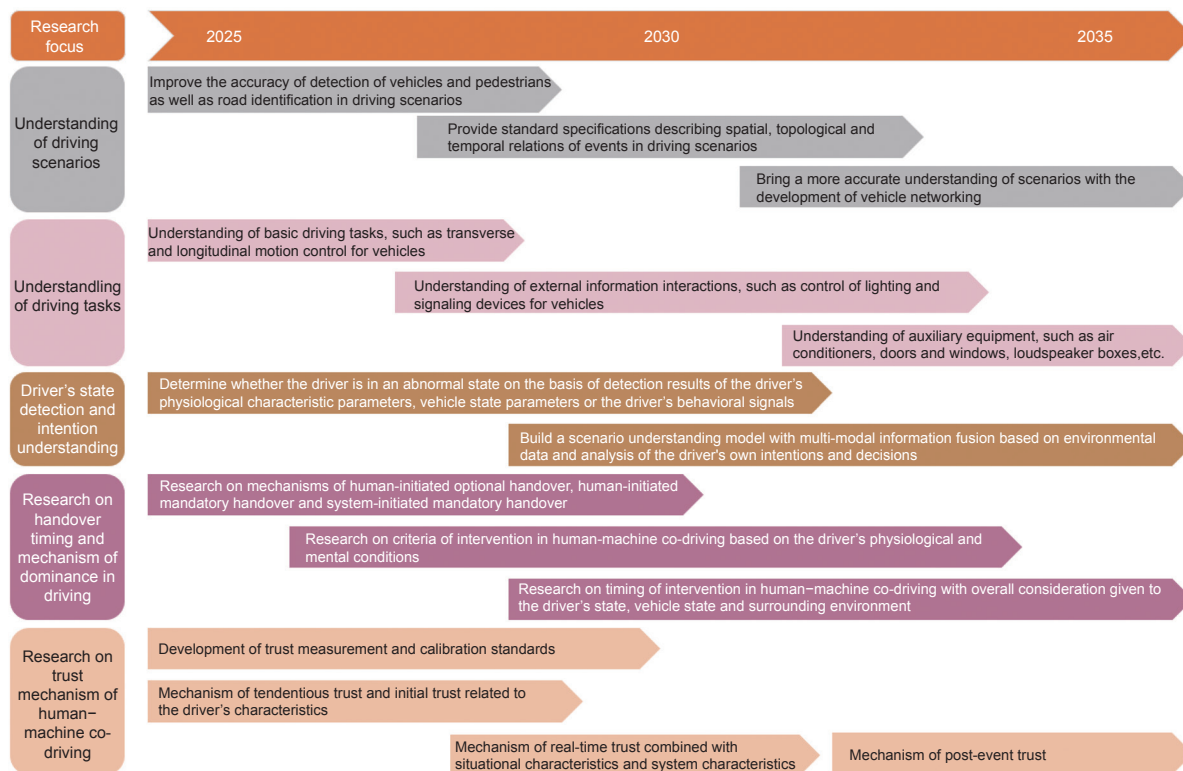


Figure 2.2.7 Roadmap of the engineering development front of “development of human-machine co-driving system with self-evolution and self-learning”

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