Engineering Focus 2017

Engineering Focus



- Mechanical & Vehicle Engineering
- Information & Electronic Engineering
- Chemical, Metallurgical & Materials Engineering
- Energy & Mining Engineering
- Civil, Hydraulic Engineering & Architecture
- Environmental & Light and Textile Industries Engineering
- Agriculture
- Medicine & Health
- Engineering Management

The CAE Centre for Strategic Studies

Higher Education Press

Clarivate Analytics

Engineering Focus

Contents

Foreword 1

Chapter 1 Data and Methodology
1 Selection of engineering research hotspots 2
1.1 Acquisition and pre-processing of paper data 2
1.2 Paper data analysis and candidate research hotspot acquisition 3
1.3 Selection and judgment of engineering research hotspots 3
2 Selection of engineering development hotspots 3
2.1 Patent data acquisition and analysis 4
2.2 Interpretation of ThemeScape patent maps 4
2.3 Selection and judgment of engineering development hotspots 5
3 Selection and deciphering of engineering research and development focus 5
4 Explanation of terms 5

Chapter 2 Reports in Different Fields 7
I. Mechanical & Vehicle Engineering 7
1 Engineering research hotspots and engineering research focus 7
1.1 Development trends of engineering research hotspots 7
1.2 Understanding of engineering research focus 11
2 Engineering development hotspots and engineering development focus 19
2.1 Development trends of engineering development hotspots 19
2.2 Understanding of engineering development focus 23

II. Information & Electronic Engineering 32
1 Engineering research hotspots and engineering research focus 32
1.1 Development trends of engineering research hotspots 32
1.2 Understanding of engineering research focus 35
2 Engineering development hotspots and engineering development focus 42
2.1 Development trends of engineering development hotspots 42
2.2 Understanding of engineering development focus 45

III. Chemical, Metallurgical & Materials Engineering 53
1 Engineering research hotspots and engineering research focus 53
1.1 Development trends of engineering research hotspots 53
1.2 Understanding of engineering research focus 57
2 Engineering development hotspots and engineering development focus 65
2.1 Development trends of engineering development hotspots 65
2.2 Understanding of engineering development focus 69

IV. Energy & Mining Engineering 78
1 Engineering research hotspots and engineering research focus 78
1.1 Development trends of engineering research hotspots 78
1.2 Understanding of engineering research focus 82

2 Engineering development hotspots and engineering development focus 97
2.1 Development trends of engineering development hotspots 97
2.2 Understanding of engineering development focus 102

V. Civil, Hydraulic Engineering & Architecture 125
1 Engineering research hotspots and engineering research focus 125
1.1 Development trends of engineering research hotspots 125
1.2 Understanding of engineering research focus 130
2 Engineering development hotspots and engineering development focus 139
2.1 Development trends of engineering development hotspots 139
2.2 Understanding of engineering development focus 145

VI. Environmental & Light and Textile Industries Engineering 154
1 Engineering research hotspots and engineering research focus 154
1.1 Development trends of engineering research hotspots 154
1.2 Understanding of engineering research focus 156
2 Engineering development hotspots and engineering development focus 169
2.1 Development trends of engineering development hotspots 169
2.2 Understanding of engineering development focus 172

VII. Agriculture 179
1 Engineering research hotspots and engineering research focus 179
1.1 Development trends of engineering research hotspots 179
1.2 Understanding of engineering research focus 181
2 Engineering development hotspots and engineering development focus 188
2.1 Development trends of engineering development hotspots 188
2.2 Understanding of engineering development focus 191

VIII. Medicine & Health 197
1 Engineering research hotspots and engineering research focus 197
1.1 Development trends of engineering research hotspots 197
1.2 Understanding of engineering research focus 201
2 Engineering development hotspots and engineering development focus 208
2.1 Development trends of engineering development hotspots 208
2.2 Understanding of engineering development focus 214

IX. Engineering Management 224
1 Development trends of engineering research hotspots 224
1.1 Fuzzy group decision method 224
1.2 Business model dynamics and innovation 225
1.3 Service platform and enterprise information system based on the Internet of Things 225

1.4 Human resources: influences of organizational performance and competitiveness 226
1.5 Container allocation and liner transport network 226
1.6 Simulation-based medical teaching 227
1.7 Optimum status-based maintenance strategy 227
1.8 Multi-objective particle swarm optimization 228
1.9 Bicycle sharing system 228
1.10 Tradable electronic right-of-way mechanism 229
2 Understanding of engineering research focus 229
2.1 Fuzzy group decision method 229
2.2 Service platform and enterprise information system based on the Internet of Things 232
2.3 Simulation-based medical teaching 236
2.4 Multi-objective particle swarm optimization 240

Chapter 3 National Performance
1 Overall comparison of the performance of the top 10 countries or regions in engineering research hotspots 246
2 Overall comparison of the performance of the top 10 countries or regions in engineering development hotspots 247
3 Relationship between research hotspots 248

Project Participants 250

Foreword

In December 2016，the Chinese Academy of Engineering (CAE) launched the Strategy Consulting Project on Global Engineering Focus (hereafter called "the Project"). The Project aims to identify the engineering research and development focus by scrutinizing hotspots in global engineering research and development. Thus, it will play an important role in offering academic guidance and assisting decision making.

As a long-term mission of CAE, the Project will be implemented on a rolling basis in every ensuing year. In collaboration with Clarivate Analytics, CAE draws upon the strengths of its different academic divisions and the "1+9" Journals of CAE (e.g. *Engineering* and nine other specialized journals). By adopting its specialty criteria of every division, every year the Project publicly releases 90 identified engineering research hotspots and 90 engineering development hotspots in both Chinese and English. (Each academic division identifies 10 research hotspots and 10 development hotspots, yet no engineering development hotspots have been issued by the Engineering Management Division this year.) Among them, 27 engineering research focuses and 27 engineering development focuses are selected for detailed elaboration.

Based on rigorous data analysis and informed expert judgment, the Project follows the principles of combining quantitative with qualitative research, using data mining and expert assessment for mutual validation, and giving equal consideration to engineering research hotspots and engineering development hotspots. As for data analysis, comprehensive use is made of data from both journal and conference papers (indexed in SCI, EI, and ISTP), as well as global patent databases, with full consideration to papers' citation frequency and life. By doing so, basic information about hotspots in each field is obtained for experts to scrutinize and select focus. Expert judgment and interpretation are emphasized at this second stage, with reference to results from the initial data analysis. Through in-depth interactions between expert opinions and data analysis, engineering research hotspots and engineering development hotspots are selected. Annual engineering research focus and engineering development focus are eventually determined through expert assessment and judgement.

In this report, "hotspots" are defined as the most active cluster of papers or patents and represent the fastest knowledge accumulation among academic papers or patents. In terms of methodology, all candidate hotspots are obtained through data mining and analysis. Experts are then invited to select hotspots. Finally, focus is obtained and deciphered through expert assessment and judgment.

Chapter 1 Data and Methodology

The Project was implemented in two parts: data analysis and expert judgment. In the data analysis stage, data on the 294 candidate engineering research hotspots and their core papers as well as ThemeScape patent maps and their core data for the 52 subject groups used for analyzing candidate engineering development hotspots were provided by Clarivate Analytics. The 318 engineering development hotspots interpreted from the ThemeScape patent maps were completed by research groups for the various fields under the leadership of the Project Team of the Chinese Academy of Engineering (CAE). In the expert judgment stage, the Project Team organized, under the guidance and assistance of CAE's academic divisions and the "1+9" academic journals, academicians and experts to obtain 10 engineering research hotspots, 10 engineering development hotspots, three engineering research focuses, and three engineering development focuses for each field through questionnaire surveys, discussions, and group interpretation.

1 Selection of engineering research hotspots

The engineering research hotspots identified in this report used journal and conference papers (indexed in SCI, EI, and ISTP) from the Web of Science™ core database of Clarivate Analytics as original data. The basis for data analysis for each field group was obtained by establishing a mapping relationship with the specialty division criteria system of CAE's academic divisions. The top 10% highly cited papers in each field were put for co-citation clustering analysis to determine their citation frequency and lifespan information and obtain 294 candidate engineering research hotspots. These candidate hotspots underwent further expert evaluation to obtain 89 engineering research hotspots. The specific process is described below.

1.1 Acquisition and pre-processing of paper data

As for data acquisition, the categories in Web of Science were matched with the specialties of CAE's academic divisions to obtain a list of corresponding journals and conferences for each field. After confirmation by experts organized by the field groups, data sources totaling 12 822 journals and 28 312 conferences were obtained for analysis for various field groups (refer to Table 1.1.1 for details). In addition, a method of individual paper categorization was adopted for 58 comprehensive journals, such as *Nature*. In other words, the field subject group of individual paper in a journal is defined by the subject to which the reference literature of this paper mainly belongs.

On the basis of this, and with a comprehensive

Table 1.1.1 Number of journals, conferences & top 10% of highly cited papers, by field

No.	Field	Number of journals	Number of conferences	Number of highly cited papers
1	Mechanical & Vehicle Engineering	457	1 768	38 676
2	Information & Electronic Engineering	986	9 632	109 507
3	Chemical, Metallurgical & Materials Engineering	1 128	2 313	219 081
4	Energy & Mining Engineering	226	785	440 641
5	Civil, Hydraulic Engineering & Architecture	359	512	28 384
6	Environmental & Light and Textile Industries Engineering	1 003	605	93 524
7	Agriculture	1 575	975	105 523
8	Medicine & Health	4 328	7 059	392 142
9	Engineering Management	755	681	32 927

Note: There are some overlapping journals, conferences, and highly cited papers between field groups.

consideration of differences between journals and conferences, year of publication, and other factors, the above literature list was searched and data were mined to obtain the top 10% of highly cited papers published in each field group between 2011 and 2016. These highly cited papers were used as the original data set for research hotspot analysis. Data collection was completed in February 2017, which was also the citation deadline.

1.2 Paper data analysis and candidate research hotspot acquisition

Based on the relationship network across research themes formed through mutual citations by researchers, highly cited papers in nine fields were put for co-citation clustering analysis to obtain the clustering themes in each field. With consideration for the total number of citations, citation frequency per paper, mean year of publication, proportion of consistently cited paper, and other indicators of each clustering theme, no less than 25 candidate engineering research hotspots and five keywords were obtained for each field group. (Since some candidate hotspots have similar themes in different field groups, some field groups had more than 25 candidate hotspots in order to ensure that each field group contains at least 25 hotspots that exclusively belong to that field group. Refer to Table 1.2.1 for details.)

In addition, because each field group has different discipline characteristics and citation patterns, some fields have a relatively small amount of cited papers. Therefore, hotspots selected from the nine field groups are only defined as the most active paper clusters in their field group.

1.3 Selection and judgment of engineering research hotspots

Based on the 294 candidate engineering research hotspots obtained from data mining analysis, all field groups organized academicians and experts to study core papers, combine similar hotspots, and modify hotspot names. Subsequently, online and printed survey questionnaires were distributed to solicit suggestions from academicians and experts and obtain their ballot opinions on the top 10 engineering research hotspots in each field. A total of 238 academicians and 632 non-academician experts in nine field groups took part in the survey. Based on the questionnaire statistics, and following expert discussions, examination, and verification by the executive committees of CAE's academic divisions, 89 engineering research hotspots were obtained.

2 Selection of engineering development hotspots

For the year 2017, the Project has obtained a total of 79 engineering development hotspots in eight fields. (For the year, the engineering management field group did not involve any engineering development hotspots.) Based on data analysis and taking the Clarivate Analytics' Derwent World Patents Index (DWPI) database as the original data, a mapping relationship was established between Derwent

Table 1.2.1 Co-citation clustering statistics, by field

No.	Field	Number of clustering themes	Number of top 10% of highly cited papers	Number of candidate engineering research hotspots
1	Mechanical & Vehicle Engineering	4 140	19 503	45
2	Information & Electronic Engineering	11 507	53 880	27
3	Chemical, Metallurgical & Materials Engineering	23 227	103 840	28
4	Energy & Mining Engineering	4 553	20 208	33
5	Civil, Hydraulic Engineering & Architecture	2 971	14 435	23
6	Environmental & Light and Textile Industries Engineering	10 239	46 846	39
7	Agriculture	11 613	51 118	26
8	Medicine & Health	40 775	181 062	25
9	Engineering Management	3 442	15 084	29

Manual Code and the specialty division criteria system of CAE's academic divisions to obtain the basic data for analysis. The top 10 000 most cited high impact patents in 52 subject groups of eight fields were clustered to obtain 52 ThemeScape patent maps. In the expert judgment stage, 318 candidate engineering development hotspots were obtained from expert interpretation of the ThemeScape patent maps. Through questionnaire surveys and expert judgment, 79 engineering development hotspots were obtained. The specific process is described below.

2.1 Patent data acquisition and analysis

For data acquisition, a matching relationship was established between Derwent Manual Code and the specialty division criteria system of CAE's academic divisions to preliminarily determine the patent search scope for eight fields. Following field group experts' deletions, supplements, and improvement, the patent search strategy was respectively constructed for 52 subject groups in the eight fields. Original data for patent analysis were obtained by searching DWPI database on Thomson Innovation. With comprehensive consideration to patent publication year, citation frequency of patent family, and other indicators, data were obtained on the corresponding top 10 000 highly cited core patents for each subject group. (The patent publication years ranged from 2011 to 2016, and the deadline of patent citation was set to February 2017). Based on the semantic similarities of patent texts, 52 ThemeScape patent maps that can visually present the distribution of engineering development hotspot technologies quickly were obtained from 10 000 high impact patents using Thomson Innovation (Figure 2.1.1).

2.2 Interpretation of ThemeScape patent maps

In line with the principle of taking data analysis as the basis for expert judgement, and with reference to ThemeScape patent maps, experts in each field group determined the positions of candidate engineering development hotspots on the ThemeScape patent maps for each subject group on the basis of the level of focus and degree of association of engineering development technologies. Subsequently, each field group studied the high impact patents contained in the hotspot positions on the ThemeScape patent maps; performed statistical analysis of keywords, number of published patents, publication country, citation frequency, citation frequency per patent, and other indicators; extracted technology development hotspots; combined similar hotspots; determined hotspot names; and obtained the candidate engineering development hotspots for each subject group. As shown in Figure 2.2.1, experts in the civil, hydraulic engineering and architecture field determined four hotspots for the architecture subject group through the interpretation of ThemeScape patent map (Hotspot 1: intelligent construction; Hotspot 2: prefabricated buildings; Hotspot 3: green urban buildings; and Hotspot 4: heating, ventilation, and air conditioning). Subsequently, through expert judgment and in light of the technical features of intelligent construction and prefabricated buildings, the latter was merged into the

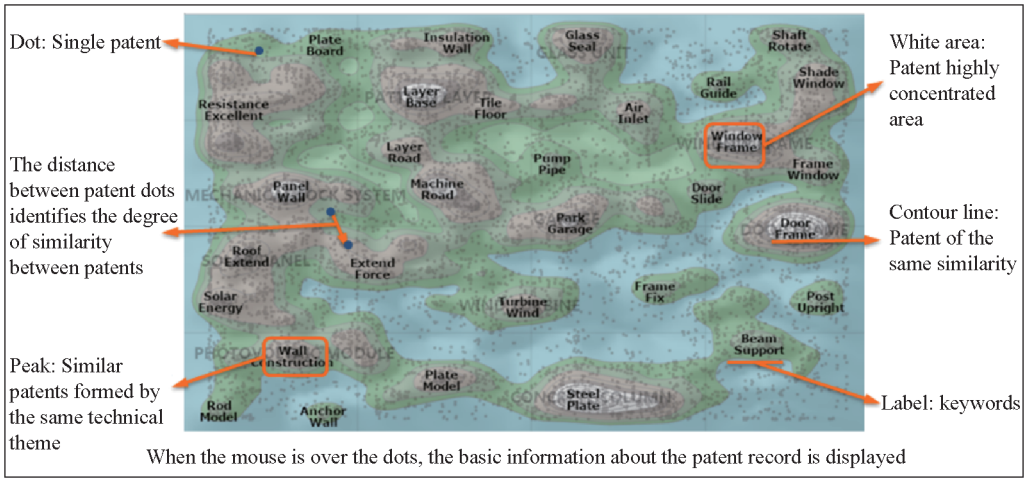

Figure 2.1.1 Basic format of ThemeScape patent maps (taking the architecture subject group as an example)

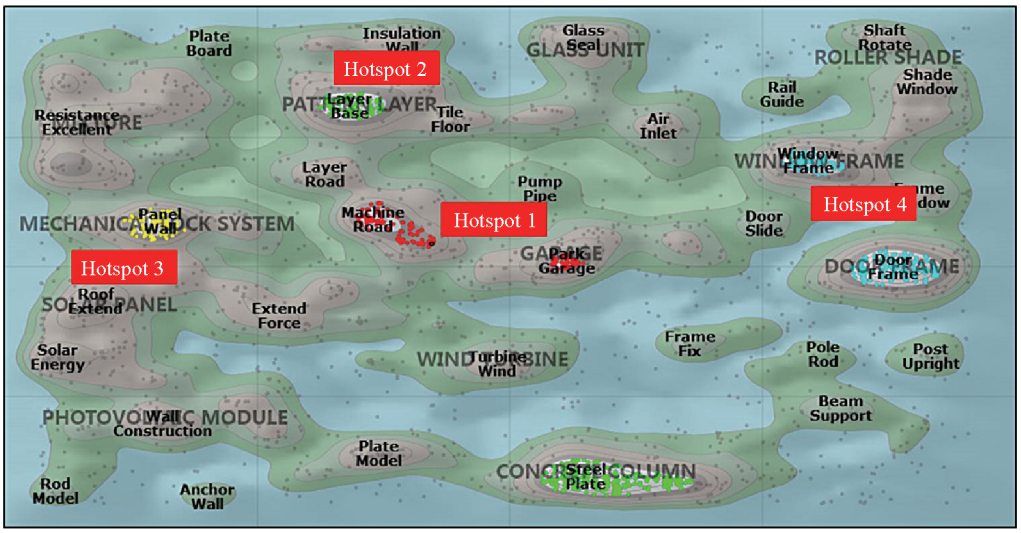

Figure 2.2.1 Hotspots of architecture subject group in the civil, hydraulic engineering and architecture field

former as a technology branch to form one candidate engineering development hotspot.

2.3 Selection and judgment of engineering development hotspots

Based on the interpretation of ThemeScape patent map, eight field groups organized academicians and experts in different subjects to hold thematic workshops to make candidate engineering development hotspot mergers, name optimization, hotspot interpretation, and indicator computations. Eventually, 318 candidate engineering development hotspots in eight fields were obtained. Subsequently, a questionnaire survey (refer to Section 1.3 for information about the questionnaire survey implementation process) was conducted to obtain the opinions of academicians and experts on the top 10 engineering development hotspots in each field. In relation to the questionnaire's statistical results, the field groups obtained 79 engineering development hotspots through expert judgment and examination, and verification by the standing committees of CAE's academic divisions.

3 Selection and deciphering of engineering research and development focus

Among the 89 engineering research hotspots and 79 engineering development hotspots, discussions, study & judgment, and deliberations by the standing committees of CAE's academic divisions were organized to select from the development prospects and level of attention 29 engineering research focuses and 26 engineering development focuses for key interpretation. Experts in the focuses-related specialties then made a detailed interpretation of the current status, development trend, and technical focal points of the engineering research focuses and engineering development focuses. For example, the meaning, development trend, and international research status of each focus were examined through expert judgment; objective data analysis was conducted to provide evidence and reveal the strengths and contributions of the major countries or regions and institutions with regard to the focuses concerned. Cooperative relationships and R&D layout between countries or regions and institutions were also explored.

4 Explanation of terms

Papers/Publications: Clarivate Analytics abstracts publications including editorials, meeting abstracts, conference proceedings and book reviews as well as research journal articles. The terms 'paper' and 'publication' are often used interchangeably to refer to printed and electronic outputs of many types. In this report the term 'paper' only covers substantive peer-reviewed research journal articles, review articles, and

conference proceedings.

Citation frequency: The citation frequency is the number of times that a citation has been recorded for a given publication since it was published. Not all citations are necessarily recorded since not all publications are indexed. However, the material indexed by Clarivate Analytics is estimated to attract about 95% of global citations.

Citation impact: "Average citation" is an index of academic or research impact (as compared with economic or social impact). It is calculated by dividing the sum of citations by the total number of papers in any given dataset (so, for a single publication, raw impact is the same as its citation frequency). Impact can be calculated for papers within a specific research field such as Clinical Neurology, a specific institution or group of institutions, or a specific country. Citation frequency declines in the most recent papers since papers have had less time to accumulate citations. For example, papers from 2011 will typically have more citations than those published in 2015.

Highly cited papers: Highly cited papers is recognized as having a greater impact and Clarivate Analytics has shown that high citation frequency correlate with other qualitative evaluations of research performance, such as peer review. In the proposed analysis, papers that are in the top 10% in terms of citation frequency are considered to be highly cited, taking into account the year of publication and journal subject category.

Clustering theme: A combination of a series of themes and keywords obtained from the co-citation clustering analysis of highly cited papers.

Core papers: In this project, highly cited papers related to the 294 candidate engineering research hotspots are core papers.

Highly cited patents: In this project, "Highly cited patents" refers to the top 10 000 patents in the Derwent Patent Citation Index (DPCI) database, ranked in terms of average annual number of patent citations.

Consistently cited papers: In the proposed analysis, papers that are in the top 10% in terms of citation velocity are considered to be consistently cited, taking into account the year of publication and journal subject category.

Mean year (Average publication year): It means the average publication year of all the core papers that constitute each research hotspots. The hotspot whose average publication year is closer to the current year has received more recent attention.

Citation velocity: Citation velocity is a measure of the rate of citation accumulation based off a certain frequency within a set time period. In the proposed analysis, the citation velocity for each publication will be a measure of the rate of citation accumulation per month, starting from the publication month and ending the month before data collection started.

Patent-cited publications: Patents may cite other patents or non-patent references (NPRs), such as research publications. In the proposed analysis, publications that were cited by patents are identified as patent-cited publications through the non-patent references available in DPCI database.

Interdisciplinarity index: This is an entropy measure of the dispersion of papers over the categories. There is an upper limit of "1", so a value of "1" indicates an equal dispersion of papers over all categories. The closer the value to "1", the more multidisciplinary the set of papers. A value of "0" indicates that only one category is represented in the dataset. The interdisciplinarity index is based on entropy in information theory and can be expressed as follows:

$$-\left(\sum_{i=1}^{n} p_i \log_2 p_i\right) \Big/ \log_2 n$$

Where p is the share of papers in category i and n is the number of categories

ThemeScape patent map: A ThemeScape patent map is a themed panoramic view that can visually reflect the overall outlook of an industry or a technical field. It is a visual presentation in map form obtained by analyzing semantic similarities in patent literature, adopting scientific statistical analysis methods for precision analysis, and sorting of patent text contents.

Specialty division criteria system of CAE's academic divisions: Includes the specialized fields covered by the various academic divisions of engineering science and technology (including agriculture and medical sciences) and determined in accordance with the *Academic Divisions and Specialty Division Criteria of the Chinese Academy of Engineering for Election of Academicians (for Trial Implementation).*

Chapter 2 Reports in Different Fields

I. Mechanical & Vehicle Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in mechanical and vehicle engineering (hereinafter referred to as the mechanical field) include mechanical engineering, naval architecture and ocean engineering, aerospace science and technology, armament science and technology, power and electrical equipment engineering and technology, transportation engineering, and other subjects (Table 1.1.1). Traditional research in mechanical engineering has focused on "Large-scale robot tactile sensors and implementations," "Neural network model and fuzzy logic," "Vibration isolation system," "Piezoelectric energy harvesting," "Fluid–solid coupling simulation," "Instability and dynamics of a gas turbine combustor," "Shape memory alloy," and "Nonlinear vibration modes in mechanical engineering." "Process design and self-adaptive control of additive manufacturing" and "Supersonic flow and aerodynamics" are emerging hotspots. Table 1.1.2 shows the annual publication of core papers involved in all hotspots in 2011–2016. The number of studies on "Process design and self-adaptive control for additive manufacturing" has significantly increased.

(1) Large-scale robot tactile sensors and implementations

A robot obtains external information through tactile sensors to perceive the external environment. Currently, tactile sensors are divided into two categories: the first category uses pressure sensing unit to detect the force, detect the vector of contact force at a single point, and form a multi-point array (e.g., an array sensor composed of many strain foils); and the second category uses an elastomer as contacting part of the sensor, and deformation occurs when the elastomer is subjected to force. Large robots have high stiffness and output power; as such, the output force in their interaction with the environment is large. To achieve accurate operation, robots should be equipped with tactile sensors with precise sensing capability. Currently, research on single-dimensional force sensor has

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

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Large-scale robot tactile sensors and implementations	49	1536	31.35	2012.35	12.2%	0
2	Process design and self-adaptive control of additive manufacturing	33	610	18.48	2013.82	12.1%	0
3	Supersonic flow and aerodynamics	41	697	17.00	2013.61	7.3%	0
4	Neural network model and fuzzy logic	47	1600	34.04	2011.64	8.5%	0
5	Vibration isolation system	35	786	22.46	2013.37	8.6%	0
6	Piezoelectric energy harvesting	39	1578	40.46	2012.51	28.2%	0
7	Fluid-solid coupling simulation	45	1442	32.04	2012.84	8.9%	0
8	Instability and dynamics of a gas turbine combustor	35	1105	31.57	2013.03	17.1%	0
9	Shape memory alloy	41	1287	31.39	2013.17	24.4%	2
10	Nonlinear vibration modes in mechanical engineering	32	646	20.19	2013.69	6.3%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in mechanical and vehicle engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Large-scale robot tactile sensors and implementations	17	11	13	4	3	1
2	Process design and self-adaptive control of additive manufacturing	2	3	7	9	11	1
3	Supersonic flow and aerodynamics	3	8	7	10	10	3
4	Neural network model and fuzzy logic	24	16	7	0	0	0
5	Vibration isolation system	3	8	7	8	8	1
6	Piezoelectric energy harvesting	10	14	5	5	5	0
7	Fluid-solid coupling simulation	9	13	3	16	4	0
8	Instability and dynamics of a gas turbine combustor	7	8	6	6	7	1
9	Shape memory alloy	8	4	10	14	2	3
10	Nonlinear vibration modes in mechanical engineering	5	1	7	7	10	2

matured. However, detecting forces in three-dimensional directions and even multidimensional directions is necessary to perceive the interaction between the robot and the environment. The main research focuses are the optimization of flexible structures and the design of base materials. Research and development of flexible multidimensional tactile sensors are important but difficult to achieve.

(2) Process design and self-adaptive control of additive manufacturing

Metal additive manufacturing techniques are categorized according to heat source into laser, electron beam, and arc methods. Laser engineering net shaping based on powdered materials, selective laser melting, and selective electron beam melting are used in the field of aerospace, biological medicine, and molding. These processes can solve complex, integrated, and personalized manufacturing difficulties that come with traditional manufacturing techniques. However, these processes exhibit limitations in forming large parts at a rapid speed and low cost because of their complex laser and electron beam control, high cost, difficult powder preparation, easy contamination, and low formation efficiency. Wire arc additive manufacture (WAAM) uses arc as energy beam; moreover, parts are accumulated by multiple welds, with uniform chemical composition and high density. The local atmosphere does not limit the forming dimension. The efficiency of WAAM can reach kilograms per hour or even higher. The wire material exhibits less pollution and lower cost than the powder material and thus can be used in low-cost high-efficiency additive manufacturing of large aerospace components. In addition, arc is easier to achieve than laser and electron beam. The wire materials can be more easily transported and collected than the powdered materials and have significant potential in the space metal additive manufacturing field. Compared with laser and electron beam techniques, the part used in arc additive manufacturing technique possesses a rough surface, low dimensional accuracy, and coarse and big interior tissues. In-situ integration with cutting, forging, and other traditional processes is the development direction of this technology and one of the research hotspots in this field to improve the accuracy and performance of structures.

(3) Supersonic flow and aerodynamics

Supersonic flow plays an important role in the design of supersonic civil and military airplanes and is affected by a number of key technical issues related to supersonic aerodynamics. An advanced aerodynamic layout design of supersonic jet can be obtained by exploring the type of boundary transition and control measures under supersonic flow; such design can be used to determine the effect of shock wave/boundary layer interference on aerodynamic layout design, clarify the perturbation modes of supersonic flow and the evolutionary characteristics of the interaction of shock waves, and understand the structure characteristics of coherent vortex in supersonic turbulent boundary layer and the generation and propagation mechanism of aerodynamic noise. Research on the characteristics of the translot jet field can optimize the mixing process of fuel, reveal the physical mechanism of the combustion stability of scramjet engine, and improve the

applications of scramjet technology and scramjet engine in engineering practices. Transverse slot jet flow plays an important role in the overall thermal protection of aircraft and the internal cooling of scramjet engine. However, unsteady aerodynamic issues (e.g., flow separation and reattachment) are prone to occur under supersonic flow due to the disturbance of shock wave and the effects of supersonic shear layer and turbulence. These issues can be addressed through the following: explore new theory and mechanism; conduct advanced experimental technology research; develop efficient numerical simulation methods; emphasize the interaction mechanism between the jet field and the main flow field; systematically understand the effect of the comprehensive coupling of shock wave, expansion wave, shear layer, and boundary layer on the mixed characteristics of jet media and mainstream moving media; and finally grasp shock wave impinging and the relationship between the resulting flow separation and peak heat flow.

(4) Neural network model and fuzzy logic

Fuzzy neural network control is an intelligent control technology that combines fuzzy control and neural network. Fuzzy logic is similar to the thinking mode of humans and is used for systematic qualitative analysis and reasoning with fuzzy rules; this tool requires strong understanding and processing ability of natural language. Fuzzy logic can solve the fuzzy information problem, which is difficult to accurately quantify in a control system. Neural network is similar to the human brain, which is made up of neurons. Neural network, which exhibits self-learning ability, can adjust the weight matrix to complete the nonlinear mapping between input and output. With the rapid development of computer science, neural network and fuzzy logic can be combined while maintaining their respective advantages. However, a mathematical model is difficult to establish when many variables and strong coupling factors exist in a nonlinear system. Compared with traditional control methods, this intelligent control method can effectively improve the intelligence level of a system and improve the quality of control. The rapidly rising deep learning technology has introduced new vitality into the artificial neural network because of the development of hardware technology. Fuzzy neural network has become the frontier and significant research direction for intelligent control technology.

Future research will focus on designing a network structure, fuzzy rules, and optimized learning algorithm on a fuzzy neural network. The intersection of fuzzy theory and neural network enables theoretical and technological breakthroughs for completing each system by combining with other advanced machine learning methods. Hence, fuzzy neutral network technology is further integrated with advanced control and large data analysis methods. This technology will play an increasingly important role in the reform of intelligent manufacturing, smart grids, and other new industrial fields.

(5) Vibration isolation system

The main method for vibration isolation is to install a vibration isolation device or adopt vibration isolation technology between vibration source and transmission path. This kind of device plays a role in vibration isolation and is referred to as a vibration isolation system. A research hotspot and challenge both at home and abroad is to satisfy the strict requirements for the working environment of the processing of ultra-precision instruments and the performance indices of remote sensing equipment and the high-precision optical equipment on the satellite as the high resolution satellites in orbit (especially the strict requirements for micro vibration and ultra-low frequency vibration, ultra-low frequency, and high-performance isolation vibration system). With the traditional linear passive vibration isolation system, research of high-performance vibration isolation system is difficult because of two major contradictions, namely, difficulty in considering the system carrying capacity and the ultra-low isolation frequency and inability to consider the suppression of the peak of resonance frequency domain and the improvement of vibration isolation in the high frequency domain. The nonlinear vibration isolation technology and the active and semi-active vibration isolation technology are the main approaches used to fabricate vibration high-performance isolation systems, such as vibration isolation device with high static and low dynamic rigidity, nonlinear vibration isolation system, and nonlinear magnetic vibration isolator based on damper, and so on. A device with negative stiffness is introduced in linear vibration isolation system to design a low-frequency vibration isolation system with high static and low dynamic stiffness and ensure the bearing capacity of the system while maintaining ultra-low frequency vibration isolation. Nonlinear vibration isolation systems based on non-viscous damper can effectively inhibit vibration amplitude in the reso-

nance frequency domain and the occurrence of jumping. Moreover, this system does not influence the vibration isolation characteristics in the high-frequency domain. A wide spectrum of effective vibration isolation systems can be achieved using intelligent materials and active control technology.

(6) Piezoelectric energy harvesting

In recent years, research on the conversion of vibration energy into electrical energy in the environment has attracted significant attention. When the piezoelectric material deforms under external force, the polarized charge will appear on the surface to form an electric field with high energy density. A device that uses piezoelectric effect to generate energy is called a piezoelectric energy collector; this device is characterized by simple structure, small calorific value, lack of electromagnetic interference, easy miniaturization, low carbon content, and environment friendliness.

Key technologies of piezoelectric energy harvesting mainly include study on high-performance piezoelectric materials and design of intelligent piezoelectric energy harvesting structure with low-power consumption, and simple and efficient energy harvesting circuit. The self-powered device based on piezoelectric energy harvesting has been applied for inspection of traffic infrastructures and wireless medical equipment, monitoring of indoor environment, and detection of tire pressure. Moreover, the conversion of human kinetic energy into electrical energy and the achievement of energy supply of wearable electronic devices have attracted significant attention because of their broad market prospect.

(7) Fluid–solid coupling simulation

Fluid–solid coupling refers to the interaction between solid and liquid media. Fluid–solid coupling simulation mainly investigates the coupling dynamic behavior between the solid and fluid. Fluid–solid coupling simulation is involved in the nonlinear behavior of fluid, the nonlinear constitutive equations of solid materials, and the nonlinearity of the fluid–solid coupling interface. Therefore, simulation of fluid–solid coupling is a frequent nonlinear dynamic problem. The coupling can be analyzed using numerical algorithms and simulation of the force transfer between the fluid and solid sub domains. With the development of fluid–solid coupling (e.g., arterial vascular simulation and parachute aerodynamics simulation), accurately solving large deformation, strong nonlinearity, multi-scale, spatio-temporal coupling, and multi-phase fluid-solid structure coupling is necessary. Highly precise and efficient fluid–solid coupling model and numerical algorithms have become research hotspots at home and abroad. For the fluid–solid coupling problem, uniform and non-uniform mesh generation techniques and space–time simulation techniques have good prospects for development. Fluid–solid coupling method considering time and space has a significant application prospect for improving the accuracy and efficiency of the solution.

(8) Instability and dynamics of a gas turbine combustor

Combustion instability is one of the most important research topics in the field of combustion and is widely investigated in internal combustion engines, aircraft engines, gas turbines, and other combustion phenomena. Instability induces flame discontinuity, local extinction, propagation velocity, and shock of flame surface to show cycle changes, decreased combustion efficiency, deteriorated pollutant emission and mechanical damage, and other hazards. Research on the combustion instability mechanism and its inhibition approaches must be improved to avoid hazards caused by combustion instability, expand the scope of work of advanced combustion mode, improve efficiency, and reduce emissions. Between China and other countries, the main gaps in designing and manufacturing gas turbines and its combustion chamber include the design, processing, and high-temperature resistant composite technology.

(9) Shape memory alloy

Shape memory alloy exhibits shape memory effect and pseudo elasticity (i.e., hyperelasticity) due to its thermoelastic martensitic transformation. Since their discovery in the 1960s, shape memory alloys, such as nickel titanium alloys, have been widely used in aviation, aerospace, biomedical, and other fields. The major unsolved problems in research on shape memory alloys include the following: ① thermomechanical coupling–cyclic deformation characteristics, including temperature dependence in the deformation of shape memory alloys, speed (frequency) dependence in the deformation process of pseudo elastic shape memory alloys, evolution law of thermal mechanical behavior under cyclic loading, and local effects of stress-induced martensitic transformation; ② numerical

simulation of the mechanical behavior of shape memory alloys with complex structure and complex load (non-proportional load); and ③ fatigue and fracture characteristics, including crack formation and expansion under cyclic phase transformation, effect of thermal mechanical coupling on fatigue fracture behavior, and stability and macroscopic fatigue criteria under high cycle fatigue loading. In this regard, experimental and theoretical studies on shape memory alloys at micro, meso, and macro scales must be conducted to establish a multi-physical field coupling model, reveal the underlying mechanism, and simulate and predict the mechanical behavior of shape memory alloys.

(10) Nonlinear vibration modes in mechanical engineering

Nonlinear phenomena are ubiquitous in engineering applications and considerably change the dynamic behavior of structures. Research hotspots at home and abroad include dynamics analysis and solving method, experimental test, system nonparametric identification, modal parameter identification, model updating, uncertainty analysis, and other engineering problems on nonlinear mechanical system. Modal theory is the core of linear vibration theory. Nonlinear modal theory is proposed to determine a simple and efficient method for solving multidimensional nonlinear systems (e.g., linear modes). In addition, the concept of modal theory is extended to nonlinear systems. Specifically, nonlinear mode is the extension of linear mode and is the basis for simplifying nonlinear systems. The modes of the linear system are determined, and nonlinear modes may produce bifurcations to increase the number of modes of the nonlinear system beyond the degree of freedom of the system. Scholars have developed direct solutions to nonlinear vibration modes, subspace iteration, and model reduction methods for nonlinear systems. These methods provide an efficient solution for dynamic study on bifurcation, jumping, modal coupling, force relaxation, and flutter. However, quantitative analysis of many influencing factors is difficult due to the complexity of the dynamic characteristics of nonlinear systems. Therefore, uncertainty analysis methods (e.g., Bayesian method) must be combined to address limitations on studying model identification, parameter identification, model updating, model reduction, and skeleton curve stability identification. Thus far, a complete system has not been established yet.

1.2 Understanding of engineering research focus

1.2.1 Large-scale robot tactile sensors and implementations

Large robots possess high stiffness, output power, and output force in their interaction with the environment. Tactile sensors with precise sensing capability are frequently required to achieve accurate operation. Research on one-dimensional force sensors has matured. However, to perceive the interaction between the robot and its environment, robot tactile sensors should detect the vertical pressure on the surface and the shear force in the horizontal direction. For example, when a robot holds an object, the tangential force must be perceived with the positive pressure. When a robot touches an object with irregular surface, the three-dimensional or even multi-dimensional force must be determined. The development of three-dimensional force tactile sensors has become an important research field on intelligent robot technology. To obtain three-dimensional force tactile sensations, scholars have used pressure-sensitive film resistors, platinum/titanium films, anisotropic carbon nanotubes, flexible capacitors, carbon black/silicone rubber, and other base materials for covering the cross structure. The main research work focuses on the optimization of flexible structures and the design of base materials.

(1) 3D shape tactile sensor with high sensitivity

A robot obtains external information through tactile sensors to perceive the external environment. Tactile sensors are categorized into two groups. The first group uses a pressure sensing unit to detect the force and the vector of contact force at a single point and form a multi-dot array (e.g., an array sensor composed of many strain foils). The second group uses an elastomer as the contacting part of the sensor, and deformation occurs when the elastomer is subjected to force. Therefore, the size and distribution of contact force are calculated by detecting the shape and deformation of the elastomer. The generalized tactile is a general term for contact, sliding, pressure perception, and so on. In addition, tactile in the narrow sense refers to the force perception on the contact surface. Three-dimensional tactile shape refers to the tactile sensation that can perceive the shape of the object being touched. Indirect perception is mainly achieved based on changes in the amount of correlated sensing in the contact sliding

process. In the current research, changes in light reflection after subjecting the fiber material to stress are used as basis to achieve a 3D tactile shape.

(2) Flexible tactile sensor

Research on flexible tactile sensor has become a hotspot in the field of robot tactile sensor, with emphases on the development and research of multi-dimensional flexible tactile sensors. Multi-dimensional flexible tactile sensors are flexible, similar to the human skin, and can attach to the surface of objects to sense and measure multidimensional information. These flexible sensors can attach to carriers with different surface shapes and roughness to rapidly and accurately sense and obtain outside information. Flexible tactile sensors fabricated with new sensitive materials and manufacturing processes exhibit flexibility and malleability, which will be increasingly similar to those of the human skin. Future research must focus on providing flexible tactile sensors with multidimensional force measurement ability.

(3) Tactile array sensor

A large amount of perceptual information, including spatial pressure and temperature distribution, can be obtained by integrating tactile sensors in large arrays. In practical applications, most tactile array sensors possess flexible structures. For making artificial skin, tactile array sensors should not only be flexible but must also be capable of measuring contact pressure on any surface of a carrier. Accordingly, tactile array sensors must partially or fully cover the surface of an actuator. However, tactile array sensors exhibit certain limitations. First, some sensing elements of tactile sensors are rigid. A rigid sensor is implanted in the flexible material used as medium to transmit tactile information. The tactile sensor itself is inflexible, and the degree of curvature is limited. Thus, obtaining other accurate continuous distribution information is difficult. Second, the sensing element of another kind of tactile array sensor is flexible. However, this sensor can only measure one-dimensional tactile information. As such, scholars aim to research and develop tactile array sensors by using capacitance, PVDF, optical wave guidance, and other technologies. The present study mainly focuses on the flexibility, multidimensional aspects, and large-scale design of array sensors.

(4) Evaluation of grasping quality based on physics

Robust grasp is the most desirable attribute of robots. Stable grasping is the basis of the physical interaction between a robot gripper and the environment and is a foundation to achieve high-order grasping motion. The tactile information in the robot grasping process can be used to evaluate the quality of robot grip and provide regulatory information for real-time grasp of a robot gripper. Abundant tactile information is the basis of the robot gripper to enable grasping and flexible operation. Tactile theory and technology research can provide impetus for eventual reappearance of hand operations and perception through robotic systems. Robot grasping quality is mainly evaluated using closeness, operability, and stability of grasping.

The top three countries or regions with the highest number of core papers in engineering research on "Large-scale robot tactile sensors and implementations" are the USA (17), Germany (11), and Switzerland (6). Countries or regions with top three average citation frequency include Switzerland (48.83), Spain (45.00), and Italy (42.25) (Table 1.2.1). Among the top 10 countries or regions producing core engineering papers, Germany–Spain and England–Italy exhibit high cooperation (Figure 1.2.1). The institutions with top two publication numbers of core engineering papers are Tech Univ Munich (4), Czech Tech Univ (4), Willow Garage Inc (3), RoyalInst Technol (3), and Columbia Univ (3). Moreover, the institutions with top three average citation frequency are ETH (97.50), Univ Zaragoza (65.00), and Univ Genoa (60.00) (Table 1.2.2). Among the top 10 institutions with the highest number of publications, the Italian Inst Technol and Univ Sheffield exhibits high cooperation (Figure 1.2.2). Countries or regions with top three publication number of core papers are Spain (3), the USA (3), and Sweden (2) (Table 1.2.3). The main institutions producing core papers are the Royal Inst Technol (2), Univ Bristol (2), and Carnegie Mellon Univ (1) (Table 1.2.4).

1.2.2 Vibration isolation system

The performance indices of high-resolution satellites, high-precision optical equipment, and so on; and the isolation and elimination of micro vibration are challenging and hot issues that should be addressed to satisfy the strict requirements for the working environment of processing and testing of ultra-precision equipment. Scholars, both at home and abroad, have focused on the previously neglected micro vibration problem of spacecraft caused by moving parts (e.g., reaction wheel, thrustor, solar panels, momentum wheel, refrigerator, antenna drive mecha-

Table 1.2.1 Major producing countries/regions of core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	17	34.69%	383	29.28%	22.53	4	0
2	Germany	11	22.45%	340	25.99%	30.91	3	0
3	Switzerland	6	12.24%	293	22.40%	48.83	0	0
4	England	5	10.20%	129	9.86%	25.80	1	0
5	Spain	4	8.16%	180	13.76%	45.00	1	0
6	Italy	4	8.16%	169	12.92%	42.25	3	0
7	Japan	4	8.16%	63	4.82%	15.75	1	0
8	Czech	4	8.16%	53	4.05%	13.25	0	0
9	Sweden	3	6.12%	94	7.19%	31.33	2	0
10	Denmark	2	4.08%	59	4.51%	29.50	1	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Tech Univ Munich	4	8.16%	211	16.13%	52.75	1	0
2	Czech Tech Univ	4	8.16%	53	4.05%	13.25	0	0
3	Willow Garage Inc	3	6.12%	123	9.40%	41.00	1	0
4	Royal Inst Technol	3	6.12%	94	7.19%	31.33	2	0
5	Columbia Univ	3	6.12%	60	4.59%	20.00	0	0
6	ETH	2	4.08%	195	14.91%	97.50	0	0
7	Univ Zaragoza	2	4.08%	130	9.94%	65.00	0	0
8	Univ Genoa	2	4.08%	120	9.17%	60.00	2	0
9	Italian Inst Technol	2	4.08%	105	8.03%	52.50	1	0
10	Univ Sheffield	2	4.08%	105	8.03%	52.50	1	0

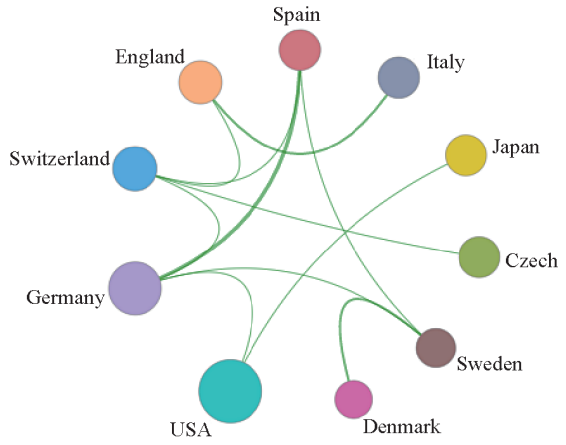

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"[1]

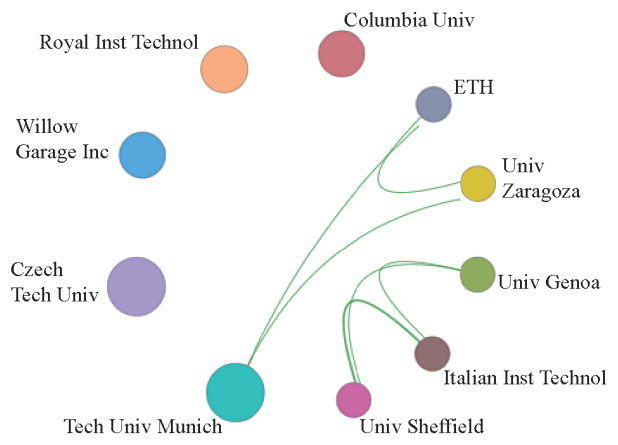

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Spain	3	18.75%	2014.33
2	USA	3	18.75%	2013.00
3	Sweden	2	12.50%	2014.00
4	Germany	2	12.50%	2014.50
5	England	2	12.50%	2015.50
6	Denmark	1	6.25%	2014.00
7	Italy	1	6.25%	2015.00
8	Japan	1	6.25%	2013.00
9	Czech	1	6.25%	2015.00

Tab 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Large-scale robot tactile sensors and implementations"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Royal Inst Technol	2	9.52%	2014.00
2	Univ Bristol	2	9.52%	2015.50
3	Carnegie Mellon Univ	1	4.76%	2013.00
4	Columbia Univ	1	4.76%	2014.00
5	German Aerosp Ctr DLR	1	4.76%	2015.00
6	Google Inc	1	4.76%	2013.00
7	Italian Inst Technol	1	4.76%	2015.00
8	Karlsruhe Inst Technol	1	4.76%	2014.00
9	MPI Intelligent Syst	1	4.76%	2014.00
10	Toyota Motor Co Ltd	1	4.76%	2013.00

nism, and other components) to progressively increase the point accuracy and point stability of spacecraft. Normal work will be affected once micro vibration resulting from the moving parts is converted into sensing elements (e.g., MW infrared sensor, laser communication equipment and space telescope, and high-precision equipment). As the core equipment of semiconductor science and technology industry, lithography is a typical representative of ultra-precision equipment. The machining accuracy of this equipment can reach the nanometer level. Micro vibration factors, which can be ignored in traditional processing and testing equipment, will have a fatal effect on the accuracy of lithography. Therefore, the inhibition of micro vibration has become one of the major bottlenecks in the development of high-resolution and high-precision spacecraft and ultra-precision equipment.

Micro vibration is mainly characterized by small amplitude, wide frequency band, and difficult controllability. The frequency of micro vibration ranges from extremely low to thousands of Hertz. Vibration energy ranges from several Hertz to hundreds of Hertz and is difficult to decay. Low-amplitude micro vibration possesses a complex propagation mechanism of mechanical structure and is thus difficult to remove from the vibration source. Nonlinear vibration isolation technology and active and semi-active vibration isolation technology are the main techniques used to suppress micro vibration; these technologies include high-static and low-dynamic stiffness (HSDLS) vibration isolation device, nonlinear vibration isolation system, active/semi-active isolation system, and so on.

(1) High-static and low-dynamic stiffness (HSDLS) vibration isolation device

The HSDLS vibration isolation device has a wide application prospect for solving the limitations of system carrying capacity and ultra-low isolation frequency. Quasi zero stiffness isolator (or the vibration isolation system with high-static and low-dynamic stiffness) formed by the parallel connection of positive and negative stiffness elements has become a hotspot in the field of global engineering. An elastic element with positive stiffness generally refers to vertical spring, and many forms of negative stiffness regulators exist. Quasi zero stiffness isolator is composed of the positive stiffness elastic element and the negative stiffness regulating mechanism in parallel. The positive stiffness elastic element is used to bear the main load. The negative stiffness regulating mechanism is used to counteract the stiffness of the positive stiffness elastic element and increase the likelihood of leading the stiffness of the system at the static equilibrium position to zero. The quasi zero stiffness vibration isolator has high static stiffness and low dynamic stiffness. High static stiffness can improve the bearing capacity of the isolator and reduce static displacement, whereas low dynamic stiffness can reduce the natural frequency of the system and obtain a wider isolation frequency band than the linear isolator.

(2) Nonlinear vibration isolation system

Advanced nonlinear isolation methods based on nonlinear damper and nonlinear stiffness technology have excellent isolation performance and high reliability. For example, vibration isolation, which can be used in low frequency and/or wide frequency ranges, has a significant application potential in the ultra-low frequency vibration isolation field. For designing a traditional linear passive vibration isolation system, a contradiction exists between the damping ratio and the high frequency attenuation capability. This contradiction can be solved through nonlinear damping technology. The design that uses nonlinear damping model to limit the amplification of resonance and improve the attenuation ability of high frequency vibration has become the focus of current research. This nonlinear damping vibration isolation system can provide a large damp in the case of slight amplitude vibration. This system not only can effectively control the resonance amplification factor at the resonance peak but also provide improved vibration isolation effect in the high frequency range. The vibration isolation performance of nonlinear damping is superior to that of linear damping in the wide frequency range. Combining nonlinear stiffness vibration isolation system (e.g., HSDLS vibration isolation system) may play an important role in the design of ultra-low frequency vibration isolator with high performance.

(3) Active/semi-active vibration isolation system

Active/semi-active vibration isolation technology can be used to effectively inhibit the micro vibration of spatial structure and ultra-precision instruments; this technology particularly solves the vibration isolation problem in the low frequency range and is characterized by low energy consumption and cost. In active vibration isolation, actuators and sensors are commonly used to provide control force and feedback signals, respectively. Active feedback of control can be used to regulate the stiffness and damping of the system. This mechanism can isolate vibration in the low frequency domain. Compared with passive vibration isolation systems, active vibration isolation systems are more advantageous in terms of the vibration isolation in the low frequency domain and resonance region and have a wide application prospect in the vibration isolation design of ultra-precision instruments. However, if micro vibration isolation in the low frequency domain is completely achieved using active vibration isolation technology, then the reliability of the system may be reduced. Semi-active vibration isolation technology, which combines the advantages of passive vibration isolation and active control, can demonstrate improved vibration isolation performance than the passive or active vibration isolation system. The technology can be effectively used to isolate the micro vibration of orbital spacecrafts in narrow-band, wide-band, and low frequency range. This technology is an effective method for suppressing micro vibration in space engineering.

Countries or regions with top three publication numbers of core papers in engineering research focusing on "Vibration isolation system" are China (26), England (9), Korea (2), Brazil (2), and the USA (2). Countries or regions with top three average citation frequency are Korea (38.50), Brazil (36.50), and India (33.00) (Table 1.2.5). Among countries/ regions with top three publication number, China and England exhibit high cooperation (Figure 1.2.3). Institutions with top two publication number of core papers are Hong Kong Polytech Univ (6), Univ Southampton (5),

Natl Univ Def Technol (5), and Tongji Univ (5). Institutions with top three average citation frequency are Univ Bristol (39.50), Univ Ulsan (38.50), and UNESP Ilha Solteira (36.50) (Table 1.2.6). Among the institutions with top ten publication number, Hong Kong Polytech Univ–Tongji Univ and Beihang Univ–Sci Technol Inertial Lab exhibit high cooperation (Figure 1.2.4). In 2011–2016, 26 core papers are related to engineering research focusing on "Vibration isolation system" published in China. Institutions with many published papers in Mainland China cover the National University of Defense Technology, Tongji University, Shanghai Jiao Tong University, Beijing University of Aeronautics and Astronautics, and so on. Countries or regions with top three publication number of core papers cited by core papers are China (15), England (2), Iran (1), and the USA (1) (Table 1.2.7). The main institutions producing core papers cited by core papers are Tongji Univ (4), Hong Kong Polytech Univ(4), and Beihang Univ (3) (Table 1.2.8).

1.2.3 Supersonic flow and aerodynamics

Supersonic flow plays an important role in the design of supersonic civil and military airplanes and is affected by a number of key technical issues related to supersonic aerodynamics. This paper aims to achieve the following: explore the type of boundary transition and control measures under supersonic flow (mainly the first mode unstable wave and transverse mode wave), determine the effect of shock wave/boundary layer interference on aerodynamic layout design, clarify the perturbation modes of supersonic flow and the evolutionary characteristics of the interaction of shock waves, understand the structural characteristics of coherent vortex in supersonic turbulent boundary layer and the generation and propagation

Table 1.2.5 Main producing countries or regions of core papers on the engineering research focus "Vibration isolation system"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	26	74.29%	401	58.88%	15.42	2	0
2	England	9	25.71%	242	35.54%	26.89	1	0
3	Korea	2	5.71%	77	11.31%	38.50	1	0
4	Brazil	2	5.71%	73	10.72%	36.50	0	0
5	USA	2	5.71%	49	7.20%	24.50	0	0
6	India	1	2.86%	33	4.85%	33.00	0	0
7	Iran	1	2.86%	13	1.91%	13.00	0	0

Table 1.2.6 Main producing institutions of core papers on the engineering research focus "Vibration isolation system"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Hong Kong Polytech Univ	6	17.14%	91	13.36%	15.17	1	0
2	Univ Southampton	5	14.29%	149	21.88%	29.80	1	0
3	Natl Univ Def Technol	5	14.29%	89	13.07%	17.80	1	0
4	Tongji Univ	5	14.29%	57	8.37%	11.40	1	0
5	Shanghai Jiao Tong Univ	4	11.43%	84	12.33%	21.00	0	0
6	Beihang Univ	4	11.43%	44	6.46%	11.00	0	0
7	Sci Technol Inertial Lab	3	8.57%	28	4.11%	9.33	0	0
8	Univ Bristol	2	5.71%	79	11.60%	39.50	0	0
9	Univ Ulsan	2	5.71%	77	11.31%	38.50	1	0
10	UNESP Ilha Solteira	2	5.71%	73	10.72%	36.50	0	0

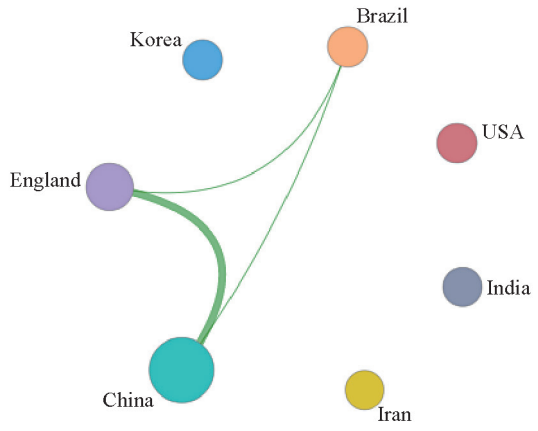

Figure 1.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Vibration isolation system"

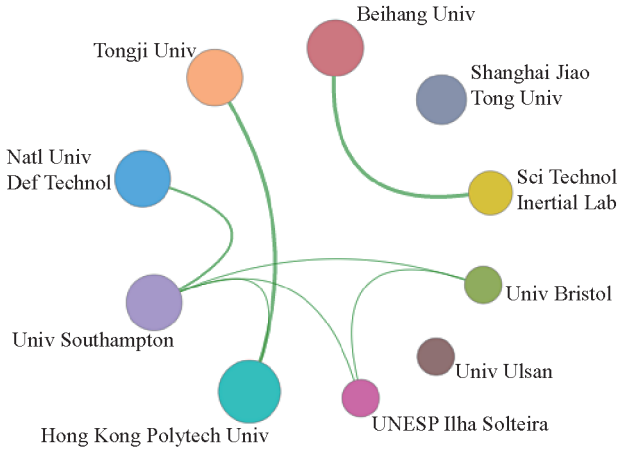

Figure 1.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Vibration isolation system"

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Vibration isolation system"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	15	78.95%	2014.27
2	England	2	10.53%	2014.00
3	Iran	1	5.26%	2014.00
4	USA	1	5.26%	2014.00

Tab 1.2.8 Main producing institutions of core papers that are cited by core papers on the engineering research focus "Vibration isolation system"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Tongji Univ	4	13.79%	2014.75
2	Hong Kong Polytech Univ	4	13.79%	2014.75
3	Beihang Univ	3	10.34%	2015.00
4	Natl Univ Def Technol	3	10.34%	2013.00
5	Sci Technol Inertial Lab	2	6.90%	2015.00
6	Shanghai Jiao Tong Univ	2	6.90%	2013.50
7	Beijing Univ Technol	1	3.45%	2015.00
8	Harbin Inst Technol	1	3.45%	2015.00
9	Harvest Technol	1	3.45%	2014.00
10	HRL Labs	1	3.45%	2014.00

mechanism of aerodynamic noise, investigate the new principle and technology of temperature reduction and noise reduction, and achieve advanced aerodynamic lay-out design for supersonic jets.

(1) Characteristics of translot jet-flow field

Translot jet flow refers to that the jet-flow direction is parallel to the main direction of movement; a condensing agent is also used in jet flow to reduce the temperature of

object surface and change the structure of the flow field.

Translot jet flow plays an important role in the overall thermal protection of aerocraft and internal cooling of detached engines. Unsteady aerodynamic problems (e.g., flow separation and reattachment under supersonic flow) are prone to occur due to the effect of shock wave interference, supersonic shear layer, and turbulence. Moreover, the relative velocity between the jet flow field and the supersonic main flow leads to a complex vortex structure in the shear layer, thereby producing strong acoustic radiation. Hence, scholars must explore new theories and mechanisms, conduct advanced experimental technology research, and develop efficient numerical simulation methods. This paper emphasizes the interaction mechanism between the jet field and the main flow field; systematically understands the effect of the comprehensive coupling of shock wave, expansion wave, shear layer, and boundary layer on the mixing characteristics of jet-flow medium and mainstream moving medium; and determines the relationship between shock wave effect, flow separation, and peak thermal flow.

(2) Characteristics of lateral jet-flow field

If Ma > 3.0, significantly increasing the propulsion thermal efficiency of gas turbine through isobaric combustion and turbofan engine is difficult. Ramjet engine is pressurized by geometry changes to meet the pressure demand in the combustion chamber. The simple structure, light weight, and improved performance of this engine under high flight Mach number have gained increased research attention at home and abroad.

In scramjet engines, the residence time of supersonic flow is extremely short. Achieving a rapid mixture between fuel and air to promote highly efficient and stable combustion in the chamber while minimizing the total pressure loss as much as possible is the most fundamental technical challenge in the design of super-combustion engine. Lateral jet flow is a common fuel injection method that exhibits deep penetration and good mixing efficiency. Study on the characteristics of lateral jet-flow field not only can optimize the mixing process of fuel but also reveal the physical mechanism of combustion stability of scramjet for early application of scramjet technology and engine scramjet in the engineering field.

Countries or regions with top three publication numbers of core papers on the engineering research focus "Supersonic flow and aerodynamics" are China (25), England (8), the USA (5), and Iran (5). Countries or regions with top three average citation frequency are England (21.38), Egypt (19), and Turkey (16) (Table 1.2.9). Among the countries or regions with top 10 publication number, China and England exhibit high cooperation (Figure 1.2.5). Institutions with top three publication number of core papers are Natl Univ Def Technol (21), Univ Leeds (6), and Univ Michigan (5). Institutions with top three average citation frequency are Univ Leeds (22.67), Mil Tech Col (19), and Univ Sheffield (19) (Table 1.2.10). Among top ten institutions, Natl Univ Def Technol and Univ Leeds exhibit high cooperation (Figure 1.2.6). In 2011–2016, 25 core papers related to engineering studies focusing on "Supersonic flow and aerodynamics". The institutions with other publication number are National University of Defense Technology and Harbin Institute of Technology.

Table 1.2.9 Major producing institutions of core papers on the engineering research focus "Supersonic flow and aerodynamics"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	25	60.98%	383	67.43%	15.32	3	0
2	England	8	19.51%	171	30.11%	21.38	1	0
3	USA	5	12.20%	72	12.68%	14.40	1	0
4	Iran	5	12.20%	50	8.80%	10.00	1	0
5	Japan	4	9.76%	50	8.80%	12.50	0	0
6	Scotland	2	4.88%	25	4.40%	12.50	0	0
7	Sweden	2	4.88%	12	2.11%	6.00	0	0
8	Egypt	1	2.44%	19	3.35%	19.00	0	0
9	Turkey	1	2.44%	16	2.82%	16.00	0	0
10	France	1	2.44%	9	1.58%	9.00	0	0

Countries or regions with top three publication number of core papers cited by core papers are China (19), Iran (4), and England(3) (Table 1.2.11). The main institutions producing core papers cited by core papers are Natl Univ Def Technol (18), Babol Univ Technol (3), and Univ Leeds (3) (Table 1.2.12).

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 8 engineering development hotspots in the field of mechanical and vehicle engineering include mechanical engineering, naval architecture and ocean engineering, aerospace science and technology, armament science and technology, power and electrical equipment engineering and technology, transportation engineering, and other subjects (Table 2.1.1). Among which, "Sensor technology," "Advanced semiconductor technology and equipment," "Power system of electric vehicles," "New propulsion systems," "Imaging technology," "Design and manufacturing of high-efficiency, and low-emission engines" are further development of traditional research; "Surgical robot and key functional components," and "Unmanned vehicles" are emerging hotspots. All core patents involved in these hotspots in 2011–2016 are disclosed in Table 2.1.2.

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Supersonic flow and aerodynamics"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Natl Univ Def Technol	21	51.22%	333	58.63%	15.86	3	0
2	Univ Leeds	6	14.63%	136	23.94%	22.67	1	0
3	Univ Michigan	5	12.20%	72	12.68%	14.40	1	0
4	Babol Univ Technol	4	9.76%	39	6.87%	9.75	1	0
5	Tohoku Univ	3	7.32%	35	6.16%	11.67	0	0
6	Harbin Inst Technol	2	4.88%	31	5.46%	15.50	0	0
7	Univ Glasgow	2	4.88%	25	4.40%	12.50	0	0
8	Islamic Azad Univ	2	4.88%	17	2.99%	8.50	1	0
9	Mil Tech Coll	1	2.44%	19	3.35%	19.00	0	0
10	Univ Sheffield	1	2.44%	19	3.35%	19.00	0	0

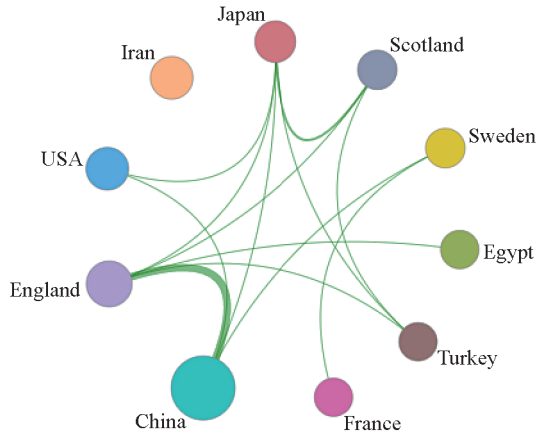

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering development focus "Supersonic flow and aerodynamics"

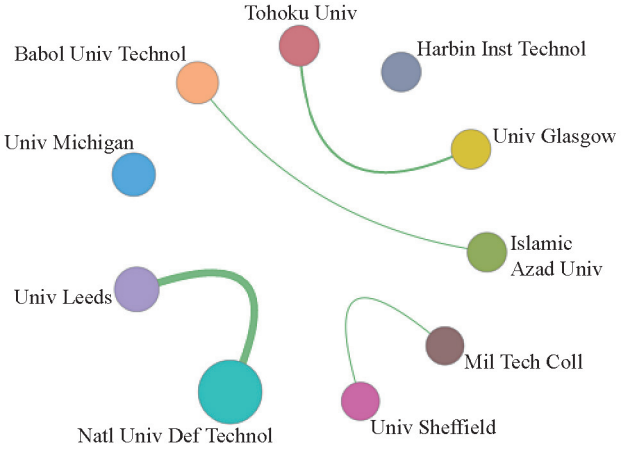

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering development focus "Supersonic flow and aerodynamics"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Supersonic flow and aerodynamics"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	19	63.33%	2014.05
2	Iran	4	13.33%	2014.50
3	England	3	10.00%	2013.00
4	USA	2	6.67%	2013.00
5	Malaysia	1	3.33%	2016.00
6	Sweden	1	3.33%	2016.00

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Supersonic flow and aerodynamics"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Natl Univ Def Technol	18	52.94%	2014.00
2	Babol Univ Technol	3	8.82%	2014.67
3	Univ Leeds	3	8.82%	2013.00
4	Islamic Azad Univ	2	5.88%	2014.50
5	Univ Michigan	2	5.88%	2013.00
6	Amirkabir Univ Technol	1	2.94%	2014.00
7	China Aerodynam R&D Ctr	1	2.94%	2015.00
8	Harbin Inst Univ	1	2.94%	2016.00
9	Isfahan Univ Technol	1	2.94%	2015.00
10	Lund Univ	1	2.94%	2016.00

Tab 2.1.1 Top 8 engineering development hotspots in mechanical and vehicle engineering

No.	Engineering research hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Sensor technology	259	3 122	12.05	2012.10
2	Advanced semiconductor technology and equipment	750	32 405	43.21	2012.30
3	Unmanned vehicles	88	3 070	34.89	2013.20
4	Surgical robot and key functional components	118	4 877	41.33	2012.86
5	The power system of electric vehicle	695	13 000	18.71	2011.80
6	New propulsion system	507	2 048	4.04	2012.79
7	Imaging technology	214	7 409	34.62	2012.07
8	Design and manufacture of high efficiency, and low-emission engines	440	2137	4.86	2012.88

(1) Sensor technology

A sensor is a device that converts acquired information into another form in accordance with certain laws of specific phenomenon in physics, chemistry, or biology. Sensor technology has been increasingly used in aerospace, transportation, machinery manufacturing, petrochemical, technical supervision and testing, and other technical fields. The focuses of sensor technology development include the

Table 2.1.2 Annual number of core patents belonging to each of the Top 8 engineering development hotspots in mechanical and vehicle engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Sensor technology	103	68	59	22	3	4
2	Advanced semiconductor technology and equipment	289	185	124	79	58	15
3	Unmanned vehicles	103	145	155	127	88	37
4	Surgical robot and key functional components	29	23	21	28	15	2
5	The power system of electric vehicle	330	220	114	22	6	3
6	New propulsion system	87	158	123	65	61	13
7	Imaging technology	91	61	31	22	6	3
8	Design and manufacture of high efficiency, and low emission engines	97	90	93	105	37	18

development of general technology for sensors and special technology in the industrial field. The innovative applications of sensors in the medical treatment, environmental monitoring, large-scale infrastructure, intelligent manufacturing, smart grid, wearable devices, and other fields will become new research hotspots. Sensors should be miniaturized, possess integrated and modular structures, and exhibit wide range, high-precision and high-reliability detection performance, strong anti-interference ability, and long service life to satisfy engineering requirements for development of sensor technology. Moreover, to meet the needs of long-term monitoring, achieving energy self-sufficiency of sensors is also the future trend of sensor technology.

(2) Advanced semiconductor technology and equipment

Semiconductor processing technology faces numerous technological change points, such as reduction in feature size and introduction of new materials and structures. New requirements and challenges have been proposed for semiconductor manufacturing technology. The feature size reduction in integrated circuits requires the implementation of ultrafine graphics processing, precise control of graph shape, and control of the shape, surface, energy, status, and multiple other factors. Ultrafine shape processing requires extreme ultraviolet lithography equipment with shorter wavelength. Moreover, other technical equipment should be used in combination for shape, surface roughness, energy, status, and others. With the improvement of the integration of large-scale circuits, new requirements for packaging technology have been proposed. 3D encapsulation technology based on through-silicon via has attracted considerable attention. With the introduction of a new structure, unnecessary shape damage should be avoided while the 3D high aspect ratio structure is precisely controlled; with the introduction of new materials, performance should be improved while the impact on process integration is avoided. In recent years, the rapid increase mobile consumer electronics on the internet has markedly promoted the growth of the semiconductor market.

(3) Unmanned vehicles

An unmanned vehicle is a mobile platform that does not require a person to drive within the vehicle. At present, unmanned vehicles have covered land, air, and water. Land unmanned vehicles, including wheeled and crawler types, are used in the field of explosive removal, reconnaissance, and others. Unmanned aerial vehicles include fixed-wing, rotor-wing, and flapping-wing unmanned aerial vehicle and others, which have been applied in disaster rescue and observation. Unmanned underwater vehicles include unmanned surface vehicles, unmanned underwater vehicles, and others, which have been preliminarily used in underwater rescue and detection. Unmanned vehicles are developing from teleoperation to autonomous control. Autonomous control of unmanned vehicles involves the design of unmanned vehicles, environmental perception, mapping, positioning, navigation, obstacle avoidance, and numerous techniques. For technical security and reliability, autonomous control should also cover condition monitoring, fault diagnosis, and maintenance. With the large-scale applications of

unmanned vehicles in the future, autonomous control of unmanned vehicles will be developed from personal intelligence to swarm intelligence.

(4) Surgical robot and key functional components

A surgical robot refers to a special robot that replaces or assists doctors in performing surgical procedures. Its key functional components refer to the precise mechanism, hardware, and software needed for the completion of the whole operation process. Based on the degree of opening of the surgical space, the two categories of robotic surgery are open and closed. The former includes orthopedic surgery, and the latter category includes various endoscopic surgeries. The development hotspots for orthopedic surgery include computer-aided design and the manufacture of preoperative artificial prosthesis, intraoperative pose detection, 3D navigation, instrument support and guidance, visual observation, and others. Personalized prosthesis design, accurate implant placement, and the integration of surgical procedures are important trends in the development of orthopedic surgical robots. For endoscopic surgeries, the development hotspots include tissue anastomat, endoscopic instrument controller, multifunctional scalpel, stereoscopic vision, haptic feedback, wireless monitoring of tissue and instrument status, and others. Minimally invasive, multi-functional integration is an important trend in the development of endoscopic surgical robots and endoscopic surgical instruments.

(5) Power system of electric vehicle

Electric vehicles refer to vehicles that are propelled by an electric motor or traction motor; these vehicles include road and rail vehicles, surface or underwater ships, airplanes, space vehicles, and others. Batteries are a core technical difficulty of electric vehicles. Lithium batteries will dominate the power battery market in the short term. Fuel cells, metal–air batteries, solid-state cell, ultra-capacitor battery composite power supplies, and several new systems and technologies will be the focus of competition for major manufacturers in the future. The application of motor and electronic control technology in electric vehicles has been approved, but the technical maturity is far from meeting the requirement. In the future, the core technology of drive motors and the chain of industry system will be integrated, and high-performance, high-efficiency, and lightweight motor system and electric drive components will be developed with the help of the third-generation large energy gap power semiconductors. The charging infrastructure system is an important obstacle to the popularity of electric vehicles. Moreover, high-efficiency, intelligent energy management technology and advanced vehicle control technology directly determine the performance indicators of electric vehicles. The electric vehicle will be an electric industrial model that is integrated with the new industry, new energy, and new information.

(6) New propulsion system

Electric propulsion refers to a propulsion method in which the electric energy is produced by the prime motor unit first; then, the motor drives the propeller, jet propulsion, and other propulsion systems. At present, the development trend of marine electric propulsion equipment is using an alternating current electric propulsion device to replace the direct current electric propulsion device, as well as the AC and DC electric propulsion device, developing superconducting electric propulsion, developing submarine fuel cell propulsion system instead of lead acid battery, and developing integrated full electric propulsion system. The pump-jet propulsor, a rotary combined type hydrodynamic propeller, consists of an axisymmetric annular duct, as well as rotating and stationary cascades within the duct, with good cavitation resistance. The propeller is widely used in ships and is an important component in determining ship performance. High efficiency, good energy saving, strong cavitation resistance, low vibration and noise, simple structure, and strong reliability are the important directions of propeller development.

(7) Imaging technology

Eighty percent of the information is acquired by humans through vision. Imaging and image processing technologies, which are widely used in the industry, agriculture, medical treatment, aeronautics and astronautics, military affairs, and other important fields, have always been research hotspots and present an important foundation of the information age. The current hotspots of the imaging technology include high-resolution imaging technology in a complex service environment, high resolution remote sensing imaging, and seabed imaging. Among these technologies, sonar technology based on multibeam seabed imaging is an important development direction in the future. The current hotspots in image processing include

contour detection, image segmentation and bottom information extraction, and others. Meanwhile, with the development, deep learning has markedly improved the results of traditional methods. In recent years, this approach has gained considerable success in the recognition, understanding, and target detection of various types of images.

(8) Design and manufacture of high-efficiency, and low-emission engines

This section mainly focuses on micro-turbine engines with the power of less than several hundred kilowatts. Being characterized by small size, light weight, high horsepower, high supercharging ratio, simple structure, micro-turbine engines are mainly used in distributed power supply, standby power supply, micro turbine-fuel cell combined power generation, alternative power for traditional piston type diesel engine, and others. Moreover, certain micro-turbine engines are used for aviation. At present, micro-turbine electric generator is a hotspot. Domestic light micro-turbine is still in its infancy in design technology and market development. The key technical problems cover structural design of turbine blades, manufacturing technology of blades and impellers, and blade materials. The outlet temperature of small and micro-turbine engine exceeds 1800 K. The turbine still does not cool. Therefore, only composite ceramic-based material can be used. Nanocoating technology is also a current technical hotspot. It should be also a thermal barrier coating, with high temperature resistance and low heat dissipation. And, it can improve the thermal efficiency of the whole machine. Another function of nanocoating is wear resistant, satisfying the rotation speed of the working axle of the turbine engine up to 10 000 turns.

2.2 Understanding of engineering development focus

2.2.1 Sensor technology

With the rapid development of science and technology, sensor technology is being widely used in aerospace, transportation, machinery manufacturing, petrochemical, technical supervision and testing, and other technical fields. At present, the focuses of sensor technology development include the development of general technology for sensor itself and that of special technology in the industrial field. The former includes sensor materials and manufacturing technique, sensor detection principle, and so on, whereas the latter mainly includes the development of composite perception sensor in the medical and health field and sensors for extreme conditions in the automotive and energy fields.

(1) Sensor materials and manufacturing technique

The performance of sensing and conversion element in sensor determines the performance of the sensor to a considerable extent. The refinement of processing technique is becoming more important in sensor fabrication. Numerous new sensors can be fabricated through micro-electro mechanical systems (MEMS). The substrate, the sensing element, and the auxiliary material can be packaged into various standard semiconductor packages by means of MEMS technology. The sensing element, processing circuit, amplifier circuit, and communication circuit are all arranged on the common substrate; thus, the power dissipation of the MEMS sensor is reduced with miniaturized structure. With a folding beam structure, the sensor can increase shear strength and effectively reduce encapsulation stress.

(2) The principle of sensor detection

Most sensors use some special properties of certain materials to obtain information. Among them, the mechanical and magnetic properties of materials are research hotspots for new sensors. Development directions of force sensor include high sensitivity, working in a harsh environment, wider dynamic range, and shorter response time. The development directions of magnetic sensors include high sensitivity, temperature stability, anti-interference, integration, and low power consumption. On the basis of signal detection, the micro-mechanical pressure sensor is divided into two types, namely, piezo-resistive and capacitive. High-precision measurement can be achieved in an environment with temperature fluctuation through forming a bridge circuit consisting of numerous sensing elements.

(3) Development of composite perception sensor in medical and health field

Medical sensors and wearable devices perform an increasingly important role in improving the quality of life, as well as improving the comfort and convenience of people. Sensors in these fields are developing rapidly, and various types of sensors are emerging. The position monitoring and energy supply of medical sensors is an

important research direction, and driving force control for medical devices is a development focus. Wearable devices generally contain multiple types of sensors for measuring heart rate, temperature, sleep, blood pressure, and so on. Pressure sensors are applied in electronic skin and instrument prostheses. With the development of sensor manufacturing technologies, wearable sensors are becoming smaller and more easily fit together with skin or human tissue, and can more sensitively acquire changes in the monitoring indices.

(4) Development of sensors in the field of vehicles, energy, and operation in harsh working environments

Safety and energy conservation are difficult problems in the fields of automobile and energy. Charging control for electric vehicles, monitoring of battery life cycle, and monitoring in power transmission depend on the important role of the sensor. Multidimensional sensing technology can effectively prevent and reduce accidents in the automotive and energy fields. The use of a new type of sensor ensures high-accuracy measurement results. Moreover, reduction of error and fault of sensors is crucial in the field of automobile safety. In charging automobiles, the application of sensors needs to be combined with charging control methods to achieve energy saving.

(5) Current situation and future development trend

Sensors have been widely used in automobiles, industrial automation, aerospace technology, military engineering, environmental detection and other fields. A variety of new sensors are emerging, and innovations and applications in medical treatment, environmental monitoring, large-scale infrastructure, health monitoring, intelligent manufacturing, smart grid, wearable devices, and other fields will become future hotspots. With miniaturization, integration and modularization structure, wide range, high precision and reliability, strong anti-interference, and long life, new engineering requirements are proposed for the development of sensor technology. The future developmental trend in sensor technology also includes meeting the requirements of long-term monitoring and achieving energy self-sufficiency of sensors.

In development focuses of "Sensor technology," the three countries or regions with the highest numbers of core patent disclosure are the USA (87), Japan (60), and China (41). The three countries or regions with the top average citation frequency are the USA (14.61), China (13.02), and the Netherlands (11.83), as shown in Table 2.2.1. Among the top 10 countries or regions in terms of patent disclosure numbers, the USA has cooperated with China, Germany, France, and the Netherlands (Figure 2.2.1). The top three institutions in terms of amounts of core patent disclosure are BOSC (13), FRSE (7), and SHIH (7) respectively. The top three institutions in average citation frequency are BERT (19.33), FRSE (16.29), and TOKE (14.5) (Table 2.2.2). Among the top 10 institutions, NXPS cooperated with AMSI more frequently (Figure 2.2.2). In 2011–2016, a total of 41 core patents related to the development focus of "Sensor technology" were disclosed in China, and the institution frequently disclosed patents in China mainland is Zhejiang University.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Sensor technology"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	87	33.59%	1271	40.71%	14.61
2	Japan	60	23.17%	648	20.76%	10.80
3	China	41	15.83%	534	17.10%	13.02
4	Germany	35	13.51%	314	10.06%	8.97
5	France	8	3.09%	50	1.60%	6.25
6	Switzerland	6	2.32%	44	1.41%	7.33
7	Korea	6	2.32%	52	1.67%	8.67
8	The Netherlands	6	2.32%	71	2.27%	11.83
9	Canada	4	1.54%	41	1.31%	10.25
10	UK	4	1.54%	8	0.26%	2.00

Tab 2.2.2 Major producing institutions of core patents on the engineering development focus "Sensor technology"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	BOSC	13	5.02%	97	3.11%	7.46
2	FRSE	7	2.70%	114	3.65%	16.29
3	SHIH	7	2.70%	81	2.59%	11.57
4	TOKE	6	2.32%	87	2.79%	14.50
5	INFN	5	1.93%	44	1.41%	8.80
6	NXPS	5	1.93%	45	1.44%	9.00
7	HONE	4	1.54%	45	1.44%	11.25
8	UYZH	4	1.54%	46	1.47%	11.50
9	AMSI	3	1.16%	31	0.99%	10.33
10	BERT	3	1.16%	58	1.86%	19.33

Note: BOSC stands for Bosch Group); FRSE stands for Freescale Semiconductor Inc; SHIH stands for Seiko Epson Corp; TOKE stands for Toshiba KK; INFN stands for Infineon Technologies AG; NXPS stands for NXP Semiconductors BV; HONE stands for Honeywell International Inc; UYZH stands for Zhejiang University; AMSI stands for Ams AG; BERT stands for Bertec Corporation.

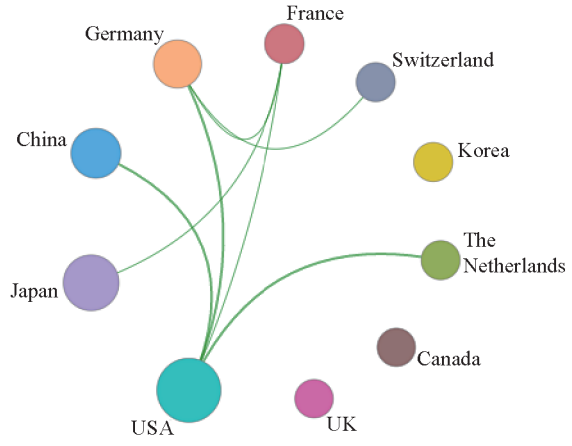

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Sensor technology"

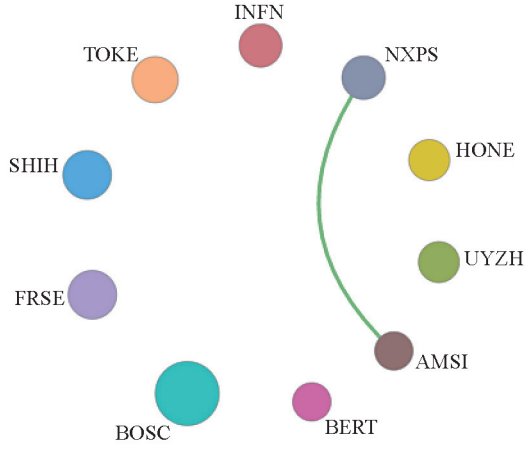

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Sensor technology"

2.2.2 Design and manufacture of high-efficiency, and low-emission engines

The design and manufacturing technologies for high-efficiency, low-emission engines are mainly directed against large-scale gas turbine engine and mini turbine engine. Mini-turbine engines are characterized by small size, light weight, huge power, high supercharging ratio, and simple structure. At present, the perspective on ground gas turbine technology is mainly based on several ongoing or unfinished projects with outstanding value, as verified by long-term air and ground fuel and relevant discipline development planning in western countries. The selection of these projects is still based on high efficiency, energy saving, low pollution, low cost, high reliability, and so on. A brief description is as follows.

(1) High parameter, high performance

Fourth- and fifth-generation aero gas turbines, T_4 = 1800–2000 K, $\pi_c \geq 30$, will be used as a prototype engine. The outlet temperature of the ground gas turbine can reach 1527 °C to 1727 °C, $\pi_c \geq 30$, and the corresponding performance will be improved.

(2) Development of heat-resisting materials

Existing super alloys are no longer applicable to meet the requirements of high operating temperature of turbine. Therefore, non-metallic super high-temperature materials, including ceramics and their composites reinforced with carbon, as well as carbon composites, will be adopted as hot end-components.

(3) Design of highly active cooling method

Combined cooling with gas film, convection current, and impact, which is currently employed by turbine blades and combustion chambers, remains applicable. As a next-generation coolant, steam has been tested on individual gas turbines. Steam cooling saves 10%–20% cooling air and improves thermal efficiency and power. However, it is only applicable to the ground combined cycle gas turbine. Ground sealing technology is the key to prevent steam leakage.

(4) Advanced design and manufacturing technology for the turbine

The aims of the aero-turbine compressor is to improve the blade design method and increase the supercharging rate, whereas those of the turbine are high efficiency, large enthalpy drop, and high temperature resistance. The results will continue to be absorbed and adopted by ground gas turbines and inject new vitality into ground gas turbines.

(5) Low pollution combustion technology

At present, most aviation and ground gas turbines adopt dry low NO_x combustion chambers, including radial and axial staged combustion chambers, sequential reheat combustion chambers, and oil–poor premixed pre-evaporation combustion chambers, which may be continuously promoted in the future. Moreover, the catalytic combustion chamber and the long-researched oil-rich combustion-quench–oil-poor combustion chamber may be adopted in the future to achieve ultra-low NO_x combustion. A currently adopted, effective desulfurization technology in integrated gasification combined cycle and the coal-fired PFBC gas turbine–steam turbine combined cycles can be adopted in the future to reduce SO_2 emission.

(6) New thermodynamic cycle and total energy system

At present, separate complex cycles or complex cycles involved in combined cycles have been adopted. Moreover, new combined cycles, such as steam (water) injection combined cycle, integrated gasification combined cycle in the coal-fired combined cycle, the coal-fired–fluidized bed combined cycle under constant and high pressure, have been employed. In the future, the IGCC and pressurized fluidized bed combined cycle will be ideal and extensively used. Other cycles will be adopted with their technical maturation.

(7) Design and manufacturing technology of micro and ultra-micro gas turbine

Centralized high power gas turbine generation and distributed micro-turbine power supply have become the two harnesses for the future power supply of vehicles. At present, the main technical keys are innovations of air-cooled bearing, high-speed micro motor, fluid viscosity, heat transfer, and combustion mechanism in small size. In the future, more attention will be focused on the development and application of this technology.

The top three countries or regions in terms of the number of core patent publications on "Design and manufacture of high-efficiency, and low-emission engines" are the USA (231), France (75), and the United Kingdom (58); the

Tab 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Design and manufacture of high-efficiency, and low-emission engines"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	231	52.50%	1230	57.56%	5.32
2	France	75	17.05%	336	15.72%	4.48
3	UK	58	13.18%	176	8.24%	3.03
4	China	23	5.23%	107	5.01%	4.65
5	Germany	18	4.09%	77	3.60%	4.28
6	Japan	12	2.73%	69	3.23%	5.75
7	Canada	11	2.50%	80	3.74%	7.27
8	The Netherlands	7	1.59%	21	0.98%	3.00
9	Austria	2	0.45%	10	0.47%	5.00
10	Belgium	2	0.45%	10	0.47%	5.00

Tab 2.2.4 Major producing institutions of core patents on the engineering development focus "Design and manufacture of high-efficiency, and low-emission engines"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	RORO	63	14.32%	201	9.41%	3.19
2	UNAC	58	13.18%	219	10.25%	3.78
3	GENE	43	9.77%	156	7.30%	3.63
4	SNEA	40	9.09%	196	9.17%	4.90
5	SUNH	31	7.05%	132	6.18%	4.26
6	EADS	22	5.00%	79	3.70%	3.59
7	HONE	17	3.86%	113	5.29%	6.65
8	SFRA	10	2.27%	60	2.81%	6.00
9	BOEI	9	2.05%	75	3.51%	8.33
10	MOTU	9	2.05%	34	1.59%	3.78

Note: RORO stands for Rolls-Royce Limited; UNAC stands for United Technologies Corp; GENE stands for General Electric Company; SNEA stands for Snecma; SUNH stands for Hamilton Sundstrand Corp; EADS stands for Airbus Helicopters; HONE stands for Honeywell International Inc; SFRA stands for Turbomeca; BOEI stands for Boeing Company; MOTU stands for MTU Aero Engines AG.

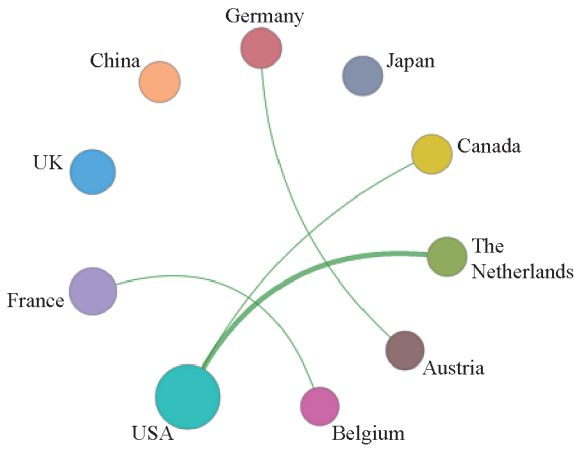

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Design and manufacture of high-efficiency, and low-emission engines"

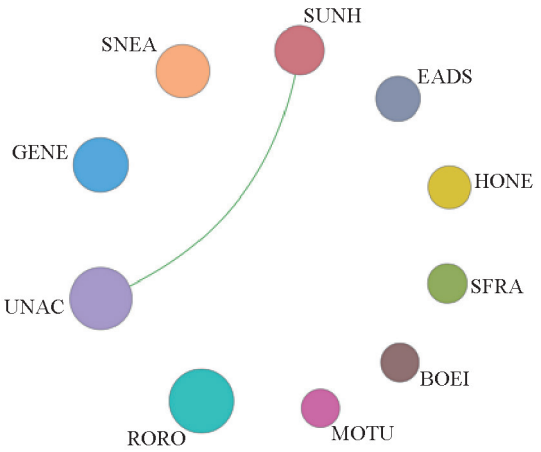

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Design and manufacture of high-efficiency, and low-emission engines"

top three countries or regions for the average citation frequency are Canada (7.27), Japan (5.75), and the USA (5.32) (Table 2.2.3). Among the top 10 countries or regions for publication amount, the USA closely cooperated with the Netherlands (Figure 2.2.3). The three institutions with the highest number of core patent publications are RORO (63), UNAC (58), and GENE (43). The top three institutions in average citation frequency are BOEI (8.33), HONE (6.65), and SFRA (6) (Table 2.2.4). Among the top 10 institutions in publication amount, UNAC cooperated with SUNH more frequently (Figure 2.2.4). From 2011–2016, 23 core patents related to the development focus of "Design and manufacture of high-efficiency, and low-emission engine" are disclosed in China, and no institution is listed in the Top 10.

2.2.3 Unmanned vehicles

An unmanned vehicle is a mobile platform that does not require a person to drive within a vehicle. Land unmanned vehicles includes wheeled and crawler-type vehicles. Unmanned aerial vehicles include fixed-wing unmanned aerial vehicles, rotor-wing unmanned aerial

vehicles, flapping-wing unmanned aerial vehicles, and others. Finally, unmanned underwater vehicles include unmanned surface vehicles, unmanned underwater vehicles, and others. Autonomous control of unmanned vehicles involves the design of unmanned vehicles, environmental perception, mapping, positioning, navigation and obstacle avoidance, status monitoring, fault diagnosis and maintenance, and numerous techniques.

(1) Bionic design of basic machine

At present, several problems in unmanned vehicles include low ratio of load weight to self-weight and low energy efficiency, among others. The basic approach to solving these problems is through learning from nature, that is, by analyzing the movement mechanism, force mechanism, and energy adjustment mechanism of animals adapting to the nature. The construction of a driver with high energy density, high dynamic response, high strength, and high energy structure, and the establishment of a multi-objective, multi-level, and multi variable design method based on motion-force-energy cooperation are the focuses of future research.

(2) Intelligent system for unmanned vehicles

Analysis of biological control behavior from the perspective of bionics, the establishment of the overall structure of information processing, logic analysis, decision selection, and system control have gradually become the research focuses in intelligent systems for unmanned vehicles. On the basis of animal behavior and movement characteristics, researchers have developed and designed reactive intelligence, deliberative intelligence, deliberative/reactive complex intelligence, and other autonomous intelligent control systems for unmanned vehicles. With the development of artificial intelligence technology, intelligent systems based on symbolic classification, intelligent systems based on depth learning and open distributed intelligent systems have attracted increasing attention.

(3) Control method for unmanned vehicles

The problem of autonomous control for unmanned vehicles is a high-dimensional hybrid system control problem. Owing to the complexity of the running environment and the diversity of the moving mode, the autonomous control system for unmanned vehicles must be polymorphic and complex, and different states should be able to be switched smoothly. Traditional kinematics-based planning and control evolved to motion-dynamic planning and control; therefore, analysis of force–position–posture cooperation planning and control will be the basic technical approach to design the autonomous control system for unmanned vehicles.

(4) Positioning and navigation

Positioning and navigation are the bases of the autonomous motion of unmanned vehicles. The positioning and navigation procedure for unmanned vehicles can be divided into three links, namely environmental modeling, positioning, and path planning, and the technical key is environmental modeling. Accurate positioning and navigation technology is based on satellite positioning and navigation information to realize multi-sensor information fusion, as well as local global seamless positioning navigation by forming a local environment map by combining inertial, visual, lidar, and other sensing information. For meeting the practical needs of unmanned vehicles, the positioning navigation technology should be developed from the structured environment space to the outdoor free environment. Therefore, the development of an all-weather high-precision sensor for environmental identification modeling is a development hotspot.

(5) Active obstacle avoidance

Active obstacle avoidance is an important problem in autonomous movement of unmanned vehicles. With the development of unmanned vehicles for practical use, unmanned vehicles need to cope with dynamic obstacles and highlight obstacles during high-speed moving in complex environments. Therefore, the development of obstacle avoidance technology focuses on improving dynamic obstacle recognition ability and dynamic decision-making ability. Recognition of dynamic obstacles, motion intentions, and motor parameters should be added on the basis of traditional geometric recognition to improve the accuracy and credibility of obstacle identification. Then, smooth path replanning is carried out in real time.

(6) Automatic parking

Automatic parking is achieved through two approaches: one is by increasing the automatic parking function in the vehicle itself, and another is by adding infrastructure in the parking lot and using autonomous parking chassis to move and park the vehicle. For the automatic parking technology against autonomous parking chassis, the

emphasis of its application development is on the omni-directional, rapid movement of large-inertia objects, automatic parking efficiency, and multi-machine cooperative scheduling. Aiming at automatic parking technology of the vehicle itself, the emphasis of its development lies in adaptability to parking spaces, reliability, and high parking efficiency because of the variety of parking spaces in urban traffic.

(7) Autonomous driving

Autonomous driving refers to the application of computer control instead of a person to accomplish the vehicle motion control task. At present, autonomous driving technology exhibits a breakthrough, but its security and reliability still hardly meet actual application requirements. Autonomous driving for unmanned vehicles includes environmental perception and pathway planning. In the future, autonomous driving needs to adapt an environmental perception mode of multi-sensor information fusion for a real-time analysis and integration of redundant information so as to ensure the safe driving of unmanned vehicles with richer environmental information. The types and amounts of vehicles will markedly increase in the future. Autonomous driving systems should offer multi-machine coordination and self-optimization to construct the intelligent traffic network through establishing a multi vehicle communication mechanism.

(8) Condition monitoring and fault diagnosis

Autonomous control for unmanned vehicles can perform condition monitoring, fault diagnosis, performance reduction, and health prediction when a failure occurs. Condition monitoring includes two parts, namely, monitoring of surrounding environment condition and monitoring of the running condition. Among these functions, recognition and extraction of environmental information and time-varying complex environment are the research focus. The main challenges in monitoring the running state of the vehicle are multi-sensor information fusion, quantization of the vehicle's running state, failure/fault criteria, and accurate fault location. Future research and development will focus on multi-fault intelligent diagnosis and preventive maintenance technology. With the development of artificial intelligence technology, intelligent condition monitoring and fault diagnosis technology based on learning will be a future development direction.

(9) Swarm intelligence

Multi-platform/multi sensor information fusion, design of efficient universal communication interface, and open control architecture are focuses of cluster intelligent technology research. With the development of bionic research, the self-organization mechanism, which draws lessons from nature, provides new ideas for the research on swarm intelligence technology. Based on the study of bionics and swarm intelligence algorithm, the swarm intelligence technology for unmanned vehicles will further achieve large scale and autonomy. Moreover, swarm intelligence technology is developed from conspecific unmanned vehicles to a variety of different unmanned vehicles to assist in accomplishing complex tasks. Thus, the technology has attracted research attention.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Unmanned vehicles"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	70	79.55%	2666	86.84%	38.09
2	Japan	6	6.82%	90	2.93%	15.00
3	Germany	4	4.55%	185	6.03%	46.25
4	China	3	3.41%	101	3.29%	33.67
5	UK	2	2.27%	17	0.55%	8.50
6	Canada	1	1.14%	17	0.55%	17.00
7	Israel	1	1.14%	4	0.13%	4.00
8	Korea	1	1.14%	9	0.29%	9.00
9	Taiwan of China	1	1.14%	30	0.98%	30.00

The top three countries or regions in number of core patent publication for "Unmanned vehicles" are the USA (70), Japan (6), and Germany (4). The top three countries or regions in average citation frequency are Germany (46.25), the USA (38.09), and China (33.67) (Table 2.2.5). Among the top 10 countries in terms of publication amount, the USA and Germany have substantially cooperated (Figure 2.2.5). The top three institutions in number of core patent publication are FORD (15), GOOG (15), and Flextronics (6), and the institutions with top 3 average citation frequency are GOOG (49.47), BOSC (46.25), and Flextronics (41.83) (Table 2.2.6). Among the 10 institutions in terms of publication amount, HONE and EMS Technologies cooperated more substantially (Figure 2.2.6). In 2011–2016, three core patents related to one development focus, that is, "Unmanned vehicles", are disclosed in China. Of which, 2 patents are from Shenzhen Dajiang.

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Unmanned vehicles"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	FORD	15	17.05%	432	14.07%	28.80
2	GOOG	15	17.05%	742	24.17%	49.47
3	Flextronics	6	6.82%	251	8.18%	41.83
4	BOSC	4	4.55%	185	6.03%	46.25
5	HONE	3	3.41%	14	0.46%	4.67
6	EMS Technologies	2	2.27%	6	0.20%	3.00
7	Shenzhen Dajiang	2	2.27%	63	2.05%	31.50
8	TOYT	2	2.27%	18	0.59%	9.00
9	TTTA	2	2.27%	17	0.55%	8.50

Note: FORD stands for Ford Inc; GOOG stands for Google Inc; Flextronics stands for Flex International Ltd; BOSC stands for Bosch Group; HONE stands for Honeywell International Inc; EMS Technologies stands for EMS Technologies Inc; TOYT stands for Toyota Motor Corp; TTTA stands for Jaguar Land Rover Ltd.

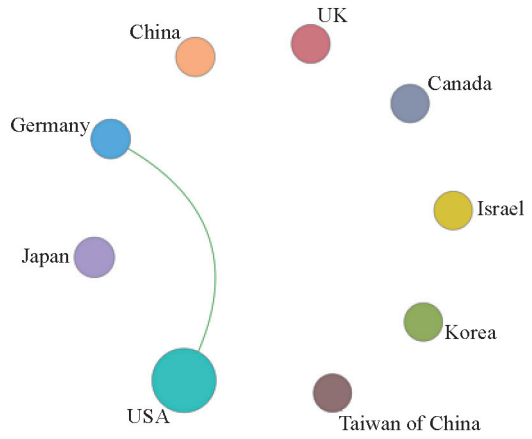

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Unmanned vehicles"

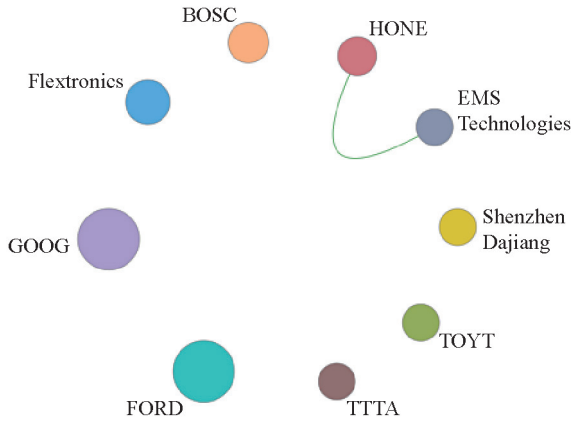

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Unmanned vehicles"

Project Participants

Field Group

Leaders of the Field Group:

DUAN Zhengcheng, GUO Dongming

Other Members:

SHI Tielin, LI Renfu, ZHAO Yingjun, WANG Shaorong, CHENG Yuansheng, XIA Qi, XIA Liang, SUN Bo, CHEN Xixi

Report Writers

SHI Tielin, ZHAO Yingjun, XIONG Caihua, WU Xinjun, LUO Xin, LI Renfu, CHENG Xiaobei, HUANG Yongan, HU Xianluo, LIU Yinshui, WEI Qingsong, XIA Qi, XIA Liang, SUN Bo, LI Li

II. Information & Electronic Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the information and electronic engineering field are summarized in Table 1.1.1. They cover the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, control science and technology, and other disciplines. Among them, "Multi-object tracking technologies," "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic," "Robust adaptive boundary control," "Ultra-wideband slot antennas," "Dynamic network visualization," "Global optimization algorithms," "Multi-criteria decision making," "Reversible data-hiding schemes," "High-utility itemset mining algorithms," and "Optical coherence elastography" are in-depth research topics of traditional research.

The numbers of core papers in each engineering research hotspot published annually from 2011 to 2016 are shown in Table 1.1.2.

(1) Multi-object tracking technologies

In recent years, multi-object tracking has emerged as an important science and technology. It is related to a variety of disciplines, including stochastic statistics, mathematical optimization, image processing, pattern recognition, artificial intelligence, and automatic control. Multi-object tracking has been widely used in military applications, especially in the application of airborne detection and remote warning.

The current issues in multi-object tracking include occlusions, the randomness of the number of objects, complex backgrounds, and real-time requirements. The focus of overseas research has shifted from multi-object tracking technology using a single sensor to multi-object tracking with multiple sensors. With the rapid movement of objects and the changing environment of multi-object tracking technology, tracking the maneuvering object has attracted a renewed interest. Another research hotspot is the implementation of artificial neural networks to achieve multi-object tracking. Owing to the potential self-organization and self-learning abilities of artificial neural networks, this will be a promising research direction for multi-object tracking.

(2) Global optimization algorithms

According to the optimization objective, the global

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

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Multi-object tracking technologies	48	1974	41.13	2012.63	8.3%	0
2	Dynamic network visualization	47	1089	23.17	2012.36	4.3%	0
3	Characteristics and analyses of neural networks/ neural network modeling and fuzzy logic	91	2856	31.38	2013.08	20.9%	1
4	Global optimization algorithms	47	2061	43.85	2013.02	14.9%	0
5	Robust adaptive boundary control	50	1961	39.22	2013.86	26.0%	0
6	Multi-criteria decision making	48	1615	33.65	2013.75	27.1%	0
7	Reversible data-hiding schemes	46	1879	40.85	2013.43	23.9%	1
8	High-utility itemset mining algorithms	48	971	20.23	2014.02	6.3%	0
9	Optical coherence elastography	45	1485	33.00	2013.33	17.8%	0
10	Ultra-wideband slot antennas	47	1281	27.26	2013.72	6.4%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in information and electronic engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Multi-object tracking technologies	12	13	7	13	3	0
2	Dynamic network visualization	17	9	9	11	1	0
3	Characteristics and analyses of neural networks/ neural network modeling and fuzzy logic	25	17	12	9	19	9
4	Global optimization algorithms	7	10	10	15	5	0
5	Robust adaptive boundary control	6	5	10	7	13	9
6	Multi-criteria decision making	11	4	4	6	13	10
7	Reversible data-hiding schemes	4	8	13	9	9	3
8	High-utility itemset mining algorithms	1	5	7	18	13	4
9	Optical coherence elastography	5	8	10	14	5	3
10	Ultra-wideband slot antennas	2	10	7	11	14	3

optimization algorithms are divided into single-objective, multi-objective, and hierarchical multi-objective optimization problems. According to the data type, they are divided into discrete, continuous, and hybrid optimization problems. Because global optimization problems often have many local optimal solutions, they are difficult to solve with the classical optimization method. Particularly in the big data environment, there may be a huge number of local optimal solutions, which creates a considerable challenge in the search for a global optimal solution. In particular, no effective global judgment criterion has been determined. Consequently, the advantages and disadvantages of different local optimal solutions are difficult to evaluate, which hinders the unification of the global optimization objective. Global optimization problems are frequently encountered in data mining, image processing, machine learning, artificial intelligence, and other fields. Different global optimization algorithms are used for different data characteristics and targets.

(3) Robust adaptive boundary control

Robust adaptive control concerns systems with uncertainties and has broad application areas, such as robotics and flight control. Robust adaptive boundary control is a rather large category and includes boundary disturbance attenuation, nonlinear active disturbance control, adaptive boundary control, and sliding mode control.

The theory of boundary measurement and control was developed within the robust adaptive boundary control research domain. It is critical to target the most challenging engineering problems that arise in real practical applications and to form novel solutions using boundary measurement and control methodologies. The challenging areas in which robust adaptive boundary control is needed include—but are not limited to—active control of combustion instabilities, structural vibration control of aerospace vehicles, active flow control, pinning control of large-scale networks, boundary measurements and related inverse problems in biologic tissues, and boundary manipulation physics and control system technologies.

(4) Multi-criteria decision making

Multi-criteria decision making can be divided into two classes, multi-attribute decision making and multi-objective decision making, based on whether the decision scheme is finite or infinite. A current means of multi-criteria decision making is to merge the effectiveness of all attributes to obtain the full effectiveness and then to rank the schemes. In 1965, Zadeh proposed the fuzzy set theory. In 1970, Bellman and Zadeh introduced the fuzzy set theory in multi-criteria decision making and proposed the fuzzy multi-criteria decision making (FMCDM) model to resolve the uncertainty problem in actual decision making; this model has become a popular research direction in the current multi-criteria decision making research hotspot.

(5) Reversible data-hiding schemes

Reversible data hiding is an information-hiding technology that can fully restore the source data after hidden data

is correctly extracted. Reversible data hiding is used mainly in covert communications, copyright protection, and content integrity authentication. Reversible data hiding is classified into three categories: ① single-pixel hiding and pixel group hiding, ② spatial domain hiding and transform domain hiding, and ③ even hiding and uneven hiding. At present, research on pixel group hiding, uneven hiding, and difference expansion is the most popular.

Anti-attack is another research topic that must be investigated simultaneously with data hiding. Attackers aim to destroy original source data or extract hidden information; therefore, anti-attack capabilities must rely on other information encryption methods.

(6) High-utility itemset mining algorithms

The high-utility itemset mining algorithms have played a more intuitive and direct-supporting role in solving the decision-making problem in some practical application scenarios. In 2004, Yao et al. proposed the concept of high-utility itemset mining. Other researchers have proposed a number of high-utility itemset mining algorithms, including the incremental high-utility pattern (IHUP) algorithm, utility pattern growth (UP-growth) algorithm, and high-utility itemset miner (HUI-miner) algorithm.

Although high-utility itemset mining has made remarkable achievements, challenges remain in the following research areas: data mining of columnar storage, development of appropriate standards for measuring high-utility itemsets, visual mining, parallel mining of high-utility itemsets, and mining of high-utility itemsets in network environments.

(7) Optical coherence elastography

Optical coherence elastography (OCE) is of great importance in the research of microstructure imaging of biological tissue. According to the mode of excitation, OCE can be classified as sound surface-wave propagation OCE, shear wave propagation OCE, acoustic radiation force OCE, pressure-type OCE, and magnetic induction OCE. OCE offers a special advantage in measuring the unique organizational level of biomechanics at the micron level, cell level, and even the molecular level. The method is a new nondestructive approach to evaluating tissue elasticity and is superior to ultrasonic imaging and magnetic resonance imaging. Its development process is the same as those of other means of elastic imaging, from static imaging to dynamic imaging, and from low resolution to high resolution. In the future, the image resolution, imaging depth, and imaging velocity of the method are expected to be gradually improved.

(8) Ultra-wideband slot antennas

The ultra-wideband slot antenna has a basic antenna form in which radiation is produced through grooving on metal and excitation with a coaxial cable, microstrip cable, or waveguide. The slot antenna can replace the oscillator antenna in the microwave section, solving problems that the oscillator antenna is too small to make and feed. The wideband characteristics of the circular and elliptic slot antennas are well known. A slot antenna can achieve ultra-wideband bandwidth and its bandwidth depends on the shape of the slot. For example, the length-to-width ratio of the slot has a significant impact on the bandwidth of an antenna with a wide rectangular slot, and the long-to-short axis ratio has great influence on the bandwidth of the elliptical slot. Improvement of the feed network can greatly improve the working bandwidth.

(9) Dynamic network visualization

In a dynamic network structure, the nodes and edges of a network evolve over time. A dynamic network can be observed and analyzed by visualization, and important insights can be obtained. In an existing network, some features can be automatically analyzed with traditional data analysis methods. However, the greatest advantage of combining traditional methods and visualization is that useful patterns can be determined by using large amounts of data and further observation with traditional methods. In dynamic network visualization, more attention must be paid to the heterogeneity of the key topology and the time dimension of the network data. Data visualization of large-scale networks is a very challenging topic and a well-known problem.

(10) Characteristics and analyses of neural networks/ neural network modeling and fuzzy logic

A neural network is a mathematical model that imitates the behavior of animal neural networks and processes information in a distributed and parallel way. The combination of modeling based on neural networks and fuzzy logic can improve the generalization ability and efficiency of the model. Currently, the main technological development orientations are: first, improving the accuracy of fuzzy systems by adjusting fuzzy logic membership functions based on neural networks; second, using fuzzy logic to improve the learning ability of the neural network and appropriate heuristic control logic

to control the learning process to increase the training efficiency and reduce the demand for data quality. Based on these methods, a combination of the fuzzy system and the neural network is constructed to improve the generation quality and the ability of the model to acquire special knowledge. A neural network is used to approximate a fuzzy logic system, which reduces the difficulty of computer implementation and improves engineering efficiency.

With the development of deep learning technology, the theory and technology of neural networks have advanced rapidly. Additionally, the integration with other disciplines has become more abundant in recent years, which has further promoted the development of neural network technology.

1.2 Understanding of engineering research focus

1.2.1 Multi-object tracking technologies

Multi-object tracking technology has been widely used in video surveillance, autonomous driving, human-computer interaction, virtual reality, and augmented reality, and has significant practical value in military and civilian fields. Multi-object tracking has been greatly enhanced by the rapid development of machine learning methods, the continuous improvement of hardware performance, and increasingly rich data sets.

To meet the demand for a high-performance and robust multi-object tracking algorithm for practical applications, a series of challenging scientific and technical problems have been introduced, including the appearance modeling of objects, visual representation and feature selection, occlusions, data association algorithms, probability inference between state changes in video sequences, and decision optimization. To address the above challenges, innovative research is needed based on the rapid development of modern artificial intelligence technology through the combination of theory and practice, model and algorithm, and new ideas and changes in model systems.

At present, the main hotspots of this research frontier can be summarized as follows.

(1) Multi-object initialization. The development of a full-time multi-object tracker with speed and accuracy but without limitations on the type of objects being tracked remains a frontier topic.

(2) Appearance modeling for multiple objects. In visual recognition, effective feature representation remains an interesting and challenging issue. Multi-object tracking requires not only the design of robust visual representations, but also accurate statistical measurements to estimate the similarities between different observations.

(3) Motion modeling for multiple objects. The movement of an object in a scene is usually erratic and it is difficult to model acceleration or stopping. The effective multi-object tracking algorithm must design and implement a nonlinear motion model.

(4) Combination of online and offline tracking. The implementation of these two dissimilar methods to obtain a simpler and more effective multi-object tracking algorithm remains a challenging topic.

(5) Object association algorithm. Overlapping and blocking between multiple objects is an inevitable fatal problem in multi-object tracking. The establishment of an effective way to deal with overlapping and occlusion is an important future development direction.

There are 61 core papers focusing on "Multi-object tracking technologies" (Table 1.2.1). The top five countries are the USA, China, Switzerland, Germany, and Korea. Papers published by authors from the USA accounted for 56.25%, more than half, and two of the three consistently cited papers are published by the USA. China ranked the second with core papers accounting for 20.83% of the total number of papers. According to Table 1.2.2, the top five institutions in paper output are the University of Southern California (Univ So Calif), the Chinese University of Hong Kong (Chinese Univ Hong Kong), Darmstadt University of Technology in Germany (Tech Univ Darmstadt), the Swiss Federal Institute of Technology in Zurich (ETH), and the University of Central Florida (Univ Cent Florida), two of which are in the USA and one is in China. From the network analysis of collaboration among researchers in different countries or regions, shown in Figure 1.2.1, Figure 1.2.2, Table 1.2.3, and Table 1.2.4, the USA occupies the core position. The cooperation among published researchers in the top four countries or regions is also closer.

Based on the results of this analysis, it is clear that the USA, regardless of the number of papers or the collaboration with other countries or regions, is the leader in this research focus, while China is following closely to

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "Multi-object tracking technologies"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	27	56.25%	824	47.71%	30.52	2	0
2	China	10	20.83%	167	9.67%	16.70	0	0
3	Switzerland	8	16.67%	601	34.80%	75.13	0	0
4	Germany	8	16.67%	434	25.13%	54.25	0	0
5	Korea	2	4.17%	31	1.80%	15.50	1	0
6	Singapore	2	4.17%	23	1.33%	11.50	0	0
7	Belgium	1	2.08%	171	9.90%	171.00	0	0
8	France	1	2.08%	36	2.08%	36.00	0	0
9	Portugal	1	2.08%	25	1.45%	25.00	0	0
10	Australia	1	2.08%	16	0.93%	16.00	0	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "Multi-object tracking technologies"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ So Calif	6	12.50%	209	12.10%	34.83	1	0
2	Chinese Univ Hong Kong	6	12.50%	110	6.37%	18.33	0	0
3	Tech Univ Darmstadt	5	10.42%	246	14.24%	49.20	0	0
4	ETH	4	8.33%	288	16.68%	72.00	0	0
5	Univ Cent Florida	4	8.33%	154	8.92%	38.50	0	0
6	Penn State Univ	3	6.25%	139	8.05%	46.33	0	0
7	Ecole Polytech Fed Lausanne	2	4.17%	244	14.13%	122.00	0	0
8	Swiss Fed Inst Technol	2	4.17%	69	4.00%	34.50	0	0
9	Oregon State Univ	2	4.17%	64	3.71%	32.00	0	0
10	Xiamen Univ	2	4.17%	35	2.03%	17.50	0	0

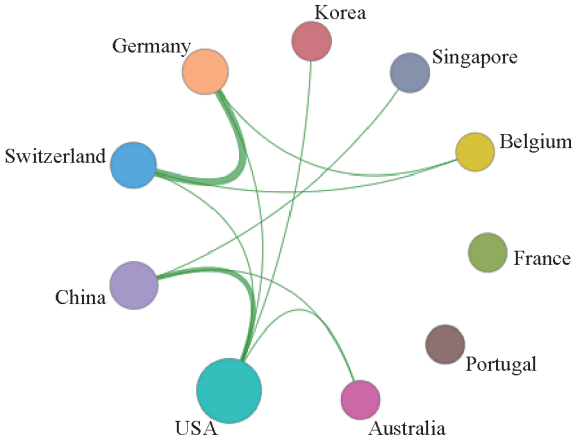

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Multi-object tracking technologies"[1]

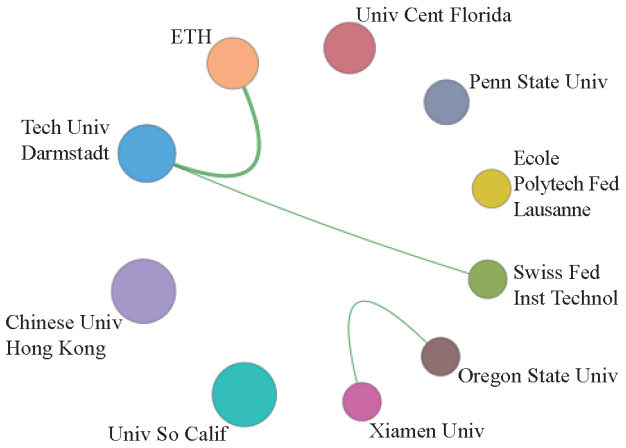

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Multi-object tracking technologies"

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Multi-object tracking technologies"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	6	33.33%	2013.5
2	China	5	27.78%	2014.2
3	Singapore	2	11.11%	2014.5
4	Korea	2	11.11%	2014.5
5	Austria	1	5.56%	2014.0
6	Germany	1	5.56%	2014.0
7	Switzerland	1	5.56%	2014.0

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Multi-object tracking technologies"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Chinese Univ Hong Kong	3	13.04%	2014.0
2	GIST	2	8.70%	2014.5
3	Adv Digital Sci Ctr	1	4.35%	2015.0
4	Anhui Univ	1	4.35%	2015.0
5	Boston Univ	1	4.35%	2012.0
6	ETH	1	4.35%	2014.0
7	Graz Univ Technol	1	4.35%	2014.0
8	Hanyang Univ	1	4.35%	2015.0
9	Hefei Univ Technol	1	4.35%	2015.0
10	KETI	1	4.35%	2015.0

the USA, which cooperates closely with other countries or regions.

1.2.2 Dynamic network visualization

Because the data produced in most computer-related and communication fields have an additional time dimension compared with traditional data, the good organization of the data and their presentation with efficient visualization methods are valuable for understanding and analyzing their inner structure. Solving this problem is of great significance to the communication industry and academic research. Scholars and experts in the field of visualization and visual analysis worldwide are trying to solve this problem.

Among the scholars studying dynamic network visualization, those in the USA produce 31.91% of the core papers in this field, ranking the first; they are followed by researchers in Germany, the Netherlands, France, China, and other countries or regions. The core papers produced in the top 10 countries or regions are cited more than 20 times (Table 1.2.5). Peking University, University of Toulouse, the French Civil Aviation University (ENAC), and University of Groningen are the top four institutions. Four papers are produced by each of these four institutions, with more than 90 citations, and a proportion of citations of more than 9% (Table 1.2.6). The collaboration networks between the major countries or regions and the major institutions on the engineering research focus "Dynamic network visualization" are shown in Figure 1.2.3 and Figure 1.2.4.

Regarding the core papers that are cited by core papers, Germany, Switzerland, and China are the top three countries based on the country or region statistics, with no less than three core papers that are cited by core papers, and the proportions of those papers are higher than 15% for each of the three countries in the list (Table

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Dynamic network visualization"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	15	31.91%	203	21.06%	13.53	1	0
2	Germany	12	25.53%	348	36.10%	29.00	2	0
3	The Netherlands	10	21.28%	239	24.79%	23.90	0	0
4	France	8	17.02%	178	18.46%	22.25	0	0
5	China	8	17.02%	152	15.77%	19.00	0	0
6	Scotland	4	8.51%	79	8.20%	19.75	0	0
7	Switzerland	4	8.51%	56	5.81%	14.00	0	0
8	Ireland	3	6.38%	74	7.68%	24.67	0	0
9	Canada	3	6.38%	50	5.19%	16.67	1	0
10	Singapore	2	4.26%	24	2.49%	12.00	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Dynamic network visualization"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Peking Univ	4	8.51%	113	11.72%	28.25	0	0
2	Univ Toulouse	4	8.51%	93	9.65%	23.25	0	0
3	ENAC	4	8.51%	93	9.65%	23.25	0	0
4	Univ Groningen	4	8.51%	93	9.65%	23.25	0	0
5	Eindhoven Univ Technol	4	8.51%	73	7.57%	18.25	0	0
6	Hong Kong Univ Sci Technol	4	8.51%	51	5.29%	12.75	0	0
7	Fraunhofer Inst IAIS	3	6.38%	129	13.38%	43.00	0	0
8	Univ Konstanz	3	6.38%	69	7.16%	23.00	1	0
9	ENAC Univ Toulouse	2	4.26%	64	6.64%	32.00	0	0
10	Univ Rostock	2	4.26%	60	6.22%	30.00	1	0

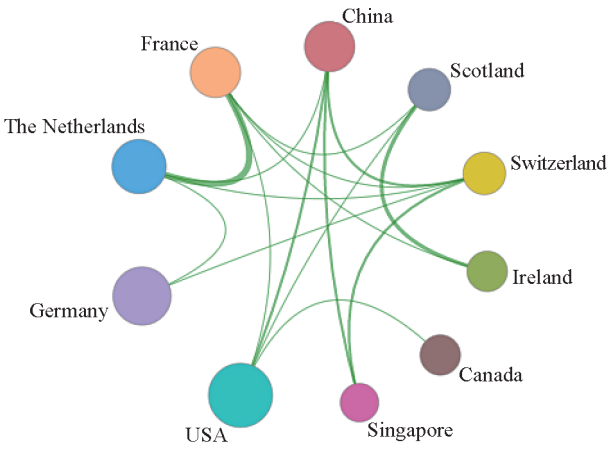

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Dynamic network visualization"

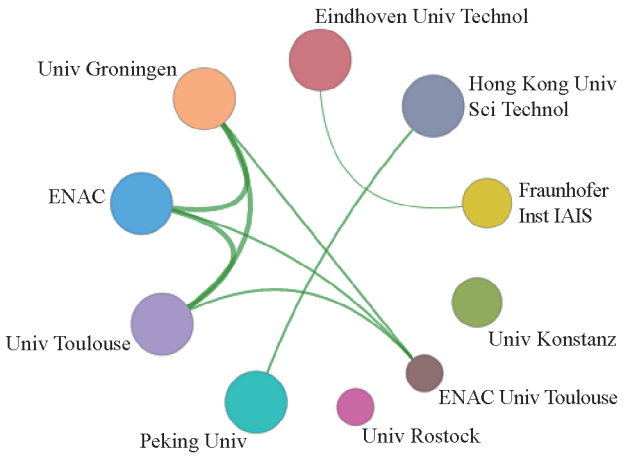

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Dynamic network visualization"

1.2.7). Hong Kong University of Science and Technology ranks the first among institutions with three papers with a proportion higher than 12%. It is followed by the Max Planck Institute for Human Cognitive and Brain Sciences, Nanyang Technological University, and the Swiss Federal Institute of Technology, with two papers each and a proportion of 8% for each institution (Table 1.2.8).

Currently, research on "Dynamic network visualization" focuses on incremental rendering on the node-connection graph, especially on some types of graphs, such as trees, strings, parallel graphs, and directed acyclic graphs. Many scholars aim to use node topology to visualize a dynamic network in the 2D plane, and visual forms with a more visual metaphor effect, such as 3D graphs, have been proposed in the literature. In addition to rendering, interesting work is being performed on the scalability of visual dynamic networks. Little information exists in the literature on the methodology for visualizing large dynamic network data sets. With an increasing amount of data, the nodes overlap and the traditional method inevitably produces complexity in visual computing. Animation is a commonly used approach to explaining dynamic network changes, and the tradeoff between data processing speed and rendering performance should be considered. Efforts devoted to these research topics will be significant for understanding the structure and relationship of dynamic network data.

1.2.3 Characteristics and analyses of neural networks/ neural network modeling and fuzzy logic

Recently, with the development of the Internet and big data, the global demand for artificial intelligence

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Dynamic network visualization"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Germany	4	21.05%	2012.75
2	Switzerland	3	15.79%	2012.67
3	China	3	15.79%	2013.67
4	Singapore	2	10.53%	2013.50
5	Australia	2	10.53%	2014.50
6	France	2	10.53%	2014.50
7	USA	2	10.53%	2014.50
8	Chile	1	5.26%	2014.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Dynamic network visualization"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Hong Kong Univ Sci Technol	3	12%	2013.67
2	Max Planck Inst Human Cognit Brain Sci	2	8%	2013.50
3	Nanyang Technol Univ	2	8%	2013.50
4	Swiss Fed Inst Technol	2	8%	2013.50
5	Fraunhofer Inst IAIS	1	4%	2013.00
6	Griffith Univ	1	4%	2014.00
7	Inria Chile CIRIC	1	4%	2014.00
8	Inria	1	4%	2015.00
9	Microsoft Res Inria Joint Ctr	1	4%	2015.00
10	Monash Univ	1	4%	2015.00

technology has become enormous. Neural networks, particularly deep neural networks that represent depth learning, have promoted the development and application of artificial intelligence in technology. The development of neural networks has been an important issue in practical applications, such as Google's AlphaGo, which further demonstrates the outstanding performance of depth learning in artificial intelligence. From the data presented in Table 1.2.9 and Table 1.2.10, we can see the technical demands and development potential of different countries or regions in this field. The combination of fuzzy logic and neural networks utilizes and balances the advantages and disadvantages of these approaches and is another important research field.

From keywords of the core papers such as neural network, deep learning, and fuzzy control, the leading edges of the research field include: optimizing neural networks, mainly by optimizing the learning algorithm; optimizing self-learning structures, mainly the model's self-adjustment ability; and optimizing fuzzy rules.

Among the leading issues of the combination of neural network learning algorithms with fuzzy logic are structure learning and parameter learning. Rule learning includes the heuristic search method, the fuzzy grid method, the tree partition method, and the learning algorithm based on fuzzy clustering. The research in this field can further

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	44	48.35%	973	37.35%	22.11	7	0
2	Taiwan of China	33	36.26%	1248	47.91%	37.82	6	0
3	Saudi Arabia	15	16.48%	259	9.94%	17.27	4	0
4	India	10	10.99%	177	6.79%	17.70	1	0
5	USA	4	4.40%	135	5.18%	33.75	0	0
6	Egypt	3	3.30%	63	2.42%	21.00	1	0
7	Romania	2	2.20%	89	3.42%	44.50	0	0
8	Canada	2	2.20%	36	1.38%	18.00	0	0
9	Spain	1	1.10%	29	1.11%	29.00	0	1
10	Turkey	1	1.10%	26	1.00%	26.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Kaohsiung Marine Univ	17	18.68%	775	29.75%	45.59	3	0
2	Pingtung Univ Educ	15	16.48%	482	18.50%	32.13	2	0
3	King Abdulaziz Univ	15	16.48%	259	9.94%	17.27	4	0
4	Cheng Kung Univ	13	14.29%	357	13.70%	27.46	3	0
5	Fac Sci	12	13.19%	208	7.98%	17.33	3	0
6	Dept Civil Engn	10	10.99%	384	14.74%	38.40	2	0
7	Southeast Univ	10	10.99%	155	5.95%	15.50	2	0
8	Cent Univ	9	9.89%	346	13.28%	38.44	3	0
9	Kaohsiung First Univ Sci &Technol	9	9.89%	224	8.60%	24.89	1	0
10	Chongqing Jiaotong Univ	8	8.79%	232	8.91%	29.00	1	0

improve the performance and training speed of neural networks, and the combination of distributed systems can enhance the generation speed of model parameters. The leading countries and regions in this field of research include the Chinese mainland, Taiwan of China, the USA, and Canada.

The optimization of structure self-learning includes mainly connection design methods and evolutionary design methods. Connection design methods include the supplementary algorithm and cut algorithm. The research in this field can reduce redundant parameters and the volume of the neural network and provides a feasible method for optimized neural network modeling, which has advanced neural network engineering. The leading countries and regions in this research field include the Chinese mainland, the USA, Canada, and Australia.

Fuzzy logic rules are often obtained empirically and have poor precision. Fuzzy logic rules with the self-adaptive characteristics of neural networks solve the network black box problem. Although scholars have proposed some methods to further promote the development of this field, no breakthrough has been achieved. In addition, other research areas, including the development of a probabilistic graph model and convex optimization theory, have made some progress in explaining the neural network black box problem by theoretically determining the characteristics of neural networks to some degree. At present, the leading countries and regions in this field include the Chinese mainland, the USA, Canada, and Taiwan of China.

Besides combining fuzzy logic and neural networks, other research has been conducted on overcoming the limitations of neural networks, such as combining the generative adversarial net of game theory to further reduce the demand quality of network data. Additionally, with the development of deep neural networks, model parameters and the compression problem have become important research topics, and the study of the neural network itself is still in progress. In recent years, the convolution neural network, recurrent neural network, and long short-term memory network have become the focus of neural network research and been implemented in engineering. Meanwhile, some specific structures, like the activation function, are being constantly developed. With the continuous progress of artificial intelligence technology, the field will be further integrated with other research areas and is expected to have wide implications and produce new technologies.

According to the network map that illustrates the collaboration among the key engineering research associations, the currently major research countries and regions are the China, Taiwan of China, Saudi Arabia, and India (Figure 1.2.5 and Figure 1.2.6). China ranks the first in the number of core papers and the number of core papers that are cited by core papers (Table 1.2.11), which demonstrates that China has become the key research country in this field. However, the number of institutions producing core papers that are cited by core papers ranks

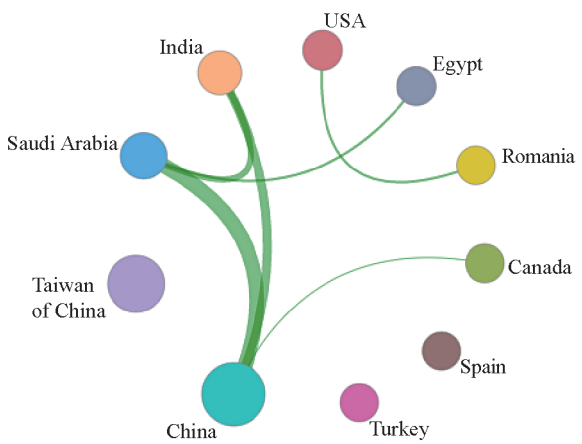

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

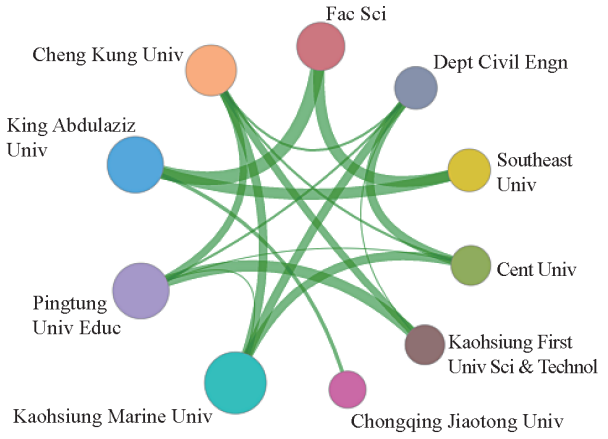

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

lower (Table 1.2.12), which shows that China must further optimize the allocation and improve the concentration of research resources in this field. In addition, China and some countries or regions that are active in this technical field rarely cooperate. Therefore, promoting academic exchange and cooperation should also be a focus of the development efforts in this technical field in China.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 engineering research hotspots, summarized by the Field Group of Information and Electronic Engineering, are shown in Table 2.1.1. They cover the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, control science and technology, and other disciplines. Among them, "Wireless mobile communication technology and equipment," "Vehicle autonomous-driving technology and its application," "Laser light source technology," "Image recognition and visual interaction technology," "Cloud computing and virtualization," and "Unmanned aerial vehicle" are areas of further study in traditional research. The annual numbers of core papers published in each hotspot from 2011 to 2016 are shown in Table 2.1.2.

(1) Image recognition and visual interaction technology

Image recognition and visual interaction technology

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	35	43.75%	2014.71
2	Taiwan of China	21	26.25%	2012.14
3	Saudi Arabia	13	16.25%	2014.85
4	India	7	8.75%	2015.14
5	Korea	1	1.25%	2015.00
6	USA	1	1.25%	2014.00
7	Canada	1	1.25%	2015.00
8	Algeria	1	1.25%	2016.00

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Characteristics and analyses of neural networks/neural network modeling and fuzzy logic"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Cheng Kung Univ	13	9.63%	2012.46
2	King Abdulaziz Univ	13	9.63%	2014.85
3	Pingtung Univ Educ	11	8.15%	2012.18
4	Southeast Univ	10	7.41%	2015.00
5	Kaohsiung Marine Univ	9	6.67%	2012.00
6	Bharathiar Univ	7	5.19%	2015.14
7	Kaohsiung First Univ Sci & Technol	7	5.19%	2012.57
8	Chongqing Jiaotong Univ	7	5.19%	2014.57
9	Huzhou Teachers Coll	4	2.96%	2015.25
10	Minist China	3	2.22%	2015.33

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

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Wireless mobile communication technology and equipment	251	9976	39.75	2012.06
2	Vehicle autonomous-driving technology and its application	234	4035	17.24	2012.67
3	Laser light source technology	151	3217	21.30	2012.26
4	Image recognition and visual interaction technology	118	4684	39.69	2011.95
5	Intelligent driving assistance system and technology	178	7890	44.33	2012.90
6	Photoelectric tracking and monitoring technology	113	2336	20.67	2012.30
7	Cloud computing and virtualization	152	9322	61.33	2012.24
8	Unmanned aerial vehicle	33	633	19.18	2013.55
9	Solar energy technology	227	4598	20.26	2012.14
10	High-speed and high-density storage technology	191	8930	46.75	2012.38

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in information and electronic engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Wireless mobile communication technology and equipment	104	65	55	17	9	1
2	Vehicle autonomous-driving technology and its application	57	61	51	39	20	6
3	Laser light source technology	53	46	21	22	8	1
4	Image recognition and visual interaction technology	50	40	15	10	3	0
5	Intelligent driving assistance system and technology	39	28	42	53	12	4
6	Photoelectric tracking and monitoring technology	45	27	14	17	9	1
7	Cloud computing and virtualization	55	41	29	18	9	0
8	Unmanned aerial vehicle	2	10	6	5	3	7
9	Solar energy technology	94	65	29	21	17	1
10	High-speed and high-density storage technology	56	54	41	35	2	3

has been widely used in many areas, including augmented reality, digital entertainment, film and television production, medical diagnostics, autonomous driving, and video surveillance. The object detection and recognition technology that is based on convolution neural networks has achieved considerable success; additionally, it has greatly improved the accuracy of facial recognition, behavior analysis, and scene comprehension, and provided the technical basis for natural interaction between users and scenes. To obtain a real-time interactive experience, the current research is focused mainly on designing specialized hardware or accelerating the depth learning algorithm by reducing the computational complexity of the model. Currently, real-time object detection and recognition has been achieved using embedded devices. Future research will focus on designing effective computational models to reduce redundancy in deep-learning systems and improve learning efficiency while reducing the dependence on annotation data using geometric physical prior knowledge. The natural interaction experience could be further enhanced with high-level semantic analysis of images. The development and improvement of such technology will lead to more innovative image recognition and visual interaction products and introduce significant changes in everyday life.

(2) Intelligent driving assistance system and technology

The rapid growth of urban car ownership, traffic congestion, traffic accidents, shortage of parking, and other issues has resulted in a sharp decline in urban

transport efficiency. This has created an urgent need to study the use of artificial intelligence in vehicle driving assistance technology and traffic management technology. Intelligent vehicle assisted driving, a primary stage of autonomous driving, is the main approach to improving current vehicle intelligence. The maturity of advanced intelligent driving assistance technology will lay the technical and industrial base for autonomous vehicle driving.

(3) Photoelectric tracking and monitoring technology

Photoelectric tracking and monitoring technology has been widely applied in industrial, agricultural, scientific, and other fields. This has entirely changed the form of competition in national military defense. In recent years, the military requires the development of photoelectric tracking and monitoring technology, which has been gradually advancing toward sensing instrument miniaturization, multi-tool information acquisition, higher accuracy, and higher intelligence.

Attitude stabilization and high precision involve the cross-disciplinary research directions of sensor technology, optical technology, computer technology, information processing technology, and control technology. The key technologies include high-precision design, manufacturing, and control technology of optoelectronic tracking servo mechanisms, advanced and efficient real-time video image target recognition and tracking, and processing technology.

(4) Cloud computing and virtualization

The close relationship between cloud computing and virtual machines can produce powerful results. Key technical issues that must be addressed in cloud computing and virtualization include multi-tenant hosting, decentralized computing, virtualized data management, virtual machine caching, virtualized GPUs, and resource provisioning. New managed cloud products, cloud security, hybrid cloud technology, and OpenStack-based open-source cloud operating systems will be an important development direction in the future.

(5) Unmanned aerial vehicle

Civilian multi-rotor unmanned aerial vehicles (UAVs) have become a new technology hotspot, and there is a very urgent need for completely independent environmental perception and intelligent control technology. In recent years, unmanned aircraft have been widely used in military operations, environmental monitoring, energy exploration, disaster assessment, power line inspection, agricultural plant protection, aviation mapping, public security, and many other fields. Therefore, UAV research is of great significance. Unmanned aircraft development must focus on key technologies such as intelligent control (single intelligence and group intelligence), broadband anti-jamming data links, environment perception and circumvention, data processing for payloads, information fusion, energy and power technologies, low-cost design, and standardization.

(6) Solar energy technology

Solar energy utilization includes mainly solar heat and solar light. With the strong support of governments worldwide, solar energy, as the main force of renewable energy, will play an increasingly important role in the global energy supply. The relatively mature solar power generation technologies are solar photovoltaic and solar thermal power generation technologies. Solar thermal power generation technology can generate electricity by concentrating light to produce high temperatures, and it is more efficient and has better application prospects than solar photovoltaic power generation technology. Although it has been studied globally for many years, only solar thermal power stations have achieved commercial operation. Tower- and disc-type power generation systems are still in the demonstration stage.

(7) High-speed and high-density storage technology

High-density, large-capacity optical storage is an area of interdisciplinary interest and includes device technology, optical technology, materials science, microelectronics technology, process technology, and computer and control technology. Studying the new generation of high-speed and high-density digital optical storage technology is of great significance to societal informatization.

Improving optical storage density has become a very important research topic. To further enhance the density and capacity of optical disks, we must introduce new technology. At present, the main two research directions in this area are super-resolution technology and three-dimensional storage technology. Three-dimensional storage technology includes mainly two-photon storage, multi-level storage, spectral hole-burning storage, waveguide multilayer storage, and holographic storage. Holographic storage with large storage capacity, high data transmission rate, short storage time, fast image matching, related-content-addressing operations, and

other characteristics is likely to lead to the next generation of mass storage technology.

(8) Wireless mobile communication technology and equipment

Currently, wireless mobile communications and network technology are entering a new period of accelerated development. Mobile communication networks and space networks tend to eventually integrate into a network architecture covering space, ground, and sea. Thus, network systems and core equipment with advanced technology that is independently controllable, safe, and credible for military and civilian integration are urgently required. The information-centric media network has been viewed as a future development direction with network IT and cloud properties provided by exchange and computing integration. Emerging network technologies, such as software-defined networking and network function virtualization, will achieve the evolution of network architecture and equipment modes. Exploring future network architecture that has reconfigurable security and is efficient, scalable, open, and definable is becoming an important research direction. With the network operating system being the core of the open-network ecological chain, high-performance, scalable, service-oriented, open network operating systems will become a key future technology. Software definition, virtualization, and open communication resources are attracting increasing attention from the industry. Research on 4G wireless mobile communication has become a global research hotspot, while 5G and beyond-5G technologies are crucial for the future of mobile communications. Additionally, system architecture is undergoing changes. Future mobile communication applications are extending from the current human communication to human-computer collaborative communication, ultra-dense connection networking, vehicle networking, industrial Internet, and other areas.

(9) Vehicle autonomous-driving technology and its application

Europe, the USA, Japan, and other developed countries and regions are committed to establishing intelligent transportation systems. Future traffic systems will be based on vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) information interaction and on integrated human, vehicle, and road intelligent transportation systems with comprehensive real-time perception that understand the capacity of the driving environment and traffic conditions. Autonomous-driving vehicles with autonomous planning, control, and coordinated man-machine operation are the key to realizing future intelligent transportation systems. A new generation of autonomous-driving vehicles based on intelligent transportation systems will have the following functions:

- Higher capacity for environmental perception and understanding.
- Ability of driving behavior decision making in complex traffic conditions.
- Assisted driving capacity in complex weather conditions.
- Capacity to analyze the driver's handling ability and application scope of the assisted driving system, to implement interactive multi-target arbitration mechanisms, and to provide valuable emergency treatment time for drivers or even handle emergencies in case of danger.

(10) Laser light source technology

Laser light source technology has been widely applied in optical fiber communications and in laser audio and video systems, and has become an important pillar of the optoelectronics industry. With the continuous development of semiconductor laser technology, other solid-state lasers based on semiconductor lasers (such as fiber lasers, semiconductor pump solid-state lasers, and slab lasers) are also developing very quickly. Particularly, the advancement of fiber lasers has been very rapid—especially the rare-earth-doped fiber laser, which has been widely applied in optical fiber communications and laser materials.

2.2 Understanding of engineering development focus

2.2.1 Wireless mobile communication technology and equipment

Research in wireless mobile communication technology and equipment has been highly valued and has attracted considerable attention by the industry. It involves many specific technical research topics such as wireless mobile networks, large-scale wireless communication antennas, radio-frequency theory and technology, and the giant-

connected-component multiple-access technology and systems.

In wireless mobile networks, breakthroughs will occur in the basic theory related to future mobile communications and in key 5G and beyond-5G technologies. More attention is being paid to the needs of users and creation of new user experiences. The realization of virtualization and flexible networking in large-scale networks, control of network resources on demand, and intelligent adaptation to the spatial and temporal distribution of business diversity have become urgent problems that must be solved. Specific research areas include: ① exploring the theory and methodology of resource representation, virtualization, and computing in large-scale interconnected wireless network systems; ② exploring comprehensive environmental perception and dynamic resource allocation methods; ③ exploring the techniques for matching resource flow and business flow; ④ coordination of communications and calculations; ⑤ proposing the theory and methods of on-demand virtual resource regulation to adapt to the space-time diversity needed and validating them by experiments; and ⑥ proposing the theory and algorithms for flexible layout and agile optimization of wireless networks.

In the area of multi-access technology and systems, the industry is aiming to expand the scope of future mobile communications from current human-to-human communication to a wider range of areas, such as cooperative human-computer communication, ultra-dense connectivity, networking, vehicle networking, and industrial Internet. In terms of antenna and radio-frequency theory and technology in large-scale wireless communications, the research and development of 4G LTE multi-channel antennas has been completed. However, existing multi-channel antennas still have difficulties meeting the high-rate transmission requirements of future wireless communications. Considering the transmission rate and directive gain requirements of future mobile communications, large-scale antennas can provide a larger number of physical channels for wireless transmission, but they also have more physical constraints and technical difficulties. Therefore, for both the base-station side and the terminal side, resources must be invested and appropriate research be conducted. In addition, considering the wider and non-continuous future radio-frequency (RF) bandwidth, highly integrated RF devices face a number of challenges, in terms of power consumption, figure of noise, nonlinearity, and size. Furthermore, RF devices must perform "analog computation" functions. Although RF theory and technology have increasingly become more advanced, more goals must be achieved and further theories and implementation technology must be developed for higher bandwidth, small integration, and other needs, including: exploring the relationship between the parameters of the cross-band large-scale array antenna, exploring the non-linearity and interference generation mechanism and behavior of the multi-channel high-integration RF circuit, and developing the large-scale array antenna of the base-station side and the large-scale antenna of the terminal side. For the system base-station side, the system architecture of large-scale antenna arrays, the selection of the unit antenna scheme, the inter-channel isolation scheme, and the amplitude and phase consistency between channels must be investigated. For the terminal side, the system layout scheme of the large-scale terminal antenna, the unit antenna scheme, and interunit decoupling must be studied.

Wireless mobile communications and related networks have become the basis of economic prosperity and national competitiveness and the basic platform for human social information sharing and collaboration. New smartphone applications have greatly increased the depth and breadth of Internet applications, and mobile communications application traffic is expected to show explosive growth in the next decade. Cloud computing, the Internet, the Internet of Things, and big data technology combine and develop, while new information products and services continue to emerge. The information industry, cultural industry, and social undertakings are further integrated and developed, and people will consequently enjoy more diverse, fast, and economical information and cultural services.

There are 304 core patents in the engineering development focus "Wireless mobile communication technology and equipment" (Table 2.2.1). The top five countries are the USA (148), Korea (48), Canada (25), Finland (23), and China (20). Among them, the patents applied by authors from the USA account for 58.96% of the total patents, which is a large proportion. Evidently, the USA is one of the key research countries in this area with an average citation of 44.64. The top three patent authorization institutions are GLDS (24), OYNO (23), and QCOM (23), and

those with high average citation are MOTI (66.42), GOOG (57.86), and IDIG (49.24) (Table 2.2.2). From the main authorization institutions, MOTI and GOOG cooperate most often (Figure 2.2.1, Figure 2.2.2). Between 2011 and 2016, the core patents related to the engineering development focus "Wireless mobile communication technology and equipment" of the Chinese mainland and Taiwan of China were 20 and 3, respectively.

2.2.2 Vehicle autonomous-driving technology and its application

The autonomous-driving vehicle is an advanced development stage of the intelligent vehicle. Autonomous-driving systems require advanced artificial intelligence, which is still in its infancy.

Recently, well-known car manufacturers in the USA, Europe, Japan, and other countries or regions have attached great importance to autonomous-driving technology research, which has been a major breakthrough for the next generation of the automotive industry. Google, Baidu, and other IT enterprises have also joined autonomous-driving research teams and progressed rapidly. Many scientific research institutions and academies have also given attention to such research, such as the US De-

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Wireless mobile communication technology and equipment"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	148	58.96%	6607	66.23%	44.64
2	Korea	48	19.12%	1675	16.79%	34.90
3	Canada	25	9.96%	917	9.19%	36.68
4	Finland	23	9.16%	1041	10.44%	45.26
5	China	20	7.97%	444	4.45%	22.20
6	Japan	16	6.37%	322	3.23%	20.13
7	Germany	8	3.19%	230	2.31%	28.75
8	UK	7	2.79%	139	1.39%	19.86
9	Sweden	6	2.39%	161	1.61%	26.83
10	Taiwan of China	3	1.20%	46	0.46%	15.33

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Wireless mobile communication technology and equipment"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	GLDS	24	9.56%	749	7.51%	31.21
2	OYNO	23	9.16%	1111	11.14%	48.30
3	QCOM	23	9.16%	891	8.93%	38.74
4	SMSU	23	9.16%	892	8.94%	38.78
5	IDIG	17	6.77%	837	8.39%	49.24
6	RIMR	15	5.98%	595	5.96%	39.67
7	MOTI	12	4.78%	797	7.99%	66.42
8	APPY	9	3.59%	380	3.81%	42.22
9	TELF	8	3.19%	389	3.90%	48.63
10	GOOG	7	2.79%	405	4.06%	57.86

Note: GLDS stands for LG Electronics Inc.; OYNO stands for Nokia Corp.; QCOM stands for Qualcomm Inc.; SMSU stands for Samsung Electronics Co., Ltd.; IDIG stands for Interdigital Patent Holdings Inc.; RIMR stands for Research in Motion Limited; MOTI stands for Motorola Mobility Inc.; APPY stands for Apple Inc.; TELF stands for Telefonaktiebolaget Ericsson L M; GOOG stands for Google Inc.

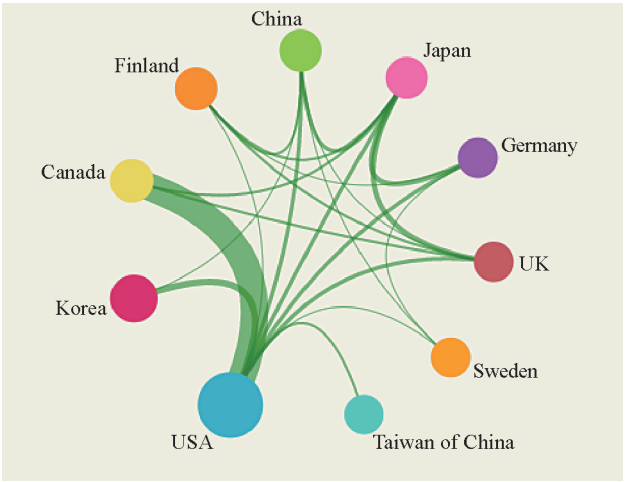

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Wireless mobile communication technology and equipment"

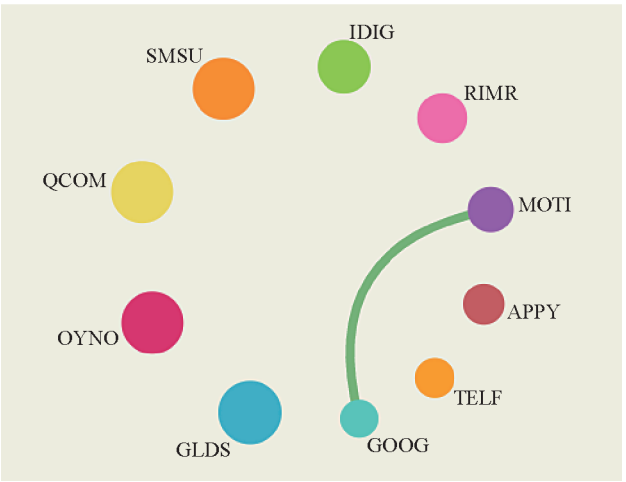

Figure 2.2.2 Collaboration network of the major producing intitutions of core patents on the engineering development focus "Wireless mobile communication technology and equipment"

fense Advanced Research Projects Agency (DARPA) and the National Natural Science Foundation of China (NSFC).

At present, Nevada, Florida, California, Texas, Michigan, and Washington, DC, in the USA have legislated to allow autonomous-driving vehicle road testing. Germany was the first country to research autonomous-driving technology. In 2013, the Mercedes-Benz S500, which has autonomous-driving ability, completed several long-distance autonomous-driving tests on urban roads and intercity roads. This vehicle actually repeated the itinerary performed by Ms. Ben Bell 125 years ago. As a car manufacturer that features automotive safety products, Volvo's autonomous-driving vehicle has been tested over 10 000 miles (about 16 093 km) on a Spanish highway and a Swedish test runway. Additionally, Volvo has published a declaration on road safety: Volvo will be fully responsible for any traffic accident that occurs while the autonomous-driving vehicle is in autonomous mode. Although foreign research on autonomous-driving started early and has contributed significant input, the technical gap between domestic and international research in this field is gradually narrowing. In recent years, under the support of the NSFC major research program Visual Auditory Information Cognitive Computing, the National University of Defense Technology, Nanjing University of Science and Technology, Beijing Institute of Technology, Xi'an Jiaotong University, Military Transportation University, Hefei Institutes of Physical Science of Chinese Academy of Sciences, Tsinghua University, Tongji University, Shanghai Jiao Tong University, and other institutions have produced a series of theoretical and key technological research advancements in the field of autonomous-driving.

Although great progress has been achieved in autonomous-driving technology, many challenges still exist; for instance, operation in complex terrains, weather, road traffic environment conditions, as well as difficulties in achieving environmental awareness, decision making, and control performance optimization with the existing theory and methodology. The technical challenges can be summarized as follows:

- Environmental perception capacity in complex weather conditions.
- Behavioral decision capability and motion planning in complex traffic conditions.
- Vehicle control technology in special traffic conditions.
- Multi-source communication technology in dense vehicle conditions.

Sounder basic theoretical research on autonomous-driving is required to obtain the following key technologies:

- Technology for ground environment perception and understanding.
- Self-propelled truck fleet control.
- Multi-level human-computer interaction technology

for autonomous driving vehicles.

• Machine learning methods and techniques for autonomous-driving vehicles.

• Autonomous-driving vehicle communication technology.

• Main technology to establish sites for demonstrating and testing the base of autonomous-driving vehicles.

• Intelligent function standards and test methods for autonomous-driving vehicles.

• Autonomous-driving vehicle control technology based on smartphones.

The study of autonomous-driving theory and technology in complex environments also provides a good platform for cross-disciplinary integration, which will promote common applications for different disciplines, learning from each other, and promoting the basic research in related fields.

In the engineering development focus "Vehicle autonomous-driving technology and its application," the top three countries in patent output are the USA (129), Japan (35), and Germany (34). Among them, the USA accounts for 55.13% of the total output (Table 2.2.3, Figure 2.2.3). The top three institutions in core patent output are GENK (18), GOOG (18), and FORD (15); it is reported that FORD cooperated closely with both BOSC and MASI (Table 2.2.4, Figure 2.2.4).

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Vehicle autonomous-driving technology and its application"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	129	55.13%	2710	67.16%	21.01
2	Japan	35	14.96%	325	8.05%	9.29
3	Germany	34	14.53%	511	12.66%	15.03
4	China	18	7.69%	273	6.77%	15.17
5	Korea	7	2.99%	69	1.71%	9.86
6	Sweden	4	1.71%	73	1.81%	18.25
7	UK	3	1.28%	47	1.16%	15.67
8	Canada	2	0.85%	12	0.30%	6.00
9	India	2	0.85%	50	1.24%	25.00
10	The Netherlands	2	0.85%	9	0.22%	4.50

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Vehicle autonomous-driving technology and its application"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	GENK	18	7.69%	292	7.24%	16.22
2	GOOG	18	7.69%	483	11.97%	26.83
3	FORD	15	6.41%	187	4.63%	12.47
4	NSUM	11	4.70%	159	3.94%	14.45
5	TOYT	11	4.70%	174	4.31%	15.82
6	BOSC	7	2.99%	119	2.95%	17.00
7	HOND	6	2.56%	117	2.90%	19.50
8	DAIM	4	1.71%	161	3.99%	40.25
9	MASI	4	1.71%	102	2.53%	25.50
10	TEVE	4	1.71%	36	0.89%	9.00

Note: GENK stands for General Motors LLC; GOOG stands for Google Inc.; FORD stands for Ford Global Technologies LLC; NSUM stands for Audi AG; TOYT stands for Toyota Jidosha Kabushiki Kaisha; BOSC stands for Robert Bosch GmbH; HOND stands for Honda Motor Co., Ltd.; DAIM stands for Daimler Trucks North America LLC; MASI stands for Massachusetts Institute of Technology; TEVE stands for Continental Teves AG & CO. OHG.

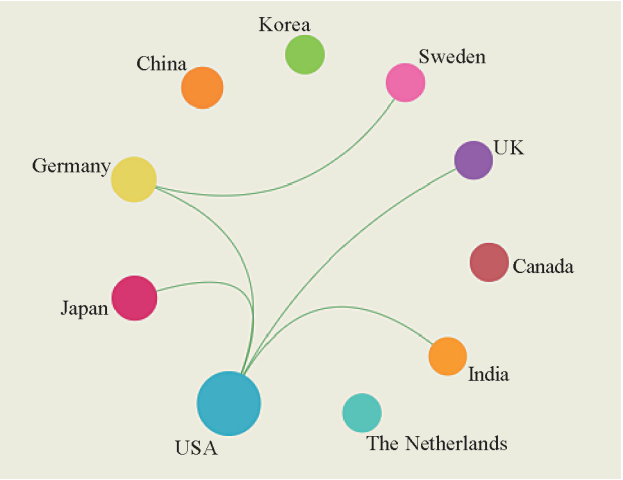

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Vehicle autonomous-driving technology and its application"

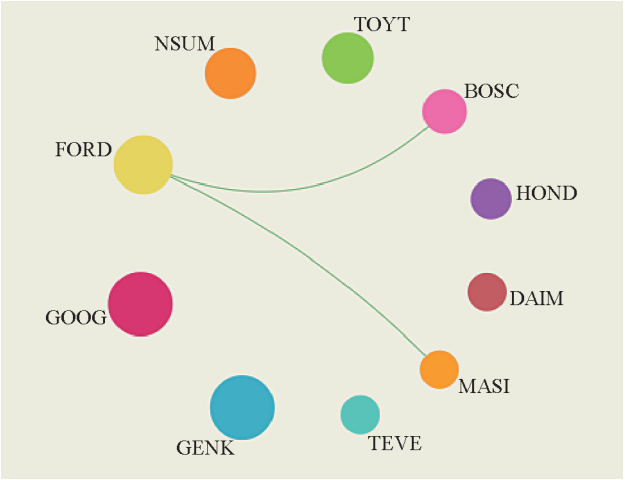

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Vehicle autonomous-driving technology and its application"

2.2.3 Laser light source technology

Over the last 50 years, laser technology has rapidly developed and has been applied in many fields, such as optoelectronic technology, laser medical and photobiology, laser manufacturing technology, laser detection and measurement technology, laser hologram technology, laser spectral analysis technology, non-linear optics, ultrafast laser, laser chemistry, quantum optics, laser radar, laser guidance, isotope separation by laser, laser controlled nuclear fusion, and laser weapons. The appearance of these cross-technologies and new subjects greatly promotes development in traditional and emerging industries. Among all types of laser source technology, the most active and fastest-growing field is semiconductor laser weapons, which has already become an important pillar of the optoelectronic industry. Meanwhile, with the continuous development of semiconductor lasers, other semiconductor-based solid-state lasers are being rapidly developed, such as fiber lasers, semiconductor pumped solid-state lasers, and slab lasers. To realize fiber lasers, special optical fiber technology must be developed. Additionally, new-generation optical fibers must be investigated, such as photon crystal fibers. Furthermore, pumped coupling cladding technology must be developed so that parts can have minimal impact on the fiber core. Finally, optical fiber technology must be improved so that optical grating can be more efficiently employed in fiber lasers.

The future development of laser sources involves the continuous improvement of their performance, including output power and beam quality, the increase of the ranges of laser wavelengths and tunable lasers, the reduction of the laser spectrum width, the development of an ultra-short-pulse high-brightness laser with extremely high peak value, and research on miniaturization, utilization, and intelligence.

The top three countries in patent output in this area are the USA (98), Japan (21), and China (17). The USA produces 64.90% of the total patents (Table 2.2.5, Figure 2.2.5). The top three institutions in core patent output are FORO (20), GIGA (8), and HONE (5) (Table 2.2.6, Figure 2.2.6), while ASML and CYME engage in the highest cooperation.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Laser light source technology"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	98	64.90%	2476	76.97%	25.27
2	Japan	21	13.91%	324	10.07%	15.43
3	China	17	11.26%	254	7.90%	14.94
4	Germany	8	5.30%	89	2.77%	11.13
5	Austria	3	1.99%	35	1.09%	11.67
6	Switzerland	2	1.32%	4	0.12%	2.00
7	Israel	2	1.32%	30	0.93%	15.00
8	Canada	1	0.66%	61	1.90%	61.00
9	France	1	0.66%	2	0.06%	2.00
10	UK	1	0.66%	3	0.09%	3.00

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Laser light source technology"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	FORO	20	13.25%	514	15.98%	25.70
2	GIGA	8	5.30%	192	5.97%	24.00
3	HONE	5	3.31%	198	6.15%	39.60
4	KLAT	5	3.31%	92	2.86%	18.40
5	ASML	4	2.65%	116	3.61%	29.00
6	CYME	4	2.65%	116	3.61%	29.00
7	ESII	4	2.65%	105	3.26%	26.25
8	LENS	4	2.65%	44	1.37%	11.00
9	LOCK	4	2.65%	130	4.04%	32.50
10	SORA	4	2.65%	182	5.66%	45.50

Note: FORO stands for Foro Energy Inc.; GIGA stands for Gigaphoton Inc.; HONE stands for Honeywell; KLAT stands for KLA-Tencor Corp.; ASML stands for ASML Netherlands BV; CYME stands for Cymer Inc.; ESII stands for Electro Scientific Industries Inc.; LENS stands for Lensar Inc.; LOCK stands for Lockheed Martin Corp.; SORA stands for SORAA Inc.

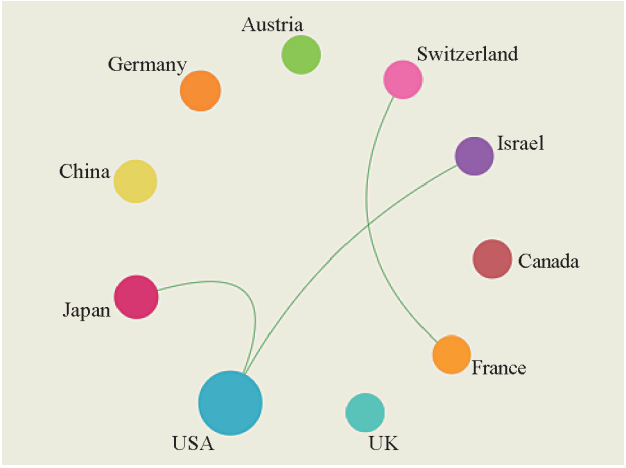

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Laser light source technology"

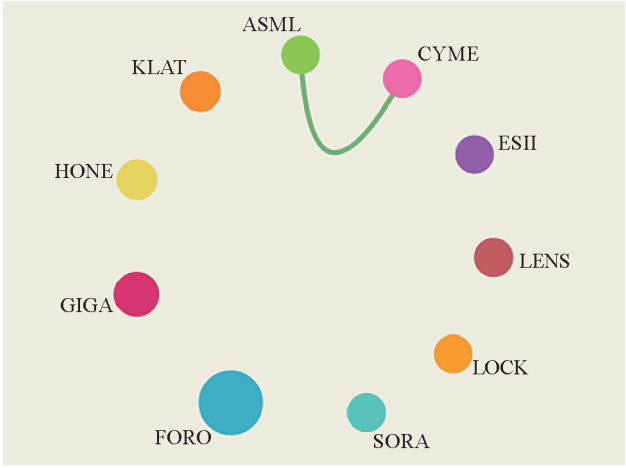

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Laser light source technology"

Project Participants

Members of the Field Group

Experts of the Field Group

Leaders of the Field Group:
PAN Yunhe, LU Xicheng
Co-leaders of the Field Group:
WU Jiangxing, JIANG Huilin
Academicians:
Group 1:
LI Tianchu, CHEN Lianghui, GONG Huixing, JIANG Huilin, ZHOU Shouheng, WEI Yu
Group 2:
WU Jiangxing, DUAN Baoyan, CHEN Zhijie, LIU Yunjie, FAN Bangkui, WU Weiren
Group 3:
PAN Yunhe, LU Xicheng, ZHENG Nanning, LI Bohu, FEI Aiguo, ZHAO Qinping, WU Jianping

Members of the Secretary Group

Researchers:
WU Zhaohui, WU Fei, ZHANG Zhaoyang
Consultant:
ZHANG Yuehong
Library and information specialists:
YANG Weiqiang, LIU Shulei, ZHAO Haiyang, QIN Li, GENG Guotong, QIAN Xu, LI Congying, LIU Qiong, CHEN Zhenying
Liaisons:
FAN Guimei, WANG Bing, ZENG Jianlin
Secretaries:
HU Xiaonv, ZHAI Ziyang

Report Writers

ZHAO Yiwu, GAN Haiyong, HUANG Tao, HU Yuan, SUN Hongbin, XIE Renchao, CUI Jin, WAN Huagen, ZHANG Guofeng, ZHU Jianke, LI Lei, XU Chao, ZHAO Zhou, HU Xiaonv, HUANG Ying, YU Wei, SHI Lei, DONG Shurong, LIU Meiqin, LI Daofei

III. Chemical, Metallurgical & Materials Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the disciplines of chemical, metallurgical, and materials engineering assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 1.1.1. Table 1.1.2 shows the numbers of their core papers that have been published in recent years. Among these 10 research hotspots, the research kernel for "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors," "Application of composite adsorbents for wastewater treatment," "Preparation and applications of functional gradient materials," "Preparation of porous surfaces and their applications in enhanced heat transfer," "Construction and application of superhydrophobic surfaces," and "Hydrogen storage alloy materials" is to obtain suitable materials for novel applications. The hotspots of "*In situ* transmission electron microscopy" and "Hydrogen sulfide sensors" mainly involve analytical and detection studies while "Carbon-hydrogen bond activation" greatly relates to synthetic chemistry. The total number of papers that have been published from 2011 to 2016 relating to each hotspots among the top 10 is about 50. For the topics of "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" and "Hydrogen sulfide sensors," the average citation for each paper exceeds 100. The average publication year for the core papers "Application of composite adsorbents for wastewater treatment," "Preparation and applications of functional gradient materials," and "Carbon-hydrogen bond activation" is 2014. The proportion of consistently cited papers of "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" and "Application of composite adsorbents for wastewater treatment" exceeds 50%. As shown in Table 1.1.2, the published papers that relate to "*In situ* transmission electron microscopy,"

Table 1.1.1 Top 10 engineering research hotspots in chemical, metallurgical, and materials engineering

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors	48	7395	154.06	2012.96	66.70%	0
2	Gas separation membranes	49	2154	43.96	2013.51	12.20%	1
3	Application of composite adsorbents for wastewater treatment	48	1756	36.58	2014.04	52.10%	0
4	*In situ* transmission electron microscopy	49	2419	49.37	2013.69	8.20%	2
5	Preparation and applications of functional gradient materials	47	2091	44.49	2014.77	44.70%	1
6	Preparation of porous surfaces and their applications in enhanced heat transfer	50	4095	81.90	2013.06	28.00%	2
7	Carbon-hydrogen bond activation	48	2349	48.94	2014.48	35.40%	0
8	Construction and application of superhydrophobic surfaces	48	2409	50.19	2013.27	10.40%	2
9	Hydrogen sulfide sensors	49	5262	107.39	2012.59	40.80%	0
10	Hydrogen storage alloy materials	49	1249	25.49	2013.76	6.10%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in chemical, metallurgical, and materials engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors	7	6	20	12	3	0
2	Gas separation membranes	6	8	7	14	11	3
3	Application of composite adsorbents for wastewater treatment	3	2	10	13	15	5
4	*In situ* transmission electron microscopy	3	9	6	15	14	2
5	Preparation and applications of functional gradient materials	1	1	4	7	23	11
6	Preparation of porous surfaces and their applications in enhanced heat transfer	8	9	16	7	9	1
7	Carbon-hydrogen bond activation	0	0	7	16	20	5
8	Construction and application of superhydrophobic surfaces	6	8	16	5	11	2
9	Hydrogen sulfide sensors	8	17	15	6	2	1
10	Hydrogen storage alloy materials	8	3	7	12	13	6

"Hydrogen sulfide sensors," "Preparation and applications of functional gradient materials," "Carbon-hydrogen bond activation," and "Hydrogen storage alloy materials" are all continuously increasing. Some experts regard "*In situ* transmission electron microscopy," "Hydrogen sulfide sensors," and "Hydrogen storage alloy materials" as the relatively new and emerging research hotspots, while others consider them to be further advancements of traditional studies. Some research, such as the development of rapid and highly sensitive detection technology in "Application of composite adsorbents for wastewater treatment," *in situ* observation and reaction control at the atomic scale in "*In situ* transmission electron microscopy," and direct conversion into high value functional chiral molecules from simple and non-functionalized substrates in "Carbon-hydrogen bond activation," may result in the emergence of revolutionary technologies.

(1) Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors

$NiCo_2O_4$ is a complex transition metal oxide, which possesses a typical spinel structure. As $NiCo_2O_4$ can store energy via a redox reaction that takes place on its surface and inner body, it has been widely used in electrocatalysis and energy storage. Meanwhile, it also attracted significant attention as an electrode material for supercapacitors owing to its excellent electrical conductivity, catalytic activity, and exceptive magnetic behavior. Although $NiCo_2O_4$ has large specific surface area, the poor electron and ion transportation weakens its cycling stability, which is a crucial problem that needs to be solved. One possible solution to overcome this limitation is to incorporate $NiCo_2O_4$ into various nanostructures such as nanorods, nanosheets, nanorings, hierarchical porous nanoflowers, and hollow nanospheres. As these nanostructures effectively cover the entire surface area of the electrode and facilitate the transport of ions, the activation performance and high ratio properties of this material can be improved. The latest trend in this area involves fabrication of thin-film and nanoarray electrode materials for use as supercapacitors. Direct deposition on the substrate makes it possible to avoid the detrimental effects arising from the use of adhesives, and results in a lower contact electrical resistance and higher surface utilization. Meanwhile, electrode films with nanoarray structures exhibit stronger ability to resist volume change, thus improving the stability and cycle life of the materials.

(2) Gas separation membranes

Gas separation membrane technology, owing to its highly efficient, energy-saving, and green attributes, is a prospective field of study in chemical separation applications. The permeation coefficients of conventional membranes are often low and unable to meet the requirements of large-scale applications. Thus, the development of membrane materials with both high permeability and high selectivity is an important research direction. Polymers with intrinsic microporosity (PIMs) are a novel organic microporous materials that have been attracting increasing attention in recent years. The microporous structure is generated as a result

of the ineffective folding of rigid, twisted molecular chains. Accordingly, PIMs are endowed with some distinct advantages such as high specific surface area, high physicochemical stabilities, and a controllable microporous structure. The design and utilization of novel, high-performance PIM membranes is expected to have a great and far-reaching impact on the sustainable development of gas separation membranes.

(3) Application of composite adsorbents for wastewater treatment

Modern industries and occasional emergencies such as a nuclear power plant leak accident are primarily responsible for environmental pollution. Pollution of natural resources is also serious, especially that of water bodies by phosphates, heavy metals, and radioactive elements. Thus, it is vitally important to investigate the visual detection of metal elements in polluted water and remove them in an efficient manner. The visual detection is based on the color change of the detectors when they come into contact with polluting elements. This method allows for the rapid and sensitive observation and identification of contaminants with the naked eye, and therefore, this technique has been attracting significant attention from the scientists. In order to efficiently absorb and remove the contaminating metal elements, it is necessary to investigate and develop novel effective composite and conjugate adsorbents. These adsorbents should be easy to regenerate and reuse, and not cause secondary environmental pollution. In particular, there is tremendous demand for the development of high-performance adsorbents for the removal of toxic elements at trace concentration levels in drinking water, as well as in presence of interfering ions in wastewater. These demands for composite and conjugate adsorbents for water treatment and visual detection of contaminants have become a hotspot in recent research.

(4) *In situ* transmission electron microscopy

In situ transmission electron microscopy (TEM) is used for real-time observation and recording of the dynamic response of the samples placed within the electron microscope to different external excitation signals. *In situ* TEM is one of the most promising techniques for the characterization of structures of materials. It has several advantages such as high spatial and energy resolution of conventional transmission electron microscopy in combination with the real-time, *in situ* observation of the dynamic microstructure of the material, and both quantitative and qualitative assessment of the response behavior to the external incentive of the material. *In situ* TEM has been applied in materials science, catalysis, and life science, and for the study of energy storage materials. Furthermore, it is possible to study reaction mechanisms by real-time observation and control gas phase and liquid phase reactions at the atomic scale by using this technique.

(5) Preparation and applications of functional gradient materials

Functional gradient materials (FGMs) lack distinct interfaces and are novel mixtures that are characterized by their gradually varying composition, density, and structure over their volume, resulting in corresponding gradual changes in their properties. The research efforts in the field of FGMs primarily include material design, preparation, and property assessment. In particular, the property assessment of the FGMs is critical in their investigation. As FGMs are distinct from the traditional homogeneous materials, the conventional test methods are not compatible with this new type of material. Currently, there is no unified standard for the assessment of FGMs, and the investigations merely focus on the heat insulation, thermal fatigue, and thermal shock, in addition to fundamental thermal and mechanical properties. The assessment of FGMs is a subject that relates to thermodynamics, theory of heat transfer, mechanics of materials, and materials engineering, among other issues. Therefore, an accurate, reasonable, and systematic standard assessment method is essential. It is also expected that further research in physics and chemistry will result in an explosion of the practical applications of FGMs.

(6) Preparation of porous surfaces and their applications in enhanced heat transfer

Porous surfaces typically exhibit good heat transfer performance, and they can be prepared following two different manufacturing methods: Either the surface is covered with a porous structure or the structure is perforated and converted into a porous surface. Specifically, the surface can be covered with a layer of porous copper, aluminum, stainless steel, and other alloys by either sintering the metal powder, or electroplating, flame-spraying, and covering the metal screen. On the other hand, a porous surface with holes used as a heat transfer surface can be also prepared

by mechanical processing, electrochemical corrosion, and laser processing. The key to preparation of high-quality porous surfaces is the precise control of pore size, uniform distribution, and porosity. A high porosity may adversely affect the strength of the material. It is also necessary to consider the long-term repeatability and reliability of the porous surface in practical applications. The material parameters of the porous surface, the dimensional parameters of the porous structure, and the boiling agent, all have a great influence on the liquid flow and heat transfer during the boiling process. The existing assumptions and theoretical models are not yet perfect, and further research on the boiling heat transfer mechanism and mathematical models of porous surfaces needs to be carried out. In addition, an important part of future research involves a combination of porous surfaces and other enhanced heat transfer measures to bolster the boiling heat transfer technology.

(7) Carbon-hydrogen bond activation

C—H activation is the process of selectively breaking a C—H bond at a specific location in the presence of a metal catalyst and converting it into either a C—X bond or a C—C bond. Many functional organic molecules can be constructed via C—H bond activation with better atom economy. As a result, this transformation has attracted intensive attention from both academia and industry, and has become one of the most important research focuses in the field of organic chemistry in recent years. However, the C—H activation reaction usually requires the presence of a directing group in the organic molecule, which greatly limits the possible structures that can produced. In recent years, the introduction of removable bidentate auxiliary group such as 1-(pyridin-2-yl)propan-2-amine and 8-aminoquinoline as directing groups has successfully expanded the scope of the C—H activation reactions. C—H activation is usually catalyzed by noble metal complexes, such as palladium and rhodium complexes. Recent studies have shown that some cheap transition metal compounds, such as nickel, copper, and even iron can effectively catalyze C—H activation reactions. The synthesis of chiral compounds via asymmetric C—H activation has also achieved a breakthrough by using a chiral ligand as the directing group. This method allows simple and non-functionalized substrates to be directly converted into functional chiral molecules with high value, representing a very attractive modern synthetic strategy. The activation of C—H bonds typically proceeds via a metal containing heterocyclic intermediate, and the subsequent oxidation of the metal center toward C—H bonds is often the rate determining step. Although significant progress has been made, the mechanism for metal ion-mediated catalytic C—H activation needs further investigation, and the efficiency of the catalysts also needs to be significantly improved. It is expected that in the future, the C—H activation reaction will be widely applied in chemical synthesis as new chelating auxiliary groups are being continually discovered and the catalyst efficiency has greatly enhanced in recent years.

(8) Construction and application of superhydrophobic surfaces

Generally, surfaces with a water contact angle larger than 150° are regarded as superhydrophobic (SH) surfaces. There are two typical SH surfaces: the lotus effect and the petal effect states, which are based on the magnitude of the water adhesive force. The SH surfaces possess a great potential in a variety of applications such as oil/water separation, self-cleaning, antifogging, anti-corrosion, drag reduction, microfluidic systems, and liquid transportation. Generally, the wettability of solid surfaces is governed by their surface free energy and surface geometry. A common approach toward imparting superhydrophobicity to a surface involves roughing a hydrophobic surface by constructing hierarchical structures and decreasing its surface energy by modifying with low-surface energy materials. Although significant advances have been made to the theory and applications of the SH surfaces, surface wettability is a complex scientific problem which involves considering many surface parameters together. In particular, some new emerging surface phenomena bring new challenges to the traditional theories and concepts. Therefore, significantly more experimental investigations are needed for practical applications of SH surfaces. Presently, their practical applications are limited by the complicated synthesis techniques, requirement of special equipment, environment polluting technologies, high costs, small size, and poor mechanical properties. A simple, low-cost, environment-friendly, and large-scale method for the construction of artificial SH surfaces is crucial and highly desirable for their adoption and use on an industrial scale. In addition, the mechanical durability of superhydrophobic surfaces remains a great challenge today for their practical applications. Therefore, further

fundamental investigations are still necessary to develop wear-resistant, anti-ageing, and large-scale SH surfaces, and such advances are expected to have a significant effect on expanding the applications and improving the performance of SH materials.

(9) Hydrogen sulfide sensors

Hydrogen sulfide sensors are utilized for the rapid detection and analysis of hydrogen sulfide (H_2S) concentration in a specific situation. Several fields such as biology, chemical industry, and environment require the determination of hydrogen sulfide concentration, particularly trace amounts. The traditional methods employed for the determination of trace H_2S include the use of infrared, electrochemical, catalytic, and semiconductor sensors. Although H_2S sensors have different requirements depending on the occasion, they generally require high precision, high sensitivity, a large linear range, strong anti-interference ability, high stability, and a reliable and reproducible performance. The current research focuses mainly on two types of sensing devices, namely, fluorescence and electrochemical sensors. The key to sensing technology is to find or synthesize materials that can selectively respond to H_2S and use them to determine its concentration. This can be achieved by evaluating the intensity change of some physical properties (such as spectral or electrochemical properties) when the sensor comes into contact with different concentrations of H_2S. In different situations, other substances coexisting with H_2S may become interfere with the sensing response. Therefore, different types of sensors need to be developed and used for different occasions in order to achieve rapid and accurate detection of hydrogen sulfide.

(10) Hydrogen storage alloy materials

Hydrogen storage materials can effectively solve the problem of hydrogen storage and transport of green energy. Magnesium-based hydrogen storage materials are widely regarded as one of the most promising materials in this category owing to advantages such as high hydrogen storage capacity, low density, abundant resources of Mg, and low price. Nevertheless, these materials exhibit some disadvantageous features such as severe hydrogen absorption and desorption conditions, highly stable hydride generation, poor hydrogen absorption kinetics, and short cycle life. Mg-Ni series alloy is an important magnesium-based hydrogen storage material, and the substitution of these elements is the main method for modification of Mg-Ni alloy. In general, Mg is partly replaced by the main group metals, and the substituted components are often less readily hydrogenated than Mg element. Other transition metal elements instead of Ni are selected to easily stabilize the components of the original compounds. Elemental substitution improves the performance of Mg-based alloys in mainly two aspects; the thermodynamic and kinetic properties of hydrogen absorption and desorption from the gaseous to the solid phase of the magnesium-based alloy and the electrochemical properties of the alloy electrode. The hydrogen storage property of the alloy can also be improved by preparation of suitable materials. The mechanical alloying method can prolong the cycle life greatly, and the maximum amount of hydrogen absorption and desorption can be improved obviously by mechanical ball milling and solid phase sintering technology.

1.2 Understanding of engineering research focus

1.2.1 Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors

Supercapacitors are chemical energy storage devices that exhibit advantages of high power density, high charge-discharge rate, and long cycle life. The safety performance of supercapacitors is even higher than that of lithium-ion batteries, which makes them more attractive alternatives for applications in the areas of energy, power grids, and electrical vehicles. However, the relatively low energy-storage density still limits their application, and the electrode material is the key component which mainly determines the performance of supercapacitor. In order to meet the requirements of rapid charge and discharge for large currents, the electrode materials should have large specific capacity and low internal resistance. Additionally, the electrode materials should also possess good chemical and mechanical stability, as well as excellent electron and ion transport properties. A mixture of aqueous sulfuric acid solution and ruthenium dioxide has been successfully used as a metallic oxide for applications as a supercapacitor, albeit the cost of ruthenium is too high for this material to be commercialized. Hence, the possible use of other cheap transition metal oxides such

as cobaltous oxide, manganese oxide, nickel oxide, and their mixtures has become the new research hotspot. The research emphasis is laid on the preparation technology and structure optimization of the electrode materials for future use as supercapacitors. Meanwhile, it is important to develop large-scale preparation methods for new and high-performance materials, in order to produce mobile power technology that is low-cost, high-performance, and shows good stability.

The main countries or regions and institutions that have produced core papers in the focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" since 2011 are listed in Table 1.2.1 and Table 1.2.2, respectively. The collaboration network among different countries or regions and institutions are illustrated in Figure 1.2.1 and Figure 1.2.2. The main countries or regions and institutions relating to the citing core papers are summarized in Table 1.2.3 and Table 1.2.4. China, Singapore, and the USA are the top three countries. It is noteworthy that the number of core papers produced in China is even larger than the sum of other countries and regions (Table 1.2.1), indicating that the research area of $NiCo_2O_4$ nanoarrays has become a hotspot in China. Nanyang Technological University in Singapore acts as the institution that is the most productive in this research topic. As for the number of core papers cited by core papers, China and Nanyang Technological University become the most productive country and institution, respectively.

Recent research content about the focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" includes the development of a controllable microstructure of $NiCo_2O_4$, its composites with carbon materials, and specifically oriented growth with a conductive substrate. The key point for future developments is the preparation of modified $NiCo_2O_4$ nanoarrays loaded onto a three-dimensional network conductive substrate. In addition, further research is required on understanding the relationship between the microstructure and properties of these materials. Meanwhile, some unified evaluation criteria should be established so that the supercapacitors are utilized for more and better applications.

1.2.2 Gas separation membranes

Gas separation using membrane technology can be conducted at ambient temperatures and is free of phase changes when gas mixtures are separated. Compared with conventional technologies such as adsorption, absorption, and cryogenic separation, gas separation membrane technology has distinct competitive advantages in economic and environmental aspects, and has attracted significant attention worldwide. The core of gas separation membrane technology is the membrane materials. The commonly used polymer membrane materials are subject to a trade-off between permeability and selectivity: Highly permeable membranes lack high selectivity and vice versa. PIM membranes can break the permeability-selectivity trade-off to some extent, i.e., these membranes exhibit both high permeability and high selectivity. Thermal rearrangement is a common method to prepare PIM membranes. Thermally rearranged polymers are a type of glassy microporous polymers, which possess superior thermal and physicochemical stabilities. Thermally rearranged polymer membranes (TR membranes) hold great promise in gas separation field. Such membranes usually have a high fractional free volume and narrow free volume cavity distribution, and thus exhibit high gas permeability. Thermal rearrangement is an important

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	35	72.92%	4358	63.33%	124.51	2	0
2	Singapore	11	22.92%	3561	51.75%	323.73	0	0
3	USA	4	8.33%	841	12.22%	210.25	0	0
4	Taiwan of China	3	6.25%	130	1.89%	43.33	0	0
5	Korea	1	2.08%	74	1.08%	74.00	0	0
6	England	1	2.08%	53	0.77%	53.00	0	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Nanyang Technol Univ	10	20.83%	3506	50.95%	350.60	0	0
2	Cent S Univ	6	12.50%	274	3.98%	45.67	1	0
3	Tum Create Ctr Electromobil	4	8.33%	1070	15.55%	267.50	0	0
4	Anhui Univ Technol	4	8.33%	691	10.04%	172.75	0	0
5	Nanjing Univ Aeronaut & Astronaut	4	8.33%	691	10.04%	172.75	0	0
6	Zhejiang Univ	3	6.25%	733	10.65%	244.33	0	0
7	Harbin Inst Technol	3	6.25%	131	1.90%	43.67	0	0
8	"Tsing Hua Univ", Taiwan of China	3	6.25%	130	1.89%	43.33	0	0
9	Georgia Inst Technol	2	4.17%	374	5.44%	187.00	0	0
10	Chinese Acad Sci	2	4.17%	294	4.27%	147.00	0	0

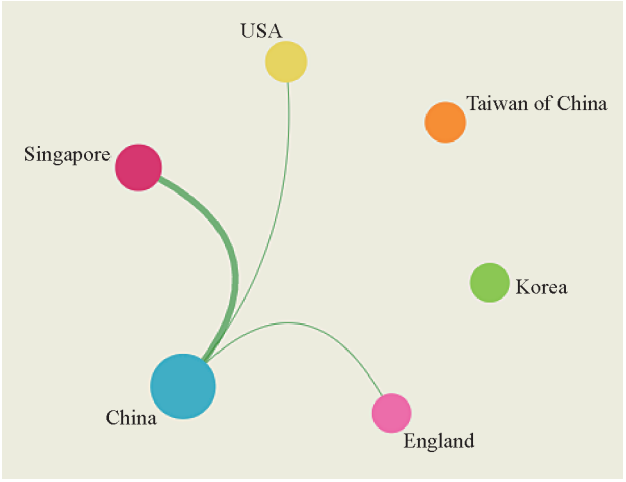

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"[1]

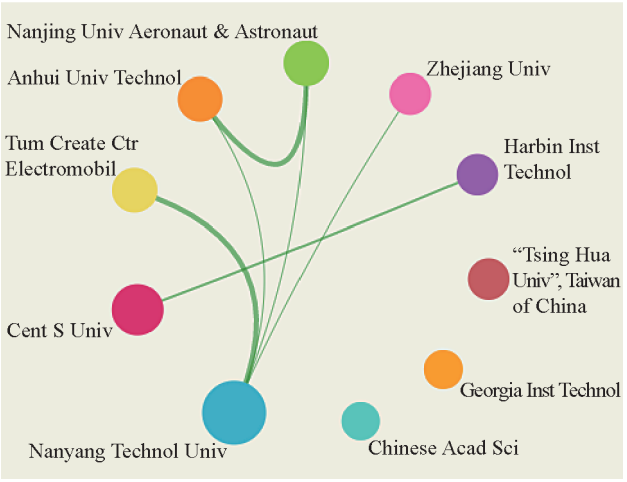

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

technique for polymer modification and involves conversion of the precursor polymers into rigid polymers via thermal reaction. For specific separation systems, tuning the size and distribution of free volume cavity can be implemented by the rational design of the molecular structure of precursor polymers.

The preparation of PIM and TR membranes primarily involves the polymer materials science and engineering discipline, whereas the application of membrane in gas separation is a subdivision of the chemical engineering discipline. To some extent, PIM membranes can be regarded as organic molecular sieving membranes which follow the core principles of molecular sieving, solution-diffusion, and facilitated transport mechanisms. The application of PIM and TR membranes in gas separation can be expected to break the trade-off between membrane

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	32	68.09%	2013.34
2	Singapore	10	21.28%	2012.50
3	USA	3	6.38%	2013.00
4	England	1	2.13%	2014.00
5	Taiwan of China	1	2.13%	2013.00

Table 1.2.4 Major producing institutions of core papers that are cited by core papers in the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Nanyang Technol Univ	9	12.50%	2012.33
2	Cent S Univ	6	8.33%	2014.00
3	Tum Create Ctr Electromobil	4	5.56%	2012.75
4	Anhui Univ Technol	4	5.56%	2012.50
5	Nanjing Univ Aeronaut & Astronaut	4	5.56%	2012.50
6	Harbin Inst Technol	3	4.17%	2014.00
7	Zhejiang Univ	3	4.17%	2012.67
8	Donghua Univ	2	2.78%	2013.50
9	Georgia Inst Technol	2	2.78%	2013.00
10	Huazhong Univ Sci & Technol	2	2.78%	2013.50

permeability and selectivity. Currently, the critical issues that require solving in PIM gas separation membrane technology are methods for structural manipulation and modification of these membranes. Structural manipulation primarily involves altering the rigidity of the benzene ring linking chains, adjusting the rotation angle and the distance between adjacent rotation angles, and incorporating substitution groups in the side chains. Such manipulations are aimed at improving the diffusion and dissolution behavior of gas molecules in the PIM membrane. The modification of PIMs mainly encompasses chemical crosslinking and physical blending. It is worth noting that the materials suitable as PIM and TR membranes are quite limited at present. Therefore, future research should be centered on developing monomers with higher rigidity and higher solubility toward specific gas molecules. In addition, it is necessary to explore more facile and controllable modification methods, in order to dramatically enhance the gas separation performance of PIM membranes. Owing to the short research history of PIM and TR membranes, the whole chain design and innovation in type of membrane materials, preparation methods, structural manipulation, structure-performance relationships, and performance intensification should be carried out. It is expected that through abovementioned efforts, the gas separation performance of PIM and TR membranes can be elevated significantly. Consequently, PIM and TR membranes may be expected to gain critical relevance in the fields of energy, environment, and resources.

The primary countries or regions and institutions that have core papers published in the focus "Gas separation membranes" since 2011 are listed in Table 1.2.5 and Table 1.2.6. The scientific collaboration of the primary countries or regions and institutions is illustrated in Figure 1.2.3 and Figure 1.2.4, while the data for the citing core papers is listed in Table 1.2.7 and Table 1.2.8. Among them, Korea, the USA, Italy, and Saudi Arabia rank as the top four in

the production of core papers. Except Saudi Arabia, the other nine countries or regions in the top 10 collaborate scientifically, and such collaboration between China and Korea is very active. The core paper amount from Hanyang University of Korea ranks the first. In China, the majority of core papers are from the Chinese Academy of Sciences. There is no significant difference in the ranking of the primary countries or regions and institutions producing core papers cited by core papers and that producing core papers.

1.2.3 Application of composite adsorbents for wastewater treatment

Composite adsorbents are usually made from two or more than two different materials. Several physical or chemical methods have been developed to impart new properties to the adsorbents. Different materials in composite adsorbents can complement each other in performance and produce synergistic effects. Upon combination, their properties are significantly improved. In the field of wastewater treatment, main research focuses on the visual detection and adsorption of heavy metal ions such as Hg(II), Cu(II), Zn(II), Pb(II), As(V), Co(II); lanthanide ions such as Ce(III), Eu(III), Sm(III), Nd(III), Yb(III); radioactive elements such as Cs(137); noble metal ions such as Au(III), Pd(II), Se(IV); and phosphates. These composite adsorbents can be classified into two types, namely, ion exchange resins and mesoporous silica

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Gas separation membranes"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Korea	19	38.78%	785	40.19%	41.32	1	1
2	USA	11	22.45%	340	17.41%	30.91	1	0
3	Italy	9	18.37%	497	25.45%	55.22	0	0
4	Saudi Arabia	9	18.37%	271	13.88%	30.11	0	0
5	China	9	18.37%	182	9.32%	20.22	0	0
6	Wales	6	12.24%	490	25.09%	81.67	0	0
7	Australia	4	8.16%	120	6.14%	30.00	0	0
8	Scotland	4	8.16%	92	4.71%	23.00	0	0
9	Spain	4	8.16%	91	4.66%	22.75	0	0
10	England	3	6.12%	77	3.94%	25.67	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Gas separation membranes"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Hanyang Univ	19	38.78%	785	40.19%	41.32	1	1
2	Univ Calabria	9	18.37%	497	25.45%	55.22	0	0
3	Cardiff Univ	8	16.33%	529	27.09%	66.13	0	0
4	King Abdullah Univ Sci & Technol	8	16.33%	259	13.26%	32.38	0	0
5	Univ Texas Austin	8	16.33%	232	11.88%	29.00	1	0
6	Univ Notre Dame	5	10.20%	176	9.01%	35.20	0	0
7	Chinese Acad Sci	5	10.20%	110	5.63%	22.00	0	0
8	Hunan Univ Arts & Sci	4	8.16%	122	6.25%	30.50	1	0
9	Univ Edinburgh	4	8.16%	92	4.71%	23.00	0	0
10	Spanish Nat Res Coun	4	8.16%	91	4.66%	22.75	0	0

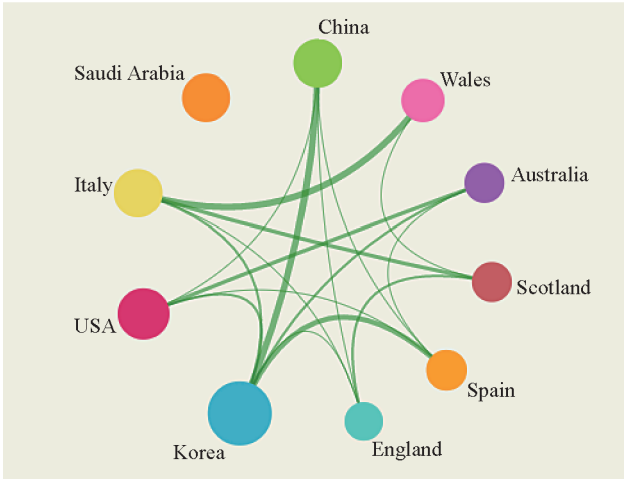

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Gas separation membranes"

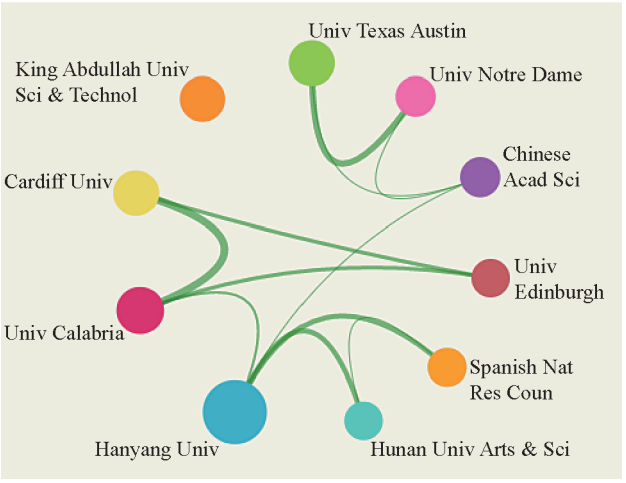

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Gas separation membranes"

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Gas separation membranes"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Korea	16	21.62%	2013.88
2	Italy	9	12.16%	2013.89
3	China	9	12.16%	2014.56
4	Saudi Arabia	8	10.81%	2014.13
5	USA	8	10.81%	2014.00
6	Wales	5	6.76%	2013.20
7	Scotland	4	5.41%	2014.25
8	Spain	4	5.41%	2013.50
9	England	3	4.05%	2013.67
10	Australia	3	4.05%	2013.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Gas separation membranes"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Hanyang Univ	16	16.67%	2013.88
2	Univ Calabria	9	9.38%	2013.89
3	Cardiff Univ	7	7.29%	2013.43
4	King Abdullah Univ Sci & Technol	7	7.29%	2014.00
5	Univ Texas Austin	6	6.25%	2014.17
6	Chinese Acad Sci	5	5.21%	2014.00
7	Spanish Nat Res Coun	4	4.17%	2013.50
8	Hunan Univ Arts & Sci	4	4.17%	2015.25
9	Univ Notre Dame	4	4.17%	2014.00
10	Univ Edinburgh	4	4.17%	2014.25

materials functionalized by organic compounds. The adsorbents and the technologies for their functionalization by organic compounds are decided according to the characteristics of the adsorbed ions.

For the adsorption treatment of phosphate containing wastewater, weak-base anion-exchange resin fibers and selective ligand exchange adsorbent fibers such as poly(vinylamine) chains grafted onto polypropylene fiber are preferentially used as adsorbents. These absorbents can selectively absorb phosphate at high feed flow rates, and do not show other ion interferences.

For the adsorption treatment of Hg(II), Cu(II), Zn(II), Pb(II), As(V), Co(II), and other heavy metal ions, the absorbents should allow visual detection, and demonstrate highly efficient adsorption at low cost. These absorbents must be able to simultaneously selectively detect and remove ions. For this purpose, research should focus on achieving rapid visual detection and highly efficient adsorption of heavy metal ions from wastewater so as to reach drinking water quality standards. At present, main references of this research field originate from the Japan Atomic Energy Agency. They have focused on using mesoporous SiO_2 as an adsorbent carrier and introduced different organic compounds to selective adsorb heavy metal ions in addition to pH sensitivity. The organic compounds used for functionalization of the adsorbents usually have N-containing heterocyclic structures, carboxylic acid groups, carbon-nitrogen double bonds, and nitrogen-nitrogen bonds. Such organic compounds adsorb heavy metal ions by forming metal-ligand complexes and after adsorption of the aforementioned metal ions, the absorbents can be washed by acids to recover the metal elements as well as the adsorbents.

For the adsorption of radioactive element Cs(137), dibenzo-18-crown-6 ether was immobilized onto mesoporous silica monoliths as an adsorbent. This conjugate adsorbent showed high adsorption efficiency and could be reused several times after recovery. For the rapid visual detection and absorption of lanthanide ions such as Ce(III), Eu(III), Sm(III), Nd(III), and Yb(III), organic ligands 4-tert-octyl-4-((phenyl)diazenyl)phenol, 4-dodecyl-6-((4-(hexyloxy)phenyl)diazenyl) benzene-1,3-diol, *N*-methyl-*N*-phenyl-1,10-phenanthroline-2-carboxamide, which contain O and N donor atoms, were synthesized and subsequently immobilized onto mesoporous silica material. These adsorbents showed rapid visual detection of lanthanide ions in water and could adsorb even ultra-trace amounts of these ions from aqueous solutions.

From 2011, the main countries or regions and institutions producing core papers in the research focus "Application of composite adsorbents for wastewater treatment" are listed in Table 1.2.9 and Table 1.2.10, as well as the collaboration networks of the main countries or regions and institutions are shown in Figure 1.2.5 and Figure 1.2.6. The main countries or regions and institutions to cite these core papers are summarized in Table 1.2.11 and Table 1.2.12. Among them, the research on composite adsorbents mainly focuses on inorganic mesoporous silica materials that have been functionalized by organic ligands. These core papers mainly came from eight countries or regions, and Japan ranked the first, having published 46 core papers, while Bangladesh ranked the second with 17 core papers. It is worth noting that the collaboration in this area is primarily between Japan and Bangladesh. Furthermore, Japan also cooperates with Egypt and Saudi Arabia; and Egypt, Saudi Arabia, and Bangladesh also cooperate with each other. The most of the published papers came from Japan Atomic Energy Agency (ranking the first), the second is Shaheed Ziaur Rahman Medical College of Bangladesh. These institutions mainly cooperate with Japan Atomic Energy Agency. Besides the institutions of Bangladesh and Saudi Arabia, other countries or regions also cooperate with each other. The main countries or regions and institutions to cite these core papers are the top five such countries or regions that also publish these papers, with Japan ranking the first. Among the top 10 institutions producing core papers cited by core papers, eight are the main institutions producing these core papers.

The application and research of composite adsorbents for wastewater treatment is one of the more recent research hotspots. It is expected that in the following couple of decades, many research papers and work will focus on this research field. For highly sensitive and visual detection of metal ions, highly efficient and specific absorbents will likely make significant progress. The research and development will mainly focus on the aspects of engineering research in the different application fields based on the laboratory results.

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan	46	95.83%	1577	96.10%	34.28	10	0
2	Bangladesh	17	35.42%	510	31.08%	30.00	1	0
3	Egypt	10	20.83%	359	21.88%	35.90	2	0
4	Saudi Arabia	6	12.50%	141	8.59%	23.50	2	0
5	Australia	2	4.17%	44	2.68%	22.00	0	0
6	Korea	1	2.08%	69	4.20%	69.00	1	0
7	India	1	2.08%	33	2.01%	33.00	0	0
8	Taiwan of China	1	2.08%	31	1.89%	31.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan Atom Energy Agcy	42	87.50%	1427	86.96%	33.98	9	0
2	Shaheed Ziaur Rahman Med Coll	12	25.00%	317	19.32%	26.42	1	0
3	Natl Inst Mat Sci	8	16.67%	405	24.68%	50.63	3	0
4	Independent Univ	8	16.67%	253	15.42%	31.63	1	0
5	Kumamoto Univ	6	12.50%	273	16.64%	45.50	2	0
6	King Saud Univ	6	12.50%	141	8.59%	23.50	2	0
7	Sohag Univ	4	8.33%	162	9.87%	40.50	2	0
8	Univ Dhaka	4	8.33%	159	9.69%	39.75	0	0
9	Suez Univ	4	8.33%	122	7.43%	30.50	0	0
10	Waseda Univ	3	6.25%	96	5.85%	32.00	0	0

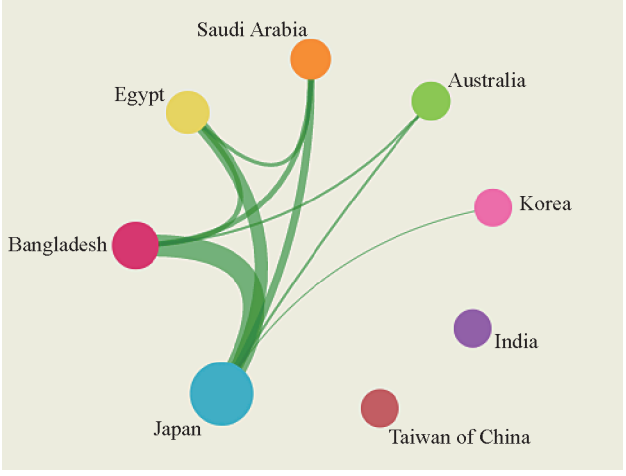

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

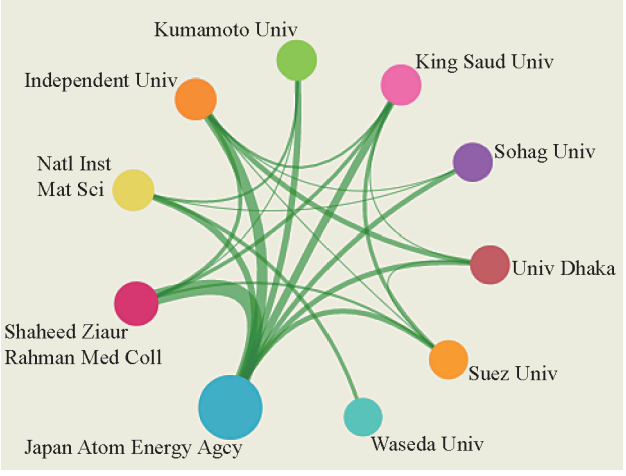

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Japan	41	53.95%	2014.37
2	Bangladesh	17	22.37%	2014.65
3	Egypt	10	13.16%	2014.00
4	Saudi Arabia	6	7.89%	2015.17
5	Australia	2	2.63%	2015.00

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Japan Atom Energy Agcy	41	44.09%	2014.37
2	Shaheed Ziaur Rahman Med Coll	12	12.90%	2014.83
3	Independent Univ	8	8.60%	2014.75
4	King Saud Univ	6	6.45%	2015.17
5	Kumamoto Univ	4	4.30%	2013.25
6	Suez Univ	4	4.30%	2014.75
7	Univ Dhaka	4	4.30%	2014.25
8	Sohag Univ	3	3.23%	2014.00
9	Curtin Univ	2	2.15%	2015.00
10	Elec Power Res Inst	2	2.15%	2012.50

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top nine engineering development hotspots in the disciplines of chemical, metallurgical, and materials engineering assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. Table 2.1.2 shows the annual number of core patents that have been published in recent years. Among these nine engineering development hotspots, "New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials" and "Development and application of new energy technologies" belong to the field of energy and its relevant technologies; while "Optimized design, preparation, and applications of novel thin films and thin-film devices," "Preparation and properties of graphene," and "Preparation and applications of nanomaterials" also partly belong to the subgroup of energy, indicating the importance of the energy issue in the current world. The average citation for each core patent exceeds 10 and their average publication year is 2012. Some experts believe that "Optimized design, preparation, and applications of novel thin films and thin-film devices," "Preparation and properties of graphene," "Biodegradable medical devices & health monitoring," and "Preparation and applications of nanomaterials" are the new and emerging development hotspots while others discussed in this category are merely further developments of the more traditional subject areas.

(1) Optimized design, preparation, and applications of novel thin films and thin-film devices

With the development trend of miniaturization and

Table 2.1.1 Top 9 engineering development hotspots in chemical, metallurgical, and materials engineering

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Optimized design, preparation, and applications of novel thin films and thin-film devices	704	10 607	15.07	2012.22
2	Preparation and properties of graphene	43	1 181	27.47	2011.70
3	Preparation and applications of aluminum, magnesium, and titanium light metal alloys	285	2 856	10.02	2012.51
4	Biodegradable medical devices & health monitoring	92	3 384	36.78	2012.48
5	New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials	258	4 435	17.19	2011.74
6	Preparation and applications of nanomaterials	172	1 954	11.36	2012.23
7	Preparation techniques for advanced resin matrix composites	169	3 194	18.90	2012.02
8	New technology of iron and steel clean production and development of high-performance steel	413	4 366	10.57	2012.17
9	Development and application of new energy technologies	41	1 128	27.51	2011.85

Table 2.1.2 Annual number of core patents belonging to each of the top 9 engineering development hotspots in chemical, metallurgical, and materials engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Optimized design, preparation, and applications of novel thin films and thin-film devices	276	186	121	63	45	13
2	Preparation and properties of graphene	26	6	9	2	0	0
3	Preparation and applications of aluminum, magnesium, and titanium light metal alloys	74	68	85	43	12	3
4	Biodegradable medical devices & health monitoring	31	16	23	15	6	1
5	New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials	133	72	45	5	2	1
6	Preparation and applications of nanomaterials	59	40	50	21	1	1
7	Preparation techniques for advanced resin matrix composites	69	54	29	10	5	2
8	New technology of iron and steel clean production and development of high-performance steel	141	112	116	37	6	1
9	Development and application of new energy technologies	21	11	5	2	2	0

integration in the field of electronics, there is an urgent need for advanced functional and structural thin films in several fields such as national defense, aviation aerospace, automobile engines, and even in all walks of the national economy. In particular, optical thin films, magnetic thin films, silicon thin films, thermoelectric thin films, piezoelectric thin films, transparent films, superhard films, and organic films have all attracted significant attentions. By optimizing the design and deposition methods of the thin film preparation process (such as chemical vapor deposition or physical vapor deposition), the synergy of advanced micro-fabrication technique can finally realize the application of micro sensors, micro actuators, micro mechanical structures, micro power supplies, and signal and control circuit processors. Research of thin films and thin-film devices is also very crucial for national development and security.

(2) Preparation and properties of graphene

Graphene has an ideal two-dimensional crystal structure with a single atomic layer, which is composed of a

hexagonal lattice. The particularity of graphene structure leads to some unique mechanical, thermal, and electrical properties. Graphene-based materials are prospective candidates for broad applications and have been used as solar battery electrode materials, super capacitors, hydrogen storage materials, lithium ion battery electrode materials, and optical materials. Such materials are foremost in the category of emerging materials and research on graphene and graphene-based materials has entered a stage of rapid development. Several countries have regarded the preparation of graphene and its application technology as a long-term strategic development direction, aiming to occupy the leading position in the industrial revolution. However, in the practical preparation, graphene is not stable and easy to reunite, which limits the use of the excellent properties of single layer structure of graphene materials. The key bottleneck for the widespread use of graphene is the dispersion technology. Graphene oxide is an important foundation for the preparation of functionalized graphene materials, and the process of preparation is simple, low-cost, and easy to modify. Thus, high-quality and large-scale preparation of graphene materials is the foundation of all future applications. The development of a simple, controllable chemical method to fabricate graphene on a large scale is the most convenient and feasible way.

(3) Preparation and applications of aluminum, magnesium, and titanium light metal alloys

With the rapid development in high technologies such as aerospace, nuclear power, automobile, and biology medical treatment, the demand for high-performance light metal alloys has increased remarkably. A great deal of work focused on light alloys of aluminum, magnesium, and titanium has been carried out. This important field includes high-performance aluminum alloys for use in structures and wires owing to their high strength and high toughness, magnesium alloys for their wear and corrosion resistance, biodegradability and biocompatibility, and titanium alloy materials for use in energy and medical devices. Significant attention has been paid to the development of high-performance aluminum alloys for their use in conductors in order to reduce the industrial cost arising from the price factor of the copper raw material. Research and development of high-performance aluminum alloys as structural materials has been the focus of aerospace and automotive fields. In contrast, magnesium alloys still cannot meet the requirements of strength, toughness, and corrosion resistance for application as structural materials. The development of magnesium alloys with the above-mentioned attributes still needs a long time. Meanwhile, biodegradable magnesium alloys have become the focus of research in recent years because magnesium-based devices circumvent the adverse effects that are ordinarily caused by foreign objects staying in the body for a long time after the implantation of inert medical metal materials such as stainless steel and titanium alloy. The focus of research and development of biomedical magnesium alloys is mainly to control the composition and microstructure of alloys such that the alloy demonstrates good comprehensive properties of mechanics, corrosion, degradation, and biocompatibility, and meets the needs of clinical applications.

(4) Biodegradable medical devices & health monitoring

With the accelerating trend of population aging and the rapidly increasing demand for medical care, it is imperative to develop next-generation, revolutionary biomedical implants and medical devices that are biodegradable or bioresorbable in the human body. These efforts aim to address the current clinical challenges such as chronic inflammation and secondary surgeries, which are associated with the use of conventional permanent implants, in order to significantly improve treatment efficacy and alleviate the suffering of patients. The research and development components of biodegradable medical devices mainly include computational design and development of novel biodegradable biomaterials, optimum structure design and precision processing for medical devices, surface modification and functional coating design and preparation, and *in vitro* and *in vivo* degradation and evaluation of biosafety and efficacy. Developments in these areas may help to achieve the integration of controlled degradation, good biocompatibility, and other adaptive functions for typical types of biodegradable medical devices. In addition, aiming at the key problems of heart failure and orthopedic disease in China's aging society, health monitoring and forecasting has become a main research focus area. With intelligent materials as the core technology, it is attractive to perform research on wearable, rapid monitoring equipment, targeted therapy, drug carriers, and artificial tissues for key intelligent materials and devices.

These advances would realize miniaturization, multifunctionality, and rapid detection toward key diseases.

(5) New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials

With the looming energy crisis and environmental problems such as haze and global warming, new electrochemical energy storage technologies have attracted more attention than ever. The development of energy storage devices has become an important research direction. Specifically, it is of urgent interest to develop energy storage devices with high specific capacity, high specific energy, long life, safe operation, and low cost. The energy storage systems that meet these requirements include solid state lithium ion batteries, high voltage positive electrode-metal lithium negative batteries, lithium sulfur batteries, lithium air batteries, sodium sulfur batteries, supercapacitors, and so on. The material employed in these energy storage devices is one of their most important components and also the key factor that determines their performance. The key technologies related to such materials mainly include controlled synthesis of nanostructured electrode materials, investigation of the electrochemical reaction mechanism, development of new electrolyte materials, study of Li-ion transport mechanism and electrolyte-electrode interface stability, light-weight technology, safety optimization of the storage systems, and so on. The energy storage devices using new materials with superior electrochemical performance will have broad applications in the fields of electric vehicles, consumer electronics, home energy storage, and utilization of renewable energy.

(6) Preparation and applications of nanomaterials

Nanotechnology has brought together modern multidisciplinary fields of science at the nanoscale, and is one of the largest and most competitive research areas worldwide. Nanomaterials are one of the current focuses and frontiers in the field of materials science, and at present, most countries have declared production and technology development of nanomaterials as an important research field. The properties of the nanomaterials (scale of 1–100 nm) are studied in terms of atomic and molecular level interactions. The goal of such studies is to manipulate the atoms, molecules, and substances such that they show novel physical, chemical, and biological characteristics, and can be used to produce materials with specific functions. The six primary aspects of such studies are: ① preparation and processing technology of new nanomaterials; ② nano characterization and standards; ③ nano biomedicine; ④ nano information materials and devices; ⑤ energy nanomaterials and technologies; ⑥ environmental nanomaterials and technologies. Nano materials are widely used in diverse fields such as nano ceramic materials, nano semiconductor materials, nanocatalytic materials, nanomedicine, and carbon nanotubes. Thus, the field of nanomaterials and integration design, from basic research to application research, is expected to achieve major breakthroughs in the important application areas of nanotechnology.

(7) Preparation techniques for advanced resin matrix composites

Advanced resin matrix composites are prepared by compound techniques. They are a combination of organic polymers acting as the matrix and high-performance fibers that act as reinforcing materials. These composites are advanced materials with properties that are remarkably better than those of the original components. They have been widely utilized in aerospace, national defense, and military industries, as automobile, mechanical and electrical apparatus, and in the field of healthcare. In aerospace engineering applications, advanced resin matrix materials display many advantages such as high specific strength and specific stiffness, excellent corrosion resistance, structure dimension stability, and convenience in large-scale integrated shaping. Currently, advanced resin matrix composites are the fourth largest aerospace structural materials after aluminum, steel, and titanium. They are mainly used in structural components of airplanes and helicopters, airborne radomes, artificial satellites, space stations, airproof adhesives, and space transportation systems. In the automobile manufacturing field, advanced resin matrix composites are extensively utilized to enhance the performance of vehicles. The demand of this material is also very extensive in the field of mechanical and electrical apparatus industry, for example, as blowers and engineering machinery. Besides, with the rapid development of integration technology, the working frequency of electronic components has increased dramatically, and the demand of integrating thermal conductivity on the interface in addition to water and thermal resistance of printed circuit boards has increased. Similarly, ion exchange resins and other advanced resin-based materials have been employed in medical treatment, e.g., for

manufacturing artificial hearts, respirators, and stents. Nowadays, advanced resin matrix materials are being developed with high performance as the key attribute, such as using high-performance fibers to strengthen the comprehensive properties of the composites, increasing their weight reducing efficiency, establishing its manufacturing standards, achieving intelligent production, as well as developing low-cost preparation technologies.

(8) New technology of iron and steel clean production and development of high-performance steel

In recent years, with the rapid development of high-speed rail, automobile, shipping, and mechanical industries, the demand of high-strength steel has become more and more exuberant. The key topics in this field include studies on developing a short and clean process in iron and steel metallurgy, involving the purification process and improvements in equipment handling molten steel and the optimization of slag type, as well as special steel, clean steel, and corrosion resistance steel in marine engineering. In the field of the high-performance steel, following objectives can be outlined: ① developing special steel for strategic applications such as national thermal and nuclear power generation, including supercritical heat resistant steel and manufacturing techniques of AP1000 forge piece; ② developing steel for energy, aviation, and marine applications which can bear high/low temperature, high pressure, or a complex medium; ③ developing high-strength and high-toughness steel in addition to corrosion resistant double metal composites, including its rolling technology and equipment; ④ preparation of high-quality heavy plate and large-scale castings and forgings with high cleanliness; ⑤ study of new strengthening and toughening mechanisms and reliable long-life mechanism of special steel, the evolution of microstructures during the preparation and service processes, the material design technique which incorporates resistance to high temperature, stress, and corrosion; ⑥ high-cleanliness smelting and quality control techniques for special steel, precise control of inclusions, homogenization and fine control of tissue, precision forming, and processing; ⑦ low-cost production and simplification of the process. The design of the entire process of iron and steel making has to be updated, with clean energy and raw materials, and advanced techniques and equipment also need to be adopted. Other measures need to be employed to improve efficiency at the management level and enable a comprehensive utilization of resources, lower the environmental pollution, enhance resource utilization efficiency, and realize a clean production of steel and iron.

(9) Development and applications of new energy technologies

With the arrival of the post-petroleum world, the energy security and environmental problems have become increasingly acute. Against this background, there is an urgent need for innovative technologies to cope with issues such as coal gasification, biomass pyrolysis and deoxidization, reclamation of inferior or heavy oil, methanation of syngas, and nuclear power. The key to achieving a successful application of new energy technologies is to develop new equipment and processes to solve problems such as the *in situ* regeneration of catalysts and integrated utilization of waste heat, which are brought by the complexity of feedstock and high process temperatures. Among these research focuses of innovative energy technologies, although coal gasification and the methanation of syngas have been realized, the demand-supply gap is greater than 40%, these technologies are running with high costs. The resource utilization of inferior or heavy oil has been realized in some industrial plants but the technical maturities are not sophisticated enough for mass production. Researches on biomass pyrolysis and deoxidization are still in their early developmental stage. Therefore, the technologies including the novel gasifier and coking furnace, the process coupling the petroleum cracking and biomass pyrolysis, and the exploitation of catalytic cracking of biomass are the research hotspots.

2.2 Understanding of engineering development focus

2.2.1 Optimized design, preparation, and applications of novel thin films and thin-film devices

With the development trend of miniaturization and integration in the electronics, thin films and thin-film devices, as well as their processing techniques have had a significant effect on the wide field of high technological industry, in the forms of large scale integrated circuits, flat-panel displays, electronic components, information recording and storage, microsensors, and thin-film solar cells. Hence, research of thin films and thin-film devices is crucial as it relates to the national development and security.

Thin-film technology has been included in the medium- and long-term development plans of many developed countries. In the USA, it tends to be applied mainly in the military and aerospace field. Japan has a leading role in the use of high-technology products. The EU emphasizes the applications of small power sources, sensors, and products with nanotechnology. As for the research of thin-film materials, while China is in the top list, there still exists a big gap in the research of new thin films and thin-film devices compared with developed countries. Therefore, it is urgent to implement industrialization of new thin films and thin-film devices in China

The different branches of engineering techniques relating to thin-film technology are as follows.

(1) Solar thin films. With the rapid development of solar photovoltaic technology, thin-film solar cells with their unique advantages and mature technology have gradually occupied the entire photovoltaic market at a tremendous growth rate. However, efficient fabrication technologies and thin-film materials are still the bottle neck of large-scale production, which demand that the following challenges be addressed for the development of thin film solar cells: ① lack of deep understanding of some physical science problems; ② making further improvement on existing technologies; ③ using new materials or structures to replace the current expensive and toxic materials; ④ further investigation of precision equipment and key technologies.

(2) Thermoelectric thin films. Thermoelectric materials are well known for their ability to convert of heat into electrical energy. These materials are usually used in the preparation of micro power supplies or electronic chip cooling devices. Furthermore, they can realize quick and efficient active cooling, and achieve refrigeration and heating transformation by changing the direction of the current. Meanwhile, they can even generate electrical power using waste heat. Efficient thermoelectric conversion devices can be prepared as bulk or film materials, and these have many attractive features compared with other methods of refrigeration. These advantages include simple construction, high reliability, no emissions of toxic gases, small volume, no moving parts, and low maintenance. Studies show that the cooling power density of a thermoelectric device is inversely proportional to their size; thin-film thermoelectric devices more effectively improve the efficiency of refrigeration. Thus, research in this field requires devising methods to improve the ZT value of the existing materials system.

(3) Transparent conductive thin films. Transparent conductive oxide thin films are very important photoelectric materials with a wide forbidden bandwidth, high light transmission rate in the visible spectrum, and low resistivity. Because of their excellent photoelectric properties, they are widely used in solar batteries, liquid crystal displays, and even as gas sensors. Presently, this field has developed into new and high technology industry. Thin metal films exhibit good electrical conductivity owing to the free electrons in metals. Therefore, they may be used as transparent conductive films. Unfortunately, metal films typically exhibit poor transparency. In contrast, semiconductor and polymer films display poor electrical conductivity but good transparency. The electrical conductivity and transparency for multilayered films are both very good. The development of transparent conductive films for mass production demands a means to coordinate the requirements of conductivity and transparency. This issue is the bottleneck which restricts the widespread applicability of transparent conductive films. With the development of carbon nanomaterials and other metal-doped composite materials, the performance and applicability of transparent conductive films is likely to increase.

(4) The application of integrated thin-film device. Thin-film integrated circuits are based on thin-film materials that have a thickness of 1 μm and are fabricated by vacuum evaporation, sputtering, electroplating process, and interconnection techniques. Although the components in thin-film circuits are characterized by high precision, good temperature frequency, wide operational wave band, high integration, and small size, the process equipment is relatively expensive, which results in high production costs. Thin-film hybrid integrated circuits are applicable to all kinds of circuits, particularly analogue circuits with the requirements of high precision, stability, and high performance. Compared with other integrated circuits, it is more suitable for use as a microwave circuit. The key issues of integrated thin-film devices that arise during thin-film circuit integration are the interface between the solid-state thin film and substrate, the design compatibility with the structure of the readout integrated circuit, microfabrication process and testing technology, and growth of large-size thin films with low defect density. Compared with the USA and Japan, China has made great progress in the

production of specialty films and has reached the international top level. However, the critical thin-film components still rely on imports. Although some countries are in a leading position in this regard, their research and production is also in its nascent stages. This suggests that the innovation space is very big. Thus, China should seize the opportunities for development and design and produce a variety of integrated structure components, modules, and devices.

At present, research on thin-film materials and devices has been attracting a lot of attention. In particular, developed countries and regions such as Europe, America, Japan, and Korea have all been the leaders in the research and development of thin-film materials and devices as well as the implementation of large-scale industrialization. The basic research performed on specific thin-film materials in China is in the international leading position, but mass production is still dependent on imports. Our independent research and development ability of thin-film materials and devices is insufficient; the overall technology is also relatively immature. In addition, functional thin films are an important part of new materials in the 21st century, such as the back film and ethylene-vinyl acetate copolymer (EVA) film for solar cells, diaphragm of lithium ion battery and nickel metal hydride battery for new energy cells, and diffusion films, optical prism films, composite films, and optical films for the flat panel display, as well as electrical insulation films, semiconductor films, and microelectronics films, which are all urgently required new materials in China. Current functional film production is highly dependent on external enterprises, leading to the immense profits earned by foreign companies. In order to achieve long-term development in China, we must fully devote our attention into developing functional thin films. The manufacturing of high-end films is the future development direction in China.

The main countries or regions and institutions that have published the largest number of core patents in the focus "Optimized design, preparation, and applications of novel thin films and thin-film devices" since 2011 are shown in Table 2.2.1 and Table 2.2.2. The major collaboration networks among countries or regions and institutions are shown in Figure 2.2.1 and Figure 2.2.2. It is evident from the patent distribution of thin-film materials and devices industry that the practical patents are mainly concentrated in European countries and the USA. Although China is in the third place, our core patents, total citation, and average citation are still far behind those in the USA. Among them, the patent agencies with the maximum number of public core patents are largely concentrated in the USA. The total citations is much higher than that of other countries, suggesting that the research in the USA is highly endorsed by the global scientific research workers. Although research in China started late and has not yet been intensively supported, the study of thin-film materials and devices has seen active engagement in recent years. Data shows that great progress in this field might be anticipated, enough to obtain the topmost rank in the world.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	304	43.18%	5320	50.16%	17.50
2	Japan	165	23.44%	2060	19.42%	12.48
3	China	85	12.07%	1015	9.57%	11.94
4	Korea	71	10.09%	1286	12.12%	18.11
5	The Netherlands	34	4.83%	591	5.57%	17.38
6	Germany	17	2.41%	141	1.33%	8.29
7	Taiwan of China	17	2.41%	205	1.93%	12.06
8	France	7	0.99%	27	0.25%	3.86
9	Belgium	6	0.85%	49	0.46%	8.17
10	UK	4	0.57%	40	0.38%	10.00

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Appl Material Ltd.	80	11.36%	1848	17.42%	23.10
2	Samsung	48	6.82%	1014	9.56%	21.13
3	ASM Int Corp	40	5.68%	849	8.00%	21.23
4	Novellus Systems Inc.	39	5.54%	979	9.23%	25.10
5	LAM Res Corp	26	3.69%	385	3.63%	14.81
6	Tokyo Elect Ltd.	26	3.69%	466	4.39%	17.92
7	FUJI Film Corp	15	2.13%	84	0.79%	5.60
8	IBM Corp	11	1.56%	127	1.20%	11.55
9	Konica Minolta Inc.	10	1.42%	119	1.12%	11.90
10	Nitto	9	1.28%	43	0.41%	4.78

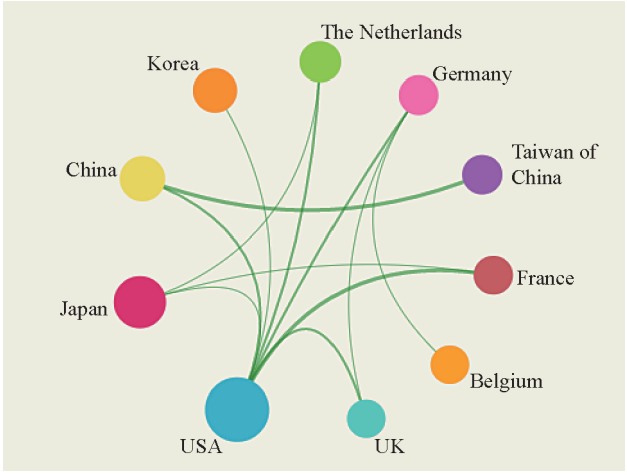

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

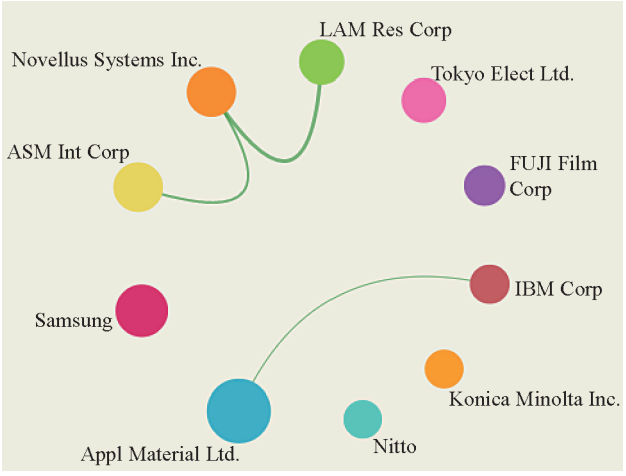

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

Nevertheless, the core institution in this field still needs to be energetically supported in our country.

2.2.2 Preparation and properties of graphene

Since graphene was discovered in 2004, research on this material has been uninterrupted. Graphene is a single-layered carbon sheet with a hexagonal packed lattice structure and shows many unique properties such as quantum hall effect (QHE), high carrier mobility at room temperature (~10 000 $cm^2 \cdot (V \cdot S)^{-1}$), large theoretical specific surface area (~2630 $m^2 \cdot g^{-1}$), good optical transparency (~97.7%), high Young's modulus (~1 TPa), and excellent thermal conductivity (3000–5000 $W \cdot (m \cdot K)^{-1}$). Owing to these features, graphene has been widely applied in batteries, supercapacitors, fuel cells, solar photovoltaic equipment, photocatalysis, sensors, and Raman enhancement. Graphene is a star among the class of similar emerging materials and research on this topic has entered a stage of rapid development. In fact, many countries now regard the research direction of preparation of graphene and its application technology as crucial for long-term strategic development. These initiatives are typically undertaken with the aim of occupying the helm in the industrial revolution.

However, in practice, graphene is not stable and its layers are easily reunited during preparation. This makes it difficult to utilize the full extent of the excellent properties of single layer structure of graphene materials. The key bottleneck for wider use of graphene is the dispersion technology. The fabrication methods of graphene mainly include chemical oxidation-reduction, physical stripping, epitaxial growth, and chemical vapor deposition. Although high-quality graphene can be obtained by using the mechanical stripping method, it suffers from shortcomings of being a low yielding and time consuming process in which it is difficult to precisely control the size of graphene. Monolayers or minority layers of graphene can be fabricated via chemical oxidation-reduction method. However, the effect of strong oxidant damages the sp^2 conjugate structure of graphene, which results in its degradation. Chemical vapor deposition and epitaxial growth methods can be used to prepare high-quality and large-area graphene, but the high cost, complex technology, and strict process conditions restrict the development of graphene. To conclude, the preparation of high-yield, low-cost, and high-quality graphene is still a challenge, leading to its limited applications in the chemical, energy storage, and catalysis fields.

(1) Micro mechanical stripping method. In 2004, scientists first fabricated monolayered graphene from highly-oriented pyrolytic graphite by using the micro mechanical stripping technology. This revealed that graphene with two-dimensional crystal structure can exist. At present, this method can only be used for small-scale laboratory preparation of graphene. Although the quality of the products is very high, the disadvantage of low production rate and the high cost cannot meet the needs for large-scale industrial production.

(2) Chemical vapor deposition method. In this method, the material in the gas phase typically undergoes a chemical reaction, and the solid deposits generated on the surface of a heated substrate form the solid material. This method first achieved the large-scale preparation of graphene. It is possible to realize large-scale preparation of high-quality graphene, but the cost is too high and the process too complex.

(3) Oxidation-reduction method. Oxidation-reduction method is the best method for the preparation of graphene. It has solved the problem of dispersion with the formation of a stable graphene suspension. By reacting with a strong acid and a strong oxidant, graphite oxide is obtained using the ultrasonic disperse technology. Then by adding an appropriate reducing agent, the oxygen-containing functional groups on the surface can be effectively removed to form monolayer graphene. However, this method produces liquid waste pollution and the product may also have some defects. Such defects lead to a loss of electrical performance, which limits the application of graphene.

(4) Solution stripping method. This method involves spreading a small amount of graphite in the solvent and using ultrasonic processes to obtain a low-concentration dispersion. The graphite layer can be peeled off by destroying the interlayer van der Waals forces to obtain graphene. This method does not damage the structure of graphene, and although the quality is very high, the yield is quite low.

(5) Solvothermal method. This method has increasingly attracted because high-quality graphene can be prepared under high temperature and high pressure in the closed system. Although this method allows the preparation of graphene on a large-scale, it inevitably has a negative effect on the electrical conductivity. The combination of the solvothermal method and other preparation methods is expected to become a hotspot in the preparation of graphene.

In recent years, European countries, the USA, Japan, and other countries have started to invest in domestic graphene science and applied research. While the USA mainly focuses on the cutting-edge application of graphene. Defense Advanced Research Projects Agency has developed a graphene-based radio frequency circuit that performs at super-fast speeds and requires very less power to operate. The National Science Foundation of the USA has funded the graphene-based supercapacitor project and continuous and large-scale nano-manufacturing project. The EU has upgraded graphene to strategic importance by considering graphene research in a Future and Emerging Technologies Flagship program, aimed at achieving complete coverage of the entire value chain, from material production to components and system integration. The academia and enterprise in UK are also playing a key role in this process. In 2011, UK's *Innovation and Research Strategy for Growth* clearly outlined graphene as one of the four future focuses. The UK will support research and commercial applications

of graphene, in order to guarantee their leading position in this field and transfer the material from laboratory preparation into the production line and finally to the market in the coming decades. The commercialization process of graphene is mainly promoted by the UK's National Graphene Institute. Germany mainly explores the electronic machinery products of graphene, and the German Research Foundation announced its aim of funding frontier research projects on graphene, whose goal is to improve the understanding and control of graphene properties, and develop new graphene-based electronic products. Korea has constructed a graphene alliance which consists of 41 research institutions including the Korea Advanced Institute of Science and Technology and six other enterprises. A special support fund has also been set up to help enterprises apply and commercialize graphene products and related technology. Japan has instead chosen diversification as the main direction for graphene. In 2007, the Japan Science and Technology Agency started financing graphene/silicon materials/device projects, and exploited advanced auxiliary switch devices and plasma resonance hertz devices. With increasing research into graphene and its applications, the stage for the industrialization of graphene has gradually been set.

It is important to note that graphene has a very wide range of applications. The data in this report comes from the "materials area" patent map, and the data volume and subordinate areas both have some limitations. The detailed analysis based on this data is as follows: Since 2011, the main countries or regions and institutions that have produced core patents in the focus "Preparation and properties of graphene" are shown in Table 2.2.3 and Table 2.2.4. The collaboration networks among the countries or regions and institutions are illustrated in Figure 2.2.3 and Figure 2.2.4. From the perspective of the patent distribution, graphene preparation technology is mainly concentrated in China and the USA, and the former has the largest number of patents in the world in this subject. It explains why China is ranked as the top of the world in this industry, but the average citation is lower than that of the USA. Hence, China should reinforce the fundamental preparation technology of graphene.

Based on the availability of solutions for the key problems in the preparation of graphene, we conclude that it will be more widely used in the future. It is expected that graphene might even replace silicon. Once the process of large-scale preparation of wafer-level graphene films has effective progress, graphene may become the core material of new-generation semiconductor devices, thus bringing a revolution in semiconductor technology and electronic information.

2.2.3 Preparation and applications of aluminum, magnesium, and titanium light metal alloys

The key technique to obtain high-performance aluminum, magnesium, and titanium light metal alloys is to precisely control their shapes and properties during the casting and deformation processes. The successful application of such materials depends on developing high-strength, tough, wear and corrosion resistant aluminum, magnesium, and titanium magnesium alloys.

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Preparation and properties of graphene"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	26	60.47%	689	58.34%	26.50
2	USA	9	20.93%	289	24.47%	32.11
3	Korea	3	6.98%	23	1.95%	7.67
4	Germany	2	4.65%	36	3.05%	18.00
5	Japan	1	2.33%	53	4.49%	53.00
6	Portugal	1	2.33%	22	1.86%	22.00
7	Saudi Arabia	1	2.33%	21	1.78%	21.00
8	Taiwan of China	1	2.33%	14	1.19%	14.00

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Preparation and properties of graphene"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Chinese Acad Sci	6	13.95%	159	13.46%	26.50
2	Nanotek	4	9.30%	133	11.26%	33.25
3	Univ China Petroleum	2	4.65%	77	6.52%	38.50
4	Nanjing Tech Univ	2	4.65%	38	3.22%	19.00
5	Shanghai Jiao Tong Univ	2	4.65%	53	4.49%	26.50

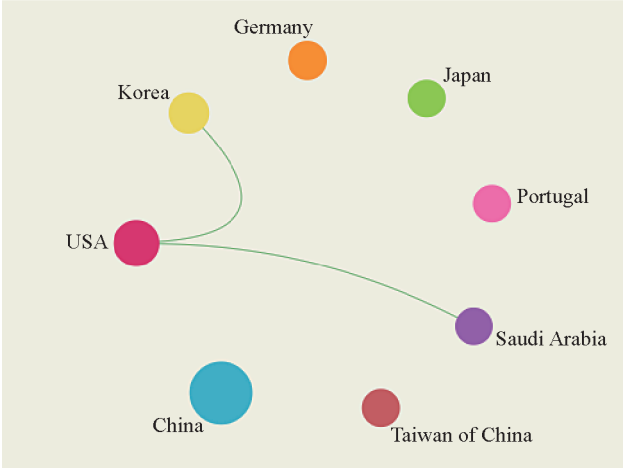

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Preparation and properties of graphene"

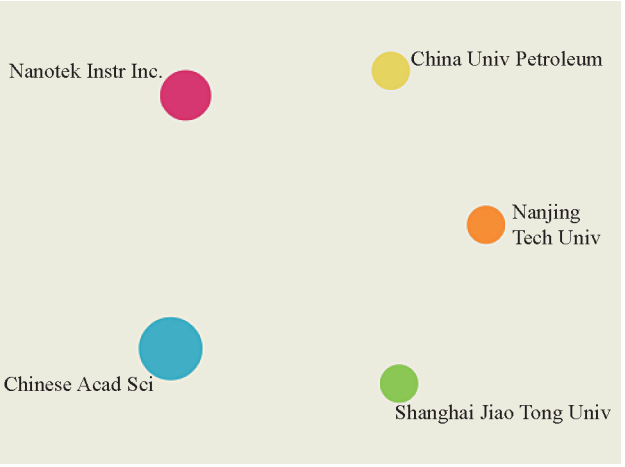

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Preparation and properties of graphene"

High-strength alloys typically include high-strength cast and wrought alloys. At present, the tensile strengths of the most advanced high-strength cast magnesium alloys and cast deformed magnesium alloys are > 400 MPa and > 500 MPa at room temperature, respectively. At present, the issue of improving the toughness of high-strength light alloys is one of the hot areas of research. In fact, improving the plasticity and toughness of high-strength light alloys by grain refinement, developing new structures (such as long period stacking ordered structure, or LPSO structure), interface optimization, and texture design are the research focuses of several countries. The development of high-strength and high-toughness flame resistance magnesium alloys and their application in the field of aerospace and automotive light weight are the future trends. The improvement of corrosion resistance of high-strength and high-toughness light alloys is also one of the important subjects.

In addition to their use as structural materials, magnesium alloys may be employed as biodegradable biomedical magnesium alloys and hydrogen storage materials in the future. Biodegradable magnesium alloys have gained significant attention in recent years because they do not cause any adverse effects typically associated with foreign objects staying in the body for a long time after the implantation of inert medical metal materials such as stainless steel and titanium alloy. The development of biomedical magnesium alloys requires regulation of the main composition and microstructure of the alloys. The comprehensive performance of the alloy depends on good mechanical properties, corrosion resistance, and safe biological degradation, a "three-in-one" requirement, in order to meet the needs of clinical application. The focus of research and development of biomedical magnesium alloys is mainly to control the composition and microstructure of alloys so that they exhibit good comprehensive properties of mechanics, corrosion resistance, safe degradation, and

biocompatibility in order to meet the needs of clinical applications.

Since 2011, the major countries or regions and institutions that have published patents in the focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys" are given in Table 2.2.5 and Table 2.2.6. Collaboration networks between the major countries or regions and institutions are shown in Figure 2.2.5 and Figure 2.2.6. Among them, China ranks the first with 225 published patents, proportion of published patents of 78.95%, total citation as 2479, proportion of citations of 86.8%, and the average citation of 11.02. Japan ranks the second and in this case, the number of published patents was 29, proportion of published patents was 10.18%. Additionally, the total citation, proportion of citations, and the average citation are 178, 6.23%, and 6.14, respectively. The USA ranks the third and the statistics show that the number of published patents, proportion of published patents, the total citation, proportion of citations, and the average citation are 14, 4.91%, 122, 4.27%, and 8.71, respectively. Among the institutions producing core patents, there are seven in China and three in Japan. From the above data, it is evident that the research output from China in this research field occupies an absolute advantage. Nevertheless, further investigations are crucial for progress in this specific research direction.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	225	78.95%	2479	86.80%	11.02
2	Japan	29	10.18%	178	6.23%	6.14
3	USA	14	4.91%	122	4.27%	8.71
4	Korea	6	2.11%	19	0.67%	3.17
5	Germany	3	1.05%	12	0.42%	4.00
6	France	3	1.05%	4	0.14%	1.33
7	Canada	2	0.70%	14	0.49%	7.00
8	Austria	1	0.35%	4	0.14%	4.00
9	Australia	1	0.35%	14	0.49%	14.00
10	Belgium	1	0.35%	9	0.32%	9.00

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	OBE Steel Ltd.	9	3.16%	44	1.54%	4.89
2	Furukawa Unic Corp	8	2.81%	57	2.00%	7.13
3	Beijing Non-Ferrous Metal Inst	7	2.46%	117	4.10%	16.71
4	China Aluminium Corp	6	2.11%	88	3.08%	14.67
5	Univ Beijing Sci & Technol	6	2.11%	47	1.65%	7.83
6	Cent South Univ	6	2.11%	61	2.14%	10.17
7	Alcoa	5	1.75%	33	1.16%	6.60
8	Anhui Xinyi Cable Co., Ltd.	5	1.75%	109	3.82%	21.80
9	UACJ Corp	5	1.75%	25	0.88%	5.00
10	Beijing Univ Technol	5	1.75%	59	2.07%	11.80

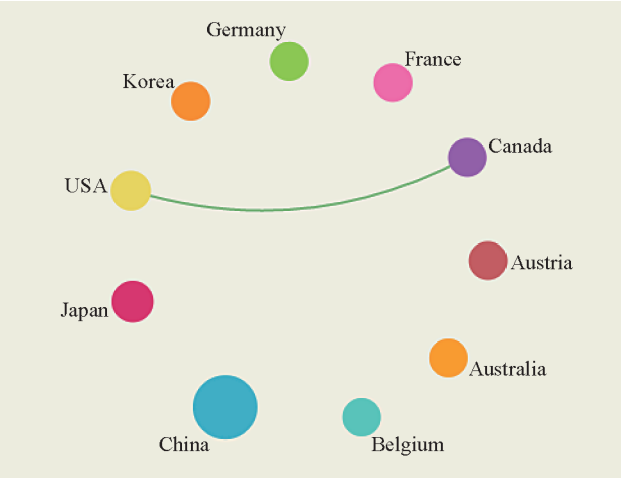

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

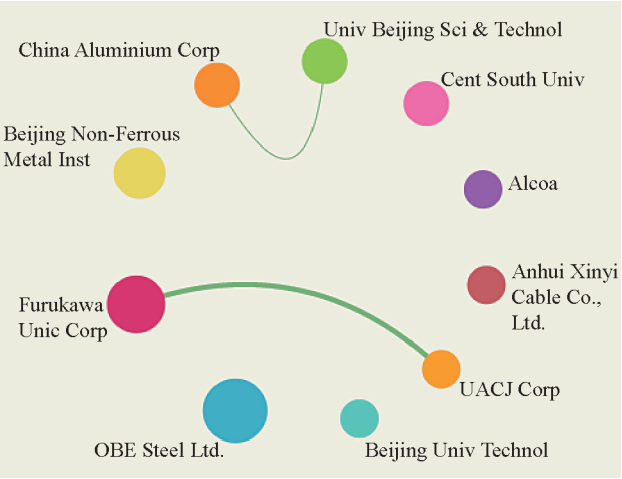

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

Project Participants

Members of the Field Group

Experts of the Field Group

Leaders of the Field Group:

WANG Jingkang, XUE Qunji

Deputy Leaders of the Field Group:

DING Wenjiang, LIU Zhongmin, MAO Xinping, XU Huibin

Other Experts:

DENG Yuan, FENG Yakai, PENG Jinhui, PENG Liming, YE Mao, ZHOU Guifeng

Members of the Secretary Group

Office of the Division of Chemical, Metallurgical & Materials Engineering, CAE:

LIU Yuanxin, WANG Aihong

Editorial office of FCSE and cooperating universities:

CHENG Luli, HUANG Yaodong, WU Yujuan, XU Lei, YANG Zuguo, ZHANG Li, ZHU Wei, ZHU Xiaowen

Report Writers

FENG Yakai, HUANG Yaodong, JIANG Zhongyi, WU Yujuan, XU Lei, ZHU Wei, ZHU Xiaowen

Acknowledgements

We are grateful to the following scholars for their contributions to the project.

Tianjin University:

JIANG Haoxi, LI Xianggao, LIU Cheng, SONG Hao, WANG Fumin, WANG Jianhui, WANG Qingfa, YIN Qiuxiang, YANG Quanhong, ZHANG Lei, ZHANG Minhua, ZHANG Xiangwen, ZHOU Zhijiang

Kunming University of Science and Technology:

DAI Linqing, HAN Zhaohui, JU Shaohua, LI Shiwei, LIU Jianhua, LUO Haoying, XUE Xiuzhen, ZHANG Lihua

Beihang University:

CAO Lili, FENG Jingjing, HAI Fengxun, HE Dalong, HE Jia, PENG Yuncheng, SHEN Shengfei

Dalian Institute of Chemical Physics, Chinese Academy of Sciences

CAO Xupeng, CHEN Jian, GUO Xin, RONG Qian, TONG Yansi, WANG Jing, WANG Quanyi, XIE Hua, XU Zhaochao

Shanghai Jiao Tong University:

DUAN Huanan, JIANG Haiyan, JIN Li, LI Zhiqiang, PEI Jia, ZHENG Feiyan

Research Institute of Wuhan Iron and Steel Company:

WANG Shuize

East China University of Science and Technology:

JI Jiuming

IV. Energy & Mining Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The Top 10 engineering research hotspots (Table 1.1.1) involve a number of research directions in the field of energy and mining engineering[1], among which "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells," "Research and optimization of hybrid renewable energy system," "CO_2 fixation, storage, and utilization," "Solar thermochemical processes," "Wave energy and its potential assessment," and "High-efficiency battery thermal management system" are emerging hotspots, whereas "Flow, heat/mass transfer, and combustion under extreme conditions," "Regional industrial energy efficiency and CO_2 emission reduction," "Stirling engine," and "Structure, materials, and performance of the vertical-axis wind turbine" are developments in traditional research hotspots. The annual numbers of papers of each hotspot published in core journals from 2011 to 2016 are listed in Table 1.1.2.

(1) High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells

The photovoltaic (PV) industry mainly employs PV materials, solar cells and modules, PV inverters, and PV system integration; the key element is the solar cell. At present, commercial solar cells can largely be divided into crystalline silicon solar cells and thin-film solar cells. Scientists, technicians, and even the human kind face the pressing task of developing more efficient, economical,

Table 1.1.1 Top 10 engineering research hotspots in energy and mining engineering

No	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells	87	7724	88.78	2014.05	35.6%	1
2	Research and optimization of hybrid renewable energy systems	49	1395	28.47	2014.24	18.4%	1
3	Flow, heat/mass transfer, and combustion under extreme conditions	212	4888	23.06	2014.00	16.0%	2
4	Solar thermochemical processes	37	1574	42.54	2013.35	16.2%	0
5	CO_2 fixation, storage, and utilization	46	2230	48.48	2014.11	19.6%	0
6	Regional industrial energy efficiency and CO_2 emission reduction	47	1655	35.21	2013.64	6.4%	1
7	Wave energy and its potential assessment	44	1538	34.95	2013.48	11.4%	1
8	Stirling engine	31	919	29.65	2014.39	54.8%	0
9	High-efficiency battery thermal management system	41	1112	27.12	2014.24	9.8%	1
10	Structure, materials, and performance of the vertical-axis wind turbine	41	1068	26.05	2014.00	12.2%	2

[1] The Standing Committee of the Department of Energy and Mining Engineering agreed, on January 15, 2017, that at the first stage of the project, the disciplines of energy and mining engineering should only involve the energy and electrical science, technology, and engineering (thermal power engineering, electrical engineering, hydropower engineering, energy new technology), the nuclear science, technology, and engineering (nuclear energy engineering, nuclear materials and nuclear fuels, nuclear safety, protection, and environment, and applications of nuclear science and technology), the geology resources science, technology, and engineering (oil and gas resources and exploration), and the mining science, technology, and engineering (coal exploration, oil and gas engineering).

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in energy and mining engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells	3	10	12	29	21	12
2	Research and optimization of hybrid renewable energy systems	1	3	6	16	19	4
3	Flow, heat/mass transfer, and combustion under extreme conditions	22	16	30	47	67	30
4	Solar thermochemical processes	5	7	9	5	8	3
5	CO_2 fixation, storage, and utilization	3	5	5	10	17	6
6	Regional industrial energy efficiency and CO_2 emission reduction	3	8	8	14	12	2
7	Wave energy and its potential assessment	6	6	9	9	12	2
8	Stirling engine	0	1	6	7	14	3
9	High-efficiency battery thermal management system	3	0	5	13	16	4
10	Structure, materials, and performance of the vertical axis wind turbine	5	5	6	4	11	10

and environmental-friendly solar cells. Up to present, owing to the flourishing development of the science and the technology of semiconductor materials—predominantly silicon—and because of the low cost and wide application of silicon, commercial solar cells based on silicon p-n junction still dominate the PV market (with a market share of over 90%). Nevertheless, silicon-based structures now have to face increasing competition from other materials, such as various semiconductor thin films and perovskite. The current trends in high-efficiency solar cells involve both the distinctive crystalline silicon (c-Si) solar cells, with an efficiency of higher than 22%, and the development of advanced thin-film solar cells. The high-efficiency crystalline silicon solar cells mainly include amorphous silicon/crystalline silicon heterojunction (a-Si/c-Si HJT) solar cells, back-contact solar cells, back-contact silicon heterojunction (BC-HJT) solar cells, bifacial solar cells, and broad-spectrum solar cells. The current research hotspots in advanced thin-film solar cells include the new perovskite solar cell, the copper–indium–gallium diselenide (CIGS) solar cell, and its substitute, the copper–zinc–tin sulfide (CZTS) solar cell. Focusing on these new PV technologies, scientists in universities and research institutions in America, Germany, Japan, and Switzerland are working together, and have already achieved remarkable breakthroughs.

(2) Research and optimization of hybrid renewable energy systems

Intermittence and fluctuation are intrinsic to renewable energies, such as solar and wind energies, and their outputs can be stabilized through a hybrid renewable energy system. Systems such as solar-wind hybrid power systems and renewable energy-gas turbine (or internal combustion engine) hybrid power systems can take full advantage of renewable energy sources as well as meet the needs of user loads. At present, there are two main categories of hybrid renewable energy systems. One category comprises the combination of different renewable energy sources—such as wind, solar, and water power—in a complementary manner to overcome the discontinuity and instability of a single energy source. The other category comprises hybrid power systems, in which a renewable energy source is combined with existing fossil fuels. Power generation in a hybrid manner can substantially improve energy efficiency, mitigate environmental pollution, and help promote a low-carbon economy and the optimization of the energy mix.

From the engineering perspective, the development of hybrid renewable energy systems calls for knowledge in disciplines such as power machinery, fluid machinery, material, power electronics, and control technologies. The current research hotspots mainly include the topological structures integration, the thermodynamic cycle analysis of hybrid energy systems, the establishment of a dynamic model of hybrid energy systems, the maximum utilization of renewable energy sources, the minimization of the utilization of natural gas, and the overall balance between the supply and demand of different energies.

(3) Flow, heat/mass transfer, and combustion under extreme conditions

Flow, heat/mass transfer, and combustion are closely related to numerous industrial applications in energy utilization systems. These applications entail various extreme conditions, such as high temperature, high pressure, and high heat flux. This engineering research focus contains mainly four branches, including evaporation and condensation, boiling heat transfer, heat transfer optimization, and combustion. Boiling, evaporation, and condensation are the main phenomena that take place in gas-liquid phase change processes, which are widely employed in the thermal management of electronic devices, the desalination of sea water, and the combustion process. Constrained by the fixed heat-transfer area of heat exchangers (heat sinks), heat transfer optimization is the maximization of heat transfer under conditions of high temperature, high pressure, ash and dust-laden settings, and high heat flux by changing the type of heat transfer (heat sink), structures, surfaces, and fluids. Combustion is a high-temperature exothermic redox chemical reaction between a fuel (the reductant) and an oxidant. Combustion devices—such as gas turbines, internal combustion engines, and industrial furnaces—are currently employed as the main method to generate power. The key technologies that are the research focus of contemporary engineering involve multi-phase, multi-component turbulent flows, chemical reactions, and multi-objective optimization; these require extensive study through theoretical analysis, high-precision numerical simulation, and advanced optical diagnostics. While developing basic theories, the theoretical guides and technologies for practical industrial production should not be neglected.

(4) Solar thermochemical processes

In solar thermochemical processes, the solar energy is converted into chemical energy that is stored in hydrocarbon fuels; therefore, the efficient conversion and high-density storage of solar energy becomes possible. This technology enables regions that are rich in solar resources to convert their resources into secondary fuels, which are then transported to different regions. This technology also serves as a solution to the instability and discontinuity of power systems that solely dependent on solar energy.

The applied research of thermochemical processes of solar energy includes fields such as hydrolysis reaction, methane reforming and coupling, coal gasification, and thermal decomposition of fossil fuels. Several advances have been accomplished in the design of high-temperature solar energy thermochemical reactors, the research and development of catalysts, the steam resistance array of complicated solar collector, and the material of high-temperature direct absorption vacuum pipe. In recent years, the utilization and fixation of CO_2 via solar thermochemical processes has attracted considerable attention. Metal oxides act as catalysts or redox mediators (oxygen carriers) to obtain CO or hydrocarbons by decomposing CO_2. The procedure mainly includes CO_2 decomposition and the two-step reaction of redox recycling via the thermochemical process. In that respect, researchers have focused on key technologies, such as the preparation of high-efficiency catalysts, the investigation of reaction dynamics and the mechanisms thereof, and the selectivity of target products.

(5) CO_2 fixation, storage, and utilization

CO_2 is the primary greenhouse gas. Carbon capture and storage (CCS) has been considered to be the predominant solution to the issue of reducing CO_2 emissions. The storage locations include geological structures (reservoirs of petroleum and methane, deep salt marshes, and unmineable reservoirs of coal) and oceans. CCS, deemed as a mature technology, has been put into practice in several regions around the world. Furthermore, attention has also been paid to the evaluation of the cost, the economic benefits, and the safety of CCS. In recent years, CO_2 fixation and utilization through chemical conversion has ignited the interest of the scientists who are committed to decreasing the emissions of CO_2.

CO_2 is put into both physical and chemical use. The physical properties of CO_2 are put into effect when it is used as an air-conditioner refrigerant, a curing hardener, and a food additive. Furthermore, CO_2 is applied in oil displacement technology as well; which also plays a role in CO_2 storage, owing to the fact that it can easily dissolve in crude oil, thus reducing its viscosity. The chemical use of CO_2 presents broader prospects. The activation of CO_2 molecules is a key technology, which is currently realized through biological methods, photochemical and electrochemical reduction, and heterogeneous and homogeneous catalytic reduction. Using CO_2 as a material, it may be realized by synthesizing small molecular compounds or the polymer materials as well (e.g., methane, formic acid, dimethyl carbonate, urea, salicylic acid, carbonate,

carboxylic acid, and hydrocarbons). Much attention has been paid to the synthesis of gases and liquid fuels by CO_2 for the purpose of energy conversion and utilization. The preparation of catalysts with superior conversion efficiency, selectivity, and stability, and both the kinetics and the mechanisms of catalytic reactions have become research hotspots.

(6) Regional industrial energy efficiency and CO_2 emission reduction

The regional industrial energy efficiency measures the benefits produced from energy consumption in the industrial production process within a given area. It is a type of input-output ratio, and it refers to the ratio of the energy cost to the benefits obtained by a company; a lower energy cost indicates higher energy efficiency.

The low comprehensive efficiency of energy utilization (particularly the industrial energy utilization efficiency) is a widespread problem in developing countries. Owing to the rapidly growing economy of China, energy consumption has greatly increased, with the emission of CO_2 rising sharply. Faced with the dual challenge of economic development and CO_2 emission reduction, the regional industry should strictly control the total energy consumption, as well as adjust the industrial structure and transform the pattern of energy utilization from extensive to intensive, thus improving the energy utilization efficiency. The efficiency of coal utilization should be enhanced, and the utilization of renewable energy should be broadened based on the existing domestic energy structure. Moreover, the process of managing the pressures of energy demands while reducing the energy-supply constraints should be improved, in the process of alleviating environment pollution problems brought by energy production. The current research hotspots mainly include energy consumption analysis based on big data, real-time energy consumption measurements and statistics, high-efficiency industrial energy-conversion technology, and CCS technology.

(7) Wave energy and its potential assessment

Energy stored in wave is usually considered as a kind of ramification of solar radiation energy, and comes from wind energy. One of advantages of the wave energy is its high energy quality—mechanical energy of vibration. Furthermore, there is little power loss during wave energy transportation over a long distance. At present, the efforts of the utilization and exploitation of wave energy is mainly focused on the method of the assessing of wave energy deposit and optimization design of power generation devices.

Based on the advanced real-time monitoring system and abundant test data, the research on the assessing method is mainly concentrated on how to adopt a reasonable mathematic model and then precisely predict and estimate distribution of the wave energy deposit in a certain ocean area during a certain future period (short or long), which can provide a theoretical basis and support for feasibility analysis of wave energy exploitation programs.

In general, power generation devices for wave energy can be classified into several types according to extracting methods, such as oscillating water column type, raft-type, pendulum type, duck-like type, overtopping type, point absorber type, and so on. Among these types, oscillating water column power generation device is the earliest developed type. Nowadays, the study of the power generation device is focused on how to develop a kind of wave energy extracting equipment, which not only owns more efficient performance but also can be stably and long-term operated in oceanic environment. In addition, the effects of power generation devices on marine ecological environment and fishery industry development are also evaluated and analyzed in recent years.

(8) Stirling engine

The Stirling engine is an externally heated piston engine that operates with gas as the working medium in a closed regenerative cycle. A typical Stirling engine work cycle includes the following processes: the working medium is heated through the heat exchanger by an external heat source; then it expands and gives out effective power; after that, the working medium is cooled and compressed, and is then reused. The ideal Stirling engine consists of a cylinder with opposed pistons, a heater, a cooler, and a heat regenerator that is installed between two pistons. The pressure-swirl nozzle is typically used in Stirling engines, and it features a simple structure, reliable performance, good atomization performance, and low energy consumption. Up to now, the research on the Stirling engine has focused on the work cycle and the performance of key components.

A wide range of energy sources can be used to power Stirling engine. In addition to conventional diesel, a variety of alternative fuels, including methane, coal-bed methane, natural gas, and even straws and wood, can be used. Therefore, the performance of the Stirling engine using alternative fuels has become a research hotspot, which

mainly focuses on applications in fields such as the combined cooling, heating, and power (CCHP) and standby power stations.

The Stirling engine can operate in environments that are entirely different from the atmosphere. The small vibrations and low noise levels during its operation render it ideal for power generation in submarines during their long voyages, without them leaving trails behind. At present, several countries are committed to the research and development of the Stirling engine used in submarines and submersibles. Therefore, the spray, combustion, and reliability of the Stirling engine under high back pressure are focal points of the research.

(9) High-efficiency battery thermal management system

Battery thermal management, which affects the safety, life, and performance of a battery, ensures that batteries operate in an ideal thermal environment. The following key technical problems should be solved: battery heat generation mechanism and heat generation prediction model, heat transfer medium materials and devices, highly efficient heat management system model and its design method, temperature control of the battery system, temperature difference control between battery cells. Active or passive heat management is performed on the batteries by means of external cooling, heating (or electric heating), or by maintaining a stable temperature throughout the heat transfer medium, which may be air, liquid and phase change materials, or a composite medium. By establishing a coupled simulation model and a method for the thermo-mechanical-electric multi-physics field of the battery system considering the entire working condition and the entire environment temperature condition, the research on the thermal energy management system model and the multi-objective design optimization can help to maintain the temperature of the battery system at an ideal level, and to control the temperature difference between battery cells. A highly efficiency thermal management of the battery system can be achieved via technologies such as heat pipes, heat pumps, and micro-channel heat exchangers. Intelligent control of the battery system temperature can be achieved through temperature feedback from multiple points; this feedback represents the distribution of the temperature field in the battery system. It is expected that the following studies will be carried out: thermal energy management technology based on advanced phase change materials combined with fluid heat transfer; the predictive control of battery thermal management based on battery heat generation prediction; active lean thermal management for battery cell or battery system partition; internal temperature adjustment thermal management technology of the battery cell through the external current pulse excitation or built-in heating circuit using the battery's own energy.

(10) Structure, materials, and performance of the vertical-axis wind turbine

The vertical-axis wind turbine is a type of small- and medium-sized wind power equipment, which can be easily installed and maintained, and has low start-up wind speed. It features prominently in the use of wind energy. It can be classified into three types, namely the drag type, the lift type, and the lift-drag type, according to the operation principle of the wheel blade. Compared with the traditional wind turbine, the vertical-axis wind turbine presents the following advantages: ① efficient use of the wind field, smaller operation area, simple structure, low weight, convenient maintenance, good response to wind from all directions, and strong wind resistance; ② longer service life and less noise pollution; ③ no need for the tail and yaw system to drive the blades; and ④ the speed-increasing gear box and generator can be installed on the ground. This type of wind turbine can be combined with solar power, small hydropower, natural gas power generation, and geothermal power to build complementary power systems.

Wind power generation technology is a comprehensive and systemic engineering that involves disciplines such as aerodynamics, computational fluid dynamics, material mechanics, automatic control, and electromechanics. The main research hotspots are the aerodynamic analysis of the blades, the high-performance blade design technology, the structural dynamics optimization, and the connection of wind turbines to the grid and control techniques.

1.2 Understanding of engineering research focus

1.2.1 High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells

(1) Concept elaboration and development status

Fossil fuels help promote the development of human

society; however, the excessive consumption of the fossil fuels leads to global warming and deterioration of the environment as well, thus posing an enormous threat to the survival of mankind. Most countries have expressed their willingness to change their energy consumption strategies and develop renewable energies. Among various renewable energy sources, solar energy has attracted considerable attention because it is an inexhaustible, clean, and safe energy that can be used in several regions. In recent decades, although renewable energies represented by solar PV power generation have been growing rapidly, solar PV accounted for only 1.2% of the global electricity generation capacity by the end of 2015. In addition, the PV-generated electricity in China was 66 200 GW·h in 2016, which only accounted for 1.1% of China's electricity consumption. It is anticipated that PV-generated electricity will account for more than 10% of the global energy supply in 2030, and will thus contribute substantially to the global energy supply and the adjustment of the global energy mix. Therefore, the solar PV industry has bright prospects both in China and in the rest of the world. The solar PV industry mainly includes PV materials, solar cells, PV modules, PV inverters, and PV system integration; the key element is the solar cell. At present, commercial solar cells can largely be divided into crystalline silicon solar cells and thin-film solar cells. It is a pressing task facing scientists, technicians and even the human kind to develop more efficient, economical and environmental-friendly solar cells.

Up to present, owing to the flourishing development of the science and the technology of semiconductor materials—which are predominantly silicon—and because of the low cost and wide application of silicon, commercial solar cells based on silicon p-n junction still dominate the PV market (with a market share of over 90%), Nevertheless, silicon-based structures now have to face increasing competition from other materials, such as various semiconductor thin films and perovskite. The current trends in high-efficiency solar cells involve both the distinctive c-Si solar cells, with an efficiency of higher than 22%, and the development of advanced thin-film solar cells. The high-efficiency crystalline silicon solar cells mainly include a-Si/c-Si HJT solar cells, back-contact solar cells, BC-HJT solar cells, bifacial solar cells, and broad-spectrum solar cells. The current research hotspots in advanced thin-film solar cells include the new perovskite solar cell, the CIGS solar cell, and its substitute, the CZTS solar cell. Crystalline silicon solar cells present great commerical potentials owing to their high efficiency, stable performance, and the abundance of silicon. Futhermore, several advanced industrial techniques are already available for c-Si solar cells. The present mainstream techniques, e.g., the passivated emitter and rear cell (PERC) and the bifacial solar cell, have both been industrialized in earnest (with efficiencies of 21.0%–21.5%). In addition, the industrial processes of a-Si/c-Si HJT solar cells, back-contact solar cells, and broad-spectrum solar cells are developing rapidly. The next-generation technology—the back-contact silicon heterojunction solar cell—is growing more and more mature. In contrast, there is room for improvement for the advanced thin-film solar cells to reach mass industrial production levels. At the present stage, the work on perovskite solar cells is mainly focused on improving the efficiency and long-term stability, increasing the cell area, and finding nontoxic substitutes, whereas the industrial process is only at the beginning. The work on CIGS solar cells technology is focused on narrowing the wide gap between the efficiency of industrial modules (~16%) and that of the small-area solar cells fabricated in laboratories, and on replacing CIGS with CZTS. It is expected that thin-film solar cells, with the flexible thin-film battery leading the way, will play an important role in the development of future PV technology as well, owing to their low material consumption, increased efficiency, and their flexibility. In fact, flexible solar cells, which use flexible materials such as plastic or metal as a substrate, have always been a subject of interest owing to their wide range of applications.

(2) Current situation in China

Since 2005, the China's PV industry has realized striking progress. Approximaely 75% of all PV modules produced in the last two years were made in China, which is expected to remain the largest PV producer in the following years. At present, the conversion efficiency of conventional single crystalline silicon solar cells has reached 20%–21%, and that of the multi-crystalline silicon solar cells has reached 18%–19%. Most China's PV companies focus on conventional crystalline silicon solar cells; therefore, the China's PV industry may obtain a leading position in this domain, establsihing the PV industry as one of the few emerging strategic industries of China with international competence. Certain important China's PV firms, universities, and research institutions are pursuing break-

throughs in the mass production of crystalline silicon solar cells that present an efficiency of over 22%. With the support of national projects—863 Program—and through international collaborations, the technologies of a-Si/c-Si HJT solar cells and back-contact solar cells have significantly progressed. However, the research on back-contact silicon heterojunction solar cells is only at its beginning, and falls behind compared to that of developed countries. In the past few years, there has been rapid progress in the research and industrialization of perovskite solar cells; China is already a competitive player in this technology. Although several universities and research institutions in China have started studying CIGS solar cells a long time ago, there is still great room for improvement to level with advanced players. In the past few years, certain key China's companies that focus on thin-film solar cells have been importing or even purchasing CIGS from PV companies with advanced fabrication techniques from Europe and the USA to improve China's CIGS technology. Consequently, China has become one of the leading players with its rapidly-growing CIGS technology. It should be pointed out that China still lacks a national PV laboratory similar to the Fraunhofer Institute for Solar Energy Systems (ISE) in Germany, the National Renewable Energy Laboratory (NREL) in America, the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, and the Energy research Centre (ECN) in the Netherlands. The research on solar cells in China is mainly conducted in universities, research institutions, and key PV companies. Although the China's Ministry of Science and Technology established two national key laboratories several years ago, they were both inside PV companies; this affects the application and spread of advanced PV technologies.

Although China is a large PV manufacturer, it is still not a major PV technology innovation center. We should be aware of the severe situation faced by the PV industry. Currently, researchers in universities and research institutions in the USA, Germany, Japan, and Switzerland closely collaborate, and have made great progress in CIGS solar cells, perovskite solar cells, a-Si/c-Si HJT solar cells, back-contact solar cells, back-contact silicon heterojunction solar cells, perovskite/crystalline silicon tandem solar cells, bifacial solar cells, and broad-spectrum solar cells. When basic research on innovative PV techniques is conducted at the highest level around the world, what strategies should China's PV specialists follow? Should China be satisfied with only being a large PV manufacturer? Only through innovation at the source and through institutional reforms can China become an advanced and innovative industrial PV power.

(3) Major countries and research institutions

In the research on distinctive high-efficiency crystalline silicon solar cells, American and Japanese companies are frontrunners. The American company SunPower and the Japanese company Panasonic have manufactured solar cells with an efficiency topping 24%, and realized the industrialization of solar cells with average efficiencies of 22.5%–23.0% by using interdigitated back contact and a-Si/c-Si HJT, respectively. Recently, the Japanese firm Kaneka has produced a crystalline silicon solar cell with a record efficiency of 26.6% by adopting the back-contact Si HJT technique. Although China has been progressing in the development of the advanced thin-film solar cells, the best techniques have been mastered in Europe, Japan, and Korea. The European thin-film solar cell alliance "Solliance" and the Ulsan National Institute of Science and Technology of Korea have both developed millimeter-sized perovskite solar cells with an efficiency that reaches 22.1%. In addition, the École polytechnique fédérale de Lausanne (EPFL) in Switzerland and the University of Oxford in England are at the forefront of the research on perovskite solar cells. The Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) in Germany and the Solar Frontier of Japan have produced CIGS solar cells with an area of 0.5 cm^2 and efficiencies of 22.6% and 22.3%, respectively. Another recently developed field is the perovskite/silicon tandem solar cell. In 2017, Stanford University, collaborating with other universities and corporations, announced that its perovskite/crystalline silicon tandem solar cells (with an area of 1 cm^2) had reached an efficiency of 23.6%.

From Table 1.2.1, it may be seen that the major countries in which high-efficiency solar cells are studied are the USA, Germany, Japan, Switzerland, and Spain. Table 1.2.2 indicates that the research institutions that develop high-efficiency solar cells mainly include Ecole Polytech Fed Lausanne, IBM Corp., and the Fraunhofer Inst Solar Energy Syst.

Figure 1.2.1 shows the collaboration relationships between the major countries that contribute to the development of high-efficiency solar cells, which include thin-film, perovskite, silicon heterojunction, back-contact, and

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	USA	28	32.18%	4351	61.97%	155.39	8	1
2	Germany	16	18.39%	929	13.23%	58.06	3	0
3	Japan	14	16.09%	763	10.87%	54.50	2	0
4	Switzerland	13	14.94%	587	8.36%	45.15	3	0
5	Spain	7	8.05%	238	3.39%	34.00	1	0
6	Australia	5	5.75%	160	2.28%	32.00	0	0
7	China	5	5.75%	157	2.24%	31.40	0	0
8	Korea	4	4.60%	205	2.92%	51.25	0	0
9	England	4	4.60%	93	1.32%	23.25	1	0
10	France	3	3.45%	164	2.34%	54.67	1	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Ecole Polytech Fed Lausanne	9	10.34%	458	6.52%	50.89	2	0
2	IBM Corp	7	8.05%	1977	28.16%	282.43	3	1
3	Fraunhofer Inst Solar Energy Syst	7	8.05%	295	4.20%	42.14	1	0
4	Grad Univ	6	6.90%	196	2.79%	32.67	0	0
5	Okinawa Inst Sci & Technol	6	6.90%	196	2.79%	32.67	0	0
6	IREC	6	6.90%	167	2.38%	27.83	1	0
7	Catalonia Inst Energy Res	6	6.90%	167	2.38%	27.83	1	0
8	Univ Calif Los Angeles	5	5.75%	572	8.15%	114.40	0	0
9	Helmholtz Zentrum Berlin Mat & Energie	5	5.75%	389	5.54%	77.80	2	0
10	Purdue Univ	5	5.75%	238	3.39%	47.60	3	0

Note: IREC stands for the Interstate Renewable Energy Council.

back-contact silicon heterojunction structures. Figure 1.2.2 shows the collaboration networks among major research institutes that focus on the aforementioned research field.

Table 1.2.3 lists the major producing countries or regions of citing core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells." It may be seen that the USA, Germany, and Switzerland are the top 3 countries. Table 1.2.4 lists the major producing institutions of citing core papers on the aforementioned engineering research focus. Ecole Polytech Fed Lausanne, the IREC, and the Catalonia Inst Energy Res are the top 3 institutions.

1.2.2 Research and optimization of hybrid renewable energy systems

Developing renewable resources is an important approach to solving the problems of energy utilization and environment pollution in the world; it is an inescapable option and an effective measure to maintain the sustainable development of energy utilization. In the past ten

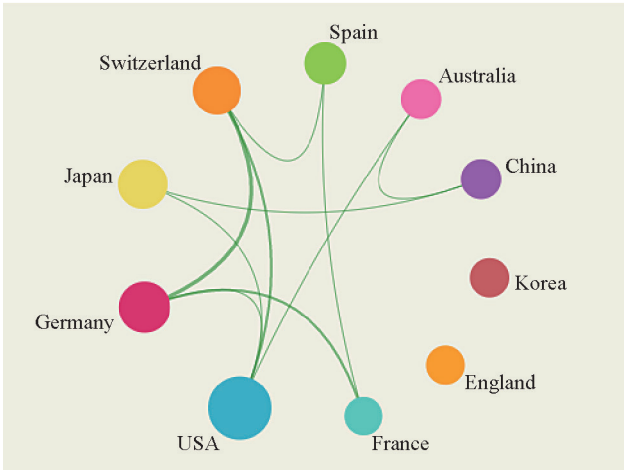

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"[1]

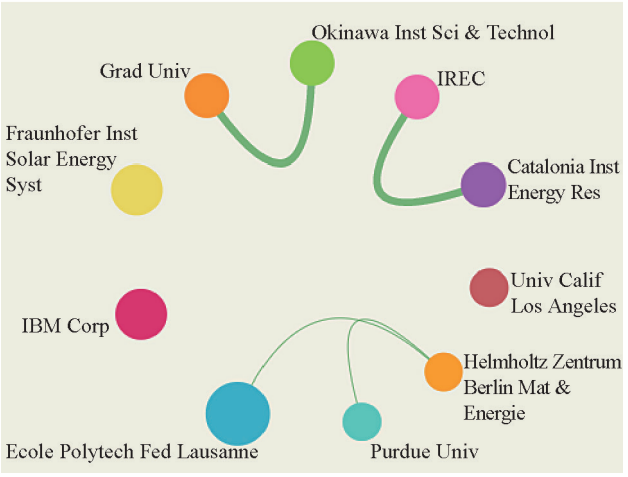

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	23	25.84%	2013.87
2	Germany	12	13.48%	2013.92
3	Switzerland	12	13.48%	2014.33
4	Japan	10	11.24%	2015.00
5	Spain	6	6.74%	2014.67
6	Australia	5	5.62%	2014.80
7	China	4	4.49%	2014.75
8	England	3	3.37%	2014.33
9	Korea	3	3.37%	2014.33
10	France	2	2.25%	2015.50

years, the hybrid renewable energy system has attracted more and more attention worldwide.

From the perspective of availability of renewable energies and technology maturity, the hydropower, the wind power, and the solar power are the most realistic energy resources with broad prospects. A hybrid energy power system typically consists of two or more sets of distributed power supplies, an energy storage system, and various power electronic control devices. At present, there are two main categories of hybrid renewable energy systems. One category comprises different renewable energy sources—such as wind, solar, and water power—in a complementary manner to overcome the discontinuity and instability of a single energy source. The other category comprises hybrid power systems, in which a renewable energy source is combined with existing fossil fuels. Power generation

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Ecole Polytech Fed Lausanne	8	5.33%	2014.50
2	IREC	6	4.00%	2014.67
3	Catalonia Inst Energy Res	6	4.00%	2014.67
4	IBM Corp	6	4.00%	2013.17
5	Univ Calif Los Angeles	5	3.33%	2013.20
6	Helmholtz Zentrum Berlin Mat & Energie	5	3.33%	2014.20
7	Grad Univ	4	2.67%	2015.50
8	Fraunhofer Inst Solar Energy Syst	4	2.67%	2013.75
9	Natl Renewable Energy Lab	4	2.67%	2013.50
10	Univ Barcelona	4	2.67%	2014.25

in a hybrid manner can substantially improve energy efficiency, mitigate environmental pollution, and help promote a low-carbon economy and the optimization of energy mix.

From the engineering perspective, the development of hybrid renewable energy systems calls for knowledge in disciplines such as power machinery, fluid machinery, material, power electronics, and control technologies.

Renewable energy sources, such as wind power and solar power, are naturally complementary, and the hydropower has the ability to adjust quickly. From the perspective of time, solar energy is abundant during daytime, whereas the wind is quite weak. However, this situation is reversed during nighttime. During sunny days, sunlight is strong, whereas wind is weak; on the other hand, this situation is reversed during rainy days. The time limitation in solar power generation and the instability of wind power generation are the inherent defects of these energy sources. Wind-solar power generation can become a reliable groundwork for the development of national economy only if they are combined with the standby powers with considerable scale and better adjustment abilities. The hydropower is a type of large-scale power supply with good adjustment performance. It can be utilized to overcome the intermittence and instability of photovoltaic and wind power generation. The wind-solar-water power system can ensure the quality of the power supply. Therefore, it is critical to ensure that the power supply of the hybrid renewable energy system is continuous and stable.

Regarding the instability of renewable energies, such as wind and photovoltaic power, China utilizes thermal power and hydropower for the peak regulation of the power system. The combined power system of renewable energies and natural gas can be used in the peak regulation of the power system; this may improve the adaptability of the power grid to the changing load, while being more environment-friendly as well. The low emission of gas turbines offers great environmental benefits; they can substitute the coal-powered engine, and can contribute to peak regulation, particularly in well-developed cities that suffer from continuously increasing pollution.

To date, domestic and foreign institutions and researchers have conducted extensive research in the field of hybrid power generation technology. The latest research trends that are related to hybrid power generation, including wind-solar systems and renewable energy-fossil fuel systems, will be introduced in the following sections.

(1) Development status of wind and solar hybrid power systems

In terms of research and development on optimization software, the US Renewable Energy Laboratory has developed the HYBRID2 and HOMER systems to simulate and optimize wind-solar hybrid power systems. Based on a genetic algorithm, the University of Zaragoza developed an optimization software package that can be applied in complementary hybrid power systems, such as wind-solar and solar-diesel engine hybrid systems. In addition, the hybrid power system of the solar-diesel engine was improved and optimized.

In terms of practical applications, a skyscraper was built

in 2007 in Dubai (United Arab Emirates), the power of which is supplied by both solar photovoltaic power equipment and wind turbines. This project is the first combination of urban buildings and solar-wind hybrid power systems, which carved a new path in the application of hybrid power systems. In 2009, China built the first national wind & solar & storage demonstration project at the wind farm located in the Shangyi and Zhangbei County in Zhangjiakou City of the Hebei Province. There are 500 MW of wind power and 100 MW of photovoltaic power generation systems, and energy storage systems with a storage capacity of 75 MW.

In recent years in China, various forms and sizes of hybrid renewable energy systems have been widely applied to street lights, remote oil well equipment, highway appliances, navigation stations, oil and gas delivery and heating devices, natural reserves, residential areas, industrial parks etc.

(2) Development status of other forms of hybrid power systems

Domestic and foreign scholars have conducted studies and analyses on hybrid power generation technologies, such as wind-hydrogen-biomass-solar hybrid power systems, wind and diesel hybrid power systems, underground coal gasification and high-temperature fuel cell hybrid power systems, solar and fuel cell hybrid power systems, and solar and geothermal flash hybrid power systems.

The first wind-hydrogen-biomass-solar hybrid power p lant in Germany was officially put into operation in 2010; this power plant uses wind and solar power to generate electricity. The electricity is partly connected to the grid, and the remaining part is used to electrolyze water in order to produce hydrogen power. The total installed capacity is 6 MW, and when the wind and solar power cannot meet the demand, the hydrogen and biomass energy can be utilized as a supplementary energy-generation capacity. Norway has built a new type of wind and diesel hybrid power plant with an installed capacity of 2000 kW, which conserves more than 50% of fuels. In the Sequoia National Park of the USA, Schatz Energy Research Center of Germany and the Yurok Tribe built together a solar-cell and fuel-cell hybrid power system, which provides electricity mainly for wireless communication relay stations in remote areas, with a total efficiency of up to 64% and a net efficiency of over 48%.

In Europe, to meet the objectives of the European Commission project entitled "Photovoltaic fuel-cell hybrid system for electricity and heat production for remote sites (PVFC-SYS)", a solar-cell and fuel-cell hybrid power system was built in France, the net efficiency of which reaches up to 50%. As geothermal energy has the advantage of stability, a solar–geothermal hybrid energy pilot plant was built in Aydin, Turkey, in 2014.

(3) Future trends

Hybrid renewable systems, a systematic engineering, utilize a variety of renewable energy resources to complement each other in accordance with the conditions of different energy resources and the applications of the generated power. Through intelligent coordination control and optimal dispatch, comprehensive energy efficiency is improved, renewable energy accommodation is promoted, and the benign cycle of ecological environment becomes facilitated. At present, there are two main models.

Terminal integrated power supply system: it mainly focuses on electricity, heating, cooling, gas, and other demands of end users. As an integrated energy supply infrastructure, it is operated in line with local conditions, and uses traditional energy and new energy in a complementary manner. This type of system could meet the objectives of coordinated supply of multiple energies and comprehensive cascade utilization of energy, typically through the use of various of modes, such as the combined heating, cooling, and electricity (CHCP) system that is fueled by natural gas, the distributed renewable energy, and smart micro-grid systems.

Wind & solar & hydropower & gas & storage multi-energy complementary system: this system mainly presents the advantage of utilizing a comprehensive energy base, where wind power, solar power, hydropower, coal, and natural gas are combined to generate electricity. Moreover, it utilizes the ability of regulating the peak electricity load of cascade hydropower stations and thermal power plants that have flexible adjustment abilities. The integrated operation can enhance the stability of the power output, promote the accommodation of intermittent renewable energies, including wind and solar power, and enhance the overall benefits.

According to Table 1.2.5, countries that produce the highest number of core papers in "Research and optimization of hybrid renewable energy systems" are India, China, Iran, Greece, and Malaysia; the proportion of core

papers in India, China, and Iran are more than 10%. From Table 1.2.6, it may be observed that the institutions with the highest number of core papers in this research field are the Hong Kong Polytech Univ, Univ Tehran, and the Univ Malaya, where the proportion of core papers in the Hong Kong Polytech Univ and the Univ Tehran is over 10%.

In Figure 1.2.3, it may be observed that Iran, Malaysia, Indonesia, and the US have placed greater focus on the collaboration with other countries and regions in this research field. Iran has a cooperative relationship with three countries, and has co-published several papers. China has large number of published papers as well, many of which are works that have been produced in collaboration with the USA. India has the highest number of published papers; however, scarce are in collaboration with other countries and regions.

According to Figure 1.2.4, Institutions that actively cooperate with other institutions are the Univ Tehran, the Univ Malaya, and the Univ Tenaga Nas, all of which have a cooperative relationship with each other; their respective number of published papers rank in the top 5 positions. Two Indian institutions maintain a cooperative relationship with each other. The Hong Kong Polytech Univ in Hong Kong of China, is the institution that has published the highest number of papers; however, it has not collaborated with other organizations.

In July, 2016, in order to accelerate the multi-energy complementary integrated optimization demonstration project, the National Development and Reform Commission and the National Energy Administration issued *Implementation suggestions on the promotion of the multi-energy complementary integrated optimization demonstration project*. This document aims to accelerate the construction of multi-energy complementary integrated optimization demonstration projects of renewable energy, so as to improve energy system efficiency, increase effective energy supply, meet reasonable demands, drive efficient investment, and promote stable economic growth.

There are two modes of integrated demonstration projects defined in the document: one is the terminal integrated system that is based on the electricity, heating, cooling, gas, and other energy needs of users; the other one is the wind & solar & hydropower & gas & storage multi-energy complementary system that has the advantage of utilizing a comprehensive energy base, where wind power, solar power, hydropower, coal, and natural gas are combined to generate electricity. The National Energy Administration announced as many as 23 first demonstration projects, including 17 projects of the first mode, and 6 projects of the second mode.

The development of the hybrid renewable energy system is important in the construction of the intelligent energy system of "Internet Plus", which is conducive to the improvement of the coordination ability of the renewable energy supply by promoting the utilization of renewable energies, reducing the waste of solar, wind, and hydropower owing to shortage in the accommodation ability of the power grid, and by enhancing the comprehensive

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	India	9	18.37%	119	9.92%	13.22	0	0
2	China	8	16.33%	329	27.42%	41.13	2	0
3	Iran	7	14.29%	175	14.58%	25.00	0	0
4	Greece	4	8.16%	124	10.33%	31.00	0	0
5	Malaysia	4	8.16%	123	10.25%	30.75	0	0
6	USA	4	8.16%	116	9.67%	29.00	1	0
7	Algeria	3	6.12%	81	6.75%	27.00	1	1
8	Canada	3	6.12%	79	6.58%	26.33	0	0
9	Indonesia	3	6.12%	75	6.25%	25.00	0	0
10	Korea	3	6.12%	46	3.83%	15.33	1	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Hong Kong Polytech Univ	5	10.20%	221	18.42%	44.20	1	0
2	Univ Tehran	5	10.20%	136	11.33%	27.20	0	0
3	Univ Malaya	4	8.16%	123	10.25%	30.75	0	0
4	Indian Inst Technol	4	8.16%	35	2.92%	8.75	0	0
5	Univ Tenaga Nas	3	6.12%	110	9.17%	36.67	0	0
6	Natl Tech Univ Athens	3	6.12%	95	7.92%	31.67	0	0
7	Univ Washington	3	6.12%	60	5.00%	20.00	0	0
8	Indian Inst Technol Roorkee	3	6.12%	29	2.42%	9.67	0	0
9	Technol Educ Inst Crete	2	4.08%	60	5.00%	30.00	0	0
10	Norwegian Univ Life Sci	2	4.08%	56	4.67%	28.00	0	0

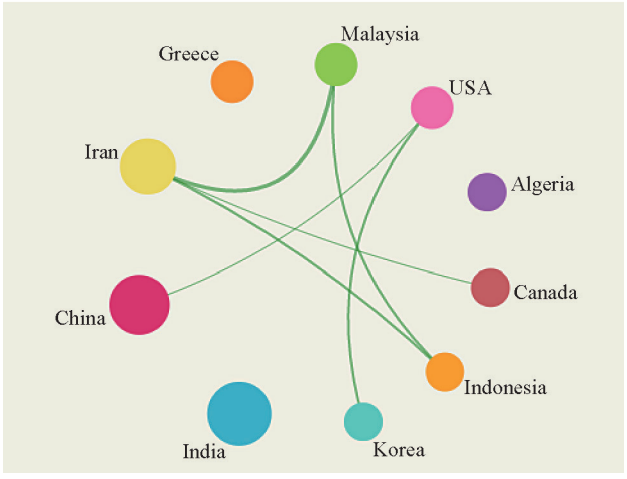

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

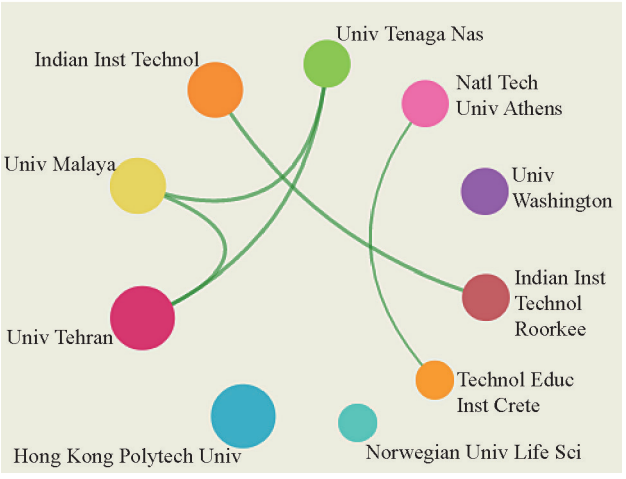

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

efficiency of the energy system, which is of great significance in terms of facilitating the shift of the energy mix and the construction of a low-carbon and high-efficiency energy system. From the perspective of technological prowess and development trend, China is leveling with or advancing with the same pace as other players; however, its development is quicker than that of the vast majority of countries.

Certain suggestions for the development of the hybrid renewable energy system of China are the following. First, policy support should be enhanced, and efforts should be made to ensure that the implementation of the introduced policy is effective. Second, the energy pricing mechanism should be improved in a manner that reflects the technical advantages and comprehensive benefits of the multi-energy complementary integrated optimization project. Third, a corresponding power dispatch and a market trading mechanism should be established to support the operation of the multi- energy complementary system. Fourth, the standardization system should be improved, and the multi-energy complementary technology and the access to the electricity (gas) network should be standardized. Fifth, the supervision of the planning and the implementation of the major multi-energy integrated optimization demon-

stration projects should be strengthened. Sixth, a sector corresponding to the "Information Management System of Renewable Energy Power Project" should be set up to facilitate the project information entry, the project management, and the electricity subsidy declaration.

Table 1.2.7 shows that the countries with the largest output of citing core papers are India, Iran, and China; the proportion of citations for all three countries tops 10%. In Table 1.2.8, it may be observed that the institutions with the most output of citing core papers are the Hong Kong Polytech Univ, the Univ Tehran, and the India Inst Technol, among which the proportion of citing core papers of the Hong Kong Polytech Univ and the Univ Tehran exceeds 5%. It can be inferred that the research output and the citations of the core papers of China in this particular research field are at the forefront compared with other countries; however, most of the research output is produced from institutions located in Hong Kong, China. There is still a gap between the institutions of China's mainland and those of Hong Kong of China and foreign institutions in terms of the number of papers.

1.2.3 Flow, heat/mass transfer, and combustion under extreme conditions

(1) Concept elaboration

This engineering research focus contains four main branches, namely the evaporation and condensation, the boiling heat transfer, the heat transfer optimization, and the combustion. Harsh extreme conditions are involved in their practical applications, such as high temperature, high pressure, and high heat flux. Boiling, evaporation, and condensation are the main phenomena that take place in gas-liquid phase change processes, which can be observed in our daily life. Evaporation and condensation play a very important role in the thermal management of electronic devices, the desalination, and the combustion process. When the fuel droplets are injected into extreme environments—such as the internal combustion engines, where the temperature is high, and wall contact takes place —the phase transition processes could directly affect the efficiency of combustion. Boiling heat transfer demonstrates great potential in the fields of heat dissipation in electronic devices and spacecraft, with very high heat flux. Under the constraints of fixed heat exchange areas of heat exchangers (or heat sinks), heat transfer optimization aims to maximize heat transfer under conditions of high temperature, high pressure, ash and dust-laden settings, and high heat flux by changing types, structures, surfaces, and fluids of the heat exchanger (or heat sink). Heat transfer optimization has been widely used in the design of heat exchangers and the system optimization of industrial processes, such as waste heat utilization. As the major means to generate power at present, combustion is widely used in several applications, such as gas turbines, internal combustion engines, and industrial furnaces. As combustion processes directly determine the power output, stability, emission, and fuel conversion efficiency of the equipment, the primary goal of the research teams in this field is to

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	India	8	17.39%	2015.38
2	Iran	6	13.04%	2014.33
3	China	5	10.87%	2014.40
4	Indonesia	3	6.52%	2014.00
5	Malaysia	3	6.52%	2014.00
6	USA	2	4.35%	2014.50
7	Canada	2	4.35%	2014.00
8	Greece	2	4.35%	2013.00
9	Korea	2	4.35%	2014.50
10	Algeria	2	4.35%	2014.50

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Hong Kong Polytech Univ	4	6.56%	2014.25
2	Univ Tehran	4	6.56%	2014.25
3	Indian Inst Technol	3	4.92%	2016.00
4	Univ Malaya	3	4.92%	2014.00
5	Grad Univ Adv Technol	2	3.28%	2015.00
6	Indian Inst Technol Roorkee	2	3.28%	2016.00
7	Natl Inst Technol	2	3.28%	2015.00
8	Syiah Kuala Univ	2	3.28%	2013.50
9	Univ Ontario	2	3.28%	2014.00
10	Univ Tenaga Nas	2	3.28%	2013.50

find a series of techniques to achieve a highly efficient, stable, and clean combustion process for a wide range of working conditions. As the basic unit affecting the macroscopic characteristics of combustion, micro-combustion is attracting growing attention.

(2) Key technologies to be explored, and developments in different countries

Evaporation and condensation are the processes of liquid vaporization and gas liquefaction, respectively. Understanding the mechanism of evaporation and condensation has become a research hotspot because these two phenomena are closely related to the combustion process. One of the main issues in this research subject is the experimental measurement and theoretical modeling of the evaporation rate under various operating conditions. The challenges arise from multi-component fluids, droplet deformation, the geometrical shape of the droplet, droplet-to-wall interaction, and temperature differences between the liquid and the gas. The research methods include the integration of theoretical models based on physical processes with computational fluid dynamics (CFD) calculations, as well as obtaining measurements through visualization methods, such as particle image velocimetry (PIV) and high-speed cameras. Future research fields may include the study of the condensation mechanism of droplets on the nano-surface, and the determination of the evaporation coefficient through molecular simulations and statistical mechanics. International research on evaporation and condensation is concentrated in Europe and Asia. European teams, including several teams in Russia and the UK as well, have conducted some research on the evaporation of droplets. Asian researchers, such as China's and Pakistani scholars, focus on the direct contact condensation.

Boiling heat transfer refers to the heat transfer between the liquid and the heating surface, when the temperature of solid wall exceeds the liquid saturation temperature; it is highly efficient because the generated bubbles remove a significant amount of heat through vaporization. By changing the morphologies and wettability of the solid heat transfer surface, and by changing the liquid properties via the addition of nanoparticles and surfactant, the heat transfer coefficient and critical heat flux can be increased, thus meeting the heat dissipation needs of high heat flux electronic devices and spacecraft, which has become a trend in the research on boiling heat transfer. In China, the studies on boiling heat transfer are mainly conducted experimentally, and numerical simulations are conducted as well. Experimental studies in China focus on changing fluid properties (adding nanoparticles and surfactant) and the morphology of the heat transfer surface, whereas numerical simulations place emphasis on the simulation of bubble growth and spatial distribution by means of lattice Boltzmann method (LBM). In China, Tsinghua University, Shanghai Jiao Tong University, Xi'an Jiao Tong University, the North China Electric Power University, and the Institute of Engineering Thermophysics (Chinese Academy of Sciences) are the major institutions where studies on boiling heat transfer have been conducted. In South Korea, the studies on boiling heat transfer

focus on understanding the mechanism of boiling heat transfer through experimental methods. In Japan, Kyoto University and Tokyo University have conducted extensive studies on boiling heat transfer. In the USA, the studies on boiling heat transfer focus on pool boiling and boiling in narrow gaps. Purdue University, the Massachusetts Institute of Technology (MIT), and Stanford University have made significant contributions.

In terms of heat transfer optimization, several basic theories have been proposed in recent decades: finite-time thermodynamics, entropy generation minimization theory, constructal theory, entransy theory, and the field synergy principle. Because there are numerous fin structures on the surface of heat exchangers, and because convective heat transfer is involved, the development of related basic theories to guide the heat transfer optimization under extreme conditions is the focus of contemporary research. The aforementioned heat transfer optimization methods have been widely used in applications in the iron and steel industry, in waste heat recovery, in heat-work conversion, and in the optimization of heat exchangers. In China, studies are focused on the development of the entransy dissipation extremum theory and the field synergy principle, as well as the combination of the entransy dissipation theory and the constructal theory. In USA and Europe, the main focus is on the entropy generation minimization theory and the constructal theory.

Combustion is a complex process, with a series of chain reactions combined on a series of microscale levels. Even slight changes in the physical or chemical process would accumulate and influence the macro characteristics of combustion. The study of the differences in combustion characteristics under various conditions, and revealing the mechanism of micro-combustion have become one of the focal interests in engineering studies both at home and abroad. In recent decades, the studies on the characteristics and mechanisms of microscale combustion have been enhanced owing to the rapid development of non-contact optical methods and to advances in CFD simulation. Meanwhile, the theoretical system of microscale combustion has been improved based on experimental and simulation studies. At present, research subjects include micro-droplets (representing the liquid fuel), coal particles (representing the solid fuel), and the coal water slurry (representing the liquid-solid fuel). The research process includes droplet breakup of secondary atomization of liquid fuel, evaporation of suspended or surface droplets, the mixture with surrounding air, the ignition, and the combustion process. The experimental methods include high-speed imaging, PIV, and laser induced fluorescence (LIF), whereas simulation studies establish accurate models of different processes based on self-developed software. Up to present, papers related to micro-combustion mainly originate from Asia and Europe. China and Russia have significantly contributed to experimental research, whereas the UK, Finland, and Iran focus on simulation studies.

(3) Current development status and future trends

Form the viewpoint of evaporation and condensation, different research teams have studied specific problems due to a number of factors involved in these phenomena, including gas-liquid temperature difference, gas flow, droplet deformation, and droplet-to-wall interaction. At present, the main research methods include visual experiments and numerical calculations. In the visual experiments, high-speed cameras, which directly observes the phase change processes, is widely used; this satisfies the need to study the mass transfer process from the macroscopic angle. Furthermore, the fluid motion inside the particles can be measured using PIV techniques. The thermogravity and thermocapillary convection during the process of droplet settling to the surface was investigated through a laser shade technique. The thermal phenomenon of the droplets was measured using a noncontact far-infrared thermal imaging technique. In the numerical calculations, one challenge is to consider a two-phase flow. The Euler two-phase, Euler-Lagrangian, and other methods are usually employed. For multicomponent fluids, the discrete multicomponent model is used when the number of components is small, while the distillation curve model and continuous thermodynamics method are used for cases in which a large number of components are involved. Future research directions include the precise determination of the evaporation/condensation rate, which directly affects the basic combustion mechanisms. In terms of theoretical modeling, possible approaches include molecular dynamics calculations and statistical mechanics modeling. In the measurement, change in the mass flux could be obtained by measuring the movement of the contact line through PIV. With all this information, the local evaporation/condensation rate can be obtained. Moreover, the local evaporation coefficient of the local heat flux can be measured using an infrared camera. In

addition, it is desirable to allow the prompt removal of the droplets from the wall to enhance heat transfer in droplet condensation. Researchers have prepared nanostructured super-hydrophobic surfaces, where the adhesion is low and droplets are more likely to bounce. Such surfaces could enhance heat transfer to some extent. However, the further optimization of the wall performance still remains a long-term topic for discussion.

In the field of boiling heat transfer, the main focus is on bubble dynamics in liquid and porous media, and the effects of wettability and morphology on bubble departure and heat transfer coefficient. Experiments in this field usually employ infrared thermal imaging instruments and a high-speed camera to reveal the temperature and flow-field information, while LBM is commonly used in numerical studies. Most of the current research is experimental rather than theoretical. With the development of aerospace and electronics industries, the heat flux values of spacecraft and electronic devices are increasing, and there has been a shift from the study of macro heat/mass transfer to that of microscale boiling heat transfer mechanisms, which are attracting increasing attention. Furthermore, the application of boiling heat transfer to industrial practices and development of highly efficient heat exchanger products are considered as an important trend.

In terms of heat transfer optimization, several theories have been developed to satisfy the requirements of practical engineering applications. Finite time thermodynamics combines thermodynamics, heat transfer, and fluid dynamics to optimize the practical processes and devices in limited time and size. Constructal theory, regarded as the thermodynamics for nonequilibrium constructal problems in thermal science, provides the theoretical basis of the explanation of the generation and design of flow structures. The entropy-generation minimization theory is applied in the analysis and optimization of heat exchanger performances. However, an entropy production paradox indicates that results obtained from the entropy-generation minimization method are not optimal. In this regard, various modified objectives were defined to address the entropy production paradox. To reveal the nature of heat transfer, Guo et al. proposed a new physical quantity called entransy, which describes the total heat transfer ability. Based on the entransy concept, the principle of entransy dissipation extremum has been established, which not only provides a new direction for heat transfer optimization, but also successfully addresses the limitations and uncertainty of thermal resistance analysis and entropy-generation minimization theory. The combination of the various heat-transfer optimization methods is a trend for future research.

In terms of microcombustion, there are plenty of influencing factors, including the physical properties of fuel, fuel components, ambient pressure/temperature, air flow, droplet structure, and droplet-wall interaction. Here, visualization experiments and numerical simulations are the primary research methods. High-speed photomicrography is widely applied to observe and analyze the variation in droplets on a microscale process. The influence of flow field and the concentration and mixing characteristics on microscale combustion could be investigated based on PIV and LIF techniques, respectively. For the viewpoint of simulating actual working conditions, various self-developed simulation methods have been employed and detailed simulation models have been used to predict the characteristics of microcombustion, including evaporation and combustion. Moreover, the comparisons between experimental and numerical results have been conducted to improve the accuracy of simulation models. Researchers from China and Russia have made outstanding contributions in experimental research, among which China's Xi'an Jiao Tong Univ and Russia's Tomsk Polytech Univ played a leading role. In addition, Europe and Asia achieved a remarkable progress in simulation studies, among which the England's University Brighton, Finland's Lappeenranta Univ Technol, and Iran Univ Sci & Technol played a vital role; until now, they have preliminarily established the evaporation and combustion model of droplets on the microscale level.

(4) Comparisons of major research countries or regions and institutions and their collaborations

Table 1.2.9 shows that China, Iran, and USA rank as the top 3 in terms of the number and proportion of core papers, citation frequency, proportion of citation frequency, and number of consistently cited papers. The statistical data indicate that these three countries have greater research prowess and input; the demand in this research field is also very strong. Note that the average citation frequency for the papers from China is only 16.08, pushing it behind the top 10 countries, among which Japan, USA, and Singapore are the top 3. This indicates that although China has conducted a large amount of research, the quality should be improved further. Figure 1.2.5

shows that USA has collaborated with many countries, including China, Iran, Malaysia, Korea, England, Japan, and India. China also shows strong collaborations with other countries, especially with Singapore. Strong connections also exist between Iran and Malaysia.

Table 1.2.10 shows that Univ Malaya, Nanyang Technol Univ in Singapore, Ferdowsi Univ Mashhad in Iran, PLA Naval Univ Engn in China, and Huazhong Univ Sci & Technol in China are very close in terms of the number of core papers. Nanyang Technol Univ in Singapore shows better performance in the number, proportion, and average citation frequency. In terms of the number of consistently cited papers, the PLA Naval Univ Engn and Huazhong Univ Sci & Technol in Wuhan, China stand out. These two universities and Xi'an Jiao Tong Univ in China account for 67% of the number of consistently cited papers; this shows their strong ability in the research field. Figure 1.2.6 shows that intensive collaborations have been established among Ferdowsi Univ Mashhad of Iran, Univ Malaya, and Islamic Azad Univ. Strong connections can also be observed between Shanghai Jiao Tong Univ and Nanyang Technol Univ, as well as between Tomsk Polytech Univ and Natl Res Tomsk Polytech Univ.

The main researchers for condensation and evaporation hail from Russia, UK, China, and some other countries. In addition, intensive collaborations exist between Russian

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Flow, heat/mass transfer, and combustion under extreme conditions"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	China	83	39.15%	1335	31.21%	16.08	14	0
2	Iran	37	17.45%	808	18.89%	21.84	7	0
3	USA	36	16.98%	1076	25.15%	29.89	5	1
4	Singapore	20	9.43%	458	10.71%	22.90	2	0
5	Malaysia	20	9.43%	347	8.11%	17.35	0	0
6	Korea	16	7.55%	282	6.59%	17.63	1	0
7	Russia	16	7.55%	262	6.12%	16.38	1	1
8	England	8	3.77%	170	3.97%	21.25	0	1
9	Japan	7	3.30%	385	9.00%	55.00	1	0
10	India	7	3.30%	160	3.74%	22.86	2	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Univ Malaya	17	8.02%	296	6.92%	17.41	0	0
2	Nanyang Technol Univ	16	7.55%	322	7.53%	20.13	1	0
3	Ferdowsi Univ Mashhad	16	7.55%	257	6.01%	16.06	1	0
4	Naval Univ Engn	16	7.55%	214	5.00%	13.38	3	0
5	Huazhong Univ Sci & Technol	14	6.60%	262	6.12%	18.71	4	0
6	Islamic Azad Univ	12	5.66%	285	6.66%	23.75	2	0
7	Shanghai Jiao Tong Univ	12	5.66%	228	5.33%	19.00	1	0
8	Xi'an Jiaotong Univ	10	4.72%	167	3.90%	16.70	3	0
9	Tomsk Polytech Univ	10	4.72%	139	3.25%	13.90	0	0
10	Natl Res Tomsk Polytech Univ	9	4.25%	133	3.11%	14.78	0	0

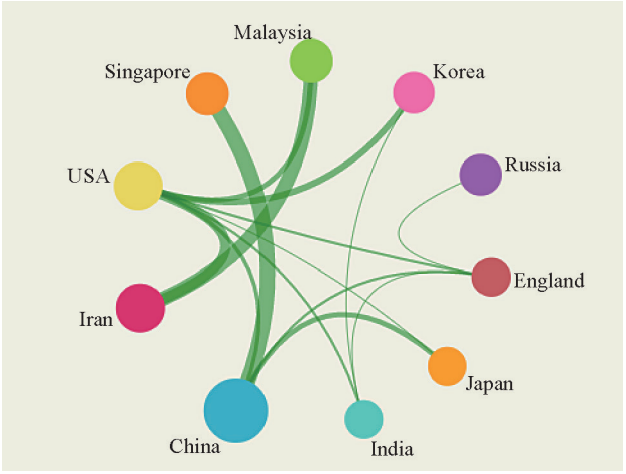

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

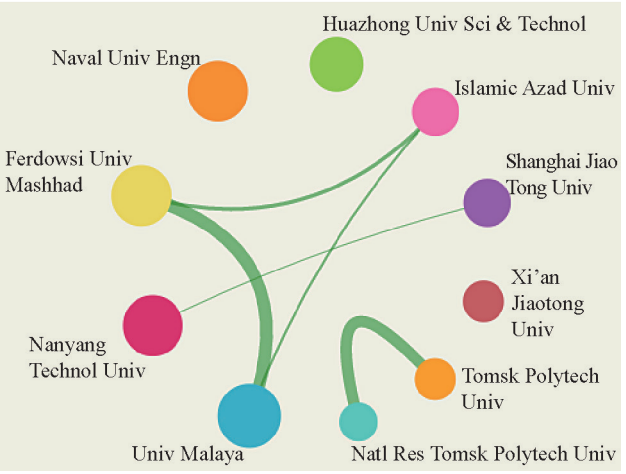

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

scholars and those from other European countries. However, researchers from USA are not active in this branch. In the field of boiling heat transfer, China, Japan, Korea, and USA comprise many scholars, while Malaysia and India do not have as many. Moreover, extensive collaborations exist between Korea and USA. In the field of heat transfer optimization, constructal theory was proposed by Professor Bejan from Duke University. This theory has been widely employed in USA, Europe, and Iran. Entransy dissipation theory was proposed by Professor Guo from Tsinghua University; it is mostly studied in China and has recently gained attention in other counties. In terms of combustion, Europe still leads in the number of studies on liquid fuel at the microscale level; nevertheless, several research teams in China have also conducted in-depth study in this field in recent years. In addition, China, Iran, and Russia are the major countries studying liquid–solid fuels, such as coal–water fuel, at the microscale level. Most of the international collaborations are in Asia, where China has a strong cooperative relationship with Singapore.

In the study of evaporation and condensation, China's scholars, such as those from Xi'an Jiao Tong University and Beijing University of Chemical Technology, have conducted several experimental and theoretical research on direct condensation, which is at the leading level. However, research on droplet evaporation is rare and requires more attention. Study on the branch of boiling heat transfer is mainly focused upon at the experimental level in China, seeking the enhancement of the coefficient of heat transfer. In recent years, some scholars in Tsinghua University, Shanghai Jiao Tong University, Xi'an Jiao Tong University, and the Institute of Engineering Thermophysics (Chinese Academy of Sciences) have made great progresses in this field. They adopted the LBM method to build liquid-vapor phase change models and explored the mechanism of phase-change heat transfer from the theoretical perspective. China's scholars play the leading role in this field, and have suggested further theoretical studies. In the field of heat transfer optimization, some optimization concepts, such as entropy, were introduced from overseas. By contrast, entransy dissipation theory proposed by Professor Guo is at the cutting edge of this field. The entransy dissipation and construtal theories form the basis of the new optimization theory for heat transfer. In terms of combustion, China has many years of an intellectual convention of solid and liquid-solid fuels at the microscale level; and the extensive research results prove that China belongs in the leading team in this area. From the viewpoint of liquid fuels, China lags the leading countries; however, it is catching up and seeking to become a leader in this field as well.

The statistical data in Table 1.2.11 shows that China, Iran, and USA rank the top 3 in citing the core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions." Furthermore, as shown in Table 1.2.12, the top 3 institutions citing the core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme condi-

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	62	30.69%	2014.90
2	Iran	33	16.34%	2014.61
3	USA	22	10.89%	2014.23
4	Malaysia	22	10.89%	2014.73
5	Singapore	17	8.42%	2014.59
6	Russia	10	4.95%	2014.90
7	Korea	8	3.96%	2014.00
8	England	4	1.98%	2014.00
9	Finland	3	1.49%	2014.00
10	Japan	3	1.49%	2012.67

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Malaya	19	7.17%	2014.79
2	Nanyang Technol Univ	15	5.66%	2014.67
3	Huazhong Univ Sci & Technol	14	5.28%	2014.64
4	Ferdowsi Univ Mashhad	14	5.28%	2015.07
5	Islamic Azad Univ	12	4.53%	2014.33
6	Naval Univ Engn	10	3.77%	2015.30
7	Amirkabir Univ Technol	8	3.02%	2013.75
8	Shanghai Jiao Tong Univ	8	3.02%	2014.38
9	Xi'an Jiaotong Univ	8	3.02%	2014.88
10	Natl Res Tomsk Polytech Univ	7	2.64%	2015.43

tions" include Univ Malaya, Nanyang Technol Univ, and Huazhong Univ Science & Technol.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 12 engineering development hotspots in energy and mining engineering research are listed in Table 2.1.1. These 12 hotspots include a number of research directions in energy and electrical (science, technology, and engineering), geological resources (science, technology, and engineering), mining (science, technology, and engineering), and nuclear (science, technology, and engineering). Among them are five emerging hotspots: "Electric vehicle battery (structure, material, efficiency, and thermal management system)," "New fracturing methods, fluids, proppants, and additives," "Geological modeling and simulation based on fracturing and rock characteristic parameters," "Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)," and "Biomass conversion and biofuel preparation." At the same time, some traditional research directions have been further expanded, including "Equipment and technology for deepwater oil and gas development," "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment," and "Transfor-

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

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Electric vehicle battery (structure, material, efficiency, and thermal management system)	696	12 707	18.26	2011.89
2	Equipment and technology for deepwater oil and gas development	162	1 382	8.53	2012.25
3	New fracturing methods, fluids, proppants, and additives	481	4 348	9.04	2012.49
4	Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment	304	780	2.57	2012.43
5	Transformation and utilization of non-traditional fossil and carbon resources	397	4 348	10.95	2012.07
6	Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits	1 036	8 379	8.09	2012.44
7	Research and development of key technologies for advanced hybrid vehicle engines	427	6 097	14.28	2012.07
8	Geological modeling and simulation based on fracturing and rock characteristic parameters	56	326	5.82	2012.61
9	Research on polymers used in the cable sheath layer in extreme conditions	110	1 570	14.27	2012.89
10	Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)	240	4 322	18.01	2012.00
11	Biomass conversion and biofuel preparation	254	4 656	18.33	2012.15
12	Assembly, monitoring, and control of wind turbines	106	1 561	14.73	2011.55

Table 2.1.2 Annual number of published core patents belong to each of the top 12 engineering development hotspots in energy and mining engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Electric vehicle battery (structure, material, efficiency, and thermal management system)	329	196	116	34	14	7
2	Equipment and technology for deepwater oil and gas development	50	58	31	13	6	4
3	New fracturing methods, fluids, proppants, and additives	114	151	118	70	19	9
4	Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment	81	77	93	41	10	2
5	Transformation and utilization of non-traditional fossil and carbon resources	151	127	84	22	3	10
6	Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits	278	300	265	125	52	16
7	Research and development of key technologies for advanced hybrid vehicle engines	187	116	56	48	17	3
8	Geological modeling and simulation based on fracturing and rock characteristic parameters	11	16	15	12	2	0
9	Research on polymers used in the cable sheath layer in extreme conditions	21	26	22	27	13	1
10	Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)	106	61	49	16	6	2
11	Biomass conversion and biofuel preparation	98	70	40	42	3	1
12	Assembly, monitoring, and control of wind turbines	69	21	12	3	1	0

mation and utilization of non-traditional fossil and carbon resources." Table 2.1.2 shows the number of published patents related to each hotspot from 2011 to 2016.

(1) Electric vehicle battery (structure, material, efficiency, and thermal management system)

As the central part of an electric vehicle (EV), batteries would significantly influence the mileage, safety, and cost of the vehicle. It is necessary to focus on the key technical problems of electric vehicle batteries: energy density, safety, environment adaptability under low and high temperature, durability, charging speed, and development of low-cost advanced rechargeable batteries, battery pack and its management. A new generation of rechargeable batteries may be developed including by nano lithium battery, lithium-air battery, lithium-sulfur battery, graphene-assisted Li-ion battery, multielement lithium-ion battery, solid-state battery, and flow battery. Battery packs with high efficiency and performance can be produced by the development of several methods and technologies, including the design optimization of thermo-mechanical-electric multi-field coupling structures, the smart evaluation and testing of multi-target dynamic/static consistency, the application of light but hard materials and lightweight structures, battery modularization, intelligent manufacturing, and robot disassembly and assembly. Concerning thermal management, active or passive thermal management of external cooling, heating (also by electric heating) or constant temperature control can be realized through diverse methods: heat transfer by a single medium such as air, liquid, and phase-change materials or composite media, heating by external current pulse excitation or built-in heating circuits, internal thermal management of the battery cell using the battery's own heat, as well as an integral thermal-management system that involves both the battery and vehicle. Finally, safety, efficiency, reliability, and durability of the batteries in the application of electric vehicles can be improved through battery condition estimation, service life prediction, fault diagnosis and prediction, charging optimization management, intelligent balancing control, and vehicle-battery dynamic coordination control by modeling, and control-oriented electrochemical modeling in particular.

(2) Equipment and technology for deepwater oil and gas development

China has rich marine oil and gas resources to be explored and exploited. Statistics have shown that South China Sea has 23 billion–30 billion tons of geological oil reserves, and 16 trillion cubic meters of natural gas reserves, of which 70% is located in deepwater. In this sense, it is essential to develop China's deepwater oil and gas resources fully. Deepwater oil and gas development has several features: expensive investment cost, complicated technologies, high risks, and high returns. The exploitation difficulty and investment cost will also increase exponentially as the depth increases. Having focused on promoting deepwater oil and gas exploitation, China has benefited from the dual modes of independent research and development and international collaboration, and has made great achievements in the equipment and technology of deepwater oil and gas development, including deepwater oil and gas development floating structures, underwater intelligent robots, deepwater drilling blowout preventers (BOP), seabed isolation valves and safety valves, vertical single-channel production tree systems, and underwater pressurization and processing equipment. At the same time, various technologies have been applied in deepwater oil and gas exploitation, such as intelligent automation, remote control, underground monitoring, pipe design, and control. Among them, the intelligent and fully automatic underwater production system, submarine remote control through radio frequency identification, multi-functional monitoring technology, and robotic deepwater monitoring technology are good examples.

(3) New fracturing methods, fluids, proppants, and additives

There are also rich non-traditional oil and gas resources in China, such as shale gas coal bed methane (CBM), and tight gas, and the exploration and development potential is huge. For example, China's shale gas resources amount to 36.1 trillion cubic meters, ranking the first in the world. However, non-traditional oil and gas reservoirs have the characteristics of low pressure, low porosity, low permeability, and low production yield. Therefore, the reservoir fracturing technology plays a critical role in the commercialization of non-traditional oil and gas development. However, traditional hydraulic fracturing is not applicable to the development of non-traditional oil and gas owing to its high cost and poor technological adaptability. In this context, infinite-stage fracturing, directional hydraulic perforation fracturing technology, steering fracturing, re-

petitive fracturing, and other new fracturing technologies came into being. Anhydrous, clean, and efficient fracturing technologies as represented by CO_2, N_2, and liquefied petroleum gas (LPG) have also been developed rapidly. For example, the technology of CO_2 (or supercritical CO_2) fracturing, if integrated with CO_2 capture, reservoir displacement, CO_2 storage, and other technologies, can achieve the comprehensive utilization of the greenhouse gas CO_2. These new fracturing technologies play a significant role in the control of fracture trends, the scale of fracture, as well as efficiency. In addition, technologies of new fracturing fluids, proppants, and related additives are developing rapidly, and a large number of new materials have been developed, applicable for different reservoirs. For example, in recent years, the popular nanomaterials have been widely used in the development of fracturing fluids, proppants and additives, such as drag-reduction agents and controllable electrolytic metal (CEM) fracturing balls.

(4) Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment

Reactor fuel assembly is an important component of the reactor core, and the major place for chain fission reaction and radioactive fission products. The working condition of fuel assembly is very harsh, for it stays in the strong neutron field and withstands high temperature, high pressure, the rapid scouring of coolant, as well as the chemical reactions of fission products and complicated mechanical load. Also, the development of advanced fuel components would contribute to the development of advanced reactor technologies. The most popular hotspots in current research include cladding materials for fuel elements, defect monitoring of fuel assemblies, corrosion, thermal margin improvement, and the use of combustible toxicants.

Nuclear power plants have mainly three categories of equipment: nuclear island equipment, conventional island equipment, and auxiliary system. Nuclear island equipment, the main location for thermonuclear reaction, is technically complicated and has the highest requirement for safety design, especially the primary-circuit pressure boundary equipment that includes the pressure vessel, evaporator, voltage regulator, nuclear-grade pump, nuclear-grade valve, nuclear-grade container, and pipelines. Current research focuses on the nuclear power equipment's reliability, security, integrity, etc., and involves many aspects of the problem including fatigue, creep, corrosion, earthquake, shock tests, radiation, lost of coolant accident (LOCA), and standardization.

(5) Transformation and utilization of non-traditional fossil and carbon resources

Traditional fossil and carbon resources (including coal, petroleum, and natural gas) are the raw materials for energy and manufacturing, thus serving as the fundamental driving force of a society. However, such resources not only brings severe environmental problems, but will also be depleted someday. As supplements to such resources, non-traditional fossil and carbon resources can help in relieving the problem of environmental pollution and achieve development sustainability. Such non-traditional resources include biomass, shale oil, shale gas, oil sands, flammable ice, crop, household waste, and CO_2, etc. It is possible to obtain products such as syngas, methane, biodiesel, and oxygenated chemicals through pyrolysis, gasification, hydrolysis, combustion, and other transformation methods, in which catalysis, thermochemical and biochemical mechanisms, and engineering issues are involved.

(6) Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits

Smart drilling equipment can significantly reduce drilling costs, speed up drilling, and reduce the number of accidents. With the assistance of underground smart drilling tools, smart drilling can acquire real-time information on downhole fluid, rock condition, tool features, and other parameters through the underground closed-loop system to calculate the well path, tool azimuth angle, reservoir location, calculate results, and then report the results for real-time parameter adjustment. Representative technologies include rotary steering drilling system, geosteering drilling system, and automated vertical drilling system. Besides, smart drill bits, pipe drilling, and other underground tools and technologies can also further improve the drilling accuracy and reduce drilling costs.

(7) Research and development of key technologies for advanced hybrid vehicle engines

Hybrid vehicles can be divided into three categories according to their power transmission routes: tandem vehicle, parallel vehicle, and mixed vehicle. Among them, parallel and mixed vehicles are both equipped with two sets of power systems (engine drive system and electric motor system) which apply a specific power coupling strategy

to power the vehicle. At the same time, the electric motor system can achieve the following functions: prevent the engine from idle speed, reduce or avoid operating in conditions of low load and low efficiency by adjusting the engine working status, and recycle braking energy to improve the power system's fuel utilization rate. A hybrid engine can not only drive the vehicle but also charge the battery so that the vehicle's driving distance will not be limited by the battery capacity. To promote the R&D of engines exclusively for hybrid vehicles, it is important to develop the Atkinson cycle regenerative combustion system, engine control strategy, optimization of engine operation with multiple parameters and objectives, vehicle matching, power battery and its management system, and to reduce the energy loss in accessory systems.

(8) Geological modeling and simulation based on fracturing and rock characteristic parameters

Geological modeling can be used to give a general assessment of the oil reservoirs. When applying the geological model for accurate oil production, it is necessary to make full use of geological parameters. At present, various modeling methods have been employed, including facies-controlled modeling based on geo-statistical inversion and reservoir classification, 3D geological modeling based on multi-dimensional geological information, quantitative reservoir description based on multiple geophysical technologies, etc. Furthermore, new geological modeling based on fracturing and rock characteristic parameters has also played a positive role, for example, advanced 3D geological modeling based on 3D laser scanning technology and terrain and geological modeling based on HPIM technology.

(9) Research on polymers used in the cable sheath layer in extreme conditions

Concerning "Cable, Layer, Conductor" (as frequently mentioned in patent publications), current research has paid close attention to the composite materials used in cable sheath layers. Such cables are mainly used in extreme conditions, e.g., power cable on ships or marine platforms, DC transmission cables that require higher insulativity, cables in aircraft and spaceship, cables for artificial lifting equipment and drilling equipment, and cables used for vehicle control. Ten properties of such cables have been improved: waterproofness, heat resistance, insulativity, fire retardance, damp proofing and corrosion protection, thermoplasticity, low volatility, weatherproofness, freezing resistance, and high stretchability. Materials for cable coating are mainly polymers, but aluminum, cuprum, and resin have also been employed for this purpose.

(10) Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)

Crystalline silicon solar cells have been and will be the mainstream product in the PV market in the next decade (their market share was 93% in 2015 and 95% in 2016). Focus points in the current PV industry are the application of limiting light and passivation technology in silicon solar cells, and the development of novel structures, including back-contact and heterojunction. For PV modules, research has focused on developing new cleansing methods, installation technologies, as well as the development of large-scale PV power stations.

(11) Biomass conversion and biofuel production

Biomass is widely distributed, storable, and transportable, and it is the only renewable carbon resource. Biomass conversion refers to the biochemical and thermochemical processes in which biomass materials are transformed into solid, liquid, or gaseous fuels and chemical products. Biofuels are high quality energy and can be widely applied. Biofuels production is a hot research topic nowadays, in which a variety of hotspots have been discussed, e.g., the improvement of the reaction mechanism through the reaction process, atmosphere, catalyst, and other factors, and the development of clean and efficient production technologies such as biodegradation, torrefaction, pyrolysis, gasification, and refinery.

(12) Assembly, monitoring, and control of wind turbines

Increasing number of wind turbines are being built with the rapid development of new energies. The assembly of wind turbines remains a frequently discussed issue, and hotspots include rotor blades' tip, the lifting tower of lifting and falling devices, the joining parts of tower bases, transporting component, and automatic sensing system. For offshore wind turbines, research is mainly focused on the offshore/submarine operating platform, and on how to reduce water oscillation. To achieve the optimal operation, real-time data should be used to control the output power of wind turbines and to measure the wind speed, blade revolving speed, and other factors. In future studies, hybrid power systems may attract more attention, e.g., a power generation system that combines wind turbines and solar cells.

2.2 Understanding of engineering development focus

2.2.1 Electric vehicle battery (structure, material, efficiency, and thermal management system)

(1) Background of electric vehicle batteries

For their features of "zero pollutants emission" and "battery-driven", EVs have been seen as a promising alternative to traditional internal combustion engine vehicles, and a major solution to the exhaust pollution problem caused by gasoline-powered automobiles. To date, hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV) have been the four most well-developed types of EVs. To promote the development and application of EVs, it is important to solve three problems: to accelerate the development of electric vehicle batteries that are affordable and perform well, to build up sufficient number of battery swap stations and/or hydrogen refueling stations, and to establish a supply chain of adequate raw materials.

Electric vehicle batteries are exclusively used in new energy vehicles, and have two categories in general—advanced secondary batteries and fuel cells. Fuel cells are beyond the scope of the discussion here since they are closely related to the utilization of hydrogen energy. Thus, in this chapter, electric vehicle batteries refer specifically to advanced secondary batteries or power batteries.

In this chapter, we focus on engineering technologies of the electric vehicle battery, including materials development, structural design and production, battery measurement, battery pack, battery management system, and power system integration.

(2) Structure and material of advanced secondary batteries

Advanced secondary batteries can be charged or discharged via redox reactions at their anodes and cathodes. According to the chemical components, there are several different types of secondary batteries, e.g., nickel-metal hydride (NiMH) battery, lithium-ion battery (LIB), lithium-sulfur battery, etc. In the 1990s, NiMH battery, an environment-friendly battery, drew much attention internationally, and numerous studies have been conducted on it since then. Japan's Toyota Motor Corporation has developed the technology for NiMH battery to a mature level, and applied it to their non-plug-in hybrid electrical vehicle, as represented by their PRIUS automobile whose market sales have exceeded one million.

LIB has become the most promising research direction for EV battery development mainly for its safety, durability, high energy density, and affordability. The cathode of the LIB is made of graphite, while lithium manganese oxide, lithium iron phosphate, and $LiNi_xMn_yCo_{1-x-y}O_2$ (NMC) are the most commonly used anode materials. At present, lithium iron phosphate and NMC account for over 90% of the EV batteries market. In particular, lithium iron phosphate has dominated the EV batteries market of China, USA, and Germany for its safety, durability, and affordability, while NMC has started to attract people's attention for its high energy density. In China, USA, and Japan, automobile manufacturers have promoted the NMC application in their production. However, the widespread commercialization of NMC may be limited due to its potential safety risk, as well as the high cost and availability of Co as one of its raw material. For HEVs, batteries that could provide high power will be preferred, while for BEVs, batteries with high energy densities will be preferred. Nowadays, China, Japan, and Korea are the three major countries manufacturing LIBs for EVs.

The pressing problem with lithium-iron-phosphate batteries is the realization of higher energy densities in them. One possible solution would be to use manganese-lithium-iron-phosphate as the cathode and silicon as the anode, and to add a proper electrolyte so that its energy density can reach up to 180 $Wh \cdot kg^{-1}$, making it possible for EVs to go for a longer endurance mileage. In light of NMC batteries, the problems of safety and system stability are more urgent to deal with.

It is the goal of future studies to further increase energy densities of single batteries and battery packs to 300 and 260 $Wh \cdot kg^{-1}$, respectively. Besides, it is important to conduct research on and develop nickel NMC materials or high-voltage cathode materials, silicon anode materials with high energy density, as well as their matching electrolytes. At the same time, all solid-state LIB, lithium-sulfur battery, and lithium-air battery remain alternatives for EVs.

(3) Power battery measurement and powerplant management information system (PMIS)

Current researches have also focused on the technology of accurate battery measurement and battery management system (BMS). The technology of accurate battery measurement includes state of charge (SOC), state of health

(SOH), state of power (SOP), battery internal resistance, and other parameters. In order to achieve this and to further promote the development of BMS and power control systems, it is critical to build an estimation model for SOC and SOH and to develop its matching computational methods, which have been the focus of many international EV battery patents.

Other critical technologies for the application of EVs are battery packing and system integration, including battery selection, battery packing, system electric and thermal management etc. Battery packing and system integration have been widely recognized among EV manufacturers as the core technologies for the combustion engines of traditional fossil fuel vehicles. Furthermore, automotive electronic technology related to system integration is crucial to realize the automatic and intelligent operation and control of EVs.

Tables 2.2.1 and 2.2.2 show that the majority of core patents on EV batteries have originated from USA, Japan, China, Korea, and Germany, and, among all the institutions, automobile manufacturers have accounted for most of the patents. Among the manufacturers, Toyota, Ford, and GM have obtained the most number of patents, followed by Tesla, Mazda, and Mitsubishi. With regard to

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	273	39.22%	6575	51.74%	24.08
2	Japan	203	29.17%	2815	22.15%	13.87
3	China	79	11.35%	1420	11.17%	17.97
4	Korea	70	10.06%	778	6.12%	11.11
5	Germany	56	8.05%	839	6.60%	14.98
6	France	8	1.15%	63	0.50%	7.88
7	Switzerland	6	0.86%	140	1.10%	23.33
8	Taiwan of China	6	0.86%	115	0.91%	19.17
9	Canada	5	0.72%	40	0.31%	8.00
10	Israel	5	0.72%	131	1.03%	26.20

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	TOYT	45	6.47%	600	4.72%	13.33
2	FORD	40	5.75%	801	6.30%	20.02
3	GENK	35	5.03%	472	3.71%	13.49
4	SAOL	35	5.03%	503	3.96%	14.37
5	SMSU	34	4.89%	429	3.38%	12.62
6	BOSC	26	3.74%	590	4.64%	22.69
7	GLDS	20	2.87%	138	1.09%	6.90
8	NPDE	19	2.73%	255	2.01%	13.42
9	SBLI	18	2.59%	248	1.95%	13.78
10	MATU	17	2.44%	278	2.19%	16.35

Note: TOYT stands for Toyota Motor Corp.; FORD stands for Ford Global Tech LLC; GENK stands for GM Global Technology Operations Inc.; SAOL stands for Sanyo Electric Co., Ltd.; SMSU stands for Samsung Electronics Co., Ltd.; BOSC stands for Robert Bosch GmbH; GLDS stands for LG Electronics; NPDE stands for Nippondenso Co., Ltd.; SBLI stands for SB Limotive; MATU stands for Matsushita Co., Ltd.

BMS and electronic control, SONY, Panasonic, Samsung, LG, and Bosch have all obtained related patents.

With more than 20 years of experience in the research and development of EV batteries, the China's government has implemented the best policy for the development of new energy vehicles. The "Energy Saving and New Energy Vehicle" and "Electric Vehicle" projects backed by the "National High-tech R&D Program of China (863 Program)" and the "National Basic Research Program of China (973 Program)" have fostered many influential EV enterprises in China. Among them, BYD is a pioneer in filing related patents. In 2016, BYD became the world's largest seller of new energy vehicles. The BYD electric bus K9 has been widely promoted in USA, Japan, UK, and many other developed countries, and the lithium iron phosphate battery equipped in K9 has passed internationally recognized strict safety tests. The German company Mercedes-Benz has adopted the BMS and power system assembly developed by BYD, and two companies are collaborating on the development of DENZA EV. Together with CATL, the LIB supplier for Bayerische-Motoren Werke, BYD has become the leading supplier of LIBs for EVs with international impact.

The integration of industry, education, and research is a major characteristic of China's new energy vehicle industry. A number of China's universities, including Tsinghua University, Shanghai Jiao Tong University, Tongji University, Beijing Institute of Technology, the Chinese Academy of Sciences etc., have vigorously collaborated with automobile and battery enterprises and contributed to the development of the industry. Consequently, there has been a significant increase in the number of related patent filings in China. In the last five years, China has filed more patents on EV batteries than any other country in the world. In particular, more than 2000 patents have been obtained by BYD, out of which more than 200 patents are international patents. The development of EVs in China is so rapid that China is no longer a follower in international competition, but even a pioneer in some areas.

During the 13th Five-Year Plan period and under the nanomaterial project of the national research program, the China's government has proposed a new strategy for the development of EV batteries and BMS, highlighting the development of an EV management system and EV batteries with good safety and durability. By reviewing the 12th Five-Year Plan period, wherein lithium battery with long endurance mileage was considered as one of the major concerns by the Chinese Academy of Sciences, we can observe that remarkable advancements have been achieved in the research and development of lithium-sulfur batteries and solid-state lithium ion batteries, and China has assumed the leading position in the engineering applications and system integration in this area.

Since 2012, the emerging new energy cars have further promoted the development of EV battery engineering to a stage where central and local governments have begun to pay significant attention to it. Consequently, the number of battery material (cathode, anode, electrolyte, and separator) suppliers and power battery manufacturers in China increased dramatically, causing the problem of excess capacity, unnecessary investment, and waste of resources. Accordingly, strengthening the layout of EV industry has been suggested, with a focus on battery materials, manufacturing, and BMS to develop EV batteries with good performance, safety, and durability, such that China can continue to assume the leading position in the research and development of EV batteries for the next generation.

Table 2.2.1 and Table 2.2.2 demonstrate that the patents related to "electric vehicle" and "battery" mainly cover the following research directions: battery performance measurement, BMS, battery pack, EV power system assembly, and technologies of battery swap stations. These patents are mainly obtained by the automobile manufacturers from USA, Japan, Korea, and Germany, whereas, in China, only BYD and Tsinghua University have obtained many related patents. In contrast, China's four traditional automobile manufacturers have obtained few patents—a sign of their insufficient investment in new energy vehicles.

Figure 2.2.1 shows the international collaboration network between countries or regions for the development of EV batteries (structure, material, efficiency, and thermal management system); Figure 2.2.2 shows the collaboration network between the institutions.

2.2.2 Equipment and technology for deepwater oil and gas development

(1) Concept elaboration

The abundant global oil and gas resources account for 34% of the total resources, but only 30% of them have been discovered so far, indicating that we are still in the early stages of exploration, and there are immense prospects in

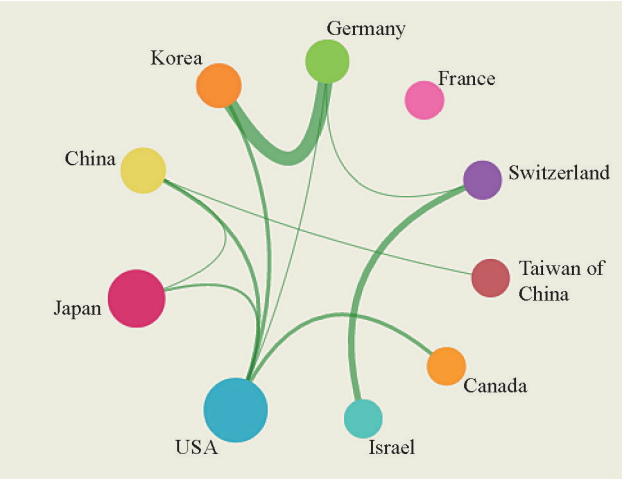

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

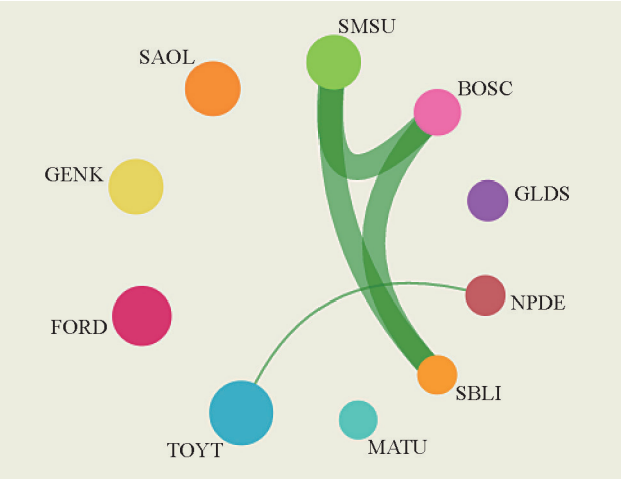

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

their exploration.

China has rich marine oil and gas resources. According to the geological survey data of the China's Ministry of Land and Resources, in China's South Sea, the geological oil reserves of the whole basin group amount to 23 billion–30 billion tons, and natural gas amounts to 16 trillion cubic meters. According to preliminary statistics, the total geological resources of the total oil and gas in the South China Sea account for one-third of China's total oil and gas resources, of which 70% are in the deep sea region. Generally, the deepwater depth is greater than 500 m, and the ultra-deepwater depth is greater than 1500 m. As we go deeper into the water, it becomes increasingly difficult to perform geophysical exploration, drilling, and resource exploitation. First, natural and weather conditions such as wind, wave, flow, and ice are significantly more complicated at such depths. Moreover, the window between pore pressure and fracture pressure narrows as the depth increases, rendering it increasingly difficult to control the drilling. Finally, as the water temperature decreases in the deep water, drilling fluid has poorer rheology, and the flow of oil and gas is more difficult to control.

Therefore, the equipment and technology of deepwater oil and gas development are important in the field of oil and gas technology innovation around the world. Deepwater oil and gas exploration involves information technology, new materials technology, new energy, and other disciplines, and is a complex systematic engineering that requires advanced technology, technological integration, high security, and reliability. Although China started relatively late in deepwater oil and gas development, we have proposed a major oceanic strategy to develop oceanic technology and improve the ability of marine resource exploitation. We feel confident that China will make rapid progress in the future in this aspect, in order to improve the safety level of energy production and contribute to China's rapid economic growth.

(2) Concept elaboration, key technologies to be resolved, future trends for the concerned engineering branches, and an overview of the development priorities in different countries.

The major engineering technology of deepwater oil and gas exploration includes drilling floating structure, underwater vehicle, deepwater riser system, underwater production system, deepwater BOP stack control system, water isolation valve system, downhole overflow monitoring technology, technologies to ensure the safety of deepwater flow, exploration technology, measurement and analysis of long cable seismic signal, and exploration technology of subtle hydrocarbon reservoirs.

• Deepwater oil and gas drilling floating structure

Deepwater oil and gas drilling floating structure mainly refers to drilling ships and a semi-submersible drilling platform. The components of drilling ships are hull, mooring or dynamic positioning system, and navigation system. Drilling ships have good flexibility, self-navigation

ability, flexibility, and are easy to anchor. The main structure of a semi-submersible drilling platform is the upper propping component, which connects a column with a rounded or square section and the lower floating box. A semi-submersible drilling platform, which is seakeeping and flexible, occupies only a small water-plane area but has a large deck area and variable load. It helps to solve the problems occurring in regional drilling when the depth is greater than 3000 m.

During the installation phase, floating structures used for deepwater oil and gas development are mainly deep water pipeline layer, deep water multi-purpose vehicle (MPV) etc. A deepwater pipeline layer is composed of a hull, pipeline welding system, pipe laying system, lifting system, power system, and positioning system. It is responsible for installing a floating platform, and laying sea pipes and standpipes. It is composed of a multifunctional robotic manipulator and a winch system with the function of heave compensation, and thus it can undertake and execute a task on its own. MPV is commonly used for underwater tasks at a depth of more than 3000 m under complex sea conditions, including hoisting large deepwater structures (oil tree, water pipe etc.), conducting submarine installation, laying flexible pipes, supporting remote-operated vehicles (ROV) and saturation diving task, examining and repairing oceanic engineering, deepwater anchor operating and anchoring etc.

During the production stage of deepwater oil and gas development, a tension leg platform (TLP), spar platform (SPAR), floating production storage and offloading (FPSO), and semi-submersible platform are the floating structures responsible for oil and gas production, storage, transportation etc. The floating structure sheds light on key technologies including concept design, prediction of dynamic properties, design and construction, service, durability, maintainability, accident load and risk assessment, and environmental and ecological impact assessment. The development trend of floating structure lies in a new FPSO with TrussSpar as its main composite structure, the light tension leg platform (miniTLP) suitable for deepwater conditions, very large floating structures (VLFS) etc. Recent related researches have started to pay attention to the modernization of floating structures and their operational ability in deeper waters.

• Underwater vehicle

Underwater vehicles mainly include human-occupied vehicles (HOV), ROV, autonomous underwater vehicles (AUV), deep sea drag system (DT), underwater glider, and bionic submersible. Underwater vehicles can quickly carry personnel and equipment to a deepwater environment, and efficiently conduct exploration and operation tasks.

A HOV can dive to a depth of more than 10 000 m, but it does not have a strong power system, and suffers from high costs and risks during operation and maintenance. In contrast, an unmanned underwater vehicle, such as ROV and AUV, can be connected to the mother ship through an umbilical cable to transmit power and information. Ship operators on the mother ship can provide commands to the manipulator in a ROV to conduct underwater operation through the umbilical cable, whereas an AUV, equipped with an independent power system, can execute operations using its pre-set program instructions, and thus can operate for a longer time and have stronger operation abilities.

The key technical challenges in underwater vehicles are a powerful driving source, accurate positioning technology, high resolution monitoring technology, and ultra-deep water operation technology. The development trend of underwater vehicles includes lowering the cost of a HOV and making it more comfortable for humans to live in it, in order to establish a mutually reinforcing and coordinative system that connects the manned and unmanned facilities.

• Deepwater riser system

The deepwater riser system includes three types of tubing systems: pipes, drilling risers, and landing strings. Drilling risers connect the drilling platform and underwater wellhead, thus playing an important role in providing a circulation channel for drilling fluid, supporting auxiliary lines, guiding drilling tools, and carrying and retrieving BOPs. When in service, a series of complex mechanical phenomena occur in deepwater drilling risers owing to the dynamic effect from the combined forces of waves and flows, including axial tension, transverse bending, coupling vibration etc., resulting in significant challenges to the safe operation of deepwater drilling. The key technical challenges include the mechanics and design control of deepwater drilling risers, out of which the primary problems are to ensure the stability and safety of the underwater wellhead, design a proper operation window for the installation of deepwater risers, assess the vortex-induced vibration and

fatigue life of deepwater risers, evaluate and control the integrity of deepwater shafts, and design the mechanical simulation of the deepwater tubing systems. In the future, deepwater risers are expected to become lighter, safer, stronger, and easier to install.

• Underwater production system

In addition to the construction of additional surface oil and gas production platforms, underwater production system has also become an important component of deepwater oceanic engineering technology in the process of deep sea oil and gas development. Underwater production systems can be categorized based on their functions: production tree system, manifold and connection system, and underwater control and umbilical cable system. The main function of the underwater production system is to guarantee that all the production fluids are properly handled under water.

Underwater production systems reduce the occurrence of sea accidents since they are not influenced by sea surface winds, waves, streams, ice, and other natural and weather conditions, thus making offshore oil and gas production safer and more reliable. The major technical challenges in this field mainly lie in underwater flow assurance technology, underwater power transmission and all-electric control technology, underwater installation technology, underwater production system reliability and integrity management technology, underwater production technology applicable for polar regions etc. The recent development trend in this area mainly focuses on improving the intelligent and automation level of the underwater production systems.

• Deepwater drilling BOP system

Deepwater drilling BOP stack is generally composed of a lower marine riser package (LMRP system), connector, lower BOP stack, and BOP frame composition. The deepwater drilling BOP system mainly includes a BOP stack and control unit, wherein the BOP control system employs a number of control technologies and is suitable for electricity, liquid, and gas. It possesses a large number of control points and a complex structure system, requiring high stability of the system and sensitivity of control units. The major technical challenges in this field include the BOP material, highly redundant modular integration technology of the control units in the deepwater drilling BOP system, and the design, production, and testing technology of the deepwater BOP control system. China's research institutions have carried out many studies on the structure of a BOP stack, its control system, and the system as a whole, e.g., theoretical analyses and researches, standardization, collection and report of the real-time feedback information from the system etc. Future studies will focus on the applicability of deepwater drilling BOP systems under high system pressure and triple redundancies, and the improvement of their reliability, intelligence, and environmental friendliness.

• Subsea isolation valve system

Subsea isolation valve (SSIV) is designed to isolate the near-end riser and submarine pipelines in order to reduce the risks of fire and explosion caused by overflow. However, SSIV requires a high investment cost; thus, it is a major challenge in current engineering projects to determine whether SSIV is necessary. Moreover, there is no proven quantitative SSIV assessment system. Since the initial cost of SSIV is too high, it becomes highly important to accurately quantify the consequences of a potential accident, and to assess the profits contributed by SSIV. Based on the historical overflow rate of offshore risers and submarine pipelines, China has successfully built an SSIV benefit evaluation system to accurately assess the benefits of employing an SSIV.

• Downhole overflow monitoring technology

According to the different features of offshore drilling and the location of the installed sensor, overflow monitoring methods for deepwater drilling can be divided into platform (wellhead) monitoring method, seawater section (near the mud line) monitoring method, and measurements while drilling (MWD) method. Downhole overflow monitoring technology for deepwater drilling is mainly used to detect the downhole overflow, but can also be used for the comprehensive monitoring of underground well pressure and wellbore pressure to provide technical support for deepwater drilling. The platform (wellhead) monitoring method mainly compares certain parameters of the drill hole returns with those measured in the wellhead, and can be further classified into conventional monitoring method, unconventional monitoring method, and wellhead comprehensive monitoring method. Seawater monitoring method is an exclusive method for offshore drilling, wherein the best place for overflow monitoring is the sea-bed mud line. The timely detection of underground overflow plays a

critical role in well control and gas cut, in particular. The downhole monitoring method includes annular pressure while drilling (APWD), logging while drilling (LWD), formation testing while drilling (FTWD), downhole micro-flow measurement, ultrasonic flow measurement etc. The key technical challenge in this field lies in the timely updating of monitoring results, and the key technologies are acoustic monitoring technology, riser ultrasonic monitoring technology, pressure monitoring technology, robotic underwater monitoring technology etc. Furthermore, the recent development trend of overflow monitoring technology for deepwater drilling is to shorten the reaction time by improving the technology of overflow monitoring and detection, and to develop an early warning mechanism, which monitors the wellbore pressure to ensure its safety.

• Technologies to ensure the safety of deepwater flow

The technology of safe deepwater flow mainly aims to solve the problems occurring in the flow of deepwater oil and gas, including submarine pipeline blockage, leakage, and other safety issues. It serves to control the flow of oil and gas within a proper range, and to reduce the costs of oil and gas transmission to guarantee an economic and safe transmission. The major technical challenges in this field are described as follows. The first challenge is the technology of multiphase flow mixing, whose primary concern lies in the determination of flow pattern of multiphase flow and the flow regularity in a mixed pipeline. The second challenge is the generation and control of the solid-state product, wherein the synergistic effect of gas hydrate, paraffin, and gas hydrate should be studied. The third challenge is the prediction and control technology of slug flows. The recent development of technologies in this field have focused on the heating technology of oil and water pipelines, which helps to ensure that the temperature of the fluid in the pipeline remains higher than the wax precipitation temperature of crude oil and the hydrate formation temperature. Thus, it can effectively prevent the deposition of paraffin in the pipeline and the formation of hydrate in order to achieve the purpose of flow safety and security. Moreover, underwater multi-phase separation technology is also significant. It separates the liquid product around the subsea wellhead, thus reducing the riser pressure and lifting energy loss, and raising the utilization rate. Moreover, the separation technology not only eliminates severe slug flows from the root, but also effectively inhibits the hydrate generation since it reduces the water content in the oil and gas mixture, thus enabling a more distant transmission.

• Deepwater oil and gas exploration technology

A frontier topic of the oil industry, the exploration and development of deep-sea oil and gas resources is riskier than petroleum exploration and drilling on land or continental shelves, since it is constrained by the present technologies for deepwater exploration, oil platform construction, and natural disaster forecasting and prevention. Moreover, many other factors contribute to its operational difficulty and complexity, e.g., the particularity of oceanic environment, complex storage conditions, and lack of reliable supporting equipment and logistical support etc. Some key technical problems remain to be solved, including the berth port of fixed offshore platform or deep-sea floating platform as a supportive structure for deep-sea drilling, unstable geological environment, floating well control in deep waters, deep-sea environment protection etc. The major challenges in these technologies include the determination of the precise location of a reservoir and the integration of high technologies involved in deepwater drilling; further, progress in the aspects of offshore drilling equipment and related logistical units is desired. Future deep-sea exploration vessels are expected to fully utilize semi-submersible drilling platforms equipped with more automated and efficient drilling equipment and improved deep drilling technology. New light materials with high strength will also be extensively employed in this industry.

• Measurement and analysis of long cable seismic signal

The measurement and analysis of a long cable seismic signal is different from that of a conventional seismic signal in its seismic offset and record length. It has a long cable and involves large amount of data processing, broad working area, significant changes in water depth, and multiple wave development. Influenced by currents and waves, a cable deviates from its set position as its length increases, rendering it difficult to fix the accurate reflection point position and offset migration during two-dimensional seismic data processing. Consequently, the best reflection imaging profile is often unavailable, leading to the problems of tensile distortion and lost Amplitude variation with offset (AVO) phenomenon. There are many

key technical difficulties to overcome, e.g., a four-order dynamic correction technology of anomalous seismic offset in a long cable signal, and AVO technology, which monitors the amplitude of seismic reflection waves to perform lithological judgments and to explore oil and gas reservoirs. Currently, efforts are being made to develop a positioning technology applicable for ultra-deep waters, long cables, seismic merging, high-order correction technology, a variety of denoising technologies etc.

• Deepwater exploration technology of subtle hydrocarbon reservoirs

According to geological science, subtle hydrocarbon reservoir refers to the nonstructural lithological reservoirs that originated during the process of deposition. Subtle hydrocarbon reservoirs are often closely linked with the nature of sedimentary rocks and stratigraphic overlap. Constrained by the tectonic environment, paleo-geomorphology, and paleo-current conditions, the distribution of deposited materials typically exhibits fast lateral changes, while with horizontal bedding it remains flat. Therefore, such reservoirs are not easy to be detected from its geophysical information. Key technical difficulties in this area are the exploration technologies of underwater alluvial fan reservoirs, turbidity sandstone lens reservoirs, and reservoirs with seismic unconformity. Currently, researchers are focusing on a novel method that uses seismic reflection amplitude information for predicting the thickness of a reservoir, measuring seismic wavelets to increase the resolution of seismic data, and developing technologies on synthetic acoustic logging and seismic modeling.

• Development priorities for different countries:

China: Considering the development in the equipment and technology of deepwater oil and gas research, China has been focusing on the design of deepwater floating structures (e.g., the design of drilling vessels, semi-submersible platforms, and FPSO with large oil storage capacity), lifting pipe laying vessels, deepwater standpipes, and risers; deepwater drilling BOP lifting devices, subsea BOP stack and its control system, as well as an intelligent well control monitoring system.

European countries: European countries have paid close attention toward the exploration technology of geomicrobiological oil and gas resources (Germany), BOP and IWOC technology, submarine electronic systems, submarine mobile control modules, underwater transformers, and a piezoelectric structure monitoring system for composite risers.

UK: UK OHM corporation has developed four generations of electromagnetic signal emitter, entitled as deepsea active field source equipment (DASI Ⅳ), to prevent underwater oil and gas overflows; other research hotspots include the BOP power accumulator system, the underwater riser hydraulic control system, the underwater workover control system, soft landing system and technology, the installation of annular safety valve, oil and gas gathering units equipped with float valve, underwater oil and gas gathering units, and a dynamic positioning system for vessels.

Norway: Norway has conducted related research on the technologies to extend the service life of the oil production tree, the floating structures for deepwater oil and gas development, the positioning anchor winch driven by hydraulic pressure, and a dynamic positioning system for vessels.

USA: US has been pioneering in the development of marine equipment and technology for its extensive research directions and advanced technology. In addition to exploration technology, the US has also devoted to underwater production safety, e.g., deepwater BOP devices and a wellhead pressure control system. Besides, a number of novel technologies have been developed, including the 4D seismic technology that can detect leakage and determine dead oil areas, small-sized all-optical sensors that can reliably be applied for seismic exploration and resources production, marine controlled-source electromagnetic survey, subsea BOP system technology that could enhance the strength and fatigue resistance of the wellhead and prime conductor, the design of plugging devices for oil well blowout, the emergency control system for subsea BOP, submarine test tree control system, deepwater container system and its operations, deployment of submarine stacking system, protective device for submarine oil leakage and its operations, the transportation and management of BOP devices, the subsea wellhead pressure control system, laser-assisted system for deepwater drilling emergencies, wellhead pressure testing devices and methods, subsea operating valves connected low pressure receivers, interface equipment connection systems applicable for submarine fluids, laser-assisted BOP devices, BOP devices for spare wellhead, well control system that decreases its mechanical energy, the integration and monitoring technology of BOP devices, submarine laser

modules and its transformation technology, and design of subsea BOP seals.

Internationally: Hotspots in the research of related fields include submarine pipelines system, wellhead BOP system, offshore oil well sealing system, submarine disperse spraying system, deepwater mixed risers system, submarine pumping method and equipment, subsea BOP control system, submarine noise control system, anti-blowout component in BOP and its operations, floating drilling ship, BOP monitoring system, the dual-gradient drilling enhancement system, and cable design.

(3) Current development status and future trends

Deepwater oil and gas development is a systematic engineering topic, as well as a cross-disciplinary technological innovation project that requires the coordinative collaboration of different institutions and units. Nowadays, all countries around the world are participating in this competition to enhance their exploration, drilling, and development technologies of deepwater/ultra-deepwater oil and gas resources. On May 9, 2012, China officially launched its "Submarine Oil 981" project in the South China Sea, thereby demonstrating that China has taken its first step in the implementation of its "deep-sea strategy" in the offshore oil industry. By far, China has accumulated rich experiences in the exploration and development in deepwater oil and gas, and is capable of executing tasks at a maximum water depth of 3000 m. However, compared with the other countries that have made considerable achievements in this research area, e.g., USA, the Netherlands, Norway, and Canada, we might be aware that there is still room for improvement. Some major challenges for current developments include the poor marine environment (low temperature area in Arctic), the difficulty of drilling well control in deep waters, the geological disaster caused by mudline shallow hydrates, and the safety risk in system operations. Future studies are expected to focus on the abovementioned issues and strive to make breakthroughs in aspects of the deepwater floating drilling platform, robotic drilling system, non-riser drilling rig, intelligent gathering, and transportation system in deep waters. The ultimate goal for us is to realize industrialization in submarine resources exploration and development (i.e., submarine automatic drilling, oil and gas processing, power supply and its automatic control, production and its automatic control, maintenance and expansion, etc.), and try to overcome the negative influences caused by ocean climate changes. Furthermore, we should face the fact that in addition to independent innovation, China still needs to learn from the west in terms of advanced technologies. Only in this manner, we can continuously enhance our development in deepwater oil and gas exploration and production, and strive to reach the international advanced level in the future.

(4) The development status of different countries and the collaboration among major research countries and institutions

Table 2.2.3 demonstrates that the USA, UK, and the Netherlands are the top 3 countries that have obtained the most core patents on technologies and equipment for

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Equipment and technology for deepwater oil and gas development"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	121	74.69%	1168	84.52%	9.65
2	UK	12	7.41%	43	3.11%	3.58
3	The Netherlands	7	4.32%	14	1.01%	2.00
4	Norway	7	4.32%	64	4.63%	9.14
5	China	6	3.70%	20	1.45%	3.33
6	France	5	3.09%	4	0.29%	0.80
7	Canada	3	1.85%	2	0.14%	0.67
8	Germany	3	1.85%	25	1.81%	8.33
9	Singapore	3	1.85%	16	1.16%	5.33
10	Denmark	2	1.23%	7	0.51%	3.50

deepwater oil and gas development. Patents from USA account for 74.69% of the total patents in the world, while China has only obtained 3.70%. It indicates that the USA is taking the leading role in deepwater oil and gas development while China is following the mainstream research of others, and remains at the early stage with respect to equipment and technologies of deepwater oil and gas development.

Table 2.2.4 shows that nine out of ten institutions are American research institutions that have obtained the most core patents on technologies and equipment for deepwater oil and gas development in the world. UK has one seat, while China has zero seat. This indicates that American institutions have mastered the core technologies of deepwater oil and gas development, e.g., Schlumberger, Halliburton, Baker Hughes, and other large oilfield technological companies.

Figure 2.2.3 illustrates that the Netherlands, France, UK, Canada, and the USA have conducted extensive collaborations for promoting the integration of the industry, education, and research in deepwater oil and gas development. Among them, the USA and the UK have made the most frequent contacts and collaborations, which are followed by the USA and the Netherlands. This indicates that the USA not only takes the lead in research and technology development, but also pioneers in initiating academic exchanges and industrial collaborations in the area of deepwater oil and gas development.

Figure 2.2.4 shows that there were extensive academic exchanges and industrial collaborations between American institutions, e.g., between SLMB and PRAD, and HYDL and VETC. Furthermore, SLMB and PRAD are the two institutions that have obtained the most patents in this area. This indicates that the USA has established an enabling environment for institutions and businesses to develop contacts and collaborations with each other, and has laid a great foundation for the full fledgling of business collaboration on the technology of deepwater oil and gas development. In contrast, only a few China's institutions have obtained core technologies in this area, and they should strengthen the integration of the industry, education, and research, and develop more contacts and collaborations with each other.

(5) Current situation and dominant trends in China

With the exploitation of deepwater oil and gas resources under progress, research in China on the relevant equipment and technologies are based primarily on three stages: well drilling, underwater installation, and commissioning. Meanwhile, constant upgrading has been witnessed in all types of equipment, including drilling apparatus, construction vessels, and underwater vehicles. Currently, research focuses particularly in four areas: floating drillships, underwater vehicles, deep water riser systems, and underwater production system. Future technological innovations in deepwater applications will continue to be vibrant and dynamic. In general, the

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Equipment and technology for deepwater oil and gas development"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	HYDL	15	9.26%	44	3.18%	2.93
2	VETC	14	8.64%	59	4.27%	4.21
3	COOI	11	6.79%	43	3.11%	3.91
4	BRPE	8	4.94%	86	6.22%	10.75
5	SLMB	8	4.94%	58	4.20%	7.25
6	PRAD	7	4.32%	56	4.05%	8.00
7	NAOV	6	3.70%	58	4.20%	9.67
8	Subsea IP Holdings	6	3.70%	136	9.84%	22.67
9	CALI	5	3.09%	86	6.22%	17.20
10	SHEL	4	2.47%	11	0.80%	2.75

Note: HYDL stands for Hydril Co.; VETC stands for Vetco Gray Inc.; COOI stands for Cooper Technologies Co.; BRPE stands for BP Chem Co. Ltd.; SLMB stands for Schlumberger Technology Corp.; PRAD stands for Prad Res&Dev Corp.; NAOV stands for Nat Oilwell Varco LP; CALI stands for Chevron Usa Inc.; SHEL stands for Shell Oil Co.

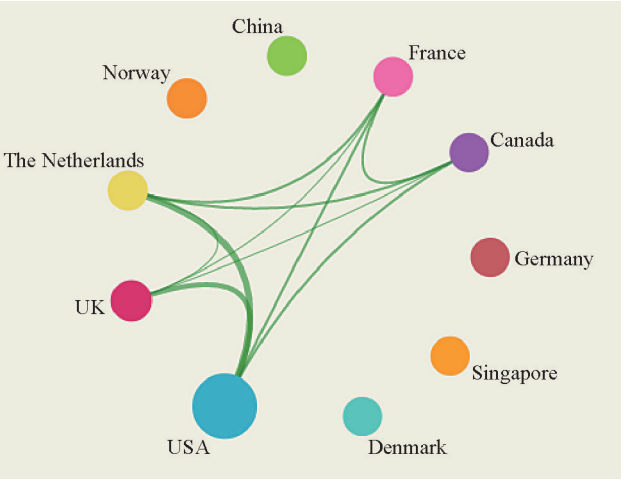

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Equipment and technology for deepwater oil and gas development"

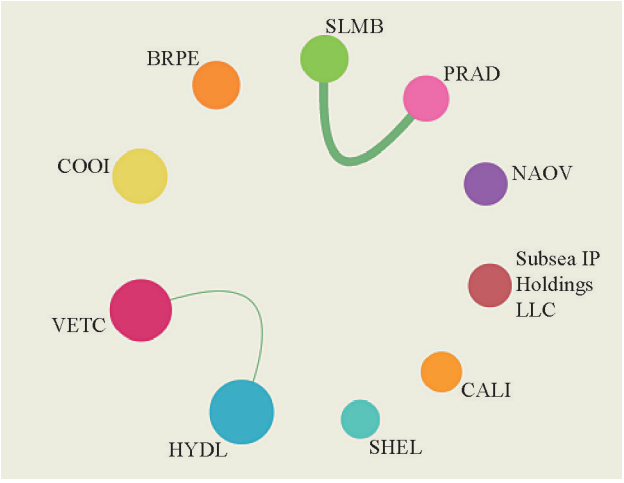

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Equipment and technology for deepwater oil and gas development"

trend in these field points is toward four directions: drilling apparatus and ancillary facilities with high degree of automation, underwater operation and facilities, multifunctionality of deepwater technologies and equipment, and innovations in deepwater high-techs. Technological innovations and breakthroughs will gradually subvert traditional exploration and exploitation methods, thereby considerably reducing the costs and risks involved and stimulating the development of onshore oil and gas operations. The share of deepwater production in global offshore oil and gas operations is expected to bypass 30%, thereby making it a strategic energy source of increasing significance.

Recently, China's investment in marine oil and gas exploration and development has increased year by year. More and more research institutions, including China University of Petroleum (Beijing), China University of Petroleum (East China), Ocean University of China, Shanghai Jiao Tong University, Southwest Petroleum University, Dalian University of Technology, Institute of Oceanology under Chinese Academy of Sciences, Guangzhou Ocean Geological Survey, CNOOC Research Institute, and China Petroleum Drilling Institute, are involved. Currently, a number of major research projects on deepwater oil and gas development have received supports from units such as the Ministry of Science and Technology and the Natural Science Foundation, including the "973" project—"Fundamental Research on Safe and Efficient Well Drilling of Deep-water Oil and Gas Applications," undertaken by China University of Petroleum (East China), along with China National Petroleum Corporation, China National Petroleum Research Institute, China National Offshore Oil Research Institute, China National Petroleum Research Institute, Chinese Academy of Sciences, China University of Petroleum (Beijing), Shanghai Jiao Tong University, China Shipping Oilfield Services Co., Ltd., and China National Petroleum Corporation Marine Engineering Co., Ltd. The project adopts the industry-university-research (IUR) joint model to form a theoretical foundation tailored for safe and efficient deepwater operations in the South China Sea, with a view to provide the theoretical support for a leapfrog development in China's deepwater oil and gas technologies.

China has constructed various types of equipment for utilizing offshore oil and gas, including HYSY981, the sixth generation of deep-water drilling platform, and HYSY201, an S-shaped lifting pipe, that are able to operate at a maximum depth of 3000 m below the sea. However, the proportion of homemade ancillary devices remains limited. For underwater production systems and technologies related to deep-sea installation, repair, and personnel rescue, we still need to rely on foreign countries.

Based on the current development of China's deepwater oil and gas equipment and related technologies, we propose the following suggestions. First, allocation of scientific and technological resources can be further optimized by establishing a special fund for "Deep-sea Oil and Gas Drilling," with an emphasis on supporting

elementary scientific research and achieving technological breakthroughs. Second, more efforts should be devoted to the development of engineering technologies and devices for deep-sea oil and gas applications, so as to enhance the proportion of key components produced at home, develop sufficient capacity for systematic deep-sea operations, and catch up with foreign counterparts. Third, steady progress should be actively made in offshore oil and gas operations in the Polar Regions to enhance China's leadership in the field of polar oil and gas drilling. Fourth, swifter action is to be observed in the implementation of human resource development strategy to strengthen innovation capacity and establish a strong talent pool of international standard in the field of deep-sea oil and gas development. Finally, collaboration with international community is to be fortified by active participation in key international research programs on deep-sea oil and gas development, and self-reflection upon what to be learned and enhanced from such experiences.

2.2.3 New fracturing methods, fluids, proppants, and additives

(1) Concept elaboration

With worldwide rapid socioeconomic development, the consumption of oil and gas resources is continuously increasing, and the conventional oil and gas resources can hardly satisfy the growing demand. Simultaneously, the mining technologies in the oil and gas industry are developing at such a rate that unconventional sources of oil and gas can be utilized economically. The past decade, in particular, viewed the increase of vigorous development in extracting unconventional oil and gas resources (such as tight oil/gas, shale gas, and coalbed gas), which has become a novel growth point of future oil and gas production. However, unconventional oil and gas reservoir generally have complex formation structure, thereby increasing the difficulty and cost of production. Therefore, in the effort to extract unconventional oil and gas resources, the problem now at hand is to determine the methods of extraction that are more reasonable, efficient, and cost-effective, among which fracturing is the most basic approach that can increase production. At present, one typical fracturing method is water-based fracturing, which, however, is plagued by issues such as excessive consumption of water, environmental and reservoir pollution, and difficult recovery. Under this background, novel fracturing methods and technologies, such as hybrid fracturing, multistage unlimited fracturing, fiber fracturing, HiWAY channel fracturing, waterless fracturing, and LPG fracturing, have embraced swift development, thereby defining the worldwide major research hotspots in the recent years. The novel techniques solve in varying degrees some existing problems of conventional fracturing, by considerably increasing the output and rate of recovery from unconventional oil and gas resources. The research and application of these technologies will play an important role in the development of unconventional oil and gas business in areas such as the lack of water resources, serious environmental pollution and difficult transportation of equipment.

(2) Concept elaboration, key technologies to be resolved, and future trends for the concerned engineering branches, and an overview of the development priorities in different countries.

Research on novel fracturing methods, fluids, proppants, and additives has achieved rapid development. Currently, researchers are focusing on the following areas:

• Multistage unlimited fracturing

Extracting unconventional oil and gas, particularly shale gas, requires long horizontal well with multistage fracturing technology. The total length of the horizontal section is 1000–3000 m, or longer, which indicates that the formation should be fractured 20–60 times, provided a spacing of 50 m between the two stages. Restricted by the width of oil tubes, conventional ball-drop fracturing can initiate 15-stage fracturing at maximum during one trip. In order to reduce the working hours and cost of fracturing, research is directed toward multistage unlimited fracturing. Coiled tubing infinite grade sliding sleeve segmented fracturing is a recent multistage fracturing technique that is capable of achieving 97 stages of fracturing in one trip, with its record being 104 stages in a single well. The maximum vertical length of the well fractured using this method is 4681 m, and the maximum depth is 6256 m. The technique uses a novel stepless casing sliding sleeves, which are included in the casing going down the well for well cementation. After fixing the casing in place, the sliding sleeves are opened one after another for staged fracturing at one shot. At present, bridge plug method and ball sliding sleeve technique are the two types of multistage fracturing technologies, which are more commonly used in the field. Different

from ordinary multistage fracturing methods, key technologies that multistage unlimited fracturing aims to achieve are how to be free from the limitation imposed by the number of fracturing stages, where is the accurate location to fracture, and how to make the fracturing fluids travel directly to the target layer and achieve real-time monitoring of fracturing pressure simultaneously. Multistage unlimited fracturing is a novel type of fracturing processes that serve as a key tool for production boost and reservoir stimulation of unconventional oil and gas resources, including oil and gas reservoirs of low permeability, thin oil layers, shale gas and coalbed gas, boasting considerable advantages in increasing the production output and efficiency for oil fields. The current trend is to increase the number of fracturing stages in a single trip, as well as in a single well, and to move toward deeper wells.

The technique was developed by Canadian energy company NCS. Following a series of record-breaking feats in 2014 on the number of stages achieved in a single well, it won the 2014 SPE Technology Award for the Canadian region and the 2014 World Oil Best Completion Technology Award. At present, NCS is the holder of this technique, whose applications in other countries are entirely relied on the technical services of the company.

• FracInsight precise fracturing

In order to solve the problem that the perforation section of many horizontal wells does not yield oil or gas during the reservoir development, Halliburton has developed a novel "fracturing positioning" module—FracInsight. The module selects accurately perforation and fracturing stage locations from formation evaluation data along the horizontal section of a well. FracInsight is a repeatable interpretation workflow, the essence of which is to create a more consistent fracturing operation by eliminating redundant perforation clusters and fracturing stage locations, and therefore reduce inconsistent breakdown and treatment pressures, and maximize the output. The key part to be tackled in this technology is to combine the production index and the fracture index to optimize stage and cluster placement for an accurate prediction of the fracture. The novel technology has been introduced into applications in North America, including countries such as Canada and Mexico. However, only several dozens of analysts have a desirable proficiency in this technology. Future development of the technology points toward a full integration of the production index and the fracture index to create fracturing with enhanced accuracy, and the cultivation of more analysts to help advance the technology in a better direction.

Building on the CYPHER2.0 Seismic-to-Stimulation Service, the technology is a brand new "fracturing positioning" module developed by Halliburton. The technology has been introduced into applications in North America, including countries such as Canada and Mexico.

• StimMORE fracture diversion technology

The technology is a novel technology developed by Schlumberger. In the process of fracturing fluid diversion, both gels and foams are commonly used diverting agents. Their residuals may have an adverse effect on long-term production of the reservoir. StimMORE technology uses a low-cost fiber-laden diversion fluid, which generates an effective blockage, and is completely degradable, thus leaving no residual formation damage. It adds fiber to the mortar and creates bridge plugs by proppants and fibers over the fractures. The low density of fibers prevents them from precipitating and in turn allows them to be carried to target locations. The shape of the fibers is such that they are able to lie across the interconnected channels and cracks, with a considerably lower solid content than that of simple particles. This temporary obstruction during the pumping increases the pressure at the end of the wellbore, thereby making it sufficient to induce the creation of additional fractures in the rest of the formation. Fibers will be degraded and dissolved a few days later, leaving no damage on the formation. The key part of this technology to be solved are how to monitor the diverting effect of the diversion fluids in real time, and how to further enhance the performance of the fiber-laden fluid so that it can be used in more adverse formation conditions such as ultra-high temperature and/or ultra-high pressure. Future development of this technology is to device more accurate monitoring apparatus and better fiber-laden diversion fluid, so that it can be applied in more complex formations with higher accuracy.

StimMORE fracture diversion technology is developed by Schlumberger. It is used in combination with StimMAP live micro-seismic monitoring technology, and it can monitor the development of cracks in real time and adjust promptly the pumping schemes, resulting in lower well completion costs and maximum reservoir contact.

Schlumberger provides guidelines on the application of the technology in all regions.

• Hybrid fracturing technology

Although water fracturing provides easy drainage and less damage to fluid conductivity of the fractures, it suffers poor sand-carrying capacity and difficulties in maintaining the crack width, rendering areas in the vicinity of the wellbore prone to sand blocks.

If proppants in the form of small particles were used for reducing their terminal speeds, fractures would be susceptible to re-closure under high formation pressures, thereby imposing a considerable impact on the stimulation effects of water fracturing. The emergence of hybrid fracturing has significantly enhanced such defects of water fracturing as high fluid loss, low viscosity, and poor sand-carrying capacity. This method allows proppants of larger particle size to be pumped in, expands the fracture width, and reduces the reservoir damage.

In hybrid fracturing, slickwater is first pumped into the wellbore to make full use of water's strong ability to generate fractures, thereby promoting the formation of long cracks. Cross-linked fluids containing gels and proppants of certain grain size are then pumped into the well, producing viscous fingering in the long fractures, which lowers the terminal velocity of the proppants and helps to sustain fracture conductivity. After a comprehensive evaluation and comparison of conventional hydraulic fracturing and the novel hybrid fracturing, the half-length of the effective fractures generated by the hybrid fracturing are longer, which allows significant elongation of the cracks and expanded scope of crack-affected zone, enhanced sand-transport capacity, and fewer fluid loss and water consumption.

One of the key issues to be solved for hybrid fracturing is how to generate longer effective fractures to achieve better sand-carrying capacity and lower fluid loss. Another central issue is how to reduce reservoir damage, as the degree of damage to the reservoir caused by hybrid fluids is significantly lower when compared with cross-linked fluids.

The technology is now heading toward longer half-length of factures and less pollution to the formations. Controlled by the two American companies, Anadako Oil and Baker Hughes, it has achieved remarkable results after its field applications in multiple shale plays in the USA.

• Fiber fracturing technology

In general, the water fracturing technology can neither make the proppants fill the hydraulic cracks properly, nor can it effectively improve issues like the permeability. The use of new fiber-based fracturing fluids (FiberFRACs) as fracturing agents can effectively ameliorate problems such as unsatisfactory crack width by hydraulic fracturing , insufficient sand-carrying capacity of the fracturing fluid, rapid sedimentation of proppants at the bottom of the fractures around the wellbore, etc.

The principle of the fiber fracturing technology relies on adding the fiber materials to the fracturing fluid to improve its apparent viscosity, so that the proppants can remain suspended during the fracturing process. Some fibrous structures can be dissolved automatically after fracturing, to further improve the conductivity of the modified fractures. This new technology has improved sand suspension and fracture conductivity without the use of large equipment, reducing the engineering costs.

Degradable fiber fracturing technology has significant benefits in suitable reservoirs, such as brittle and shallow shale reservoirs, and works better with slickwater fluids and light proppants.

Future development trends of this technology are aimed at further improving the performance of the fracturing fluid and choosing more suitable proppants with better compatibility, to expand its range of applications.

This technology has been developed and put into use by a few companies like Schlumberger. Further, the technology has performed well in tight gas reservoirs in North America. It is also accessible to Petroleos Mexicanos, which has achieved good results when exploiting a tight sandstone gas in the Burgos Basin.

• Waterless hydraulic fracturing technology

Waterless hydraulic fracturing technology mainly comprises: nitrogen fracturing, CO_2 fracturing, LPG fracturing, and other technologies.

Nitrogen fracturing uses nitrogen as a fracturing matrix, to generate fractures and enhance reservoir permeability, with the goal of increasing productivity This fracturing process is free from water and solid particles, which not only eliminates water sensitivity and water lock damage caused by the water content of conventional fracturing fluids, but also eliminates the blockage of perforations and fractures by solid particles. However, the low density of the nitrogen results in poor proppant-transport

properties. The lack of proppants in the fracturing process leads to gradual closure of newly opened fractures after a certain period of time, adversely affecting the end effects of fracturing and the economic benefits of this technology.

Recently, the liquid nitrogen fracturing technology has garnered a lot of research interest. This technique uses of liquid nitrogen (–195.8 °C) as a fracturing fluid to perform reservoir stimulation. The mechanism of its auxiliary functions in crack initiation is divided into two components: the thermal shock caused by the contact of extremely low temperature liquid nitrogen with the rock, and the thermal stresses acting on the fracture surface during the abovementioned process, which shatters the rock surface when it exceeds the tensile strength of the rock.

Liquid CO_2 fracturing technology uses liquid CO_2 as a fracturing medium, which is injected into the reservoir for fracture generation, sand transport, and displacement. Simultaneously, the liquid CO_2 is rapidly gasified under the temperature of formation, mixing with the crude oil and greatly reducing the viscosity of the oil, while increasing its fluidity. CO_2 can react with the water in the reservoir to generate carbonic acid, mitigating the swelling of clay minerals, removing crack congestion, increasing gas solubility of the reservoir, and eventually, achieving the goal of increased productivity.

In recent years, some scholars have proposed the use of supercritical CO_2 fracturing, where CO_2 is in a supercritical state, as the temperature and pressure exceeds the critical values of 31.1 °C and 7.38 MPa, respectively. A supercritical fluid is neither a gas nor a liquid, with different basic properties. With its density close to that of a liquid, its viscosity is closer to a gas (about 5% that of water). It has very low surface tension, but a diffusion coefficient higher than a liquid, giving it a strong permeability.

It is easy to reach the supercritical state under the stimulation conditions in wells, as both the critical pressure and temperature of CO_2 are fairly low. Supercritical CO_2, one of the most widely used supercritical fluid for the time being, supercritical CO_2, when used as fracturing fluid for stimulation, has demonstrated its own advantages over slickwater-fracturing and foam-fracturing: (1) CO_2, cheap and easy to obtain, is neither flammable, explosive, nor corrosive in the supercritical state. (2) The viscosity of supercritical CO_2 is low, similar to a gas, with low (near zero) surface tension, high fluidity, and low friction coefficients. (3) No clay swelling is observed in the reservoir with supercritical CO_2, eliminating the water lock effect, rock wettability alteration and other hazards from the root, effectively protecting the reservoir from damage. (4) Being a cleaning fluid that generates little damage, the use of supercritical CO_2 for fracturing promises rapid and thorough flow back, which shortens the production cycle. (5) Compared with conventional fracturing fluids, supercritical CO_2 has strong diffusivity and permeability, allowing it to readily penetrate into the pores and micro fractures in the reservoir, which is conducive to creating a large number of micro fracture networks.

The main aspect of the technology to be addressed is the solid particulate transport ability of supercritical CO_2, and further modification of fracturing equipment. Currently, many countries have shown interest in CO_2 fracturing. In-depth research has been conducted on CO_2 fracturing by the USA and China, among other countries.

- The application of novel nanomaterials in fracturing

Traditional cross-linked guar-gum fracturing fluids cause a great deal of damage to the geological formation. In order to reduce the amount of polymers remaining in the cracks, a wide range of oxidants, enzymes, and other gel breakers have been researched, but their effects on oil and gas production are unsatisfactory. Therefore, the use of water as a fracturing fluid has resumed in some areas. On one hand, this method has low cost and good performance in the field, but on the other hand, it has high fluid loss. Therefore, methods of increasing viscosity and reducing filtration loss based on less formation damage have become a new research topic. Conventional elastic surfactant fracturing fluids have been used for gravel packing and hydraulic fracturing for over twenty years. In this method, the surfactant can be naturally arranged in the brine to form threadlike micelles (TLMs). TLMs, similar to polymers, are thickened by overlapping and entangling micelles. Generally, the TLM system can be rapidly filtered in porous media, resulting in a low efficiency of crack creation, which limits its application in this field.

To mitigate this problem, some researchers abroad added nano-particles to the surfactants to create associations between the surfactant micelles in the fracture fluids, forming a three-dimensional network of surfactant micelles. In this way, wall stimulation, lower fluid loss and higher liquid efficiency are achieved. The micelles contain gel breakers, and are able to reach any place within the system, ensuring a thorough breakdown of the gels. Frac-

turing fluids with nanoparticle-enhanced surfactants can be applied in several types of reservoirs. Compared with conventional guar gum, its yield is higher and more sustainable. It is especially suitable for wells sensitive to damage due to fluid conductivity. In addition, additives such as gel breakers have also been developed for this system.

Further, nanomaterials, such as controllable electrolytic metals (CEMs), also find applications in downhole equipment, because CEMs have the unique properties of high strength, low weight, and controllable dissolution rate. CEMs are ideal materials for downhole tools used in repair-free well operations. They facilitate fluid control and can be dissolved in the liquid within the wellbore, ensuring unimpeded flow of the fluids after each stage of fracturing, thereby enhancing production capacity.

Nanomaterials have been gradually put into use in modern fracturing technology, and are playing an increasingly important role in it. Nanomaterials will gradually become low cost, and be used in customized applications (catered to different formation conditions) in the future.

• New types of proppants

Proppants are injected into the ground along with the fracturing fluids. They help keep the fracture open to facilitate gas extraction. With the emergence of sand transport with higher viscosity, proppants have gradually evolved into many types, including sand, resin-coated sand, ceramic particulate, glass microsphere, walnut shell, steel ball to polymer microspheres, etc. The proppant should be able to sustain the closure pressures, which range from 35–70 MPa for typical formations. Its type, shape, strength, hardness, wear resistance, acid and alkali resistance, corrosion resistance, toughness, grain size, filling density, distribution state, and flow conductivity will have a direct impact on its fracturing effects.

During transport, proppants are susceptible to accumulation inside cracks, creating "islands", and causing other phenomena such as backflows, diagenesis, compaction, burial, and dissolution. They are prone to forming plugs or contributing to crack closure, reducing the production of oil or gas. Therefore, new proppants with ultra-high strength, ultra-low density, self-suspension, new rod-shape and functional orientation have recently received widespread attention. Ideal proppants should have the following features: high strength, smooth surface, chemically inertness, low cost, low density, convenient and practical, resistant to backflows, and not easily buried.

However, at present, even the best proppant is not able to satisfy all these conditions. It is hoped that, in the future, technology can create a proppant that is not only easily transported to the target location, but also has excellent fracturing effects and good stability, so that lasting benefits are possible in every single operation.

• Surface-modification agent (SMA) coating technology

In SMA coating technology, a thin layer of polymer coating is deposited onto the proppants to create an adhesive surface, and thereby increase surface friction. This technology promises rapid coating, stable molecules, strong acid and alkali resistance, and good compatibility with fracturing fluids. It also prevents backflows by improving the viscosity of the fracturing fluids, reducing both sedimentation ratio and deposition rate, and enhancing liquidity. In addition, the coatings are versatile and can be applied to the surfaces of sand and ceramic particles alike. However, it is yet to be determined whether this method can maintain its good performance in different pressure ranges. Moreover, SMA coatings are difficult to dissolve, making equipment cleaning difficult. To tackle this problem, Halliburton developed a water-soluble surface modifier ASMA, which is environmental friendly and has good compatibility with fracturing fluids.

Future development of the surface modifiers should be aimed at consistent performance at different pressure ranges, while simultaneously enhancing the performance of the fracturing fluids.

(3) Current situation and future trends

The rapid development of new fracturing technologies and related materials can be credited to the large-scale development of unconventional oil and gas resource extraction that employs these methods. The development of fracturing technologies for unconventional oil and gas resources is a gradual process. From the gel and N_2 fracturing used in the beginning, to the extensive application of water fracturing and research conducted on new fracturing methods, every innovation brings a revolutionary breakthrough.

At present, in order to meet the needs of the large-scale commercial development of unconventional oil and gas resources, such as shale gas and coalbed methane, fracturing technologies have accomplished multi-stage unlimited fracturing, with control of crack propagation to a certain extent. Fracturing diversion technology has been applied on a large scale, and hybrid fracturing is in the stage of field application. Fiber fracturing and channel

fracturing have seen successful on-site trials. Waterless fracturing technologies using LPG, N_2, and CO_2 are still under research and local testing. Research breakthroughs occur every now and then in the USA, Canada, and China, especially in CO_2 (or supercritical CO_2) fracturing. China is now a world leader in this research. Rapid progress has been made in research on fracturing fluids, proppants, additives, small molecules, and guar gum of small molecules with little harm. In addition, new nanomaterials have been widely used in fracturing, such as in nanomaterial-induced association of surfactants and nano-scale downhole equipment. It was found that for proppants, the range of usable densities increases with tensile strength.

In the future, to satisfy the requirements of developing unconventional oil and gas resources that are more economically effective, both conventional water-based fracturing technologies and waterless fracturing technologies will gradually become more efficient and environment-friendly methods with low costs.

(4) Comparisons of major research countries or regions and institutions and their collaborations

From Table 2.2.5, it can be seen that the top 3 countries in terms of the number of core patents on engineering development focus "New fracturing methods, fluids, proppants, and additives" are the USA, China, and Canada. The USA accounts for 78.59% of the world's total patent output, while China accounts for only 11.43%. The data indicate that the USA is a world leader in deepwater oil and gas development, while China is still at the preliminary stage of research.

From Table 2.2.6, it can be seen that seven of the top 10 institutions that produce these patents are from the USA, with the remaining three institutions from China and Russia. The proportion of China's institutions is small, which further shows that core technologies in the new fracturing methods are all controlled by American institutions, giving the USA an absolute advantage. Among the American institutions, three oil giants—Halliburton, Schlumberger, and Bakerhughes—control the core technologies. It can be concluded that China is still lacking in this field.

Collaboration networks of major countries or regions and institutions that produce most core patents in the engineering development of new fracturing methods, fluids, proppants, and additives is shown in Figure 2.2.5 and 2.2.6.

From Figure 2.2.5, it can be seen that the USA, the country with highest number of patents, has Canada, UK, France, and China as its top 4 collaboration partners. The top 5 countries with the most fracturing-related inventions, namely, the USA, China, Canada, Holland, and France, are also the largest collaboration partners to each other. Countries or regions like British Virgin Islands and Russia follow the above-mentioned inventor countries, with fairly considerable research on fracturing. The collaboration between these countries has jointly determined which technologies to further develop for new types of fracturing, fluids, proppants, and additives，which are the representatives of new technologies.

It can be seen from Figure 2.2.6, that the number of patents obtained by SLMB and PRAD account for the majority of the patents obtained by all enterprises. collaboration

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "New fracturing methods, fluids, proppants, and additives"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	378	78.59%	3686	84.77%	9.75
2	China	55	11.43%	390	8.97%	7.09
3	Canada	47	9.77%	220	5.06%	4.68
4	The Netherlands	35	7.28%	152	3.50%	4.34
5	France	34	7.07%	135	3.10%	3.97
6	UK	29	6.03%	107	2.46%	3.69
7	Virgin Islands	23	4.78%	93	2.14%	4.04
8	Russia	18	3.74%	40	0.92%	2.22
9	Germany	6	1.25%	32	0.74%	5.33
10	Saudi Arabia	5	1.04%	49	1.13%	9.80

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "New fracturing methods, fluids, proppants, and additives"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	HALL	200	41.58%	2226	51.20%	11.13
2	SLMB	73	15.18%	554	12.74%	7.59
3	PRAD	51	10.60%	299	6.88%	5.86
4	BAKO	34	7.07%	250	5.75%	7.35
5	CNPC	16	3.33%	121	2.78%	7.56
6	SNPC	9	1.87%	69	1.59%	7.67
7	Trican Well Service Ltd.	6	1.25%	38	0.87%	6.33
8	Carbo Ceramics Inc.	5	1.04%	64	1.47%	12.80
9	Self-Suspending Proppant LLC	5	1.04%	42	0.97%	8.40
10	Tatneft	5	1.04%	2	0.05%	0.40

Note: HALL stands for Halliburton Energy Services Inc.; SLMB stands for Schlumberger Technology Corp.; PRAD stands for Prad Res &Dev Corp.; BAKO stands for Baker Hughes; CNPC stands for China Nat Petroleum Corp.; SNPC stands for Sinopec Corp.

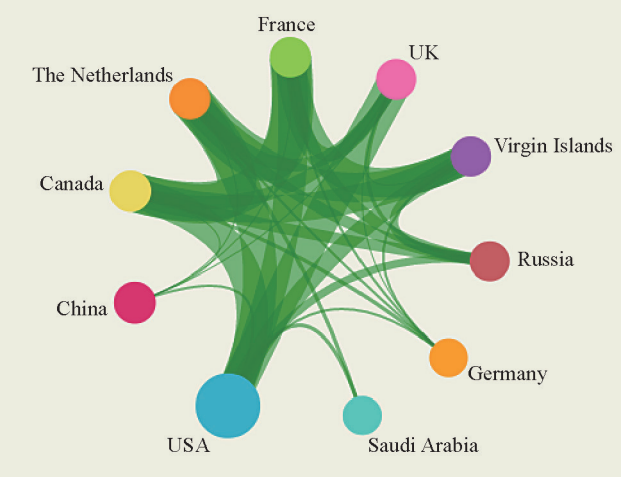

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "New fracturing methods, fluids, proppants, and additives"

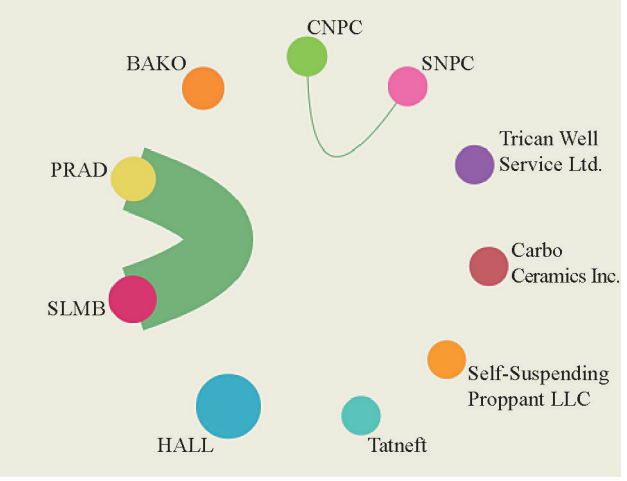

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "New fracturing methods, fluids, proppants, and additives"

between the two institutions leads to an absolute advantage over the others. Patents from other institutions take up comparatively small shares in the market. Therefore, the two institutions are at the forefront of innovation and technology in this field, while other research institutions are falling behind at the initial stages of research.

China is now at an early stage in development of new types of fracturing technologies. Quite a large proportion of this development is introduced from abroad. China is still lagging behind in most technologies in this field. Major research and application of new types of fracturing proppants is also undertaken by foreign countries, while domestic researchers are still in the process of catching up. Material performance is the fundamental reason for this slow domestic development.

(5) Current situation and dominant trends in China

Presently, China is still in the preliminary stages of the research on new fracturing technologies, and a large number of technologies draw inspiration from other countries. According to the number of patents that China has disclosed in this regard, China is still catching up to other countries.

As more advanced fracturing methods are being proposed by foreign companies or institutions, China's re-

search units are following and reproducing their research, such as in the cases of multi-stage unlimited fracturing and fracturing diversion. However, due to problems encountered regarding materials, manufacturing, and further processing, breakthroughs in core technologies have not been possible yet. For example, consider the reusable rubber packer. Imported rubber packers can undergo the process of setting and de-bonding a dozen times, while China's rubber can only do so two to three times. These performance problems of China's rubber materials become a hindrance to the overall development of related technologies.

In order to study a development method suitable for extracting unconventional oil and gas resources in China, many organizations in our country have begun researching waterless fracturing. China now has built up considerable advantage. In particular, research on liquid nitrogen and supercritical CO_2 fracturing has entered the stage of field trials, and is expected to see large-scale application within the next five years, while supercritical CO_2 fracturing will be combined with oil and gas displacement, replacement, and burial, to realize green development and utilization of oil and gas.

At present, the main research direction for unconventional oil and gas fracturing in China focuses on large-scale hydraulic jet fracturing, multi-stage unlimited fracturing, channel fracturing, waterless fracturing, new nano-surfactants, new fracturing fluids, super-light and ultra-high strength proppants, etc. In order to speed up the development of new fracturing technologies in China, setting up a special fund for the "new fracturing technology of unconventional oil and gas", that focuses on the support of basic scientific research to break the bottlenecks existing in the development of unconventional oil and gas, has been proposed. Interdisciplinary IUR teams can be set up by integrating advantages of university and industry research and starting from the basic problems of theoretical design, material processing, etc., to address the key problems in current technological development. Moreover, international collaboration and active participation in major international development programs on unconventional oil and gas will enhance the progress of China's unconventional oil and gas development.

2.2.4 Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment

Nuclear power equipment technology is the key technology to achieve the thermo-hydraulic function of the reactors, and ensure economical and safe operation of nuclear power plants. It includes design, materials, processing and manufacturing, inspection and testing, safety assessment, acceptance, transportation, decommissioning, and other technologies. Public concerns on the safety of nuclear power keep growing, as do safety requirements of nuclear power equipment, which include higher seismic rating, increased durability, more stable operation, more reliable passive technology, stronger disaster mitigation capacity, etc. At present, only the USA, France, and Russia have developed a complete set of standardized technologies in nuclear power equipment. With an advantageous domestic market for nuclear power equipment, China has been able to fabricate equipment capable of generating a million kilowatts by independent design, manufacturing, and innovation, after cycles of introduction, assimilation, and recreation in recent years.

Fuel assembly is an important component of the reactor core, and is the only component where chain fission reactions take place, and where fission products are contained. The reactor pumps and valves are important devices for driving the circulation of reactor coolants, and performing the thermo-hydraulic functions of the reactor. Reactor pressure vessels and pipelines are important pressure boundaries in the loops of a reactor system. The integrity of the pressure boundary plays a key role in preventing the leakage of radioactive substances. The reactor containment is the last safety barrier of the reactor. The nuclear power equipment mentioned above is different from ordinary energy equipment. During normal operation, this equipment has to not only withstand high temperature and pressure, but also absorb strong radiation from fission and decay. According to nuclear safety regulations, nuclear power equipment should have a certain degree of safety and structural integrity in case of accidents depicted in the basic reactor design. With the development of the safer 3G and 4G advanced reactor heaps, such as offshore floating nuclear power plants and small modular reactors, more stringent safety requirements have been set for nuclear power equipment.

Fuel assemblies in nuclear reactors are mainly combined rod fuel assemblies, spherical fuel assemblies, liquid molten salt fuel assemblies, etc. Fuel assemblies are used in the strong neutron field inside the reactors for three to five years, and subjected to harsh working conditions, such as

high temperature, high pressure, erosion due to rapidly flowing coolants, chemical effects from the fission products, and complexly applied mechanical load. At present, mainstream pressurized water reactors adopt 17×17 rod-like fuel assemblies without any channel boxes, worldwide. Fuel components consist of the fuel rod, draft tube, positioning grid, and the upper and lower headers. The fuel pellets contained in the fuel rods are made from 3% to 5% concentrated uranium. The fuel cladding is the second safety barrier of the reactor, and the positioning grid is an important skeleton that supports the fuel assembly. In order to improve the burnup and increase the economic benefits of nuclear power, countries around the world have actively developed new types of high-performance fuel components with the following characteristics: long cycle time, high burnup, high reliability, operational flexibility, lower storage of spent fuel, longer power plant life, and lower fuel manufacturing costs. Currently, AFA3G is a high-performance fuel component used in commercial operations worldwide.

Nuclear power pumps and valves are divided into two categories, nuclear safety related equipment and non-nuclear safety equipment. Nuclear safety related pumps include reactor coolant pumps, charging pumps, residual heat removal pumps, containment spray pumps, etc; while pressurizer safety relief valves, proportional spray valves, the main steam isolation valves, blasting valves, etc. are some of the nuclear safety related valves valves. The reactor coolant pump (referred to as the nuclear main pump) is an important piece of equipment, used to drive the reactor-loop coolant cycle and discharge the heat inside the core. Reactor coolant pumps are mainly divided into two types—seal and shield. The key technologies of reactor coolant pumps include efficient hydraulic model development, high reliability water lubricated bearings, high stability rotor dynamics, high integrity and moment of inertia flywheels, complex clear flow in the shielded motor main pump, three-stage dynamic and static pressure sealing of the shaft seal core pump, the processing and installation of the stator and rotor of the shield motor main pump, seismic technology, etc. The shaft seal type is adopted in most designs, based on French nuclear power technology, while the shielded motor main pump is based on third generation nuclear power technology developed by the USA firm Westinghouse. The key technologies of nuclear power valves include low flow resistance spool structure design, transient flows at the valve and force distribution on the valve stem, flow vibration and noise control, a large thrust valve-driven mechanism, spool wear and life assessment, and evaluation of valve reliability.

The reactor pressure vessel refers to the pressure vessel of the reactor body, which forms an important part of the reactor coolant pressure boundary. The material it is made of requires a high degree of integrity, high strength and toughness, low radiation sensitivity, ease of manufacture, and low cost. The life of the pressure vessel is directly related to the life of the nuclear power plant. The key technologies of pressure vessels include: manufacturing of large forgings, flange sealing and leakage detection, retention of the molten core in case of accidents, in-service inspection, flange bolt locking mechanisms, irradiation supervision, and underwater maintenance. The reactor pipeline includes a main loop and a secondary loop, where the key technology is pipeline welding and anti-corrosion.

The reactor containment is the outermost structure that constitutes the pressurized water reactor. It is intended for the accommodation and isolation of the reactor pressure vessel, and forms a part of the security system (which includes the main loop and its equipment and shutdown cooling system), serving as a safety barrier. The containment is the last protection against the release of fission products into the surrounding environment. The containment, hemispherical at the top, is usually a pre-stressed concrete cylinder imbedded with steel plates. There are many forms of containment structure with varying structural materials, such as steel, steel-reinforced concrete, pre-stressed concrete, and composites of steel and reinforced concrete or pre-stressed concrete. The third-generation nuclear power containment structure adopts a double-containment design that permits exterior cooling.

Major institutions that produce nuclear power equipment include: Shanghai Electric, Dongfang Electric, Harbin Electric, Westinghouse, Mitsubishi Heavy Industries, Heavy Industries, Busan Heavy Industries, Areva, KSB (Germany), etc.

Through scientific and technological breakthroughs, and infrastructural development for local production of nuclear power equipment, China has become capable of manufacturing and supplying improved second generation nuclear power equipment, with the capacity to generate a million kilowatts. Owing to the introduction, digestion, and absorption of the technologies of the third generation

like AP1000, China has successfully manufactured, with independent IP rights, key nuclear power equipment components like the Hualong One and CAP1400, as a part of major national projects on nuclear power development. An industrial system for obtaining nuclear fuels, which includes uranium mining, uranium concentration, fuel component manufacturing and reprocessing of spent fuel, has been developed.

Shanghai Nuclear Engineering Research and Design Institute, a part of the State Nuclear Power Technology Corporation (SNPTC), established a strategic collaboration initiative with Shanghai Jiao Tong University for the development of nuclear materials, key technologies of nuclear pumps, retention tests on molten cores, and containment water film cooling tests. SNPTC established a research institute with Tsinghua University, as a joint effort to carry out passive safety thermo-hydraulic tests for third generation nuclear power plants. Dalian University of Technology joined hands with Shenyang Blower Works Group Corporation, and set up a research institute to develop reactor cooling pumps and nuclear Class II & III pumps. Although China is still catching up in the design of nuclear power equipment, it is getting close to the world leader in this field, after years of introduction, assimilation, and re-creation. In terms of the manufacturing of nuclear power equipment, governmental support and self-upgrading by enterprises have improved China's competitiveness, making it a world leader in this area.

Table 2.2.7 and Table 2.2.8 show that benefiting from the national strategy of actively and steadily developing nuclear power in China, China has made outstanding achievements in the field of independent research and development of nuclear power technology. The USA remains the leading position in the rapid development of nuclear power technology because of its abundant accumulation of nuclear power technology, original innovation and technology. Although the Japanese Fukushima nuclear accident, but the electric power market demands and the development of nuclear power equipment technology do not stop. Korea independently developed the APR1400 Generation-III nuclear power technology and has achieved good overseas performance, with a certain independent intellectual property rights. Although the French nuclear power accounted for relatively high, in recent years, as it is trapped in Areva's decline in performance, there is no outstanding performance in the field of technological innovation.

As can be seen from Figure 2.2.7, cooperation between the USA and other countries is relatively close, but there is a lack of cooperation between China and other countries.

As can be seen from Figure 2.2.8 is the cooperation between CNNC and CGNPC, and the cooperation between Korea Atomic Energy Agency and Korea Electric Power is more closely.

Table 2.2.7 Major producing countries or regions of core patents on the engineering development focus "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	97	31.91%	265	33.97%	2.73
2	Japan	79	25.99%	191	24.49%	2.42
3	USA	64	21.05%	211	27.05%	3.30
4	Korea	40	13.16%	92	11.79%	2.30
5	France	8	2.63%	6	0.77%	0.75
6	Russia	7	2.30%	8	1.03%	1.14
7	Canada	5	1.64%	1	0.13%	0.20
8	Sweden	3	0.99%	2	0.26%	0.67
9	Germany	2	0.66%	4	0.51%	2.00
10	UK	2	0.66%	1	0.13%	0.50

Table 2.2.8 Major producing institutions of core patents on the engineering development focus "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	CNNU	31	10.20%	93	11.92%	3.00
2	GENE	31	10.20%	98	12.56%	3.16
3	TOKE	25	8.22%	48	6.15%	1.92
4	KAER	21	6.91%	32	4.10%	1.52
5	CGNP	17	5.59%	53	6.79%	3.12
6	MITO	14	4.61%	18	2.31%	1.29
7	WESE	13	4.28%	43	5.51%	3.31
8	BABW	11	3.62%	57	7.31%	5.18
9	UYQI	11	3.62%	36	4.62%	3.27
10	KEPC	10	3.29%	17	2.18%	1.70

Note: CNNU stands for China Nuclear & Power Eng Co. Ltd.; GENE stands for General Electric Co.; TOKE stands for Toshiba Co.; KAER stands for Korea Atomic Energy Res; CGNP stands for China Guangdong Nuclear Power Group Co.; MITO stands for Mitsubishi Electric Corp.; WESE stands for Westinghouse Electric Corp.; BABW stands for Babcock & Wilcox Co.; UYQI stands for Tsinghua Univ; KEPC stands for Korea Electric Power Corp.

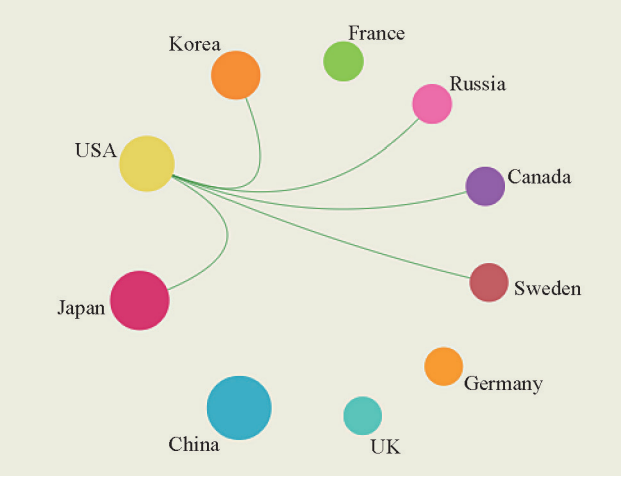

Figure 2.2.7 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment"

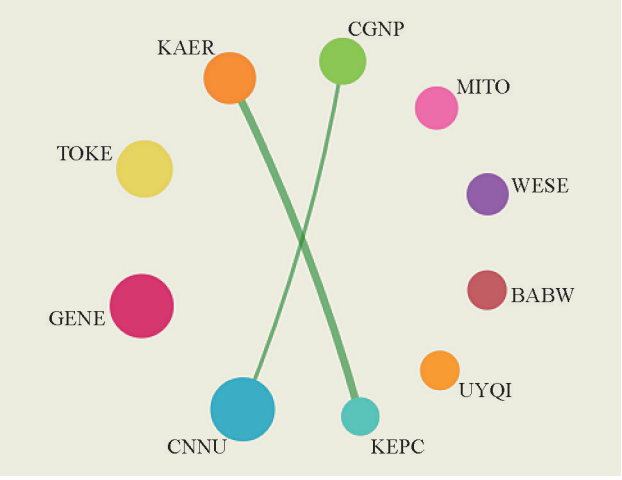

Figure 2.2.8 Collaboration network of the major producing institutions of core patents on the engineering development focus "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment"

Project Participants

Members of the Field Group

Leaders of the Field Group:

WENG Shilie, NI Weidou, PENG Suping

Leader of the Secretary Group:

YUAN Shiyi

Deputy Leaders of the Field Group:

HUANG Zhen, JU Yonglin

Academicians (sorted by family name)**:**
CHEN Senyu, GU Jincai, HE Duohui, HUANG Qili, LI Gensheng, LI Licheng, MA Yongsheng, QIU Ai'ci, SU Yi'nao, XIE Kechang, XUE Yusheng, YU Junchong, YUAN Liang, YUE Guangxi, ZHANG Yuzhuo, ZHAO Xian'geng, ZHOU Shouwei

Members of the Secretary Group:
WANG Zhenhai, ZONG Yusheng, ZHANG Ning, HUANG Dongping, LIU Ruiqin, CHEN Tiantian, YAN Shaoyun

Report Writers

Writers of Engineering Research Hotspots and Focus (sorted by family name)**:**
DING Xiaoyi, SHANGGUAN Wenfeng, SHEN Wenzhong, WANG Qian, WENG Yiwu, YANG Bo, YANG Lin, ZHANG Wugao, ZHAO Changyin

Writers of Engineering Development Hotspots and Focus (sorted by family name)**:**
CAO Xuewu, LI Gensheng, LI Junshi, LUO Yonghao, LV Xingcai, MA Zifeng, SHEN Wenzhong, WANG Haizhu, XIAO Wende, YAN Zheng, ZHANG Jige

V. Civil, Hydraulic Engineering & Architecture

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the field of civil, hydraulic engineering and architecture are summarized in Table 1.1.1, and they cover various disciplines including architecture, structural engineering, bridge engineering, engineering mechanics, construction materials, geotechnical and underground engineering, hydraulic engineering, infrastructural engineering, and survey engineering. Among these hotspots, "Material biological remodeling" and "Mixed-pixel decomposition and spatiotemporal location big data analysis" are the emerging frontiers, while in the other aforementioned hotspots, the traditional research is extended in the fields of civil, hydraulic engineering and architecture. Table 1.1.2 presents the statistical data of publications on these hotspots from 2011 to 2016. From among the top 10 hotspots, the number of published papers is the highest in "High-performance civil, hydraulic, and building engineering structures" and "Structural defect analysis."

(1) High-performance civil, hydraulic, and building engineering structures

High-performance civil, hydraulic, and building structures are structures in key civil and hydraulic engineering and multi-functional building structural systems with high-performance in safety, serviceability, constructionability, environment-friendliness, durability, maintenance, and cost-efficiency throughout the life-cycle. This topic includes the following scientific and technological challenges: ① development of novel design principles and implementation tools for consistent compatibility of architecture (spatial arrangement), function, and structures; ② development of new concepts and methods of structural analysis and design that combine the rational optimization of the structural system and refined design; ③ development of new theories and techniques for an optimal design that takes into consideration the life-cycle and multi-performance tradeoffs while accounting for planning, design, construction, service maintenance, and demolition. To address these issues, there is a requirement for a novel concept and the revolution of the implementation

Table 1.1.1 Top 10 engineering research hotspots in civil, hydraulic engineering and architecture

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	High-performance civil, hydraulic, and building engineering structures	377	9948	26.39	2014.06	23.60%	3
2	Ultra-high performance and multi-functional cement-based composite materials	36	948	26.33	2013.78	11.10%	0
3	Methods for the analysis and simulation of complex structures	135	3699	27.40	2014.83	39.30%	2
4	Built environment and occupant behavior	34	716	21.06	2013.88	17.60%	0
5	Removal of heavy metals and other high-risk pollutants	29	1243	42.86	2012.79	20.70%	0
6	Reliability of civil engineering structures	42	1138	27.10	2013.43	23.80%	1
7	Material biological remodeling	34	1345	39.56	2012.59	20.60%	0
8	Mixed-pixel decomposition and spatiotemporal location big data analysis	95	3887	40.92	2013.31	12.60%	1
9	Structural defect analysis	30	483	16.10	2013.90	0%	0
10	Numerical simulation of fluid-structure interaction	89	2694	30.27	2012.89	7.90%	1

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in civil, hydraulic engineering and architecture

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	High-performance civil, hydraulic, and building engineering structures	28	37	58	73	122	59
2	Ultra-high performance and multi-functional cement-based composite materials	2	6	5	10	11	2
3	Methods for the analysis and simulation of complex structures	0	5	17	15	57	41
4	Built environment and occupant behavior	2	3	7	9	11	2
5	Removal of heavy metals and other high-risk pollutants	9	5	3	8	3	1
6	Reliability of civil engineering structures	6	6	11	7	7	5
7	Material biological remodeling	11	6	8	4	5	0
8	Mixed-pixel decomposition and spatiotemporal location big data analysis	14	12	20	32	14	3
9	Structural defect analysis	3	1	6	7	12	1
10	Numerical simulation of fluid-structure interaction	21	15	18	24	10	1

systems as well as the innovative investigations enabled by modern scientific development, which can be realized by combining physical and numerical modeling; macro-, meso- and micro-scale studies; and qualitative and quantitative synthesis. The current hot subjects are as follows: ① applications of novel materials; ② innovative structural systems; ③ refining of analysis and modeling of structures; ④ structural performance monitoring and control; and ⑤ life-cycle reliability analysis and design. From 2011 to 2016, 377 core papers were published on this hotspot, and they received a total of 9948 citations and 26.39 citations per paper.

(2) Ultra-high performance and multi-functional cement-based composite materials

Owing to the rapid development of construction technology, traditional cement-based materials with low toughness and high brittleness could not meet the high-performance demands of several special applications. Hence, ultra-high performance and multi-functional cement-based composites have become the focus of current research. Since their discovery, carbon nanotubes have been widely studied in physical, chemical, and material areas owing to their excellent performance properties. Carbon nanotubes can greatly improve the strength or toughness of materials and their conductivity. Ultra-high performance civil-engineering materials can be obtained by adding carbon nanotubes and carbon fibers into cement-based materials. The following are some common ultra-high performance civil-engineering materials: self-sensing carbon nanotube cement-based composites, multi-walled carbon-nanotubes-reinforced cement paste, and carbon-fiber-reinforced Portland cement mortar. Carbon nanomaterials in the cement matrix equip the composites with good physical and chemical properties, thus greatly enhancing the safety and reliability of concrete structures, and they can be used for high-strength intelligent cement-based materials testing. Therefore, carbon nanomaterials have broad applications in improving cement-based traditional building materials. From 2011 to 2016, 36 core papers have been published on this hotspot, and they received a total of 948 citations and 26.33 citations per paper.

(3) Methods for the analysis and simulation of complex structures

Owing to the rapid developments in computer science and technology in recent years, numerical simulations have played an increasingly important role in the study of complex structures. The two main concerns in the development of modern computational techniques are the modeling of complex material behaviors and the modeling of complex geometries. Engineering materials often sustain damage and fractures when they are subjected to external loading. The cracks could be considered as discontinuities within continuum fields. Thus, the extended finite element method (XFEM) introduces discontinuous enrichments based on the concept of the partition of unity. Owing to its mathematical accuracy and convenience in application, XFEM has been well accepted by researchers

and engineers. In recent years, several researches have focused on the further development of XFEM. According to the continuum damage theory, cracks are often smeared within a certain domain and the effects of crack initiation and propagation are described by the continuum evolution of the damage variables. Damage theory is suitable for the simulation of complex structures without changing the framework of structural finite element models. The recent developments in damage models have focused on nonlocal theory based on which the issue of mesh sensitivities could be eliminated. Several new materials have been developed and designed in recent works, e.g., fiber-reinforced composites and functional graded material. The numerical methods for the simulation of newly designed materials mainly belong to the class of multi-scale methods. For structures with a rather complex geometry, the finite element meshing is quite complicated and time-consuming. In order tackle this issue, the concept of isogeometric analysis is proposed, for which the basic functions used for the geometric modeling (e.g., NURBS) are also used for the interpolation of state variables. Isogeometric analysis has been developing very quickly, and it has recently found application in the problems of vibration, buckling, and fracture. From 2011 to 2016, 135 core papers have been published on this hotspot, and they received a total of 3699 citations and 27.4 citations per paper.

(4) Built environment and occupant behavior

This hotspot involves the study of the relationship and interaction between the built environment and human comfort as well as behavior. It includes the study of the methods for meeting the psychological requirements of occupants and improving their living environment through city planning, urban design, architectural design, and building equipment system design. In addition, it includes the study of the interaction and adjustment between the occupant and environment. The main topics of research include the requirements of human comfort with respect to temperature, humidity, air velocity, radiation, and other environmental factors; the evaluation and prediction of thermal comfort based on thermal adaptation theory and dynamic thermal comfort theory; and the description and simulation of occupant adjustment to the built environment. The study of the built environment and occupant behavior comprises the following engineering science branches: outdoor microclimate and thermal comfort, thermal adaptation to climate, and adjustment to the built environment. Building environment and occupant behavior is currently a research hotspot. The traditional thermal adaptation model and design theory of the indoor air-conditioning environment have been satisfactorily developed and thoroughly investigated. In recent years, research has been focused on outdoor environmental thermal comfort, dynamic thermal comfort and thermal adaptation, thermal comfort under special environments (such as high altitudes, public transport, and aerospace environments), and interaction between thermal comfort and occupants. These topics supplement the development of existing thermal comfort and occupant behavior theory. With the improvement in the quality of life and the popularization of the concept of green and sustainable development, this subject will continue to be a research hotspot in the field of built environment and will develop new connotations based on traditional theories. From 2011 to 2016, 34 core papers were published on this hotspot, and they received a total of 716 citations and 21.06 citations per paper.

(5) Removal of heavy metals and other high-risk pollutants

Scientific and engineering methods were applied to restore water, air, or soil that had been contaminated by heavy metals and other high-risk pollutants. These methods can be used to transform the pollutants into less toxic forms or maintain their concentrations within a safe range. Heavy-metal pollution occurs when the concentrations of mercury, cadmium, lead, chromium, arsenic, and their compounds exceed their safe value in water, air, soil, or other carriers. They can cause significant harm to the environment and to lives. To prevent heavy-metal pollution, the control of the total amount of the pollutants should be combined with concentration control. Furthermore, source prevention, process disruption, cleaner production, and terminal treatment should be realized while focusing on the key prevention and control zones, key prevention and control industries, and key sources of pollution. In addition, to control the emission of heavy metals from the source, the removal of discharged metals is particularly critical, and the main technologies for achieving this presently include leaching, adsorption, ionic liquid extraction, oxidation-reduction, the electrochemical method, and photocatalytic method. Furthermore, increasing attention has been focused on the recycling field. Other high-risk

pollutants in the environment include pharmaceuticals and personal care products, which can be eliminated mainly via adsorption and oxidation. Though these high-risk pollutants exist in low concentrations, long-term exposure to them is relatively risky. From 2011 to 2016, 29 core papers were published on this hotspot, and they received a total of 1243 citations and 42.86 citations per paper.

(6) Reliability of civil engineering structures

Reliability is the probability that civil structures, under normal service conditions and/or subject to disastrous conditions, satisfy the prescribed demand function and safety and durability conditions, and it also includes the theory for reliability-based structural design. The key scientific issues with respect to this reliability include the identification and modeling of uncertainty in the structural properties and actions , the structural life-cycle performance and complete process behaviors under loading, and the reliability analysis and design of structures. Since the late 1940s, structural reliability theory gradually became the core of structural design theory, and the golden epoch was from the late 1960s to early 1980s, which was enriched by the concept of performance-based design that originated in the early 1990s. Since the beginning of the 21st century, owing to the increasingly frequent effects of natural and manmade disasters, increasing importance has been attached to engineering reliability. Meanwhile, with the decreasing cost of data collection, emerging big data techniques, rapid development of the fundamental theory of mechanics and high-performance computation, and with the emerging uncertainty quantification theory in various fields, structural reliability theory is embracing new ideas. Presently, the hot subjects in this field include the modeling of uncertainty, the reduced model for engineering structures and systems, and high-efficiency stochastic analysis methods. Simultaneously, the research subjects are extended from overground structures to geotechnical and underground structures, the mathematical basis is expanded from probability theory to uncertainty modeling including the imprecise probability and interval methods, and the physical-mechanical basis is extended from simplified semi-empirical models to modern multi-scale physical mechanics. The structural reliability theory is transitioned from approximate probability to full probability and risk based decision-making, and from more mathematics-emphasized to physical-based global reliability analysis and design. From 2011 to 2016, 42 core papers were published on this hotspot, and they received a total of 1138 citations and 27.10 citations per paper.

(7) Material biological remodeling

Biological materials are formed with perfect structural morphology and unique superior performance during their long evolution process. Inspired by these materials, researchers have attempted to reveal the structural features and mechanisms of the biological system, which is then applied to the design and preparation of building materials. The research on structural biomimetic materials is an important branch of bionics. Based on the study of the structural characteristics and structure-activity relationship of the biomaterials, the bionic simulations of materials, structures, and systems are performed to improve the engineering structural efficiency. Biological remodeling of materials is one of the main subjects of biomimetic research. It focuses on the non-uniform expansion and mechanical influence of gels and biomaterials on healing and strengthening during the stage of hardening deformation and biological growth. The main research includes material constitutive relations and the mechanics analysis method, the modeling of the boundary growth mechanics problem, and the solutions of static and dynamic problems. Owing to inspiration from biological materials, bionic materials will become more and more microcosmic and intelligent. Future research will focus on constructing various biomimetic micro-devices using functional materials and by assembling bionic micro systems with various structures and functions. Such studies will be widely used in the military, industries, and building. From 2011 to 2016, 34 core papers were published on this hotspot, and they received a total of 1345 citations and 39.56 citations per paper.

(8) Mixed-pixel decomposition and spatiotemporal location big data analysis

The contents of mixed-pixel decomposition and spatiotemporal location big data analysis include mixed-pixel decomposition, real-time precise point positioning, and spatiotemporal big data analysis. The breakthrough sensor spatial resolution limit in mixed-pixel decomposition depicts the true nature of the mixed-pixel distribution at sub-pixel accuracy, and high-spatial-resolution image classification results can be obtained from a coarse-

spatial-resolution image by scaling down in order to improve the accuracy of extraction of the image information. The real-time precise single-point positioning method uses a precise satellite ephemeris and precise clock product to obtain higher-precision spatial location data with a pseudorange and carrier-phase observations using the global navigation satellite system (GNSS) receiver. The spatiotemporal data acquisition method is aimed at obtaining high spatial resolution and spatiotemporal position accuracy in order to achieve the acquisition, storage, and reconciliation of high-dimensional spatial-temporal big data. Spatiotemporal big data analysis techniques are used for automatically discovering and extracting the implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data and for excavating values from the volume, velocity, and variety big data. From 2011 to 2016, 95 core papers were published on this hotspot, and they received a total of 3887 citations and 40.92 citations per paper.

(9) Structural defect analysis

Various imperfections including cracks, defects, and material degradations are created in civil materials and structures during their construction and service processes, owing to the comprehensive interior and exterior factors such as changes in the service environment, fire, earthquakes, and explosion shocks. These imperfections also cause various types of serious accidents and even civil engineering disasters. Therefore, there is an urgent requirement for developing fundamental theories of fracture mechanics for bearing capacity analysis and safety assessment of civil structures with defects and diseases in the fields of civil engineering, hydraulic engineering, and construction engineering. The relevant research topics are listed as follows: crack initiation criterions and crack propagation theories for civil materials and structures; fracture analysis theories of plates and shells for civil engineering; fracture behaviors, ultimate load-bearing capacity analyses, safety assessments, plastic fatigue, and fracture failure analyses for civil components and structures with odd-shaped notches under complex loading conditions; classifications, distribution surveys, characteristics, and statistical analyses of various defects or imperfections in civil structures and their suitable simulation models; and development of various types of defective specimens for various research purposes with materials such as polymethylmethacrylate, steels, and graphite, and research on the corresponding new theories and methods for physical tests and fracture analysis. Currently, the hot research direction in the field of structural defect analysis is the development of new theories and methods for the simulation of structural fractures and failure processes. Some examples are nonlocal damage models for cracked structures that are free of challenging issues such as the effects of mesh sensitivity and size, new numerical methods such as XFEM and meshless methods that circumvent the difficulties of mesh refinement and mesh movement for the simulation of the fracture propagation process, and multiscale theories and methods that can be used for analyzing new engineering materials and structures with fiber-composite and functionally graded materials ranging from the micro to the macro scope. From 2011 to 2016, 30 core papers were published on this hotspot, and they received a total of 483 citations and 16.10 citations per paper.

(10) Numerical simulation of fluid-structure interaction

Fluid-structure interaction is the interaction of structures with the surrounding fluid flow, and it includes various mechanical behaviors of a deformable solid structure under the action of the flow field and the influences of the position and shape of a deformable structure on the flow field. Fluid flow problems comprise a large number of nonlinear phenomena, and for a fluid-structure coupling system, these problems may further involve large nonlinear geometrical deformation, nonlinear elastic-plastic materials, and nonlinear problems induced by uncertainty and coupling at the contact interfaces. Generally, fluid-structure interaction systems are often complex nonlinear systems, and they are mainly analyzed using numerical simulations. The important studies on this subject include water/air flow-structure interaction and the corresponding modeling technique. The key to the successful numerical simulation of fluid-structure interaction lies in adopting a unified coordinate system and considering the coordination problem at two-phase interfaces. In the case of nonlinear coupling problems, it is necessary to find a method for obtaining the solutions in the entire fluid and solid domain, and it is also a challenge to combine the effective methods of solving the nonlinear flow equations and the structural equations. From 2011 to 2016, 89 core papers were published on this hotspot, and they received a total of 2694 citations and 30.27 citations per paper.

1.2 Understanding of engineering research focus

1.2.1 High-performance civil, hydraulic, and building engineering structures

Civil, hydraulic, and building structures are the major material carriers in human society. The development of modern society, economy, and technology has raised the performance demands of engineering structures and has resulted in the development of new high-performance engineering structures. In general, high-performance civil, hydraulic, and building structures exist in key civil and hydraulic engineering and multi-functional building structural systems with high life-cycle performance in safety, serviceability, constructionability, environment-friendliness, durability, maintenance, and cost-efficiency. With the development of economy, society, and technology, the population is becoming increasingly concentrated, and the function and structure of civil infrastructures are becoming increasingly specific and complicated. However, the losses incurred owing to natural and manmade disasters are increasing. Therefore, superior performance is required of engineering structures for protecting human lives and property. Meanwhile, rapid developments in modern science and technology (particularly in material science, fundamental physics and mechanics, information and data science, and high-performance computing techniques) have provided unprecedented opportunities for realizing high-performance structures.

Attempts to develop high-performance engineering structures raise scientific and technological challenges: ① development of novel design principles and implementation tools for the consistent compatibility of architecture (spatial arrangement), function, and structures; ② development of new concepts and methods of structural analysis and design that combine the rational optimization of structural systems and refined design; ③ development of new theories and techniques for optimal design involving life-cycle and multi-performance tradeoffs while accounting for planning, design, construction, service-maintenance, and demolition. To resolve these issues, we require a novel concept and a revolution in the implementation systems as well as innovative investigations that are enabled by modern scientific development by combining physical and numerical modeling, macro-, meso-, and micro-scale studies, and qualitative and quantitative syntheses.

The following are presently the hot subjects in "High-performance civil, hydraulic, and building engineering structures."

(1) Applications of novel materials

The development of novel materials is one of the major forces advancing innovation in engineering structures. In the past decades, material science has transited from the traditional paradigm of material fabrication—mechanical property studies—engineering applications to the paradigm of macro-microscale unified material design—integrated material-structure design. Various demands for high-performance civil, hydraulic, and building engineering structures have given rise to the development and application of materials of unique performance or comprehensive high performance (e.g., intelligent materials, high-damping materials, high-modulus materials, and high-durability materials). However, affordability is a bottleneck of high-performance civil, hydraulic, and building structures as massive amounts of materials are required in this field. Reducing the cost and improving the comprehensive or unique performance, in particular via material modification, is an important alternative.

(2) Innovative structural system

An innovating structural system is one of the major approaches for achieving high structural performance. In recent years, appreciable advances have been made in the development of new composite structures, new disaster-resistant structures (e.g., resilient structures and intelligent structures), and auto-growing structures based on bionics and topological optimization.

(3) Refined analysis and modeling of structures

The advancement of fundamental physics and mechanics (e.g., the constitutive law of solids and soft materials) and high-performance computational facilities and techniques (e.g., smoothed particle hydraulics, mesh-free method, extended finite element method, and isogeometric analysis, large deformation and strong nonlinear analysis methods) greatly promoted the refined analysis theory and methods for complex civil, hydraulic, and building structures. In this aspect, the multi-scale physical-numerical hybrid simulation incorporating the modern experimental techniques and numerical computation is a significant direction for future investigations.

(4) Structural performance monitoring and control

Structural performance monitoring will become a routine task for maintaining important civil, hydraulic,

and building structures. The new multi-parameter sensors and sensing networks with high accuracy, disturbance insensitivity, superior weather-resistance performance, long service life, low-energy-consuming and wireless or remote transfer performance; analysis and high-efficiency property extraction techniques for big data; warning, intelligent control, and resilience or even self-healing of engineering structures are the challenging frontiers.

(5) Life-cycle reliability analysis and design

The hot subjects include uncertainty quantification, theory of reduced or surrogate model, big data techniques, and life-cycle management systems. In particular, uncertainty quantification and disaster-resistant reliability of civil, hydraulic, and building structures received a great deal of attention, which resulted in various breakthroughs. The life-cycle global reliability analysis and optimal design of engineering structures that incorporates monitoring and control is a promising research direction and is supported with refined physical-mechanical models and big data.

The focus of research varies in different countries owing to their different geographical environments, development phase, economic status, scientific and technological level, and history and social thought. In the past two decades, researches conducted in the USA are transitioning from massive construction to maintenance, management, and post-disaster recovery, and thus included leading research on performance-based seismic design, structural health monitoring, and life-cycle cost evaluation. Recently, they evolved from the structure scale to the community scale. The focus of research in Europe is very different. Reliability analysis and design theory for engineering structures and systems has received a great deal of attention in Norway, Denmark, and Germany; the fundamental theory for solid mechanics analysis plays a leading role in research in France and Spain; and the experimental and theoretical investigations in disaster-resistant performance of engineering systems has gained importance in Italy. Japan leads the world in the development and applications of new disaster-resistant structural systems and devices. In the past decade, with massive infrastructure construction, the investigations into the above subjects have improved greatly in China. China now plays an important role in the study of novel materials, innovative structural systems, refined analysis theory and methods, monitoring and control of structural performance, and reliability design of structures and systems; China is expected to play a world-leading role in one or several of these subjects.

As presented in Table 1.1.1, a total of 377 core papers in "High-performance civil, hydraulic, and building structures" have been published with an average of 26.39 citations per paper. As shown in Table 1.2.1, the top five countries or regions producing the most core papers are China (excluding Taiwan of China), Italy, Australia, the USA, and Algeria, and the core papers from China account for 31.03% (the Chinese mainland 21.14%; and Hong Kong, Macau, and Taiwan 9.33%), indicating that China is an important contributor in this subject. According to the average citations, the top five countries or regions are Portugal, Algeria, Germany, China, and the USA. The number of average citations from China is 24.11, which is higher than the average value, and this indicates that Chinese researchers are receiving global attention. As indicated by the collaborative network of countries or regions shown in Figure 1.2.1, it can be observed that close collaborations exist among all the top five countries or regions except Algeria.

The top five institutions producing core papers are the Univ Djillali Liabes Sidi Bel Abbes in Algeria, University of Hong Kong, City University of Hong Kong, University of Adelaide, and Univ Roma La Sapienza. The collaborative network of the major institutions (Figure 1.2.2) indicates frequent collaborations in the same country or region.

As can be observed from Tables 1.2.3 and 1.2.4, the top five countries or regions producing the most citations are China, Australia, the USA, Italy, and Portugal. The citations from China account for 24.30%, and three of the top five institutions producing the most citations are from China (i.e., University of Hong Kong, City University of Hong Kong, and Wuhan University). This indicates that Chinese researchers are at the frontiers of these investigations.

In summary, China is maintaining the same pace as other countries or regions in frontier research in "High-performance civil, hydraulic, and building structures" and has the potential for playing a leading role. It is essential to allocate more funding to research on these topics in order to advance such studies and to play a leading role in the world.

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	117	31.03%	2821	33.03%	24.11	31	1
2	Italy	71	18.83%	1191	13.94%	16.77	0	0
3	Australia	69	18.30%	1524	17.84%	22.09	23	0
4	USA	43	11.41%	1032	12.08%	24.00	10	0
5	Algeria	39	10.34%	1169	13.69%	29.97	5	0
6	Germany	31	8.22%	858	10.05%	27.68	6	2
7	Singapore	24	6.37%	544	6.37%	22.67	6	0
8	Portugal	20	5.31%	712	8.34%	35.60	5	1
9	France	20	5.31%	276	3.23%	13.80	0	0
10	Iran	19	5.04%	306	3.58%	16.11	4	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Djillali Liabes Sidi Bel Abbes	39	10.34%	1169	13.69%	29.97	5	0
2	Univ Hong Kong	38	10.08%	930	10.89%	24.47	14	0
3	City Univ Hong Kong	29	7.69%	790	9.25%	27.24	10	0
4	Univ Adelaide	23	6.10%	644	7.54%	28.00	8	0
5	Univ Roma La Sapienza	23	6.10%	310	3.63%	13.48	0	0
6	Lab Struct & Mat Avances Genie Civil & Travaux Pu	21	5.57%	629	7.36%	29.95	3	0
7	Wuhan Univ	20	5.31%	460	5.39%	23.00	7	0
8	Univ Sci	19	5.04%	672	7.87%	35.37	6	0
9	Bauhaus Univ Weimar	18	4.77%	620	7.26%	34.44	5	1
10	Univ Aquila	16	4.24%	256	3.00%	16.00	0	0

1.2.2 Built environment and occupant behavior

The study of "Built environment and occupant behavior" has been developed based on traditional steady state thermal comfort for approximately the past century. Its main aim is to examine the human body's reactions in a steady state thermal environment, which can be represented using a thermal comfort model proposed by Professor P. O. Fanger of Danish Technical University. The model became the basis of the standards used by American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) and International Standardization Organization (ISO) for developing indoor thermal environments. China's thermal environment design standards generally cite these standards.

Based on the clustering analysis of keywords in core papers, the mainstream of engineering science and the branch engineering sciences focused on in this engineering research include the following: outdoor microclimate and thermal comfort, thermal adaptation to climate, and adjustment to built environments.

(1) Outdoor microclimate and thermal comfort

This includes the adjustment of outdoor micro-climate parameters, building of comfortable outdoor thermal environments, and proposing an evaluation index of safety

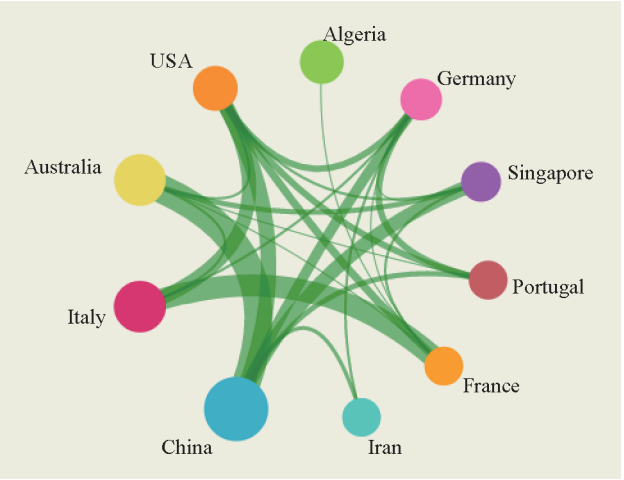

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"[1]

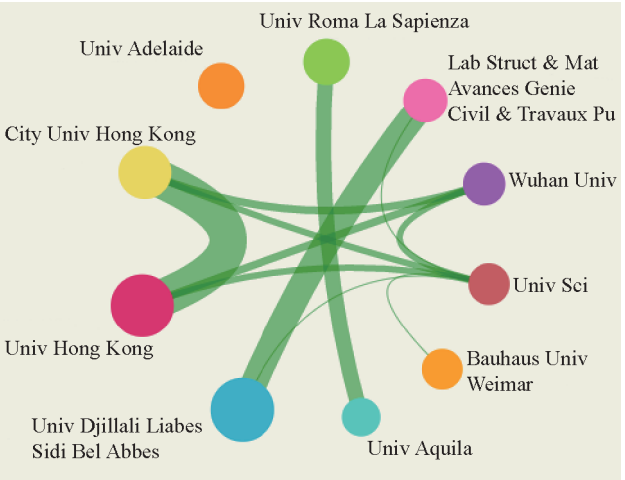

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	87	24.30%	2014.17
2	Australia	54	15.08%	2014.11
3	USA	27	7.54%	2014.07
4	Italy	24	6.70%	2014.67
5	Portugal	16	4.47%	2013.56
6	Iran	15	4.19%	2014.93
7	Algeria	15	4.19%	2015.33
8	Germany	14	3.91%	2014.21
9	Singapore	12	3.35%	2014.42
10	Korea	8	2.23%	2013.88

and comfort for an outdoor thermal environment through methods involving building layout design, outdoor floor pavement, the application of shade parts, residential and urban greening, the use of accumulated rainwater, the use of windshields and fountains, and other technical measures. The key technologies to be solved includes: the influence of short-wave and long-wave radiation on outdoor thermal comfort; outdoor thermal comfort evaluation index and outdoor microclimate evaluation; and outdoor microclimate control measures based on thermal comfort. The currently developing trends include the development of urban-level planning theory, which is shifting from outdoor microclimate adjustment; the development of a solution for the urban heat island effect, urban ventilation corridor, and other urban-scale climate issues; the development of an index of comfort shifting from index of outdoor labor safety; efforts to meet the demand of thermal comfort in large-scale outdoor waiting areas and cultural and recreational activity areas. The key countries and regions conducting research on these subjects include

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Hong Kong	28	5.32%	2014.61
2	City Univ Hong Kong	23	4.37%	2014.57
3	Univ Adelaide	21	3.99%	2013.86
4	Univ Sci	18	3.42%	2013.94
5	Wuhan Univ	18	3.42%	2014.61
6	Univ Djillali Liabes Sidi Bel Abbes	15	2.85%	2015.33
7	Univ Minho	12	2.28%	2013.33
8	Bauhaus Univ Weimar	10	1.90%	2014.30
9	Natl Univ Singapore	10	1.90%	2014.60
10	Hong Kong Univ Sci & Technol	9	1.71%	2013.78

Taiwan of China, Egypt, Malaysia, Singapore, Greece, the Chinese mainland, Australia, France, Argentina, Italy, and Hong Kong of China.

(2) Thermal adaptation to climate

This includes the difference of the human comfort index between non-air-conditioned naturally ventilated buildings as well as free-running buildings and the traditional air-conditioned environment; the mechanism of thermal adaptation, such as physiological acclimatization, psychological adaptation, and behavioral adjustment; and the thermal comfort prediction model reflecting thermal adaptation. In this branch of engineering science, the key issues to be resolved include the investigation of the physiological parameters reflecting the thermal adaptation; the integration of the thermal adaptation model and the traditional thermal comfort model; the investigation of the design parameters and the control measures of the indoor environment while taking into consideration the thermal adaptation. The currently developing trends include the establishment of a worldwide database of on-site surveys regarding thermal comfort and experimental results; the study of interdisciplinary relations between medical-physiological indications and thermal comfort research; the development of a thermal adaptation dynamic evaluation model and indoor environment design theory for the thermal response of occupants to various climatic zones and economic development conditions. The key countries and regions conducting research on this subject include Australia, the Chinese mainland, Hong Kong of China, Japan, India, and the USA.

(3) Thermal adjustment to built environment

This includes the driving factors of occupant adjustment behavior in a built environment, the quantitative description methods and software simulation tools of occupant behavior, and the relation between occupant behavior and environmental parameters as well as the investigation of the influence of building energy consumption for meeting the practical requirements of scientific research and engineering applications through test data acquisition, model establishment and validation, questionnaires, and case studies. The key issues to be resolved include the development of a standardized testing method of occupant behavior in a building environment, realization of parameter descriptions and regression of the occupant behavior model, and the simulation and validation of the occupant behavior model. The currently developing trends include the development of standardized testing techniques and a quantitative description of multi-person occupancy and action; the study of environmental driving factors of occupant behavior and the interaction of multiple persons; and the development of a coupled computing platform for the occupant behavior model, indoor environment parameters, and building energy consumption. The key countries and regions conducting research on this subject include the Chinese mainland, the USA, Germany, Britain, Australia, and Canada.

"Built environment and occupant behavior" is a research hotspot. The traditional evaluation model of thermal comfort and the design theory of an indoor air-conditioned environment have been satisfactorily developed

and thoroughly investigated. In recent years, research has been focused on thermal comfort in outdoor environments, dynamic thermal comfort and heat adaptation, thermal comfort in special environments (such as high altitudes, public transport, and aerospace environments), and the relation between thermal comfort and occupant behavior. These hotspots are supplementary to the development of existing thermal comfort and occupant behavior theory. With the improvement in the quality of life and the popularization of the concept of green and sustainable development, this subject will continue to maintain its status as a research hotspot in the field of built environments and will develop new connotations based on traditional theories. There were 34 core papers on the field of "Built environment and occupant behavior," with 21.06 citations per paper (Table 1.1.1). The top five countries or regions with the greatest number of published core papers were Italy, the USA, India, China (excluding Taiwan of China), Japan, and Australia. Papers published by Chinese researchers accounted for 14.71% of the total core papers (8.83% by the Chinese mainland and 5.88% by Hong Kong and Macao; Table 1.2.5), marking China as one of the main countries or regions conducting research in this field. The top five countries or regions with the highest average citations are England, Taiwan of China, Germany, Japan, and India. Chinese researchers' papers were cited 16.2 times per paper on average, up to 87% of average level (Table 1.2.5), which indicates there exists an increasing possibility for Chinese researchers in this field.

In the collaborative network of countries and regions (Figure 1.2.3), the top five countries or regions with the greatest number of core papers have a close collaborative relation.

In terms of the core-paper publishing institutions (Table 1.2.6), the top three are the University of Rome La Sapienza, Roma TRE University, and Tokyo City University. However, according to the collaboration network of the top 10 publishing institutions (Figure 1.2.4), the inter-agency cooperation is not very close.

As can be observed from Table 1.2.7 and Table 1.2.8, the top five countries or regions by number of published core papers also have a greater number of cited papers. China has the second highest number of citations (along with India and Italy), which indicates that Chinese scholars pay close attention to and track the trends of research in this field.

Based on the above statistical analysis, in "Building environment and occupant behavior" engineering research, China is currently on par with similar researches being conducted abroad. It is recommended that China continue to increase investment in such research in order to promote the relevant research to the world-leading level.

1.2.3 Mixed-pixel decomposition and spatiotemporal location big data analysis

The *Nature* special issue on "Big Data" in 2008 and the *Science* special issue on "Dealing with Data" in 2011 pointed out the arrival of the big data era. The interdisci-

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Built environment and occupant behavior"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Italy	10	29.41%	164	25.04%	16.40	1	0
2	USA	6	17.65%	105	16.03%	17.50	2	0
3	India	5	14.71%	90	13.74%	18.00	1	0
4	China	5	14.71%	81	12.37%	16.20	1	0
5	Japan	4	11.76%	91	13.89%	22.75	1	0
6	Australia	4	11.76%	53	8.09%	13.25	1	0
7	Taiwan of China	3	8.82%	74	11.30%	24.67	0	0
8	Germany	3	8.82%	70	10.69%	23.33	0	0
9	England	2	5.88%	61	9.31%	30.50	0	0
10	Greece	2	5.88%	33	5.04%	16.50	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Built environment and occupant behavior"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Roma La Sapienza	7	20.59%	118	18.02%	16.86	0	0
2	Univ Roma TRE	6	17.65%	114	17.40%	19.00	0	0
3	Tokyo City Univ	4	11.76%	91	13.89%	22.75	1	0
4	Univ Calif Berkeley	4	11.76%	72	10.99%	18.00	2	0
5	Univ Tokyo	3	8.82%	61	9.31%	20.33	1	0
6	Natl Formosa Univ	2	5.88%	65	9.92%	32.50	0	0
7	Univ Freiburg	2	5.88%	56	8.55%	28.00	0	0
8	Indian Inst Technol	2	5.88%	47	7.18%	23.50	0	0
9	Univ Hong Kong	2	5.88%	37	5.65%	18.50	1	0
10	Tianjin Univ	2	5.88%	33	5.04%	16.50	0	0

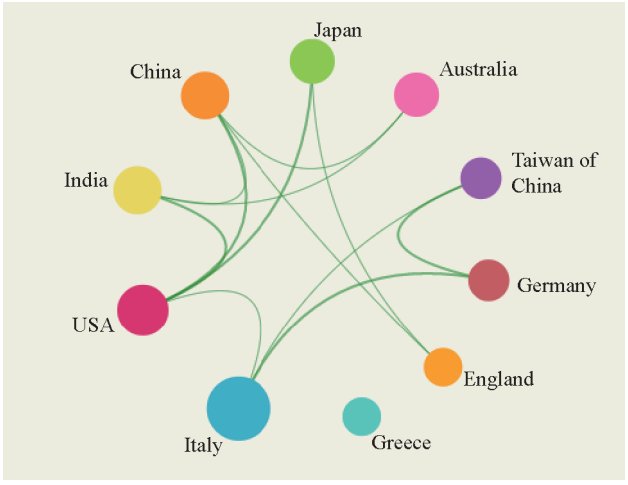

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Built environment and occupant behavior"

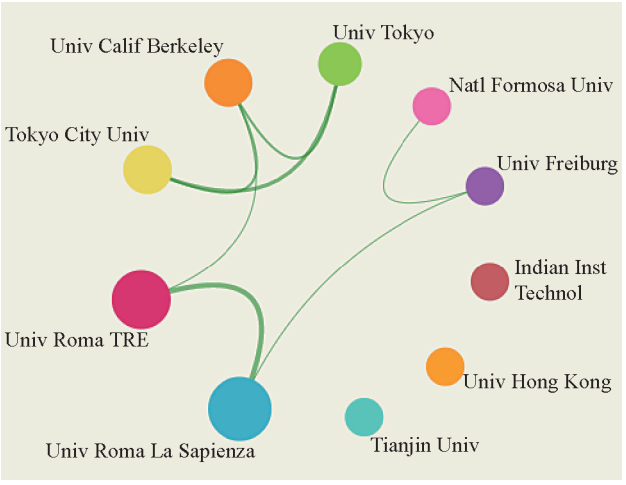

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Built environment and occupant behavior"

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Built environment and occupant behavior"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	5	18.52%	2014.00
2	India	4	14.81%	2015.00
3	Italy	4	14.81%	2015.25
4	China	4	14.81%	2014.50
5	Australia	2	7.41%	2015.50
6	Japan	2	7.41%	2013.50
7	Taiwan of China	2	7.41%	2014.00
8	Argentina	1	3.70%	2015.00
9	Germany	1	3.70%	2015.00
10	Greece	1	3.70%	2014.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Built environment and occupant behavior"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Calif Berkeley	3	6.98%	2014.00
2	Univ Roma La Sapienza	3	6.98%	2015.33
3	Purdue Univ	2	4.65%	2014.00
4	Tianjin Univ	2	4.65%	2014.00
5	Tokyo City Univ	2	4.65%	2013.50
6	Univ Rome Tre	2	4.65%	2015.50
7	Univ Tokyo	2	4.65%	2013.50
8	Built Environm Grp	1	2.33%	2014.00
9	CEPT Univ	1	2.33%	2016.00
10	China Vanke Co Ltd	1	2.33%	2014.00

plinary fusion of surveying and mapping and information technology, is pushing the development of earth observation, perception, and cognition to multiplatform, multiscale, multi-resolution, multi-temporal, and space-air-ground integration. The integration of various means and methods of achieving spatial data acquisition, information extraction, network management, knowledge discovery, space perception, and intelligent service location on the earth, the solid object and human activities, to provide spatial information framework, basic mathematics and information processing technique for earth science research problems, to offer reliable massive spatiotemporal information for people to fully accurate judgment and decision making.

The focus of engineering research—"Mixed-pixel decomposition and spatiotemporal location big data analysis"—presented in the retrieval results of core papers is representative of the development trend. Mixed-pixel decomposition and spatiotemporal location big data analysis include mixed-pixel decomposition, real-time precise point positioning, and spatiotemporal big data analysis. Mixed-pixel decomposition can be used to obtain high-spatial-resolution classification results from a coarse-spatial-resolution image. The real-time precise single-point positioning method makes use of a precise satellite ephemeris and precise clock product to obtain high-precision spatial location data with a pseudorange and carrier phase observations using the GNSS receiver. The aim of the spatiotemporal data acquisition method is to realize higher spatial resolution and spatial-temporal position accuracy in order to achieve the acquisition, storage, and reconciliation of high-dimensional spatial-temporal big data. Using the spatiotemporal big data analysis techniques for automatically discovering and extracting implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data, the values from the volume, velocity, and variety big data can be excavated.

(1) Decomposition of mixed pixels

Owing to the spatial resolution of the remote sensor and the complex diversity of the ground, the mixed pixels are spread widely in the remote sensing image—several different land cover types exist at a single pixel. The breakthrough sensor spatial resolution limit in mixed-pixel decomposition depicts the true nature of the mixed-pixel distribution at sub-pixel accuracy, and high-spatial-resolution image classification results can be obtained from a coarse-spatial-resolution image by scaling down in order to improve the accuracy of extraction of the image information. The key problem in mixed-pixel decomposition is to determine the land cover types and their spatial proportions. According to the interaction of various objects in the mixed pixels, the current spectral mixture model can be categorized as a linear model or nonlinear model, and the linear model is the most widely used. The development trend of mixed-pixel decomposition mainly includes the following aspects: ① research on nonlinear unmixing based on various scattering models; ② development of the endmember extraction model under spectral variability; ③ investigation into spectral unmixing combined with

spatial information; ④ multi-source image fusion based on the spectral mixture model; ⑤ decomposition of mixed pixels combined with machine learning technology such as sparse decomposition and deep learning; ⑥ unmixing accuracy verification and validation problems; and ⑦ application of decomposition of mixed pixels in the fields of vegetation, water-quality survey, environmental monitoring, etc. At present, the research on pixel unmixing is more focused on the solution of the existing spectral mixture model. Because this model lacks sufficient physical basis, the testing data also have great limitations, and there thus exist some problems that are difficult to generalize in practice.

(2) Real-time precise point positioning

Precise point positioning (PPP) is an absolute position method that makes use of a precise satellite ephemeris and precise satellite clock product to obtain a precise location with a pseudorange and carrier phase observations. Compared with the multi-reference station-network real-time kinematic, real-time PPP has the advantage of a global-scale operation range, flexible station arrangement strategy, and simple operation mode. As compared with the double-difference observation data processing, the use of real-time PPP using non-difference data can improve the utilization of data. Real-time precise positioning is widely used in crustal deformation monitoring, near-real-time global positioning system (GPS) meteorology, satellite orbit determination, mobile carrier precision positioning, sea level monitoring, tsunami and earthquake monitoring, and other fields. The development of PPP mainly includes the following aspects: ① research on the estimation theory and method of developing a precise satellite clock provides real-time high-precision satellite clock products; ② study on uncalibrated phase delay and separation method for undifferenced ambiguity, fixing of the undifferenced integer ambiguity, and exploring the ambiguity fixing method at the client terminal; ③ research on PPP using multi-system integration, speeding up of the PPP of the initial time, and enhancing the reliability of the positioning results.

(3) Spatiotemporal big data analysis

Spatiotemporal big data is the result of the integration of big data and spatiotemporal data, which considers the earth as the object, and the spatiotemporal location data and activity data are acquired using a unified space-time reference. Spatiotemporal big data analysis can be used to automatically discover and extract the implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data; pay more attention to discovery rather than demonstration; put more emphasis on relationships rather than causes and effects; and focus more on prediction. The development trend of spatiotemporal big data is the study of basic theories and methods of spatiotemporal data representation, measurement, and understanding, and revealing the corresponding laws between spatiotemporal big data and real world objects, behaviors, and events.

This subject of engineering research—"Mixed-pixel decomposition and spatiotemporal location big data analysis"—has a total of 95 published core papers, and each article has been cited 40.92 times on average (Table 1.1.1). The top five countries or regions that published these core papers include China (excluding Taiwan of China), Australia, America, Germany, and the Netherlands, and the proportion of papers published by Chinese authors was 56.84% (47.37% from the Chinese mainland and 9.47% from Hong Kong and Macao; Table 1.2.9). China has the greatest proportion in the statistics and is one of the most important countries or regions in this area. The top five countries or regions producing the most core papers in this subject include Portugal, Spain, France, the USA, and Belgium, and the citation frequency of the papers published by Chinese authors is 26.3, which is approximately 60% of the average value (Table 1.2.9). This shows that Chinese scholars are increasingly focusing on this research focus. As can be observed from the cooperation network shown in Figure 1.2.5, there exists a close cooperative relation between the top five countries or regions.

According to the statistics of institutions publishing these core papers (Table 1.2.10), the top five institutions include the Wuhan University, Chinese Academy of Sciences, Curtin University, University of Extremadura, and Delft University of Technology. As can be observed from the cooperation network of the top 10 paper publishing institutions shown in Figure 1.2.6, there exists a closer cooperation between foreign institutions.

According to the statistics of the cited papers (Table 1.2.11 and Table 1.2.12), the top five countries or regions that published the most core papers on this subject include China, Australia, the Netherlands, Germany, and England, and the proportion of Chinese core papers cited was 45.59% (the Chinese institutions among the top five

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	54	56.84%	1420	41.36%	26.30	9	0
2	Australia	17	17.89%	476	13.87%	28.00	3	1
3	USA	11	11.58%	708	20.62%	64.36	0	0
4	Germany	11	11.58%	385	11.21%	35.00	1	0
5	The Netherlands	11	11.58%	266	7.75%	24.18	0	0
6	Spain	8	8.42%	1010	29.42%	126.25	1	0
7	France	7	7.37%	748	21.79%	106.86	3	0
8	Belgium	7	7.37%	315	9.18%	45.00	1	0
9	Portugal	6	6.32%	900	26.22%	150.00	1	0
10	England	6	6.32%	150	4.37%	25.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Wuhan Univ	24	25.26%	618	18.00%	25.75	4	0
2	Chinese Acad Sci	13	13.68%	264	7.69%	20.31	1	0
3	Curtin Univ	11	11.58%	283	8.24%	25.73	1	1
4	Univ Extremadura	8	8.42%	1010	29.42%	126.25	1	0
5	Delft Univ Technol	8	8.42%	169	4.92%	21.13	0	0
6	Hong Kong Polytech Univ	7	7.37%	128	3.73%	18.29	1	0
7	Inst Telecomunicacoes	5	5.26%	881	25.66%	176.20	1	0
8	Inst Super Tecn	5	5.26%	850	24.76%	170.00	1	0
9	Curtin Univ Technol	5	5.26%	169	4.92%	33.80	1	1
10	Univ Toulouse	4	4.21%	661	19.25%	165.25	2	0

institutions included Wuhan University, Chinese Academy of Sciences, and Hong Kong Polytechnic University), which shows that Chinese scholars paid relatively close attention to the dynamics of this subject.

Based on the presented statistics, in the case of this engineering research subject—"Mixed-pixel decomposition and spatiotemporal location big data analysis"—Chinese scholars are keeping abreast of their foreign counterparts and gradually developing into world leaders in this research subject area. We suggest that the Chinese government should continue supplying funds to this research area in order to accelerate its development to the world-leading level.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 engineering development hotspots in the fields of civil, hydraulic engineering and architecture are listed in Table 2.1.1, and they include "Green city and green building," "New materials for civil engineering," "Intelligent building construction," "Intelligent urban transportation systems," "Digital urban planning," "Seismic and vibration control," "Monitoring, inspection, and informatization of geotechnical and underground

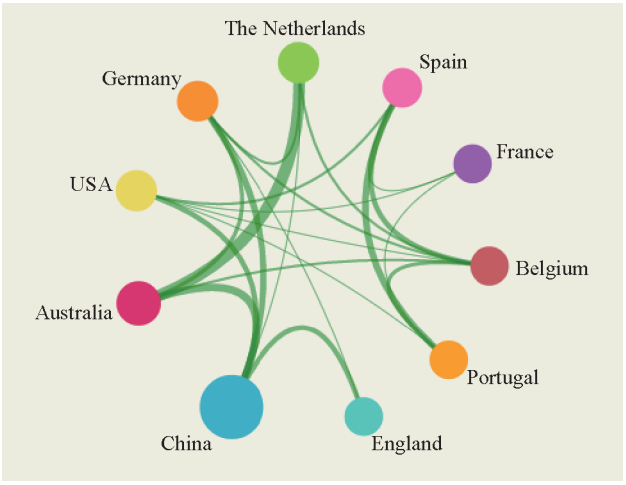

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

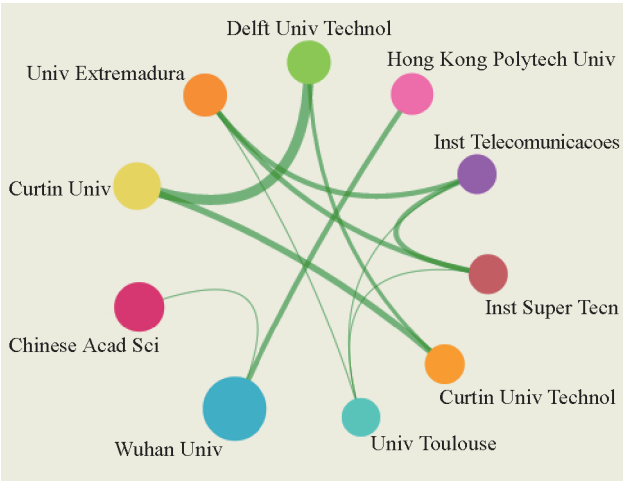

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	31	45.59%	2014.10
2	Australia	11	16.18%	2014.64
3	The Netherlands	7	10.29%	2015.14
4	Germany	7	10.29%	2014.00
5	England	3	4.41%	2014.67
6	USA	2	2.94%	2013.50
7	Belgium	1	1.47%	2015.00
8	Canada	1	1.47%	2013.00
9	Czech	1	1.47%	2014.00
10	Italy	1	1.47%	2016.00

engineering," "Global positioning navigation," "Bridge and steel structure industrialization," and "Urban rainwater flood control and utilization." The patents involved in the hotspots from 2011 to 2016 are shown in Table 2.1.2.

(1) Green city and green building

Green city and green building is the future trend of new urbanization and one of the prerequisites for realizing sustainable development. It requires the conservation of energy and resources, improvement of energy efficiency, and utilization of renewable energy while maintaining a healthy and comfortable living environment during the whole life cycle of the urban built environment. Green city and green building involves a number of research fields and is cross-disciplinary in nature. Based on the state of the art of building science and technologies, the research on this subject should explore the potential of passive energy saving strategies followed by improvement in system energy efficiency and investigations into renewable energy potential. Some of the innovative research topics include the assessment of the microclimate and energy performance of high-density urban morphology, climate-responsive and low-energy building design and optimization, smart grid and energy internet in high-density urban environments, development of passive techniques

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Wuhan Univ	15	15.63%	2014.33
2	Chinese Acad Sci	8	8.33%	2013.88
3	Curtin Univ	7	7.29%	2014.86
4	Delft Univ Technol	6	6.25%	2015.17
5	Hong Kong Polytech Univ	6	6.25%	2014.33
6	CSIRO	3	3.13%	2014.33
7	Curtin Univ Technol	3	3.13%	2014.00
8	Deutsch Zentrum Luft & Raumfahrt	3	3.13%	2013.67
9	E China Normal Univ	3	3.13%	2014.33
10	German Res Ctr Geosci GFZ	3	3.13%	2014.00

Table 2.1.1 Top 10 engineering development hotspots in civil, hydraulic engineering and architecture

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Green city and green building	889	5 907	6.64	2012.82
2	New materials for civil engineering	848	10 274	12.12	2012.39
3	Intelligent building construction	334	1 797	5.38	2012.91
4	Intelligent urban transportation systems	609	5 531	9.08	2012.52
5	Digital urban planning	165	1 625	9.85	2012.08
6	Seismic and vibration control	444	5 230	11.78	2012.30
7	Monitoring, inspection, and informatization of geotechnical and underground engineering	537	6 907	12.86	2012.39
8	Global positioning navigation	731	11 470	15.69	2012.50
9	Bridge and steel structure industrialization	316	2 533	8.02	2013.04
10	Urban rainwater flood control and utilization	192	310	1.61	2014.96

in challenging high-density urban environments, adaptive human comfort and behavior modeling, and integrated environment quality assessment framework. During the period from 2011 to 2016, 889 patents have been published in relation to this development hotspot, the total number of citations is 5907, and the average number of citations per patent is 6.64.

(2) New materials for civil engineering

With the increasing environmental awareness and demand for the higher performance of building materials, in contrast to traditional building materials (such as lime, cement, asphalt, concrete, reinforced concrete, and steel structures), new materials for civil engineering tend to be sustainable (such as recycled material, materials procured from waste, and energy-saving and environment-friendly materials), be functional (such as sensing or protection sound, light and magnet, etc.), and possess superior performance properties (such as lightweight, high strength, and high durability). The new materials for civil engineering mainly include green cement, sustainable cement, industrial waste cement, geopolymers (alkali-activated materials), carbon-fiber reinforcements, polymer-based materials, and ceramic materials. The key to the development and research of new materials is the long-term collaborative working of various components (for example, the coordinative working of new and old concrete, the reinforced components and the initial system, and the various components in a new type of system), low-energy-

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in civil, hydraulic engineering and architecture

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Green city and green building	225	215	171	115	100	63
2	New materials for civil engineering	274	213	176	139	32	14
3	Intelligent building construction	75	78	55	70	40	16
4	Intelligent urban transportation systems	166	158	135	112	31	7
5	Digital urban planning	68	41	35	17	4	0
6	Seismic and vibration control	155	115	86	68	12	8
7	Monitoring, inspection, and informatization of geotechnical and underground engineering	153	139	150	79	11	5
8	Global positioning navigation	211	205	147	102	41	25
9	Bridge and steel structure industrialization	56	69	73	54	53	11
10	Urban rainwater flood control and utilization	0	0	0	37	125	30

consumption preparation methods, high-performance technology, and functionalized technology. The effective methods for realizing the aforementioned technologies are to explore the theory of designing long life-span civil engineering materials, to develop key materials suitable for civil construction (such as multifunctional mineral admixtures and chemical admixtures), and to explore high-efficiency and low-energy-consumption preparation methods for new materials. The new materials mentioned above can be used in several areas in civil engineering (such as housing construction, bridge tunnels, and port terminals). They have been in use and will have a wider usage in the future. From 2011 to 2016, the number of patent publications on this hotspot was 848, the total number of citations was 10 274, and the average citation frequency for each patent was 12.12.

(3) Intelligent building construction

As an important part of the national strategy "Made in China 2025," intelligent building construction is the necessary approach for transforming the technological revolution in the construction industry into the industrial revolution. Using building information modeling (BIM) and robotic architecture fabrication as the core and BIM-based intelligent building construction as the platform, architectural design, construction, operation, and management were integrated into the whole engineering information process. Using the combination of robotic architecture construction technology and BIM, the upgradation of the automation and information technology in construction processes will be achieved, which will promote accurate analysis and precise construction in the entire life cycle of architecture, thus encouraging the architecture industry to transform from labor-intensive to technology-, knowledge-, and management-intensive. BIM combines the Internet of Things and cloud computing technology, effectively integrates the various stages of the construction period data, processes, and resources as well as completely outlines the project, which supports intelligent building construction as a main platform and model. As the key to intelligent building construction, robotic architecture construction technology applies advanced manufacturing technology from the fields of aerospace and automotive industry into the architecture industry based on the research on "digital building equipment integration systems" and "digital construction of innovative technology." Robotic architecture construction technology contributes to solving the problems of extensive, low-efficiency manufacturing and backward technical and management methods in industry production systems. Therefore, it could be used to realize a highly flexible, customized building product for the services and production mode. Intelligent building construction plays a key role in the advancement of the construction industry and is an inevitable choice for achieving green, high-efficiency, and customized development of the architecture industry. From 2011 to 2016, the total number of patents published on this hotspot was 334, the number of citations was 1797, and the average citation frequency was 5.38.

(4) Intelligent urban transportation systems

Urban intelligent transportation systems (ITS) are defined as the real-time, precise, and highly effective comprehensive urban transportation management systems that are based on fundamental traffic flow theory and make use of advanced and modern information, communication, sensing, control, and computer technologies. The main purposes of an ITS include reducing the stochastic of traffic flow, improving the utilization and availability factors and safety level of existing transport infrastructures, and reducing the energy consumption of the whole system and the pollutant discharge. Traditional ITSs are developed around traffic signal control systems and regional guiding systems, and these two key technologies remain the hotspot of ITS research today while the integration of control and guiding has already been observed. Intelligent vehicle/autonomous driving and intelligent transportation infrastructure technologies are the emerging hot issues for modern engineering development in this field. Among these, vehicle infrastructure cooperative systems are becoming the focus of engineering development. From 2011 to 2016, there have been 609 published patents with a total number of citations of 5531 and an average citation per patent of 9.08.

(5) Digital urban planning

Digital urban planning (DUP) focuses on computer technology, multimedia technology, and large-scale storage technology as the basis and makes use of a broadband network as a link. Through the use of remote sensing, GPS, geographic information systems, telemetry, simulation and virtual reality technology, and multi-resolution, multi-time, and three-dimensional descriptions, DUP makes use of information technology to analyze the city's past, present, and future content in a digital virtual implementation over a network. Based on the virtual reality implementation, the digital planning analysis and the diagnosis and evaluation are carried out, the multi-program comparison is performed, and the public participation is taken into consideration such that the planning and decisions are made more rationally. DUP includes large data (large-scale storage), telemetry, virtual simulation, intelligent city design, smart city design, flow and operational simulation, maintaining and promoting digital change in urban planning and design and management with multidimensional sensing systems in the city, as well as government and corporate data and other large data based on the web. From 2011 to 2016, the total number of patents published on this hotspot was 165, the number of citations was 1625, and the average citation frequency was 9.85.

(6) Seismic and vibration control

Seismic and vibration control technology prevents or mitigates structural vibrations induced by earthquake excitations. Traditional seismic resisting structures dissipate energy by means of inelastic deformations of the main load resistance members. This mechanism can cause significant deformation, damage, and even collapse of the structure, and therefore compromises the structural safety level. In contrast, seismic and vibration control technology, which minimizes the damage level or controls the location of the damage, can lower the risk of collapse of structures in the case of strong earthquakes and, as a result, reduce life and economic losses. Seismic control technology often involves data collection and interventions from the perspectives of the seismic source, seismic wave propagation, and structural performance; and vibration control technology aims to decrease the input energy to the structures. The main research trends and focuses include ① dampers with various energy dissipation mechanisms, ② energy-absorbing devices, ③ seismic isolators, and ④ self-centering technology. From 2011 to 2016, 444 patents have been published, and the total number of citations of these patents was 5230. The average number of citations per patent was 11.78.

(7) Monitoring, inspection, and informatization of geotechnical and underground engineering

Based on site investigation, monitoring, and inspection, the informatization of geotechnical and underground engineering is to digitalizes, networks, intelligentializes and visualizes geotechnical and site data with spatial and temporal variability. It is one of the crucial technologies for implementing intelligent refined construction and for the operation of geotechnical and underground engineering. The obstacle faced with this important technology is the complex geotechnical environment with high spatial variability and the strong nonlinear interaction behavior between geomaterials and underground structures. The solution to this obstacle lies in the drilling techniques such as deep-ground and deep-water drilling used in peculiar environments, application of geophysical technology, micro-seismic monitoring/inspection, application of optical fiber and laser technology, signal processing, and informatization of massive data. It can be applied for site

evaluation, construction monitoring, and heath inspection of geotechnical and underground engineering such as slopes, foundations, excavations, and tunnels in the design, construction, and operation stages. Current development is focused on quantitatively characterizing complex geotechnical environments and acquiring real-time information of underground structures using rapid and accurate methods. Much research will be focused on big data integration systems catering to intelligent geotechnical and underground engineering and the virtual reality technique in the future. From 2011 to 2016, the number of patents published in this field was 537, while the total number of citations was 6907 and the average number of citations was 12.86.

(8) Global positioning navigation

Global positioning navigation refers to the GNSS and the global all-weather continuous high-precision navigation positioning service. In 1989, the USA successfully launched the first GPS satellite, and by the end of 2016, there were a total of 108 navigation satellites in the sky over the earth. The global satellite navigation field comprises a pattern of coexistence of multiple systems including GPS, GLONASS, BeiDou, and GALILEO; the application of multiple systems improves the navigation positioning precision and real-time computing speed greatly. With the development of technology, the availability, continuity, reliability, positioning accuracy, and computation efficiency of global navigation and positioning will be continuously improved. Differential positioning technology, precise positioning technology, GNSS radio occultation technology, GNSS-R technology, integrated navigation technology, and all types of mobile terminal embedded application technologies are key technologies for GPS at present and in the future. The successful application of GNSS in geodesy, engineering surveying, aerial photogrammetry, vehicle navigation and control, crustal movement monitoring, engineering deformation monitoring, resource exploration, earth dynamics, and other disciplines brought a profound technological revolution to the field of surveying and mapping. From 2011 to 2016, the number of published patents on this hotspot was 731, the number of citations was 11 470, and the average number of citations per patent was 15.69.

(9) Bridge and steel structure industrialization

A bridge is a structure that spans over obstacles. Industrialization means the standardization of the design, production, construction, and management. The key technologies for bridge and steel structure industrialization include the design of large-span structure systems with flexible supports and transverse and longitudinal links, the fabrication of a high-performance steel bridge structure, bolt welding and riveting assembly and composite structure connection, fatigue-resistant vibration isolation and energy dissipation ancillary facilities, and bridge construction monitoring and control techniques. In bridge engineering, especially super-large-span bridge structure engineering, the steel structure or the steel-structure-based composite structure system is widely adopted. The industrialized manufacturing of a steel bridge includes the prefabrication of steel beams, columns, and trusses using standard steel and steel plates; the assembly of the components to form the mechanical performance optimization system of the large-span flexible structure; the connection using bolts and welding to form the structure; the monitoring and control of the bridge state in construction and in operation using optical and electrical equipment; the installation of bearings, dampers, wind barriers, and other ancillary facilities for structure disaster prevention and safety. The components of the construction include the main cable and cable net flexible support system and anchor; high-performance main truss, braces, corrugated webs, and orthotropic bridge deck precast; high-strength bolts, screws, and shear stud connections; repairable bearings, dampers, and the asphalt deck pavement; and bridge construction and operational monitoring based on BIM. From 2011 to 2016, the number of published patents on this hotspot was 316, the number of citations was 2533, and the average number of citations per patent was 8.02.

(10) Urban rainwater flood control and utilization

With the rapid development of urbanization and social economy, urban rainwater and flood issues have become increasingly critical and are mainly manifested in the increase in flood disaster risk, the loss of enormous rainwater resources, the serious urban river pollution, and the degradation of the urban ecological environment. The concept of urban rainwater flood-control and utilization has been put forward to deal with the urban rainwater and flood issues. Some measures pertaining to infiltration, storage, stagnation, purification, utilization, and drainage are taken to manage urban rainwater and runoff, thus effectively controlling urban rainwater floods and non-point source pollution at the source, halfway, or

to the end. The source-control technologies include roof greening, low-elevation greenbelts, permeable pavements, rainwater gardens, grassed swales, and rain barrels. The halfway-control technologies include sewage wells, infiltration pipes and channels, and rainwater filters. The end-control technologies include rain pools, rainwater wetlands, buffer zones, ecological embankments, and biological floating islands. These technologies have been used for water resource utilization, flood control and disaster mitigation, and ecological environment protection.

In recent years, China has experienced a rapid development in urban rainwater flood-control and utilization. Some cities have attempted to build a system for rainwater flood management and to construct several demonstration projects, but the overall levels and degrees of application are still low. The transformation of rainwater and sewage diversion of the urban pipeline network is slow, the capacity of rainwater utilization facilities is too low, and there is a lack of waterlogging prevention facilities for rainstorms with intensities that exceed the drainage capacity of other existing facilities, rainwater collection facilities, underground space data, and important softwares. Thus, it is difficult to prevent urban rainwater floods in a comprehensive manner.

It is therefore necessary to speed up the construction of large-capacity drainage systems, the development of multi-scale water quantity-quality coupled simulation software and digital rainwater resources management platforms, and the study on the classification and regulation of rainwater flood resources in the future. During the period from 2011 to 2016, the number of published patents was 192, the number of citations was 310, and the average citation frequency was 1.61 for the patents concerning urban rainwater flood-control and utilization.

2.2 Understanding of engineering development focus

2.2.1 Green city and green building

Green city and green building is the future of the new type of urbanization and one of the prerequisites for realizing sustainable development. It comprises the conservation of energy and resources, improvement of energy efficiency, and utilizing of renewable energy while maintaining a healthy and comfortable living environment during the whole life cycle of the urban built environment. Green city and green building involves a number of research fields and is cross-disciplinary in nature. Based on the state of the art of building science and technologies, the research should explore the potential of passive energy-saving strategies followed by improving the system energy efficiency, and discovering the renewable energy potential. Some of the innovative research topics on this subject include the assessment of microclimate and energy performance of high-density urban morphology, climate-responsive and low-energy building design and optimization, smart grid and energy internet in high-density urban environment, innovation of passive techniques in challenging high-density urban environments, adaptive human comfort and behavior modeling, and integrated environment quality assessment framework. During the period from 2011 to 2016, 889 patents have been published. The total number of citations was 5907, and the average number of citations per patent was 6.64.

(1) Assessment of microclimate and energy performance of high-density urban morphology

Facing the challenge of increasing population density and deteriorating physical environment, contemporary urban design requires the development of climate-responsive planning and design strategies in order to lower building cooling-energy consumption, improve thermal comfort, and thus create dynamic and user-friendly urban spaces. The existing research covers the urban microclimate and building energy load. The key question in urban microclimate research is what are the critical urban morphological parameters and what are the relationships between them and the microclimate parameters in dense and complex urban areas? The studies compute and map the key morphological parameters in digital urban spaces using urban morphometric and geographical information system (GIS) spatial analyst extension tools. Empirical measurements can facilitate the establishment of empirical models that can be used to explain the relationship between the morphology and microclimate parameters. A comprehensive assessment framework that can be a useful method and tool in climate-responsive urban design will be developed.

(2) Climate-responsive and low-energy building design and optimization

During the rapid globalization process, green building

design innovation inspired from regional and vernacular architecture has gained increasing attention in research. Understanding the climate and its impact on the built environment is the prerequisite for successful green building development. On one hand, one should learn from traditional architecture owing to its ecological wisdom, while on the other hand, recent advances in digital technology should be applied in the development of the methodology of green building design and research in order to manipulate urban and building morphology for optimized environmental performance.

(3) Smart grid and energy internet in high-density urban environment

Massive renewable energy production based on a distributed-energy system, smart grid, and internet connection is considered to be the future of urban energy networks. The triple-E (energy, environment, and economy) system based on the GIS platform will be the pillar of green energy internet in future cities. Renewable energy sources including solar and geothermal energy will be increasingly included in urban distributed-energy systems through building-incorporated renewable-energy-system integration.

(4) Innovation of passive techniques in challenging high-density urban environments

Passive design strategies such as natural ventilation, solar heating, and daylighting are being challenged in today's high-rise high-density urban environment. Owing to mutual shading, air stagnation, and air quality degradation caused by high-density urban development, the effectiveness of the above-mentioned strategies should be re-evaluated. Re-evaluating the potential of utilizing natural energy to heat, cool, and ventilate indoor and outdoor urban spaces under a complicated and often compromised urban boundary condition requires intense research.

(5) Adaptive human comfort and behavior modeling and assessment

Adaptive comfort modeling is an important research topic in passive urban and building design. New indices including PET and UTCI have been developed to assess human thermal comfort in urban spaces, and new empirical models are being formulated based on field survey data from around the globe and especially emerging economies in sub-tropical climates. Building-occupant behavior modeling is receiving increasing attention in building-energy modeling research as this is an important but long-been-neglected factor in the determination of building energy consumption. It is important to investigate the occupant behavior while integrating qualitative approaches and data-driven quantitative approaches and employing appropriate tools to guide the design and operation of a sustainable, comfortable, and healthy urban environment.

(6) Integrated environmental quality assessment framework

Under the circumstances of climate change and increasing occurrences of extreme weather events, rapid urban development should take into consideration the consequences and impact of urbanization on the urban physical environment and carefully evaluate the measures for integrating various design intervention strategies while aiming at energy efficiency, thermal comfort, and air quality improvement. Research should be focused on investigating the effective combinations of passive and active energy-saving strategies in realizing a green city and green building and creating a synthetic-environmental quality control and assessment framework.

During the period from 2011 to 2016, 889 patents that were related to the “Green city and green building” engineering development focus were published. The total number of citations was 5907, and the average number of citations per patent was 6.64 (Table 2.1.1). The top five countries or regions in patent publication were China (excluding Taiwan of China), the USA, Korea, France, and Japan (Table 2.1.1). Among these, patent applications from Chinese institutes or individuals comprised 40.94% of the total publications, and the average number of citations per patent was 5.35, indicating that China is a key player in this field of research (Table 2.1.1). According to the corporation network of major countries or regions in the “Green city and green building” engineering focus (Figure 2.2.1), the USA is the central hub of the international corporation. The top five institutes in the publishing of core patents are Beijing University of Technology, China Construction Eighth Engineering Bureau Co., Ltd., Certain Teed Corp., Vermont Slate & Copper Services Inc., and Tianjin University. Judging from the collaboration network of major institutes in the “Green city and green building” engineering focus (Figure 2.2.2), the corporation is generally not very active.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Green city and green building"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	364	40.94%	1946	32.94%	5.35
2	USA	329	37.01%	3084	52.21%	9.37
3	Korea	46	5.17%	228	3.86%	4.96
4	France	28	3.15%	126	2.13%	4.50
5	Japan	26	2.92%	122	2.07%	4.69
6	Germany	23	2.59%	87	1.47%	3.78
7	Canada	21	2.36%	84	1.42%	4.00
8	UK	13	1.46%	62	1.05%	4.77
9	Belgium	9	1.01%	55	0.93%	6.11
10	Australia	7	0.79%	23	0.39%	3.29

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Green city and green building"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	UYBT	23	2.59%	235	3.98%	10.22
2	CSCE	15	1.69%	76	1.29%	5.07
3	CERT	14	1.57%	140	2.37%	10.00
4	Vermont Slate & Copper Services Inc.	14	1.57%	189	3.20%	13.50
5	UTIJ	11	1.24%	57	0.96%	5.18
6	OWEN	10	1.12%	97	1.64%	9.70
7	COMP	9	1.01%	30	0.51%	3.33
8	UYQI	9	1.01%	53	0.90%	5.89
9	Huahui Eng Design Group Co., Ltd.	8	0.90%	49	0.83%	6.13
10	Jiangsu Huning Steel Mechanism Co., Ltd.	8	0.90%	34	0.58%	4.25

Note: The institute is represented by its patent holder code if it is listed in the normalized database, otherwise it is represented by its formal title. The top 10 institutes in patent publication are Beijing University of Technology, China Construction Eighth Engineering Bureau Co., Ltd., Certain Teed Corp., Vermont Slate & Copper Services Inc., Tianjin University, Owens-Corning Intellectual Capital LLC., Compagnie de Saint-Gobain (Saint-Gobain Glass, France), Tsinghua University, Huahui Engineering Design Group Co., Ltd., and Jiangsu Huning Steel Mechanism Co., Ltd. A patent holder code may represent a number of institutes and only the major one is listed here.

2.2.2 Intelligent urban transportation systems

The development of urban intelligent transportation systems (ITSs) began between the 1950s and 1960s. The early systems only included road transportation and mainly about sporadic product development on automatic vehicle control and electronic route guidance. During the next 30 to 40 years, several countries and regions invested much capital and manpower in this field, thus resulting in the rapid development of traditional ITSs, especially traffic signal control systems and regional guiding systems. Traditional ITSs are aimed at aiding authorities in intelligentizing transportation management through key technologies such as traffic guidance, regional traffic control, and congestion management. The integration technology of control and guidance will be the future direction of traditional ITSs.

(1) Intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology

As the emerging development hotspot in this field, vehicles and infrastructure are becoming the intelligent elements in transportation systems owing to advanced technologies of electronic sensing, communication and smart materials, etc. The development of technologies in this field has entered the phase of scaled on-site testing.

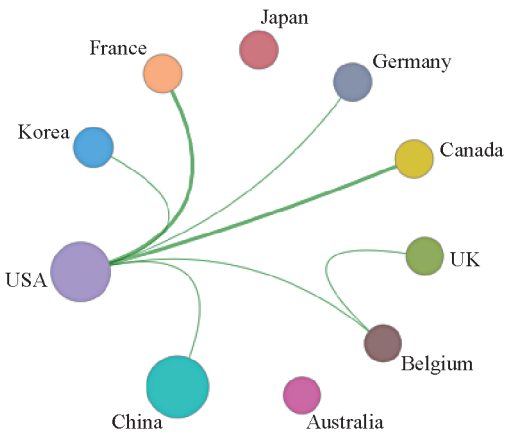

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Green city and green building"

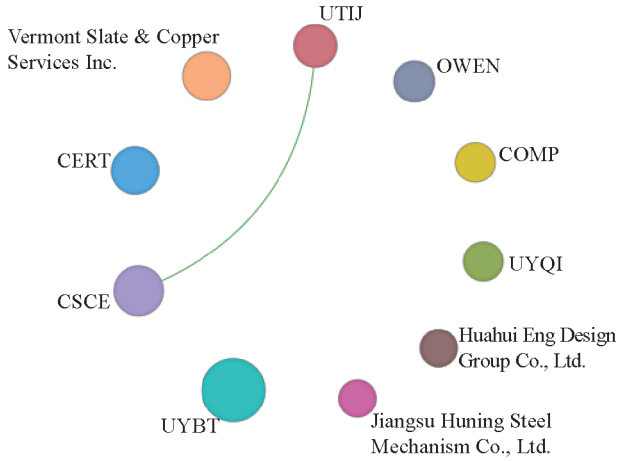

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Green city and green building"

The development of intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology has brought a huge challenge to traditional ITSs. In recent years, intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology have comprised the cutting edge of ITSs. Since its official proposal in 2011, the research and development of intelligent vehicle/autonomous driving have been continuously promoted by automobile enterprises, internet enterprises, etc. and have become dominant in ITS development strategies in several countries. The content involves important technologies such as automatic environment perception, vehicle-to-vehicle communication (V2V), and vehicle-to-infrastructure (V2I) communication.

(2) Vehicle-to-infrastructure (V2I) communication technology and system

Following the trends of emerging technologies, V2I systems are becoming a hotspot in ITSs. V2I technology integrated traditional ITS technology and modern intelligent vehicle/autonomous driving/intelligent infrastructure technology and utilized them in the whole process of urban transportation data collection, smart analysis, and scientific decision-making with the main purpose of building a brand-new comprehensive urban transportation system that could both fit and lead emerging technologies. V2I technologies utilize and integrate the advantages of both emerging technologies and traditional ITS technologies to achieve cooperation between vehicles and infrastructure, thus building a new comprehensive urban transportation system. V2I, which includes the technology of the Internet of Things and cloud computing, is a hot issue in ITS research.

(3) Technologies of intelligent environmental perception of transportation infrastructure, damage repair, energy harvesting, and pollution absorption

With the rapid development of both traditional and emerging ITS technologies, the trend of the integration of the two technologies became apparent; V2I technology was invented, and it grew into a major direction of ITS in several countries. Therefore, the technologies of intelligent perception, damage repair, energy harvesting, and pollution absorption were inspired. The number of published core patents in the engineering development of ITSs was 609 with an average number of citations of 9.08 (Table 2.1.1). The top five countries or regions in the publishing of core patents on this subject are China (excluding Taiwan of China), the USA, Japan, Germany, and Korea. Among these patents, 55.34% were obtained by institutions or persons from China, which makes China one of the main researching countries in this area. The average number of citations from China was 8.19 (Table 2.2.3). It can be observed that the USA is at the core position in the collaboration network between countries or regions (Figure 2.2.3). From Table 2.2.4, it can be observed that the institutions ranking among the top five are Yamanashi Toyota Jidosha KK from Japan, Southeast University from China, Dalian Shuangdi Innovative Technology Inc., INRIX Inc. from the USA, and Robert Bosch GmbH from Germany.

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Intelligent urban transportation systems"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	337	55.34%	2759	49.88%	8.19
2	USA	122	20.03%	1806	32.65%	14.80
3	Japan	55	9.03%	354	6.40%	6.44
4	Germany	34	5.58%	190	3.44%	5.59
5	Korea	21	3.45%	125	2.26%	5.95
6	Canada	6	0.99%	56	1.01%	9.33
7	UK	5	0.82%	28	0.51%	5.60
8	Austria	4	0.66%	37	0.67%	9.25
9	The Netherlands	4	0.66%	24	0.43%	6.00
10	Taiwan of China	4	0.66%	63	1.14%	15.75

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Intelligent urban transportation systems"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	TOYT	19	3.12%	117	2.12%	6.16
2	UYSE	18	2.96%	172	3.11%	9.56
3	Dalian Shuangdi Innovative Technology	15	2.46%	72	1.30%	4.80
4	Inrix Inc.	9	1.48%	275	4.97%	30.56
5	BOSC	8	1.31%	35	0.63%	4.38
6	AMTT	6	0.99%	51	0.92%	8.50
7	Beijing CenNavi Technologies Co., Ltd.	5	0.82%	45	0.81%	9.00
8	GOOG	5	0.82%	44	0.80%	8.80
9	HOND	5	0.82%	42	0.76%	8.40
10	IBMC	5	0.82%	68	1.23%	13.60

Note: Top 10 ranking institutions in publishing patents are Yamanashi Toyota Jidosha KK, Southeast University, Dalian Shuangdi Innovative Technology, INRIX Inc., Robert Bosch GmbH, AT&T Intellectual Property I LP (AT&T Mobility II LLC), Beijing CenNavi Technologies Co., Ltd., Google Inc., Honda Motor Co., Ltd., and International Business Machines Corp.

2.2.3 Seismic and vibration control

The main research trends and focuses related to the seismic and vibration control technology include ① dampers with various energy-dissipation mechanisms, ② energy absorbing devices, ③ seismic isolators, and ④ self-centering technology.

(1) Energy dissipation dampers

Energy dissipation dampers are devices that facilitate the reduction of vibration responses of structures in the case of earthquakes. Depending on the energy-dissipation mechanism, dampers can be categorized into two types, namely, displacement-dependent dampers and velocity-dependent dampers. Displacement-dependent dampers include metal dampers and friction dampers. Metal dampers use the satisfactory plastic deformation abilities of low-carbon steel under cyclic loading to dissipate energy, and friction dampers dissipate energy by means of friction caused by the relevant displacement of two blocks that are firmly in contact with each other. In contrast, velocity-dependent dampers mainly include fluid viscous dampers (walls) and viscoelastic dampers. These dampers often allow an increase in the damping ratio with little influence on the initial stiffness of the structure, but it should be noted that some of the damping materials may provide a certain level of stiffness. Fluid viscous dampers (walls) dissipate energy by taking advantage of the viscose

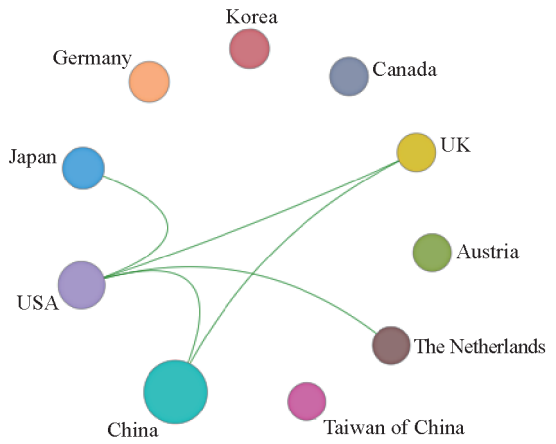

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Intelligent urban transportation systems"

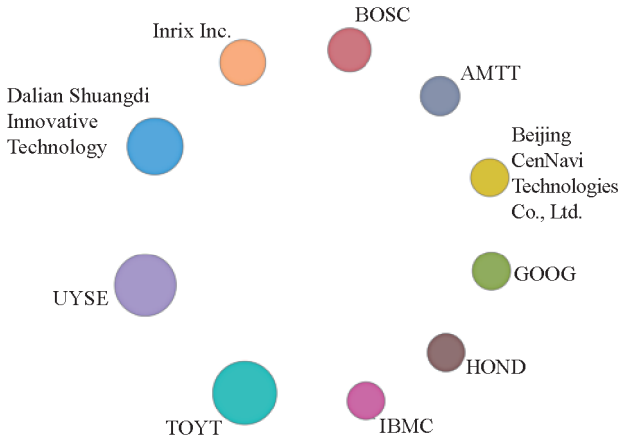

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Intelligent urban transportation systems"

property of the fluid. Viscoelastic dampers comprise viscoelastic materials and restraining plates, and these components are attached using a vulcanization process. The viscoelastic material dissipates energy by means of large shear deformations. The current research interests and future research trends of energy dissipation dampers include the principle of high-durability dampers, fatigue responses, special-purpose dampers, and smart materials and dampers.

(2) Energy absorbing devices

Energy absorbing devices aim to reallocate the energy that is transferred into the structure by incorporating a substructure that absorbs dissipated energy, thus reducing the vibration response of the main structure. When the main structure vibrates under external excitations, the relative motion of the substructure tends to apply an inertia force onto the main structure, and if the inertia force is properly controlled, the vibration response of the main structure can be effectively reduced. Common energy absorbing devices include tuned mass dampers (TMDs), tuned liquid dampers (TLDs), and suspension mass pendulum dampers (SMPDs). A TMD comprises a spring system, damping system, and mass block, and when its natural period matches that of the building, an optimal controlling effectiveness can be achieved. A TLD comprises a rigid container that is filled with liquid and is mounted on a structure to realize passive control. An SMPD consists of a pendulum system that swings and provides inertia forces to control the structural vibration. The current research interests and future research trends of energy absorbing devices include innovative energy absorbing mechanisms and active-passive hybrid energy absorbing technology.

(3) Seismic isolation technology

Seismic isolation technology is aimed at establishing an isolation layer between the superstructure and the foundation, such that the superstructure is separated from the ground, and thus, the energy input is significantly reduced. Currently, most of the seismic isolation technologies focus on horizontal seismic actions, where the lateral stiffness of the isolation layer is significantly smaller than that of the superstructure. Thus, the natural period of the structures equipped with the seismic isolation devices can be prolonged, and the induced acceleration is effectively reduced. Seismic isolation devices commonly include rubber bearings, roller bearings, and friction bearings. Rubber bearings employ a number of rubber layers and steel shim plates placed in alternation, and the appropriate anti-corrosion measures are often taken. Generally, rubber bearings are supposed to have sufficient stiffness in order to resist wind loads, and under extreme conditions, exhibit degraded stiffness that helps increase the natural period of the structure. Roller bearings employ a series of rollers between the superstructure and the foundation in order to enable smooth slippage and thus an increase in the natural

period of the structure. Similarly, friction bearings use the friction that is generated between the plates mounted at the superstructure and the foundation. Static friction can provide sufficient lateral stiffness against wind loads, and sliding friction can promote energy dissipation. The commonly used friction materials include sliding layer coating and silt layer coating. The current research interests and future research trends of seismic isolation technology include durability design, degradation behavior under corrosive environments, smart materials and base isolators, and multi-function base isolators.

(4) Self-centering structures

Self-centering structures are innovative structural systems that exhibit limited residual deformation after earthquakes. Self-centering technology has become one of the most attractive strategies for structural resilience design. From the perspective of the self-centering driving mechanism, two approaches have been widely investigated, namely, the post-tension (PT) approach and shape memory alloy (SMA) approach. The PT approach uses post-tensioned reinforcement or cables to enable a self-centering tendency, in which case, energy dissipative devices are often used in parallel. The SMA approach uses the superelastic property that enables a recoverable strain of up to 10%, and thus, hysteresis loops are induced, which are inherent damping characteristics of the SMA material. From an implementation point of view, self-centering members can be categorized into self-centering connections, self-centering bracings, self-centering column feet, and self-centering shear walls. Both the PT and SMA approaches are suited to the first three member types, whereas the last type often requires the PT approach. The current research interests and future research trends of self-centering technology include self-centering construction technology, self-centering maintenance strategy, fiber-reinforced post-tension bars, a low-cost SMA approach, and hybrid self-centering technology.

In relation to the engineering development focus "Seismic and vibration control," 444 core patents have been published, and the average number of citations per patent is 11.78 (Table 2.1.1). The top five countries or regions in publishing patents on this subject are China (excluding Taiwan of China), the USA, Germany, Japan, and France. China is the most active country in this area of research, and Chinese organizations or individuals contributed to 49.55% of the total patents, with an average number of citations of 11.23 per patent (Table 2.2.5). From Figure 2.2.5, it can be observed that extensive collaborations exist among various countries. From the perspective of the number of patents shown in Table 2.2.6, the top five institutions are CGG Services SA, Baker Hughes Corp., Schlumberger Canada Ltd., Westerngeco LLC., and Beijing University of Technology. According to the network information shown in Figure 2.2.6, there are limited collaborations between various organizations.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Seismic and vibration control"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	220	49.55%	2471	47.25%	11.23
2	USA	129	29.05%	2000	38.24%	15.50
3	Germany	23	5.18%	205	3.92%	8.91
4	Japan	22	4.95%	212	4.05%	9.64
5	France	21	4.73%	129	2.47%	6.14
6	UK	14	3.15%	115	2.20%	8.21
7	Canada	9	2.03%	37	0.71%	4.11
8	The Netherlands	9	2.03%	77	1.47%	8.56
9	Norway	7	1.58%	53	1.01%	7.57
10	Korea	6	1.35%	45	0.86%	7.50

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Seismic and vibration control"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	CGGV	16	3.60%	105	2.01%	6.56
2	BAKO	14	3.15%	278	5.32%	19.86
3	SLMB	14	3.15%	178	3.40%	12.71
4	WGSC	11	2.48%	168	3.21%	15.27
5	UYBT	10	2.25%	125	2.39%	12.50
6	CNPC	9	2.03%	86	1.64%	9.56
7	ESSO	9	2.03%	159	3.04%	17.67
8	HALL	8	1.80%	235	4.49%	29.38
9	China Univ Petroleum	8	1.80%	92	1.76%	11.50
10	PGSG	7	1.58%	66	1.26%	9.43

Note: The top 10 organizations in patent publishing are CGG Services SA, Baker Hughes Corp., Schlumberger Canada Ltd., GECO Technology B.V., Beijing University of Technology, China National Petroleum Corp., Exxonmobil Upstream Research Company (Exxonmobil Research & Engineering Co.), Halliburton Energy Services Inc., China University of Petroleum, and PGS Geophysical AS.

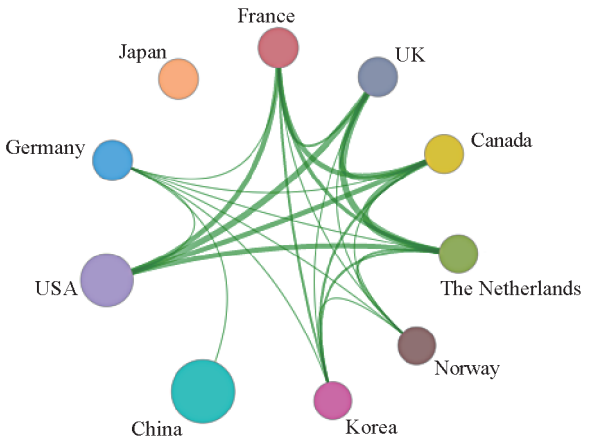

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Seismic and vibration control"

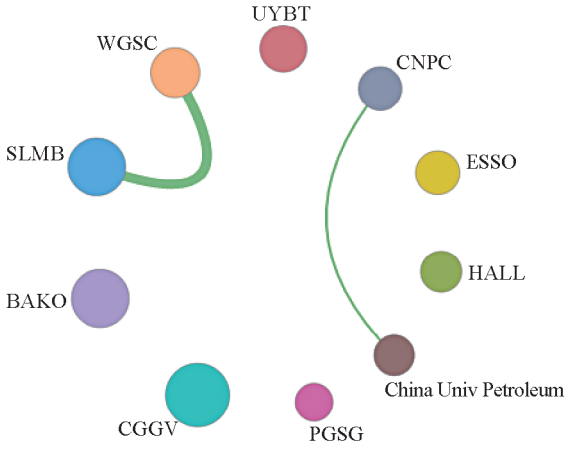

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Seismic and vibration control"

Project Participants

Members of the Field Group

Experts of the Field Group

Leaders of the Field Group:

CUI Junzhi, SHEN Zuyan

Academicians:

CUI Junzhi, JIANG Huancheng, JIANG Yi, ZHOU Fulin, OU Jinping, SHEN Zuyan, LIANG Wenhao, MIU Changwen, LIU Jiaping, XIAO Xuwen, NIE Jianguo, HU Chunhong, GUO Renzhong, CHEN Zhengqing, ZHENG Jianlong

Other Experts:

CHEN Yiyi, GE Yaojun, GU Chongshi, GUO Ronghuan, HAN Guorui, HAN Linhai, HE Pengfei, HONG Kairong, LI Angui, LI Dapeng, LI Deying, LI Hui, LI Guoqiang, LIU Renyi, LIU Shuguang, LIU Xukai, LING Jianming,

LUO Yaozhi, MA Jun, MAO Zhibing, NIU Ditao, QIAN Feng, QIAO Pizhong, REN Weixin, RU Jiping, SHI Caijun, SHI Beiling, SUN Lijun, TAN Yiqiu, TANG Haiying, TAN Guangming, SUN Limin, TONG Xiaohua, WANG Weidong, WU Zhiqiang, XU Shilang, XU Zhaodong, YU Shuili, ZHANG Jianmin, WU Jiang, ZHANG Xigang, ZHANG Xu, ZHAO Tiejun, ZHENG Gang, ZHU Hehua, ZHU Ruolin

Members of the Secretary Group

The Civil, Hydraulic Engineering and Architecture Office at CAE:
TANG Haiying, XING Huixian
FSCE Journals Editorial Office:
Structure engineering:
CHEN Yiyi, ZHAO Xianzhong, WANG Wei
Bridge engineering:
GE Yaojun, SUN Zhi
Geotechnical and the underground engineering:
ZHU Hehua, ZHUANG Xiaoying, LIU Fang
Hydrolical engineering:
HUANG Wenrui, CAI Yi
Other Institutes at Tongji University:
Architecture:
LI Zhenyu, HE Yong
Air condition:
ZHANG Xu, ZHOU Xiang
Urban and rural planning and landscape:
ZHANG Shangwu, PANG Lei
Road and railway engineering:
SUN Lijun, LING Jianming, SHAO Minhua
Civil building materials:
JIANG Zhengwu, CHEN Qing
Engineering mechanics:
LI Yan, WANG Huaning
Surveying and mapping engineering:
TONG Xiaohua, CHEN Peng
Municipal engineering:
DAI Xiaohu, XU Bin
The library at Tongji University:
CHEN Xin, YAO Junlan
Secretary:
WU Yuqing from FSCE editorial office,
PAN Zuanfeng from Tongji University College of Civil Engineering
YAO Junlan from the library at Tongji University
GUI Xiaolan from Higher Education Press

Report Writers

Leaders:
CHEN Yiyi, GE Yaojun, ZHU Hehua
Other Writers:
Structural engineering:
ZHAO Xianzhong, LI Jie, CHEN Jianbing, WANG Wei, WU Yuqing, REN Xiaodan, PAN Zuanfeng
Bridge engineering:
LI Jianzhong, SUN Zhi
Geotechnical and underground engineering:
ZHUANG Ziaoying, CAI Yongchang, LIU Fang
Hydrolical engineering:
HUANG Wenrui, CAI Yi
Architecture:
LI Zhenyu, YUAN Feng, HE Yong
HVAC:
HOU Xiang, ZHANG Xu
Urban planning and landscape architecture:
ZHANG Shangwu, PANG Lei
Road and railway engineering:
SUN Lijun, LING Jianming, SHAO Minhua
Civil building materials:
JIANG Zhengwu, CHEN Qing
Engineering mechanics:
LI Yan, WANG Huaning
Surveying and mapping engineering:
TONG Xiaohua, CHEN Peng
Municipal engineering:
DAI Xiaohu, XU Bin
The library at Tongji University:
CHEN Xin, YAO Junlan

VI. Environmental & Light and Textile Industries Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the field of environmental and light and textile industries engineering (hereafter referred to as environmental engineering), which includes the subfield of environmental science, environmental engineering, marine science, and climate science are summarized in Table 1.1.1. The in-depth study on traditionally engineering research hotspots includes "The chemical composition of aerosols," "Topographic survey and soil erosion management," "Applications of ligand-based composite adsorbents in water treatment," "Remote sensing inversion techniques and estimation of fluxes for greenhouse gases," "Estimation methods and models of solar radiation," "Assessment and control of greenhouse gas emissions in wastewater treatment plants," and "Analytical techniques of atmospheric CH_4 emissions and sources." The emerging engineering research hotspots include "Arctic sea ice and mid-latitude climate responses," "Regional climate response to global change," and "Hyperspectral unmixing methods." The annual number of core papers for individual research hotspots between 2011 and 2016 are summarized in Table 1.1.2.

(1) The chemical composition of aerosols

Please refer to Section 1.2.1.

(2) Arctic sea ice and mid-latitude climate responses

Please refer to Section 1.2.2.

(3) Hyperspectral unmixing methods

Three-dimensional (3D) hyperspectral images contain both spatial information and a wealth of spectral reflectance information with wide-band coverage, rapid non-destructive, full spectral information content, and other characteristics. Based on the abundant spectral information of hyperspectral images, the effective classification and recognition of imaging objects can be realized by image analysis and pattern recognition algorithms. Therefore, hyperspectral imaging technology has a wide range of applications in agriculture, military, land use, and environmental science. In the field of environmental science, eco-

Table 1.1.1 Top 10 engineering research hotspots in environmental engineering

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	The chemical composition of aerosols	50	2766	55.32	2013.58	24.00%	1
2	Arctic sea ice and mid-latitude climate responses	49	2743	55.98	2014.06	51.00%	0
3	Hyperspectral unmixing methods	45	2924	64.98	2012.64	22.20%	0
4	Topographic survey and soil erosion management	44	1721	39.11	2014.70	40.90%	0
5	Remote sensing inversion techniques and estimation of fluxes for greenhouse gases	41	2503	61.05	2012.95	9.80%	0
6	Assessment and control of greenhouse gas emissions in wastewater treatment plants	42	1484	35.33	2013.45	14.30%	1
7	Applications of ligand-based composite adsorbent in water treatment	40	1393	34.83	2014.08	40.00%	0
8	Estimation methods and models of solar radiation	40	771	19.27	2013.98	7.50%	0
9	Analytical techniques of atmospheric CH_4 emissions and sources	42	1737	41.36	2014.21	16.70%	0
10	Regional climate response to global change	96	3191	33.24	2012.99	10.40%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in environmental engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	The chemical composition of aerosols	5	7	12	10	12	4
2	Arctic sea ice and mid-latitude climate responses	0	8	6	14	17	4
3	Hyperspectral unmixing methods	12	9	8	15	1	0
4	Topographic survey and soil erosion management	0	2	4	8	21	9
5	Remote sensing inversion techniques and estimation of fluxes for greenhouse gases	11	6	7	10	5	2
6	Assessment and control of greenhouse gas emissions in wastewater treatment plants	6	4	11	9	10	2
7	Applications of ligand-based composite adsorbent in water treatment	3	2	10	6	12	7
8	Estimation methods and models of solar radiation	1	2	11	10	15	1
9	Analytical techniques of atmospheric CH_4 emissions and sources	0	5	8	7	17	5
10	Regional climate response to global change	25	16	13	25	11	6

logical/environmental monitoring can be achieved through large-scale hyperspectral data; river water quality and eutrophication status can be evaluated using hyperspectral imaging; and hyperspectral remote sensing data can be used to determine aerosol thickness and composition.

Due to the complex diversity of nature and limited resolution of image sensors, one pixel may have mixed spectra of different materials. Such pixels are called mixed pixels. Mixed pixels greatly reduce the accuracy of the classification of surface features because they cannot be divided into a certain category. In order to solve the problem of mixed pixels, it is necessary to decompose the mixed pixels at the sub-pixel level through unmixing. Unmixing is the use of geometric and statistical methods and models to decompose the proportion of basic components (endmembers) and basic materials (abundance). Although there are many well-established methods, they have their own advantages and disadvantages and their applications differ. The accuracy and stability of the unmixing results have yet to be improved. Therefore, the efficient unmixing of hyperspectral images is still a popular and challenging topic in the applications of hyperspectral imaging technology.

(4) Topographic surveys and soil erosion management

Topographic surveys refer to measuring the projection position and elevation on the horizontal plane of a feature and terrain on the earth's surface, reducing them to a certain proportion, and drawing topographic maps with symbols and notes. Soil erosion refers to the process of destruction, denudation, transportation, and deposition of soil and soil parent material under the external stress of water, wind, freeze, thaw, or gravity. The key technical issue with this research topic is to develop economical, efficient, and accurate mapping techniques, and apply them to monitoring, evaluation, and management of soil erosion. With respect to topographic surveys, aerial photogrammetry a rapidly developing filed. Notably, the applications of high-precision photographic mapping, light direction and ranging (LIDAR) mapping, and remote sensing (RS), and geographic information system (GIS) technologies based on the unmanned aerial vehicle (UAV) mapping have significantly improved the efficiency and accuracy of mapping. With the maturing UAV technology, high-precision aerial photogrammetry and mapping with UAV have gradually become the foci of current research efforts. This technique has led to the continued development of traditional terrain monitoring research and is widely used in earth science for the modeling, evaluation, and management of soil erosion; terrain modeling; and disaster prevention and mitigation. In the future, the development of economical, efficient, and accurate topographic survey techniques will remain a major research challenge in this field.

(5) Remote sensing inversion techniques and estimation of fluxes for greenhouse gases

Remote sensing technology for atmospheric methane (CH_4) includes space-based and ground-based spectral

detection techniques. There are some observation methods for ground-based greenhouse gases, such as Fourier transform spectrometry, grating spectrometry, and LIDAR. For green house gas detection techniques, the tendency of research and development in the future lies towards higher spectral and spatial resolution. Currently, the UK, Germany, France, and the USA are trying to develop a technique based on infrared laser heterodyne spectroscopy. This technique offers many advantages including high spectral resolution, high sensitivity, small volume, and ability to detect carbon dioxide (CO_2) and CH_4 through remote sensing. Therefore, the research focus of this project is to delve deeper into the development of the traditionally available techniques.

(6) Assessment and control of greenhouse gas emissions in wastewater treatment plants

Nitrous oxide (N_2O) is the third largest contributor to global warming after CO_2 and CH_4. The warming effect of N_2O is 350 times that of CO_2. N_2O has a significant impact on ozone depletion and causes serious damage to ecosystems. Wastewater treatment is an important source of N_2O emissions, and the problem of N_2O production in the traditional process of sewage denitrification has attracted the attention of many scholars. It is widely acknowledged that N_2O is the intermediate product or by-product of nitrification and denitrification. The total amount of N_2O emissions has increased with the widespread use of the sewage denitrification process.

This research topic focuses on emissions, reaction mechanisms, temporal variation, control strategies, and factors influencing biological nitrification and denitrification in sewage treatment processes. Key areas of research include the influence of sewage treatment processes and operation modes on N_2O emissions, application of mathematical modeling in the prediction of N_2O emissions during sewage treatment, the effect of pH on N_2O loss and nitrogen removal, and the effect of inorganic carbon on the interaction of microorganisms within the biofilm in the process of nitrification/ammonia oxidation. The influence of different technologies on N_2O emission characteristics in the process of sewage denitrification will continue to remain an important research direction in the future.

(7) Applications of ligand-based composite adsorbent in water treatment

Please refer to Section 1.2.3.

(8) Estimation methods and models of solar radiation

Solar radiation is a major source of energy for physical, biological, and chemical processes on the earth's surface, and also the basic driving force dictating the behavior of the weather and climate. However, due to the restrictions in funds, technology, and environmental conditions, compared to conventional meteorological observation data, such as temperature, humidity, and precipitation, only a few weather stations in China provide solar radiation data, which fails to satisfy research requirements. Different mechanisms and empirical models have been established by researchers from all over the world. Empirical models utilize probability theory and statistical theory as the foundation to build the relationship between solar radiation and meteorological factors, but there are uncertainties in the estimation of solar radiation. Therefore, the research focus of this project is to delve deeper into the development of the traditionally available techniques.

(9) Analytical techniques to determine atmospheric CH_4 emissions and sources

After CO_2, CH_4 is the most important greenhouse gas, and plays a significant role in global warming and chemical destruction of the ozone layer. CH_4 emission sources can be divided into anthropogenic and natural sources. Anthropogenic sources include rice fields, fossil fuel combustion, landfills, and livestock. Natural sources include wetlands, termites, seas, and geological formations. Estimation of global CH_4 sources is based on the observation of CH_4 fluxes but the constraints of time, space, and effects of environmental factors on CH_4 emissions increase the uncertainty of estimations. In the study of biological emission sources, different industries carry out research on emissions from rice fields, wetlands, and livestock but studies on urban emissions are lacking. Therefore, it is necessary to strengthen the research on CH_4 observations and source estimation techniques to obtain more accurate CH_4 source distribution and flux data.

(10) Regional climate response to global change

Please refer to Section 1.2.4.

1.2 Understanding of engineering research focus

1.2.1 The chemical composition of aerosols

China has faced serious atmospheric pollution problems in recent years, especially in autumn and winter. Aerosols in the atmosphere not only influence air quality but also have a significant effect on cloud formation and precip-

itation. Atmospheric aerosols include primary particles, directly emitted from human activities, and secondary species, converted from gases emitted to the atmosphere. Research on transformation processes, dry and wet deposition, chemical scavenging processes of different types of pollutants in atmospheric aerosols (including cloud, fog, and haze aerosols), and the degradation due to hazardous materials in aerosols to the environment, climate, and human health can provide a theoretical and scientific basis for solving the problem of atmospheric pollution and climate change. Data on the chemical composition of aerosol particles during heavy pollution events in autumn and winter, the composition of oxygenated organic aerosols, and the formation of aerosol chemical species will provide help form the public perception of pollution risks and the government's response.

Many countries in the world consider aerosol pollution as the focus of atmospheric pollution research. Many disciplines with a long-term research direction study the influence of aerosols on health, environment, and climate, and the emission characteristics and secondary transformation characteristics of aerosols.

The review of 50 core papers on aerosol chemical composition revealed that these studies were cited as many as 2766 times, with a per paper citation frequency of 55.32, mostly from 2013 to 2015. Frequently cited papers account for 24.00% of all papers (Table 1.1.1). The number of patents is relatively small. Almost all 50 core studies were conducted in the USA and China, and the citation frequency per paper for both countries is 44.14 and 43.93, respectively (Table 1.2.1). The Chinese Academy of Sciences published 40% of the papers, which were cited866 times (Table 1.2.2). The core papers are mainly about aerosol composition, their physical and chemical properties, and sources, and to a lesser extent, about formation mechanisms, transformation processes, and wet and dry deposition. Studies on aerosol formation mechanisms and transformation processes can not only provide a technical basis for the reduction of aerosol formation but also a scientific basis for efficient government decision-making. Therefore, it is crucial to strengthen research in these two aspects.

In order to control and improve environmental quality without affecting economic development, aerosol chemical composition, formation mechanisms, and transformation processes need in-depth scientific research. Aerosol chemistry has become an important direction with regard to environmental improvement and economic development.

When analyzing the engineering research focus of "The chemical composition of aerosols," the top three countries or regions that published the highest number of core papers are the USA (29), China (29), and Switzerland (14), and the top three countries or regions with highest average citations are Germany (49.13), Spain (48.00), and the USA (44.14) (Table 1.2.1). Among these countries or regions, China and the USA extend the highest level of cooperation to each other, followed by Germany, Switzerland, and England (Figure 1.2.1).

The top three institutions that published the highest number of core papers are the Chinese Academy of Sciences (20), the Paul Scherrer Institute (14), and Aerodyne Research, Inc. (12), and the top three cited institutions per core paper are University of Colorado (82.86), French Alternative Energies and Atomic Energy Commission (CEA) (55.33), and Aerodyne Research, Inc (54.75) (Table 1.2.2). The institutions with the highest number of published papers in China include the Chinese Academy of Sciences, Nanjing University, Nanjing University of Information Engineering, and Peking University (Table 1.2.2).The Chinese Academy of Sciences has a tie-up with Nanjing University of Information Engineering, Nanjing University, and University of California-Davis (Figure 1.2.2).

The major research institutions with regard to the citing core papers include the Chinese Academy of Sciences, Nanjing University, Nanjing University of Information Engineering, and Peking University in China; and Aerodyne Research, Inc. and University of California, Davis in the USA; and the Paul Scherrer Institute in Switzerland (Table 1.2.3 and Table 1.2.4).

1.2.2 Arctic sea ice and mid-latitude climate responses

The Arctic is one of the most sensitive areas to global climate change. The average temperature rise in the last 30 years is twice the rate of global warming, and this phenomenon is known as the "Arctic amplification." Since the 1970s, global temperatures have increased and have had a profound impact on the Arctic, decreasing the Arctic sea ice coverage. By 2012, the area of Arctic sea ice has reduced to less than 40% of the original. With the influence

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "The chemical composition of aerosols"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	29	58%	1280	52.83%	44.14	2	1
2	China	29	58%	1274	52.58%	43.93	1	1
3	Switzerland	14	28%	602	24.85%	43.00	0	0
4	France	9	18%	330	13.62%	36.67	0	0
5	Germany	8	16%	393	16.22%	49.13	0	0
6	Spain	4	8%	192	7.92%	48.00	0	0
7	England	4	8%	81	3.34%	20.25	0	0
8	The Netherlands	3	6%	124	5.12%	41.33	0	0
9	Norway	3	6%	117	4.83%	39.00	0	0
10	Greece	3	6%	106	4.37%	35.33	0	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "The chemical composition of aerosols"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Chinese Acad Sci	20	40%	866	35.74%	43.30	0	0
2	Paul Scherrer Inst	14	28%	602	24.85%	43.00	0	0
3	Aerodyne Res Inc	12	24%	657	27.12%	54.75	1	0
4	Univ Calif Davis	12	24%	531	21.91%	44.25	1	0
5	Nanjing Univ	10	20%	489	20.18%	48.90	0	0
6	Nanjing Univ Informat Sci & Technol	9	18%	379	15.64%	42.11	0	0
7	Peking Univ	8	16%	365	15.06%	45.63	1	1
8	Univ Colorado	7	14%	580	23.94%	82.86	1	0
9	CEA	6	12%	332	13.70%	55.33	0	0
10	Leibniz Inst Tropospher Res	5	10%	231	9.53%	46.20	0	0

Note: CEA stands for French Alternative Energies and Atomic Energy Commission.

of global warming, internal positive feedback is the key process for the Arctic amplification, which not only leads to polar climate change but also has a significant effect on the global climate, resulting in many extreme weather and climate events. One of these typical events occurred at 11 a.m. on December 30, 2015, when a powerful storm from the Atlantic moved into the Arctic Ocean. At that time, the temperature near the North Pole was approximately the same as that in Beijing. Affected by this event, the Arctic temperature had broken the record of 0 °C, nearly 30 °C higher than the normal temperature in winter. The event also led to extreme cold wave events in China and other mid-latitude regions.

The accelerated melting of sea ice in the Arctic and the dramatic reduction in the sea ice extent will also have an impact on the global economy. Research shows that navigation time in the Arctic Channel is getting longer. By 2030, the airworthiness time may reach 120 d per year. The possible effect on the huge value of commercial shipping has drawn the attention of all stakeholders. In addition, the melting of sea ice has increased the potential for oil exploitation in the Arctic. The rich oil, gas, and mineral resources in the Arctic have attracted attention from many countries or regions. The change in the Arctic sea ice

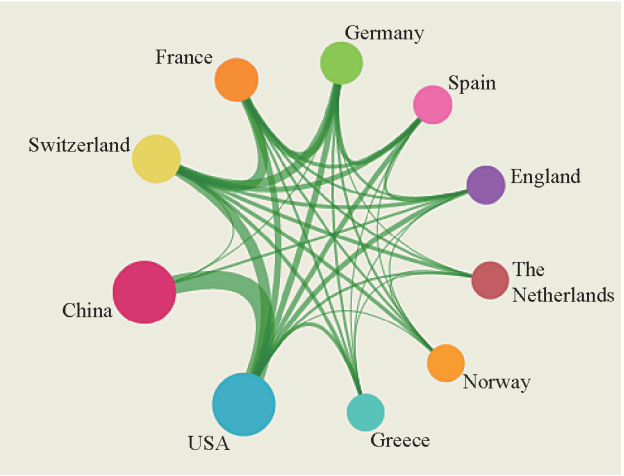

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "The chemical composition of aerosols"[1]

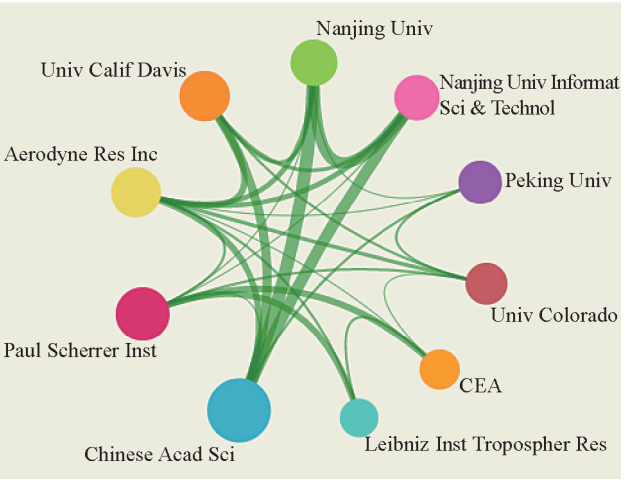

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "The chemical composition of aerosols"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "The chemical composition of aerosols"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	25	22.32%	2013.88
2	China	23	20.54%	2013.87
3	Switzerland	14	12.50%	2013.57
4	France	9	8.04%	2013.78
5	Germany	8	7.14%	2013.63
6	England	4	3.57%	2015.00
7	Spain	4	3.57%	2014.00
8	The Netherlands	3	2.68%	2012.67
9	Norway	3	2.68%	2013.33
10	Greece	3	2.68%	2013.67

extent is not only a climate issue but has also brought about a new focus on engineering exploitation techniques in the 21st century.

Although the Arctic sea ice covers only a small part of the global ocean, it plays an important role in Earth's weather and climate. Sea ice has relatively high albedo, which forms a feedback effect in the global climate system. At the same time, the thermal conductivity of sea ice is very low and can block atmospheric heat and water vapor exchange in sea-ice-covered areas, affecting the atmospheric circulation system and weather conditions, leading to large-scale extreme weather events. Therefore, the study of the interaction between the Arctic sea ice reduction and the atmospheric circulation in the Northern Hemisphere is very important and necessary to reveal the role of Arctic sea ice in climate change. One of the important missions of Arctic science is to investigate the mechanisms underlying these positive feedback processes. Major scientific problems related to Arctic amplification mainly concern atmosphere-ice-sea interactions, sea ice being the most active factor. To solve these problems, the changes in the structure of the sea ice should be determined,

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "The chemical composition of aerosols"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Chinese Acad Sci	16	6.96%	2014.13
2	Paul Scherrer Inst	14	6.09%	2013.57
3	Aerodyne Res Inc	9	3.91%	2014.22
4	Univ Calif Davis	9	3.91%	2014.22
5	Nanjing Univ Informat Sci & Technol	9	3.91%	2014.22
6	Nanjing Univ	9	3.91%	2014.22
7	CEA	6	2.61%	2013.50
8	Peking Univ	6	2.61%	2013.33
9	Leibniz Inst Tropospher Res	5	2.17%	2013.60
10	Univ Colorado	5	2.17%	2013.60

and thermodynamic characteristics of the change should be quantitatively expressed. Thus, factors such as melting pool, lateral melting, and snow and sea ice drift should be fully considered. The ocean is a key source of energy for changes in the Arctic. In winter, sea ice spreads over the ocean, creating an insulating layer that prevents much heat from escaping from the ocean to warm the air. Ocean currents also bring heat from warmer regions into the Arctic Ocean. Therefore, we need to understand the distribution of ocean heat flux (the mechanism of energy storage and release) and the effect of the changes in freshwater and thermocline structure on sea-air coupling.

The rapid changes in the Arctic sea ice extent have attracted significant attention. Implemented research projects include WCRP (World Climate Research Programme), CliC (Climate and Cryosphere), ACSYS (Arctic Climate System Study), SHEBA (Surface Heat Budget of the Arctic Ocean Experiment), LOIRA (Land-Ocean Interactions in the Russian Arctic), JWACS (Joint Western Arctic Climate Study), DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies), and NABOS (Nansen and Amundsen Basins Observational System). These projects have focused on the Arctic and global climate change using on-site observations and numerical simulations. The response to the changes in sea ice extent on climate change was investigated through the research and development of the atmosphere-ocean-sea-ice coupling model. Among them, launched in 1993, ACSYS, one of the important subprograms of WCRP, mainly studies the effect of the Arctic climate change (primarily reflected in the reduction of sea ice) on the global environmental system.

The understanding of Arctic sea ice and atmospheric-ocean interactions has not been translated into the physical essence of sea ice change. The results of the existing studies attributed the changes in Arctic sea ice to global climate change and positive feedback processes it caused in the Arctic. The studies suggest that these processes make the ocean absorb more heat and strengthen the interactions among the atmosphere, ocean, and ice, and result in further decreases in sea icecover. However, it is not easy to determine these processes because most of them involve the physical processes of ocean and sea ice changes, which are not clearly understood. As a result, research on changes in the Arctic has not progressed much in recent years. In order to improve this situation, it is necessary to study the physical processes in the Arctic in depth, focusing on new and degenerative processes caused by Arctic warming. In addition, studying the physical processes based only on the assimilation data and reanalysis is far from sufficient. It is necessary to carry out large-scale field observations to obtain on-site data from the Arctic to understand the physical processes.

The analysis of the core papers and the main producing countries or regions (Table 1.2.5) shows that the USA, England, and Germany are the top three countries or regions with regard to the number of papers published on this research topic, followed by Australia, Japan, Korea, China, Norway, Switzerland, and Finland. The USA has published 61.22% of the core papers, indicating that the USA has a greater research interest in this field. England comes second, accounting for 30.61% of all papers on the

subject. The total citation reflects the subsequent effects of the study; the ranking is consistent with the proportion of core papers by country or region. Although China's rank with regard to the total number of papers on the index is not the highest, the average citation of each paper from China ranks first (157.00 times).

The University of Exeter in England and the National Center for Atmospheric Research and Rutgers State University in the USA are the top three institutions publishing core papers, followed by the University of Melbourne (Australia), the National Oceanic and Atmospheric Administration (the USA), the University of Colorado (the USA), the Potsdam Institute for Climate Impact (Germany), the Colorado State University (the USA), the National Institute of Polar Research (Japan), and the Atmospheric and Environmental Research, Inc. (the USA) (Table 1.2.6). Six institutions out of ten are located in the USA as well. Chinese research institutions do not appear within the top 10 rankings, indicating that most research activities are conducted by other institutions.

The main research partnerships are among the USA, England, Germany, and Australia, while China has a relationship only with the USA (Figure 1.2.3). Except for the National Institute of Polar Research (Japan), there is extensive communication among the top 10 institutions, which illustrates the importance of cooperation and communication in scientific research on the Arctic (Figure 1.2.4).

Arctic sea ice reduction has a major impact on the climate of mid-latitude regions, including the USA, Europe, and China. Its impact on the USA has been thoroughly researched, and studies of the impact on Europe have also yielded some accomplishments. China's studies in the Arctic began in the 1990s; despite starting late, the activities have developed rapidly.

China established the Arctic Yellow River Station in 2004 and carried out seven Arctic scientific surveys in 1999, 2003, 2008, 2010, 2012, 2014, and 2016. In response to worldwide attention on the exploitation of the Arctic, China's research in the Arctic has developed rapidly.

On December 10, 2013, ten Arctic research institutes from China and the Nordic countries (Iceland, Denmark, Finland, Norway, and Sweden) signed an agreement in Shanghai and announced the establishment of the China-Nordic Arctic Research Center (CNARC).

On December 20, 2016, construction of an icebreaker was started in the Jiangnan Shipyard. It is the first independently built Chinese polar scientific expedition icebreaker. The ship is expected to be completed in 2019 and then become part of a polar expedition fleet with the *Snow Dragon*. With these developments, China's abilities with regard to polar oceanographic surveys and support have improved.

In December 2016, China launched the first fully owned overseas satellite ground station near the North Pole in Kiruna, Sweden. With this station, China has made great technical progress and is able to access remote sensing data much more quickly. This development is of vital significance for rapid response to natural disasters and will promote international cooperation in this field.

The literature analysis shows that the number of core papers published by Chinese scientists in this research field rank among the top 10 (seventh), but most of them have been published by different research institutions; therefore, China fails to enter the top 10 list of the core paper producing institutions. The top 10 countries or regions and institutions ranked by the number of producing citing core papers on sea ice change are listed in Table 1.2.7 and Table 1.2.8. The USA, England, and Germany and their research institutions appear at the top of the list, while China is missing from the list (Table 1.2.7 and Table 1.2.8). China's two core papers (Table 1.2.5) focuses on the relationships between Arctic sea ice ablation and winter snowfall and between Arctic sea ice ablation and extreme weather events in the Northern Hemisphere. The main research institutions in China are the Chinese Academy of Sciences and Beijing Normal University.

In general, the USA, Germany, and England have published the largest number of core papers. Although the number of core papers published by Chinese scientists ranks within the top 10 and the papers are cited frequently (Table 1.2.5), there is no leading research institution on the list. Korea and Japan also ranked among the top 10 in several lists (Table 1.2.5, Table 1.2.6, and Table 1.2.8) given their close attention to research in this field. China's research focuses mainly on the impact of Arctic sea ice on East Asia and China's climate rather than the global climate. Therefore, even though more papers have been published, the number of publications that cited the papers about sea ice change is relatively small.

Moreover, there is close cooperation among the top-ranked countries or regions, which shows the importance of international cooperation in research in the Arctic. The

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	30	61.22%	1839	74.70%	61.30	6	0
2	England	15	30.61%	674	27.38%	44.93	3	0
3	Germany	9	18.37%	480	19.50%	53.33	1	0
4	Australia	5	10.20%	343	13.93%	68.60	1	0
5	Japan	5	10.20%	188	7.64%	37.60	1	0
6	Korea	3	6.12%	111	4.51%	37.00	1	0
7	China	2	4.08%	314	12.75%	157.00	1	0
8	Norway	2	4.08%	48	1.95%	24.00	0	0
9	Switzerland	2	4.08%	34	1.38%	17.00	0	0
10	Finland	1	2.04%	33	1.34%	33.00	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Exeter	9	18.37%	526	21.36%	58.44	2	0
2	Natl Ctr Atmospher Res	7	14.29%	235	9.55%	33.57	0	0
3	Rutgers State Univ	5	10.20%	665	27.01%	133.00	2	0
4	Univ Melbourne	5	10.20%	343	13.93%	68.60	1	0
5	NOAA	5	10.20%	109	4.43%	21.80	1	0
6	Univ Colorado	5	10.20%	85	3.45%	17.00	1	0
7	Potsdam Inst Climate Impact Res	4	8.16%	291	11.82%	72.75	1	0
8	Colorado State Univ	4	8.16%	187	7.60%	46.75	0	0
9	Natl Inst Polar Res	4	8.16%	119	4.83%	29.75	0	0
10	Atmospher & Environm Res Inc	3	6.12%	301	12.23%	100.33	1	0

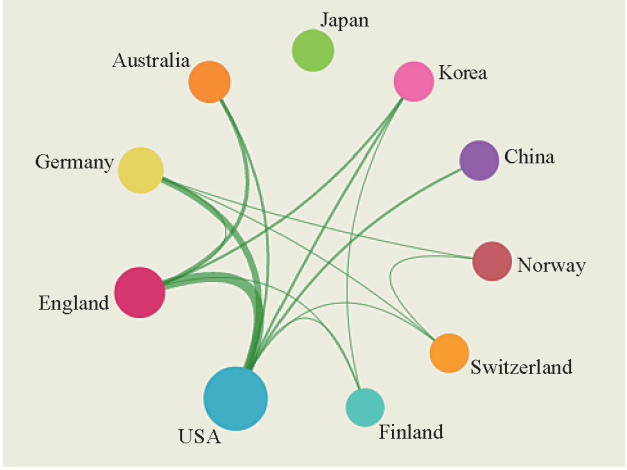

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

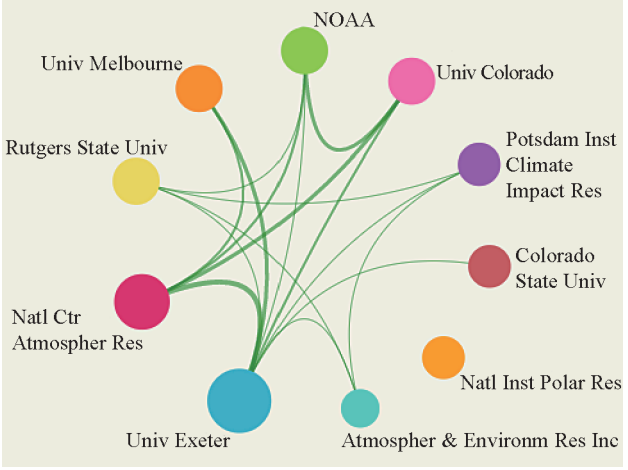

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	28	41.18%	2014.14
2	England	12	17.65%	2014.58
3	Germany	8	11.76%	2013.75
4	Japan	5	7.35%	2014.20
5	Australia	4	5.88%	2013.50
6	Korea	3	4.41%	2014.67
7	Switzerland	2	2.94%	2015.50
8	Canada	1	1.47%	2016.00
9	Finland	1	1.47%	2015.00
10	Sweden	1	1.47%	2015.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Arctic sea ice and mid-latitude climate responses"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Exeter	8	6.84%	2014.50
2	Natl Ctr Atmospher Res	7	5.98%	2014.71
3	NOAA	5	4.27%	2015.20
4	Potsdam Inst Climate Impact Res	5	4.27%	2013.80
5	Rutgers State Univ	5	4.27%	2013.80
6	Univ Colorado	5	4.27%	2014.60
7	Colorado State Univ	4	3.42%	2014.25
8	Univ Melbourne	4	3.42%	2013.50
9	Natl Inst Polar Res	4	3.42%	2014.75
10	Korea Polar Res Inst	3	2.56%	2014.67

Chinese government has recently set the goal of becoming a maritime power. Maintaining and expanding interests in the Arctic is an important part of becoming a maritime power. It requires serious scientific research and surveys in the Arctic as well as abundant funds. China needs to build and consolidate bilateral and multilateral international platforms to promote multi-level communication and cooperation in this field.

1.2.3 Applications of ligand-based composite adsorbent in water treatment

Heavy metals are a group of harmful pollutants in the water environment. Due to their persistence and bio-enrichment and bio-accumulation effects, heavy metals pose threats to the environmental and ecological health. Wastewater discharge containing excess heavy metals into surface water or groundwater leads to pollution in the aquatic and soil environments. Through intake and enrichment by plants and animals, heavy metals could be transferred to the human body via water and food, which increases cancer risks. With growing concerns over public health and the ecological threat induced by heavy metals, the maximum allowable regulated contaminant levels for heavy metals in wastewater, drinking water, and natural waters are becoming increasingly stringent worldwide. Such stringency in standards and water shortages underscore the need for the complete removal of heavy metals from water to ensure drinking water safety, protect the aquatic/ecological environment, and improve water utilization efficiency. Adsorption is one of the most efficient technologies to remove heavy metals from water due to its easy operation and low cost. Moreover, various types of

reactors can be designed for adsorption to fulfill the practical demand of different scales, from point-of-use (POU) to full-scale applications.

The development of efficient adsorbents is the key to improving adsorption technologies. Complexation is an important type of specific interaction between heavy metals and organic/inorganic ligands. Through the immobilization of ligands onto adsorbents, various ligand-based composite adsorbents have been developed for selective removal of heavy metals from water. On the one hand, efforts have been made to design and synthesize ligands with high selectivity and high affinity for heavy metals. On the other hand, the adsorbents of multiple functions, such as optical sensing, photocatalysis, and antibacterial features, have been developed.

This research focus covered 40 core papers, which have been cited 34.83 times on average; 40.00% of these are consistently cited papers, showing a rising trend. Thus, these articles have a high impact on the related studies. The average publication year of these articles is 2014.08, indicating rapid citation and impact (Table 1.1.1). The numbers of articles containing the topics "ligand," "composite," "conjugate," "fibrous," and "complex" are 28, 23, 18, 18, and 14, respectively. These articles are mostly on the removal of Cu(II), Pb(II), Cs(I), As(V), Pd(II), Ce(III), Co(II), and the lanthanides. Eight and seven core papers refer to the removal of Cu(II) and Pb(II), respectively. Five core papers study the removal of Cs(I), which is radioactive and present in nuclear waste. In addition, several core papers are about the multi-functional materials for separation of heavy metals, optical sensing, antibacterial features, and photocatalysis. The ligands of interest in those core papers mainly include N-substituted heterocycles, S-containing ligands, azo-based ligands, Schiff bases, crown ethers, and molybdophosphates. Most ligands are of complicated structures; three typical structures are listed in Figure 1.2.5. Ligands (a) and (b) could possess visible light absorption or fluorescence feature due to their large conjugation structures. Ligand (c) could selectively sequester Cs(I) through size effect. These ligands are immobilized on hosts such as mesoporous silica to synthesize the ligand-based composites as adsorbents, which can be separated from water after adsorption.

Among the 40 core papers, 25 (62.5%) were published in *Chemical Engineering Journal*, indicating the popularity of this topic. Japan contributed the largest number of articles (31 core papers) within the list of major countries or regions (Table 1.2.9), accounting for 77.50% of core papers and 85.49% of total citations. Saudi Arabia, Egypt, Bangladesh, and India contributed 5 to 12 core papers, and the other countries or regions published only one core paper. Among the top 10 institutions (Table 1.2.10), Japan Atomic Energy Agency ranked first with 27 core papers, which

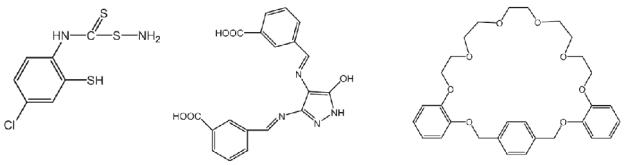

Figure 1.2.5 Three typical structures of ligands studied in the core papers regarding ligand-based composite adsorbents

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan	31	77.50%	1102	85.49%	35.55	3	0
2	Saudi Arabia	12	30.00%	285	22.11%	23.75	2	0
3	Egypt	6	15.00%	248	19.24%	41.33	0	0
4	Bangladesh	6	15.00%	186	14.43%	31.00	0	0
5	India	5	12.50%	96	7.45%	19.20	1	0
6	Korea	1	2.50%	69	5.35%	69.00	0	0
7	Australia	1	2.50%	25	1.94%	25.00	0	0
8	Spain	1	2.50%	10	0.78%	10.00	0	0
9	China	1	2.50%	4	0.31%	4.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan Atomic Energy Agency	27	67.50%	971	75.33%	35.96	3	0
2	King Saud Univ	12	30.00%	285	22.11%	23.75	2	0
3	Natl Inst Mat Sci	8	20.00%	416	32.27%	52.00	1	0
4	Kumamoto Univ	5	12.50%	248	19.24%	49.60	0	0
5	Independent Univ	4	10.00%	127	9.85%	31.75	0	0
6	Shaheed Ziaur Rahman Med Coll	4	10.00%	78	6.05%	19.50	0	0
7	Shoolini Univ	4	10.00%	72	5.59%	18.00	0	0
8	Suez Univ	3	7.50%	93	7.21%	31.00	0	0
9	Waseda Univ	3	7.50%	89	6.90%	29.67	0	0
10	Univ Dhaka	2	5.00%	108	8.38%	54.00	0	0

accounted for 67.5% of core papers and 75.33% of total citations. King Saud University and National Institute for Materials Science contributed 12 and 8 core papers, respectively. The other institutions in Table 1.2.10 contributed 2 to 5 core papers.

A total of 30 out of the 40 core papers were contributed by M. R. Awual from Japan Atomic Energy Agency. M. R. Awual published 26 of these as the first author and corresponding author, two as the corresponding author, and two as co-author. The 30 core papers have been cited 1176 times, amounting to 39.20 times per article on average. Moreover, among the 436 papers citing the above 30 core papers, 49 were from the same author and 387 were published by other researchers, indicating the leading position of author M. R. Awual in the present research focus. Among the 12 core journal articles of other corresponding authors, four were contributed by M. Naushad from King Saud University, three by S. A. El-Safty from the National Institute of Materials Sciences in Japan (of which two were with M. R. Awual as co-author), and three were contributed by D. Pathania from Shoolini University in India. Yuxiang Li from Southwest University of Science and Technology in China and A. Kumar from Shoolini University in India both contributed one core papers. It can be seen from their cooperative history (not limited to the core papers) that M. Naushad and M. R. Awual cooperatively published 11 articles in 2015—2016, S. A. El-Safty and M. R. Awual cooperatively published 10 articles in 2011—2013, while D. Pathania and M. Naushad cooperatively published 17 articles in 2014—2017. The cooperative networks are shown in Figure 1.2.6 and Figure 1.2.7. The role of the other countries or regions and institutions in the figures is mainly limited to participating in the above core papers. The distribution of the main contributing countries or regions (Table 1.2.11) and institutions (Table 1.2.12) with regard to the papers citing the above core papers is similar to those of the core papers (Table 1.2.9 and Table 1.2.10), indicating the citations are primarily generated by the main contributing research groups, and the present research focus is being led by the institutions listed in this paragraph.

China contributed one core papers, the corresponding author being Prof. Yuxiang Li from Southwest University of Science and Technology. The paper focused on the removal of cesium (Cs) using a composite ion exchanger of silica matrix impregnated with ammonium molybdophosphate. According to the results of the literature search, hundreds of articles from China have been published on topics related to this engineering research focus. However, the number of citations is relatively lower than the 40 core papers, suggesting the possibly lower popularity of this engineering research focus. Nevertheless, the 40 core papers were selected through data mining using the keyword "clustering analysis," which is subject to limitations of whether the related papers belong to this research focus. On the other hand, various ion-exchanger-based nanocomposites and chelating resins have been developed by Chinese institutions to remove heavy metals from water. Such composite materials have appropriate hydrodynamic properties for practical applications and

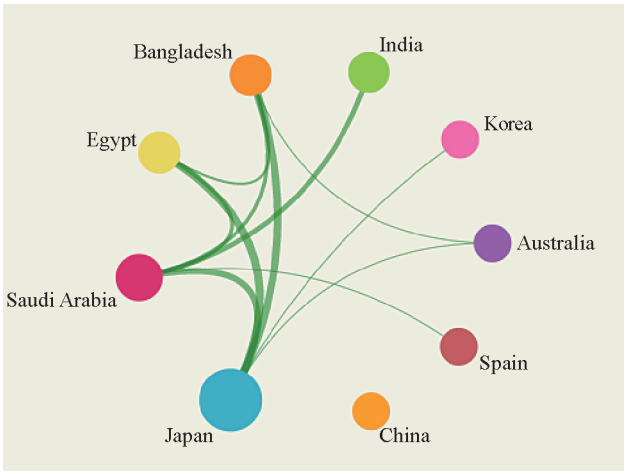

Figure 1.2.6 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

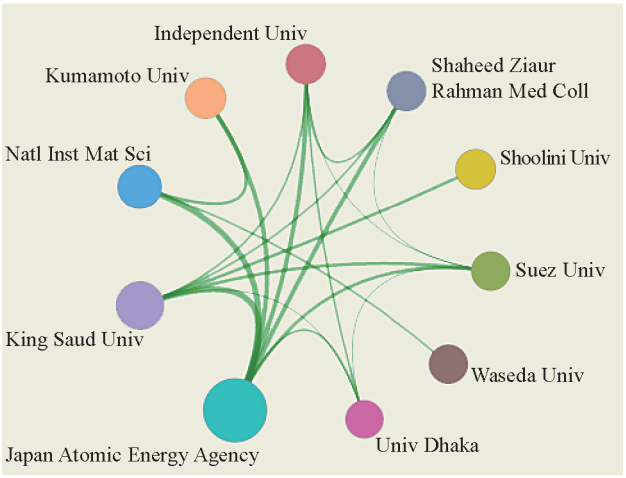

Figure 1.2.7 Collaboration network of the major producing institutions of core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Japan	42	50.00%	2014.19
2	Bangladesh	17	20.24%	2014.65
3	Egypt	10	11.90%	2014.00
4	Saudi Arabia	9	10.71%	2014.89
5	India	3	3.57%	2014.67
6	Australia	2	2.38%	2015.00
7	Korea	1	1.19%	2011.00

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Applications of ligand-based composite adsorbent in water treatment"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Japan Atomic Energy Agency	40	30.77%	2014.35
2	Shaheed Ziaur Rahman Med Coll	12	9.23%	2014.83
3	King Saud Univ	9	6.92%	2014.89
4	Independent Univ	8	6.15%	2014.75
5	Kumamoto Univ	7	5.38%	2012.29
6	Suez Univ	4	3.08%	2014.75
7	Univ Dhaka	4	3.08%	2014.25
8	Natl Inst Mat Sci	3	2.31%	2011.67
9	Shoolini Univ	3	2.31%	2014.67
10	Sohag Univ	3	2.31%	2014.00

some of them have been produced at the full scale. Technologies of in-depth removal and resource reuse of heavy metals based on the above composite materials have also been developed and industrially applied. However, the research articles concerning the above composite materials were not included in the selected core journal articles of the research focus due to the absence of keywords such as "ligand" and "conjugate." Nevertheless, the research articles from China concerning the composite materials for heavy metal removal are influential in a broad sense.

The number of the core papers containing the word "nano" in the topic reached 24, indicating that nanotechnology is an important future direction for the removal of heavy metals in water treatment. However, there is still a long way to go from the laboratory-scale research to industrial application of nanomaterials due to the diversity of materials, target contaminants, and treatment objectives. To achieve the applicability of the nanomaterials in water treatment, the development and structural tuning of the applicable environmental nanocomposites, performance and mechanisms of contaminant purification, development of appropriate reactors, and integration with other technologies are worthy of systematic investigations. It is also essential to consider the interdisciplinary subjects such as nanomaterial sciences, surface analysis, and mathematical modeling.

1.2.4 Regional climate response to global change

The response of regional climate to global change is closely related to human life and social development. These issues are also the focus of scientific research on climate change. Research on regional climate response to global change is conducted using a regional climate model with higher resolution, satellite remote sensing methods, numerical simulations, and theoretical analysis.

Regarding the research focus of "Regional climate response to global change," the top three countries or regions that published the largest number of core papers are China (45), Germany (30), and the USA (29). The largest number of average citations belongs to the Netherlands (50.00), France (41.93), and Sweden (41.00) (Table 1.2.13). With regard to the number of most citing papers, China ranks first (32), followed by Germany (24) and the USA (21). China also ranked first in the proportion of citing core papers (Table 1.2.15).

The top three institutions issuing the largest number of core papers are Chinese Academy of Sciences (27), Lanzhou University (12), and Senckenberg Research Institute (11). The largest number of average citation belong to Natural History Museum (41.20), University of Quebec (41.00), and Senckenberg Research Institute (39.36) (Table 1.2.14). With regard to the main output institutions of citing core papers, the Chinese Academy of Sciences ranked first (18), followed by University of Bonn (9) and Lanzhou University (8) (Table 1.2.16).

In summary, China always ranks first in the number and the main output institutions of citing core papers for this research focus. According to Table 1.2.13, the average citation is 35.70 but the corresponding number for China is 28.33.

Table 1.2.13 Major producing countries or regions of core papers on the engineering research focus "Regional climate response to global change"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	45	46.88%	1275	44.52%	28.33	3	0
2	Germany	30	31.25%	1060	37.01%	35.33	2	0
3	USA	29	30.21%	799	27.90%	27.55	2	0
4	Italy	17	17.71%	624	21.79%	36.71	2	0
5	England	16	16.67%	441	15.40%	27.56	0	0
6	France	14	14.58%	587	20.50%	41.93	2	0
7	Sweden	9	9.38%	369	12.88%	41.00	1	0
8	Canada	9	9.38%	332	11.59%	36.89	0	0
9	Switzerland	9	9.38%	285	9.95%	31.67	0	0
10	The Netherlands	8	8.33%	400	13.97%	50.00	0	0

Table 1.2.14 Major producing institutions of core papers on the engineering research focus "Regional climate response to global change"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Chinese Acad Sci	27	28.13%	732	25.56%	27.11	3	0
2	Lanzhou Univ	12	12.50%	356	12.43%	29.67	1	0
3	Senckenberg Res Inst	11	11.46%	433	15.12%	39.36	1	0
4	Nat Hist Museum	10	10.42%	412	14.39%	41.20	0	0
5	Univ Bonn	10	10.42%	356	12.43%	35.60	1	0
6	Nanjing Univ	8	8.33%	168	5.87%	21.00	0	0
7	Univ Helsinki	7	7.29%	255	8.90%	36.43	0	0
8	E Tennessee State Univ	7	7.29%	214	7.47%	30.57	1	0
9	Open Univ	7	7.29%	137	4.78%	19.57	0	0
10	Univ Quebec	6	6.25%	246	8.59%	41.00	0	0

Table 1.2.15 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Regional climate response to global change"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	32	16.08%	2013.19
2	Germany	24	12.06%	2013.00
3	USA	21	10.55%	2013.81
4	Italy	12	6.03%	2014.08
5	France	10	5.03%	2013.20
6	Switzerland	9	4.52%	2013.67
7	England	9	4.52%	2014.11
8	Canada	7	3.52%	2013.29
9	The Netherlands	7	3.52%	2012.57
10	Sweden	6	3.02%	2014.00

Table 1.2.16 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Regional climate response to global change"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Chinese Acad Sci	18	5.68%	2013.39
2	Univ Bonn	9	2.84%	2011.78
3	Lanzhou Univ	8	2.52%	2013.25
4	Senckenberg Res Inst	7	2.21%	2011.86
5	Nanjing Univ	6	1.89%	2013.83
6	Nat Hist Museum	6	1.89%	2012.67
7	Open Univ	6	1.89%	2013.83
8	Peking Univ	6	1.89%	2012.67
9	Univ Utrecht	6	1.89%	2012.67
10	Univ Rennes	5	1.58%	2012.80

China frequently cooperated with Germany, the USA, Italy, France, Sweden, and Canada (Figure 1.2.8); it appears at the core of the cooperative network map. There is also significant cooperation between the Chinese Academy of Sciences and other universities (Figure 1.2.9). Research in China on this topic is gradually taking the lead globally; therefore, the country should continue investing in this research area and promoting related research to accelerate the development and continue occupying the top ranks.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 engineering development hotspots in the field of environmental engineering are summarized in Table 2.1.1. The in-depth development of traditional hotspots include: "Separation, treatment, and recovery of exhaust gas," "Wastewater treatment technology and preparation of functional materials for water treatment," "Early disaster risk warning systems," "The application of evaporators in seawater resources development," "Producing organic fertilizer by comprehensive utilization of agricultural wastes," "Radar observation and data retrieval technology," and "Satellite and aviation technology." The emerging hotspots include "Preparation of separating membrane material for environmental pollutants and membrane separation technology," "Renewable energy from biomass" and "Biomass energy from seaweed." The number of patents between 2011 and 2016 related to these individual topics are summarized in Table 2.1.2.

(1) Preparation of separating membrane materials for environmental pollutants and membrane separation technology

Please refer to Section 2.2.1.

(2) Separation, treatment, and recovery of exhaust gas

Please refer to Section 2.2.2.

(3) Wastewater treatment technologies and preparation of functional materials for water treatment

Wastewater treatment technologies purify wastewater by separating pollutants from the water or transforming them into harmless and stable substances. The key technical problems of this development topics include two aspects: ① the development of new technologies, methods, and devices for wastewater treatment; ② preparation of new functional materials for water treatment, including functional catalytic materials, high-efficiency adsorption materials, and compound coagulants. For the development of wastewater treatment technologies, current research mainly focuses on the treatment and recycling of refractory organic wastewater, the treatment and resource recovery of heavy metal-contaminated wastewater, zero discharge of industrial wastewater, desalination and recycling of wastewater, and new techniques for advanced denitrification and phosphorus removal. In the field of functional materials for water treatment, current research and development mainly focus on new catalytic

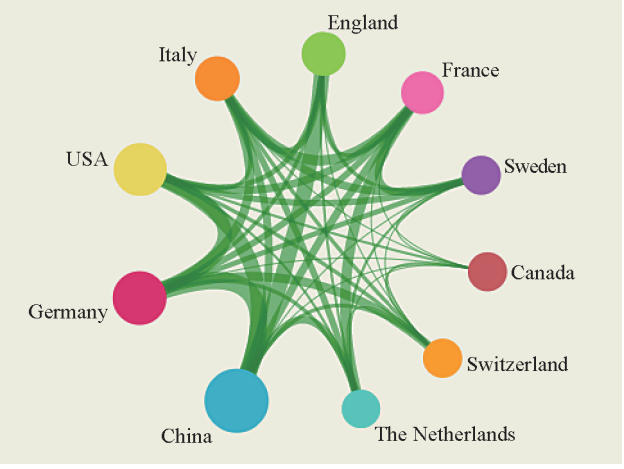

Figure 1.2.8 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Regional climate response to global change"

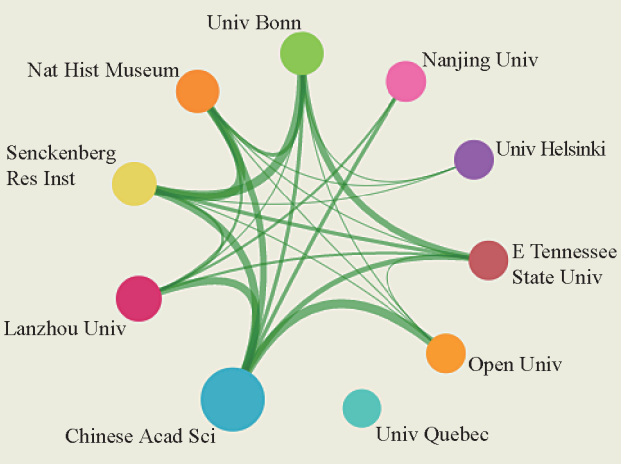

Figure 1.2.9 Collaboration network of the major producing institutions of core papers on the engineering research focus "Regional climate response to global change"

Table 2.1.1 Top 10 engineering development hotspots in environmental engineering

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Preparation of separating membrane material for environmental pollutants and membrane separation technology	194	2 709	13.96	2012.16
2	Separation, treatment, and recovery of exhaust gas	827	11 571	13.99	2012.14
3	Wastewater treatment technology and preparation of functional materials for water treatment	470	7 251	15.43	2012.29
4	Renewable energy from biomass	94	2 156	22.94	2011.97
5	Early disaster risk warning systems	85	958	11.27	2012.24
6	The application of evaporator in seawater resources development	42	397	9.45	2012.15
7	Producing organic fertilizer by comprehensive utilization of agricultural wastes	216	3 340	15.46	2012.48
8	Radar observation and data retrieval technology	145	1 311	9.04	2012.33
9	Satellite and aviation technology	133	1 262	9.49	2012.29
10	Biomass energy from seaweed	64	654	10.22	2012.30

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in environmental engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Preparation of separating membrane material for environmental pollutants and membrane separation technology	77	54	32	18	12	1
2	Separation, treatment, and recovery of exhaust gas	360	215	112	78	44	18
3	Wastewater treatment technology and preparation of functional materials for water treatment	132	146	132	45	13	2
4	Renewable energy from biomass	36	33	18	6	1	0
5	Early disaster risk warning systems	22	33	19	10	1	0
6	The application of evaporator in seawater resources development	21	22	14	7	1	0
7	Producing organic fertilizer by comprehensive utilization of agricultural wastes	40	77	57	40	2	0
8	Radar observation and data retrieval technology	51	36	29	21	4	4
9	Satellite and aviation technology	47	38	25	13	5	5
10	Biomass energy from seaweed	20	19	12	12	1	0

materials, high-efficiency adsorption materials, membrane separation materials, and preparation of complex agents for water treatment. In recent years, research on the preparation of nano environment functional materials based on graphene and carbon nanotubes has had wide application prospects in the advanced purification of municipal sewage, treatment, and recycling of organic industrial wastewater, and recycling of heavy metal-contaminated wastewater.

In the future, the development of environmental functional materials based on nanotechnology will remain a popular research topic in the field of wastewater treatment.

(4) Renewable energy from biomass

The demand for and consumption of energy have dramatically increased since the industrial revolution. With the excessive development and use of fossil fuels, environmental problems are becoming more serious and the development of renewable energy is attracting more attention. The biomass-based renewable energy has become an important means to reduce environmental pollution and maintain the balance between energy supply and demand.

According to the United States National Energy Security Ordinance, biomass refers to renewable materials, including agricultural products and waste, timber and its waste, animal waste, urban waste, and aquatic plants. In China, biomass is usually referred to as organic matter generated from "photosynthesis," including both plants and their processed residues, crops and their residues (straw), and non-plant materials (e.g., livestock manure and sewage), and organic ingredients in wastewater and in waste.

Various straw, agricultural byproducts, recombinant microorganisms, algae, and other biomass are used for the generation of renewable energy. Renewable energy can save non-renewable resources while being conducive to environmental improvement. In the premise of protecting the environment, the transformation of traditional energy production and consumption is the only way to achieve sustained economic growth through the development of low-pollution, renewable energy technologies.

(5) Early disaster risk warning systems

Please refer to Section 2.2.3.

(6) The application of evaporators in seawater resource development

Seawater resource development mainly refers to desalination along with chemical element extraction from seawater. At present, there are two major seawater desalination technologies. The first is the membrane method, represented by reverse osmosis (RO), and the other is the distillation method, represented by multi-stage flash (MSF) and low-temperature multi-effect distillation (LT-MED). The evaporator is the key equipment for distillation technology application.

The distillation method is the earliest seawater desalination technology that was put into industrial application. The technology is characterized by high-purity producing water and suitable for use even in seriously polluted or biologically active seawater. Compared to the membrane method, distillation technology can utilize low-grade heat from power plants or other factories and offers advantages of lower raw water quality requirements and larger production capacity. Therefore, it has been one of the mainstream technologies for seawater desalination. In desalination applications, the development of high thermal conductivity and corrosion resistant materials, the technology of high-efficiency utilization of heat energy, and structural design are the main directions pertaining to progress in research on evaporators. Countries or regions such as the USA, Israel, Japan, Singapore, Korea, Spain, Germany, France, and the UK are leaders in this technical field and the main exporting countries or regions for technologies and products regarding seawater desalination. The Middle East is the largest producer of desalinated water in the world.

Seawater desalination increases the availability of freshwater resources at the expense of energy consumption. To achieve the high-efficiency utilization of seawater resources, the primary problem that must be solved is to reduce the energy consumption and cost of desalination.

(7) Producing organic fertilizer by comprehensive utilization of agricultural wastes

Solid waste is the main material used to produce bio-organic fertilizer via aerobic composting technology. This technology is characterized by thorough decomposition and fewer odors. Composting technology uses microorganisms to decompose organic matter in waste into organic-rich soil that contains nitrogen, phosphorus, potassium, and other nutrients in clinker. Depending on the requirements pertaining to the natural soil ecological structure and nutritional elements, trace elements, beneficial microorganisms, nitrogen, potassium, phosphorus for the growth and other activities of crops are converted into liquid products. The solid agent produced by the compost can be combined with the bacterial fluid produced by the cultured microorganisms to produce a biological fertilizer with widespread effect. The development of bio-organic fertilizer not only provides crops with nutrition, but also increases agricultural production and income, protects soil fertility and the rural environment, and maintains the circular economy. Irrespective of the purpose (developing green agricultural products, under taking sustainable agriculture, ensuring pollution-free production, reducing pesticide and fertilizer use, producing less environmental pollution, lowering production costs, promoting biotechnology, or producing bio-organic fertilizer), these applications have good future prospects.

(8) Radar observation and data retrieval technology

This research focus belongs to the field of meteorology, which is a traditional research field. The meteorological radar can detect the three-dimensional structure and evolution trend of the precipitation system and obtain the three-dimensional structure of precipitation with the highest spatial and temporal resolution. The key technologies of radar observation and data retrieval include

the development of new detection technologies, such as dual polarization radar, phased array weather radar, and multiband vertical observation radar; the inversion method for microphysical and dynamical parameters of cloud precipitation; and the radar data assimilation method. Dual-polarization radar is one of the key technologies adopted by the next generation radar in China. Radar-phased arrays shared by meteorological, aviation, and military industries comprise a more advanced radar system.

(9) Satellite and aviation technology

Satellite observation is an important component of a comprehensive observation network of meteorological science. However, significant scope for improvement remains: internationally, China lags behind with regard to research on key technical problems associated with meteorological satellites, such as quantitative aspects, product quality, and application capability. Therefore, mastering the core processing and data inversion technologies of meteorological satellites are core topics for future research. At the same time, key technologies of meteorological satellites and their applications should be developed in a planned, hierarchical, and phased way, so that they can play an important role in monitoring floods, earthquakes, forest fires, and other disaster events.

(10) Biomass energy from seaweed

Seaweed, with its high photosynthetic efficiency, is an ideal biomass resource. Compared to terrestrial plants, it facilitates higher yields of biomass production. The report from the Global Oil Club shows that 1 ha of seaweed can generate 96 000 L of biodiesel per year, which is much higher than the amount generated by coconuts (5950 L) and soybeans (446 L).

The production of biodiesel from seaweed contains four main steps including large-scale seaweed cultivation, seaweed oil extraction, lipid exchange reaction, and biodiesel post-treatment. The most critical step concerns large-scale seaweed cultivation. Other countries have made headwayin using seaweed to prepare biofuel. Many large international petrochemical companies such as Exxon, DuPont, and Dow Chemical are very optimistic about the biofuel technology and have been actively researching and developing new techniques. To date, they have successfully produced fuel using CO_2 and seaweed. Using seaweed to produce ethanol and biodiesel has become the new favorite topic in the energy sector in many countries. The development of biofuel technology in China keeps pace with global advances and is mainly contributed by domestic institutes with strong research programs, such as the Institute of Oceanology CAS and Ocean University of China. The Chinese Academy of Sciences has been instrumental in creating a key technology for biodiesel production.

Overall, the current technology is still in the early stages of development and is highly affected by the international energy market. The main problems are the high cost of industrial applications and poor industrial design. Large-scale industrial production remains to be achieved.

2.2 Understanding of engineering development focus

2.2.1 Preparation of separating membrane material for pollutants and membrane separation technology

Membrane technology has been applied to water treatment since the 1960s and has become one of the technologies with great potential for developments in water treatment. Membranes are used in various processes such as microfiltration, ultrafiltration, and nanofiltration. Reverse osmosis membranes intercept and hold onto pollutants of various sizes such as colloid particulates, organics, heavy metal ions, and saline ions. Membrane separation is a physical separation process free of chemical agents and secondary pollution; thus, it can compete with other water quality purification processes on the premise of non-interference or less interference with water. Therefore, it is considered a “green” water treatment technology. In addition, water treatment technologies based on membrane separation are characterized by their compact unit structure, and may or may not include simple pretreatment systems to directly carry out membrane separation using limited resources and land. With the constant and rapid improvement in membrane materials, continuous optimization of membrane modules, and gradual perfection of technology, the membrane separation technology decreases specific energy consumption and lowers investment and operation costs. Membrane separation technology has already become a mainstream technology with the greatest promise for water and wastewater treatment.

The type of membrane material lies at the core of this technology. Membrane materials are made from organic polymer and ceramics, carbon nanometer materials such as grapheme, and metal oxide nanometer materials such

as titanium dioxide. The utilization of the modified membranes is the main focus of future development. New materials are developed to improve membrane flux, reduce membrane pollution, prolong the service life of membrane materials, and enhance their efficiency to intercept and remove pollutants.

Of the 194 patents relevant to membrane separation granted in the last 5 years, patents on membrane materials account for 60% of total patents. Five of the most cited patents originate from the USA, indicating that this country is the world leader in investment and research and development in membrane technology. Regarding the core patents listed in Table 2.2.1, the USA ranks first with regard to the number of patents related to membrane separation, with 41.24% of the total patents, and total and average citation frequencies of 1,167 and 14.59, respectively.

China produced 51 patents, ranking second in the field, with an average citation frequency of 12.88, indicating that

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Preparation of separating membrane material for environmental pollutant and membrane separation technology"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	80	41.24%	1167	43.08%	14.59
2	China	51	26.29%	657	24.25%	12.88
3	Japan	30	15.46%	465	17.17%	15.50
4	Korea	10	5.15%	124	4.58%	12.40
5	UK	9	4.64%	126	4.65%	14.00
6	German	8	4.12%	76	2.81%	9.50
7	The Netherlands	6	3.09%	91	3.36%	15.17
8	Singapore	4	2.06%	73	2.69%	18.25
9	Austria	2	1.03%	36	1.33%	18.00
10	Australia	2	1.03%	14	0.52%	7.00

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Preparation of separating membrane material for environmental pollutant and membrane separation technology"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	TORA	16	8.25%	206	7.60%	12.88
2	DOWC	12	6.19%	169	6.24%	14.08
3	FUJF	11	5.67%	189	6.98%	17.18
4	GENE	7	3.61%	57	2.10%	8.14
5	Oasys Water	5	2.58%	61	2.25%	12.20
6	SIEI	5	2.58%	98	3.62%	19.60
7	SMSU	4	2.06%	86	3.17%	21.50
8	Celgard LLC	3	1.55%	65	2.40%	21.67
9	EVON	3	1.55%	41	1.51%	13.67
10	IBMC	3	1.55%	65	2.40%	21.67

Note: TORA stands for Toray Industries Inc.; DOWC stands for Dow Global Technologies Inc.; FUJF stands for Fuji Film Co., Ltd.; GENE stands for General Electric Co.; SIEI stands for Siemens Water Technologies Corp.; SMSU stands for Samsung Electronics Co., Ltd.; EVON stands for Evonik Fibers Gmbh; IBMC stands for Machines Corp.

it holds an influential global position in patent technology. Table 2.2.1 shows that Japan, Korea, the UK, Germany, Singapore, Austria, and Australia follow the USA and China.

Table 2.2.2 shows the major organizations that produce the core patents in the world for this technology. Five of them are located in the USA, two are in Japan and Germany, and one is in Korea. Toray Industries, Inc., Dow Chemicals, FUJI, and General are leading organizations for research, development, and production of membrane materials in the world; in particular, they benefit from a larger market share in the high-end reverse osmosis membrane field. China has no enterprises in the top ten list related to this focus, indicating that research and development in this field are yet to be established and improved.

In the field of membrane materials, ultra-filtration and micro-filtration are relatively simple technologies to develop, and thus the market is not monopolized. Membrane materials, membrane production mechanisms, and membrane modules, together with system integration and application technology, are undergoing many developments with each passing day, and the technological monopoly in this area is missing. China has more than 200 ultra-filtration and micro-filtration membrane manufacturers, with new manufacturers emerging in large numbers every day.

In contrast, a higher level of technology is needed for reverse osmosis membranes; thus, the market is still monopolized by large membrane producing corporations in the USA and Japan. Homemade ultra-filtration membranes are undergoing rapid growth. They have been successfully applied to many large-scale projects and have started to dominate the market in terms of quantity. Beijing Origin water Technology Co., Ltd and Tianjin Motimo Membrane Technology Co., Ltd. have been listed on the Growth Enterprise Market as leading membrane manufacturers in China. It is imperative for China to address technological problems in reverse osmosis membranes, to be able to market them as high-end membrane materials and play an influential role globally.

Figure 2.2.1 shows that there is a cooperative relationship among the leading countries or regions. The UK has close relations with the Netherlands and China; the USA works with Singapore and Australia for research and development on patent technology. There is no cooperation among the primary enterprises on patent technology (Figure 2.2.2).

2.2.2 Separation, treatment, and recovery of exhaust gas

In recent years, the problem of air pollution in China has attracted worldwide attention due to the frequent occurrences of fog and haze. Industrial emissions and automobile exhaust are now recognized as major sources of air pollution. Exhaust gas separation, treatment, and recovery have been studied for a long time in Europe, the USA, and other developed countries. China is gradually paying attention to relevant work in this area. At present, the development in this field is divided into two parts: industrial waste gas separation treatment and engine exhaust treatment. Industrial waste gas treatment focuses on

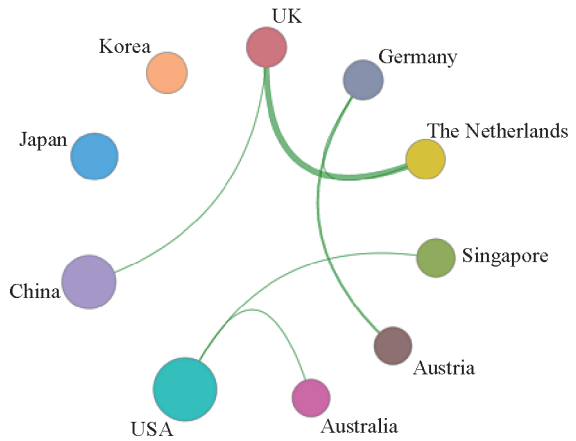

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Preparation of separating membrane material for environmental pollutant and membrane separation technology"

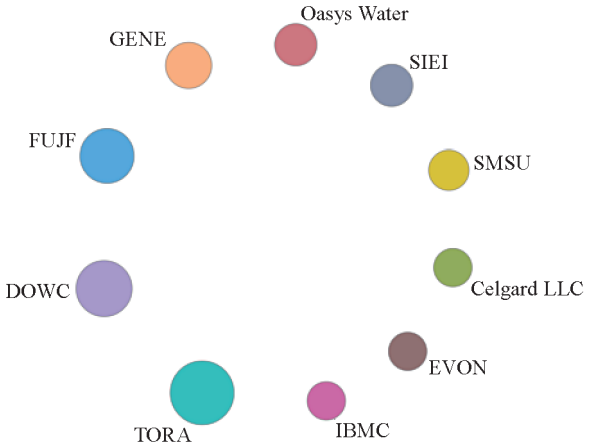

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Preparation of separating membrane material for environmental pollutant and membrane separation technology"

the removal of industrial nitrogen oxides (NO_x), volatile organic compounds (VOCs), and heavy metals (Hg and Pb)in industrial furnaces (steel, cement, glass, and waste incineration furnaces); coupled selective non-catalytic reduction (SNCR) and low-temperature selective catalytic reduction (SCR) technology; multi-pollutant control parameters and pollution purification efficiency; zero emissions power generation; combined removal of flue gas pollutants (SO_2/NO_x/composite particles/VOCs) via wet electrostatic purification; efficient removal of multiple pollutants ($PM_{2.5}$ and SO_3, mercury, and other acidic gases); SCR base spray; co-removal of mercury, the optimization design of flue gas chimney, research and development regarding high-temperature gas filtration materials; high-efficiency purification technology of flue gas denitrification and mercury removal; and key technologies of new SCR denitrification. With regard to engine exhaust gas treatment technology, developed countries focus on the application of the DOC (diesel oxidation catalyst) + DPF (diesel particulate trap) + SCR combination purification technology on diesel engines, as well as the quantity and quality of pollutant emissions. For diesel vehicles, the engine exhaust gas treatment technology also focuses on the development of a wide temperature window, high heat resistant SCR catalyst, high thermal stability and low thermal expansion DPF material; on optimization of device and engine matching and integrated post-processing. Break through technical problems concern high efficiency, combination, purification, and matching control. For gasoline vehicles, key research focuses on automobile exhaust purification, creation of three-way catalyst using low noble metal content and providing long service life; developing new close-coupled catalytic converters to solve the issue of emissions discharged during the cold start phase; studies on gasoline vehicle purification technology under lean burn conditions, and combining the fourth generation automobile fault diagnosis system with remote diagnosis and vehicle networking.

Core patents on exhaust gas separation, processing, and recycling are mostly from the USA (425 patents; Table 2.2.3). The top 10 list of core patent institutions includes eight American institutions. Japan and Germany rank second and third with 159 and 85 patents, respectively. China ranks fourth with 58 patents followed by the UK, Korea, Switzerland, France, Canada, and Sweden. The top 10 countries or regions are mainly located in Europe and America given their pace of local industrial development, especially that pertaining to the automobile industry.

The total and average citation frequencies of the patents from the USA are 6740 and 15.86 respectively, much higher than those of the other countries or regions (Table 2.2.3). The gaps between China (58 patents) and the USA and Japan are still quite large, showing the lack of originality and influence of China's patented technology in this area.

The top 10 institutions (Table 2.2.4) with the highest number of patents include some large car and petrochemical, and clean diesel technology companies. Chinese institutions do not appear in the top 10 list, indicating the

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Separation, treatment and recovery of exhaust gas"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	425	51.39%	6740	58.25%	15.86
2	Japan	159	19.23%	1908	16.49%	12.00
3	Germany	85	10.28%	1016	8.78%	11.95
4	China	58	7.01%	793	6.85%	13.67
5	UK	36	4.35%	329	2.84%	9.14
6	Korea	33	3.99%	502	4.34%	15.21
7	Switzerland	14	1.69%	166	1.43%	11.86
8	France	11	1.33%	119	1.03%	10.82
9	Canada	9	1.09%	104	0.90%	11.56
10	Sweden	9	1.09%	71	0.61%	7.89

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Separation, treatment and recovery of exhaust gas"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	FORD	70	8.46%	967	8.36%	13.81
2	CLEA	39	4.72%	410	3.54%	10.51
3	GENE	31	3.75%	465	4.02%	15.00
4	GENK	30	3.63%	296	2.56%	9.87
5	BADI	29	3.51%	435	3.76%	15.00
6	JOHO	29	3.51%	274	2.37%	9.45
7	TOYT	23	2.78%	373	3.22%	16.22
8	CUND	20	2.42%	387	3.34%	19.35
9	KOMS	20	2.42%	201	1.74%	10.05
10	CATE	15	1.81%	312	2.70%	20.80

Note: FORD stands for Ford Global Tech LLC; CLEA stands for Clean Diesel Technologies Inc.; GENE stands for General Electric Co.; GENK stands for GM Global Technology Operations Inc.; BADI stands for BASF Corp.; JOHO stands for Johnson Matthey PLC; TOYT stands for Toyota Motor Corp.; CUND stands for Cummins IP Inc.; KOMS stands for Komatsu Seisakusho KK; CATE stands for Caterpillar Inc.

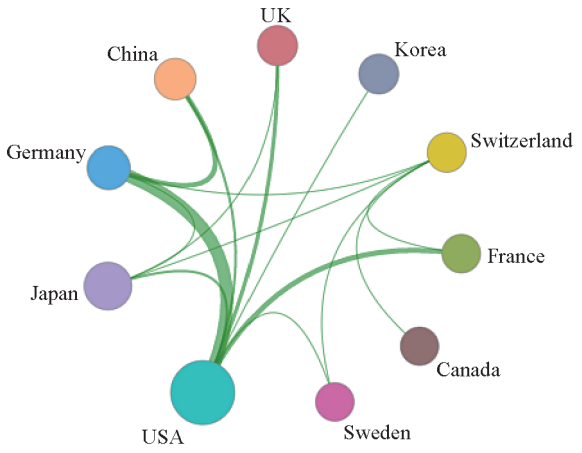

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Separation, treatment and recovery of exhaust gas"

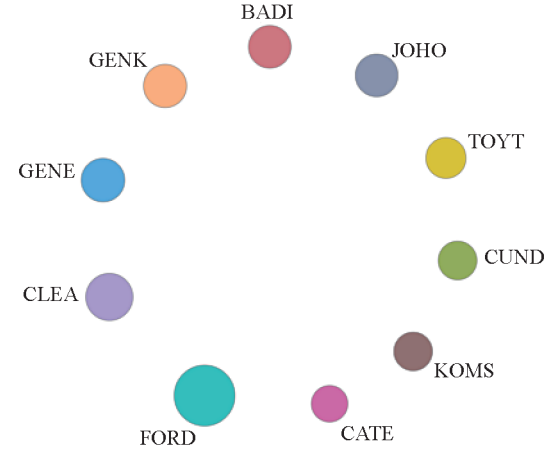

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Separation, treatment and recovery of exhaust gas"

scattered distribution of institutions in China.

Out of 15 patents related to the automobile exhaust treatment, 7 belong to universities (including 2 from Shanghai Jiao Tong University), 3 to individuals, and 5 to enterprises. The dominance of the companies in the list of the top 10 core institutions suggests the need for further industrialization in this area in China.

Figure 2.2.3 shows the close relationships between the USA and Germany, which also have cooperative tie-ups with China. The USA, the UK, France, and Korea are leaders in patent technology research and development in this field. Figure 2.2.4 shows that there is no research and development cooperation between individual enterprises.

2.2.3 Early disaster risk warning systems

This research focus is related to meteorology. Early warning mainly emphasizes repairs and restoration after disasters and does not concern disaster prevention and preparedness. Since the losses and damages caused by disasters in the world are becoming increasingly serious, early warning of disaster risks has become an important aspect of disaster risk mitigation. At this stage, early

warning systems and monitoring networks for floods, droughts, and other disasters are established using multi-source observation data to monitor disasters automatically. However, the current network is far from meeting the requirements. Therefore, conducting research on satellite remote sensing, radar data processing, and early warning systems with excellent visualization and high security is key to reducing the damage from disasters.

Among the main output countries of cited papers, China ranks first (72), followed by the USA (9) and Germany (2). With regard to total citations, China still ranks first (790), followed by the USA (160) and Germany (3) (Table 2.2.5).

The output institutions for the core patents in the top three spots are SGCC (6), ROCW (3), and Chinese Academy of Sciences Chengdu Institute (2). The top three institutions with the largest average citations are UNBA (17.50), Chinese Academy of Sciences Chengdu Institute (14.00), and SGCC (13.67) (Table 2.2.6).

China ranked first for the number of core patents and it is gradually taking the global lead. Therefore, the country should increase investment in this research field and promote related research fields to accelerate development efforts in this area.

There is no cooperation among the leading countries (Figure 2.2.5) or the institutions, except for that between the China National Grid and Beijing University of Aeronautics and Astronautics (Figure 2.2.6).

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Early disaster risk warning systems"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	72	84.71%	790	82.46%	10.97
2	USA	9	10.59%	160	16.70%	17.78
3	Germany	2	2.35%	3	0.31%	1.50
4	France	1	1.18%	2	0.21%	2.00
5	Korea	1	1.18%	3	0.31%	3.00

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Early disaster risk warning systems"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	SGCC	6	7.06%	82	8.56%	13.67
2	ROCW	3	3.53%	29	3.03%	9.67
3	Chinese Acad Sci Chengdu Inst	2	2.35%	28	2.92%	14.00
4	CRCC	2	2.35%	12	1.25%	6.00
5	First Inst Surveying & Mapping Province	2	2.35%	26	2.71%	13.00
6	IWHR	2	2.35%	19	1.98%	9.50
7	Shanghai CEE TEK Co., Ltd.	2	2.35%	20	2.09%	10.00
8	UCHA	2	2.35%	20	2.09%	10.00
9	UNBA	2	2.35%	35	3.65%	17.50
10	Univ Qingdao Technological	2	2.35%	20	2.09%	10.00

Note: SGCC stands for State Grid Corporation of China; ROCW stands for Rockwell Collins Inc.; CRCC stands for China Railway Construction Corporation Limited; IWHR stands for China Institute of Water Resources and Hydropower Research; UCHA stands for Chang'an University, China; UNBA stands for Beijing University of Aeronautics and Astronautics.

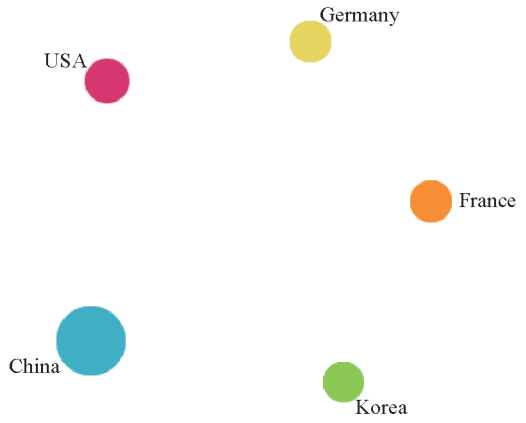

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Early disaster risk warning systems"

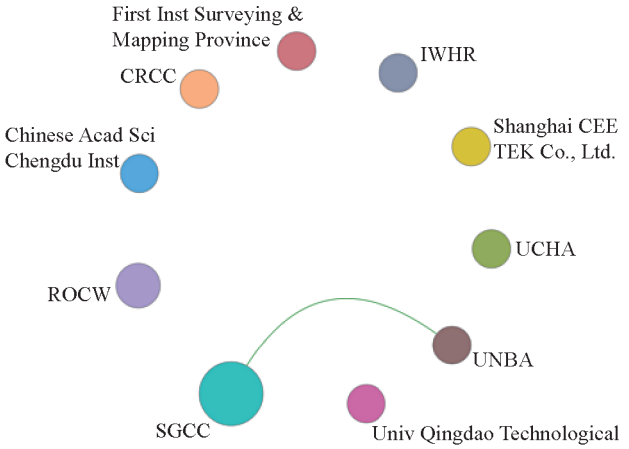

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Early disaster risk warning systems"

Project Participants

Members of the Field Group

Leader of the Field Group:

HAO Jiming

Experts of the Field Group:

DING Yihui, WEI Fusheng, PAN Delu, HOU Baorong, ZHANG Quanxing, QU Jiuhui, MENG Wei, XU Xiangde, ZHANG Si, ZHANG Yuanhang, YANG Zhifeng

Members of the Secretary Group:

HUANG Xia, LU Xi, SONG Yonghui, PAN Bingcai, XU Ying, BAI Yan, YAN Peng, LI Jie, HU Min, PEI Yuansheng, XU Renji, MA Xiumin, HU Chengzhi

Office Staff:

ZHANG Jian, LIANG Zhenzhen, XIONG Qiang, ZHU Jianjun, ZHANG Xiangyi

Report Writers

HUANG Xia, LU Xi, XU Ying, XU Renji, HU Chengzhi, LI Teng, SHAN Chao, GUO Qingfeng, WEI Jian, CHEN Xueqing, LI Jie, BAI Yan, ZHENG Honglin, YAN Peng, PEI Yuansheng, HU Min, SONG Yonghui, PAN Bingcai, MA Xiumin

VII. Agriculture

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 hotspots in agricultural engineering research are classified into two categories:

• *Hotspots involving in-depth traditional research.* They include "Conservation farming systems" in crop science, "Healthy growth of livestock and poultry" in agricultural bioengineering and veterinary medicine, "Vegetation diversity and classification" and "Soil fungal communities" in agricultural resource science, "Grazing and lactating dairy cows" in livestock science, and "Behavior among wild animals" in applied ecology.

• *Emerging research hotspots.* They include "Soil organic carbon mapping," "Reduction of methane emission," and "Soil moisture data assimilation" in agricultural resource science and "*In vitro* antibacterial activity" in animal medicine.

There are no revolutionary research hotspots in this category. The number of core papers supporting each hotspot is approximately 50, and the average citation frequency is approximately 30. Among hotspot papers, the proportion of consistently cited papers is less than 30%, with an average of approximately 16%. The number of papers cited in patents is relatively small, with an average of less than two (Table 1.1.1). In addition, the data indicate that the core papers in the top 10 research hotspots have been generally published around 2013. Among them, the overall number of core papers on "Healthy growth of livestock and poultry" and "Reduction of methane emissions" reveals an upward trend, whereas no clear pattern is found for the rest hotspots (Table 1.1.2).

Brief descriptions of all the top 10 hot engineering research topics are provided below.

1.1.1 Conservation farming systems

Conservation farming systems is a hotspot in crop science, which involves in-depth traditional research. It ensures crop yield and quality improvement based on considerations from the levels of soil, crop, and environmental stress. Techniques included in this hotspot are as follows:

(a) Conservation tillage technique: After harvest, the crop residues are crushed and left as ground cover. In the next season, cultivation is carried out without tillage to reduce mineralization, erosion, soil and water loss, and the chemical inputs, and to increase crop yields and agricultural income.

(b) Crop genetic improvement technique: The traditional breeding, cell engineering, chromosome engineering, transgenic techniques, and other methods are utilized

Table 1.1.1 Top 10 engineering research hotspots in agriculture

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Conservation farming systems	44	1396	31.73	2013.11	29.5%	0
2	Soil organic carbon mapping	49	1328	27.10	2013.47	2.0%	0
3	Healthy growth of livestock and poultry	90	2251	25.01	2013.89	20.0%	1
4	*In vitro* antibacterial activity	46	1329	28.89	2014.24	21.7%	4
5	Vegetation diversity and classification	48	1614	33.63	2013.17	12.5%	2
6	Reduction of methane emission	48	872	18.17	2013.98	18.8%	1
7	Soil fungal communities	50	1637	32.74	2013.30	10.0%	2
8	Grazing and lactating dairy cows	49	1083	22.10	2013.02	14.3%	4
9	Soil moisture data assimilation	47	1385	29.47	2013.02	6.4%	2
10	Behavior among wild animals	46	1310	28.48	2013.43	23.9%	1

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in agriculture

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Conservation farming systems	6	11	9	8	10	0
2	Soil organic carbon mapping	7	9	4	16	9	4
3	Healthy growth of livestock and poultry	11	9	7	27	24	12
4	*In vitro* antibacterial activity	4	4	4	8	17	9
5	Vegetation diversity and classification	9	12	6	11	3	7
6	Reduction of methane emission	2	6	3	18	18	1
7	Soil fungal communities	7	12	9	7	11	4
8	Grazing and lactating dairy cows	6	11	15	11	5	1
9	Soil moisture data assimilation	7	10	11	14	4	1
10	Behavior among wild animals	10	6	8	7	6	9

for the alteration, transfer, and recombination of crop genetic materials, to promote crop yield, and to improve quality.

(c) Environmental stress prevention technique: Biological environmental stress, such as pests and diseases, is an important factor restricting crop production. Most strategies for crop protection involve increasing the ability of crops to resist pests and pathogens or using chemicals. Non-biological environmental stress, such as drought, low temperature, high temperature, and wind damage, will lead to the decline in crop yield and quality.

1.1.2 Soil organic carbon mapping

This is an emerging research hotspot in agricultural science. Soil organic matter (SOM) refers to the collection of humus, animal and plant residues, and microbiome formed by microbial action The carbon in SOM is referred to as soil organic carbon (SOC). SOC content is the balance between the input of organic matter (e.g., biological debris) into the soil and the loss of organic matter mainly caused by microbial decomposition. SOC content and distribution are important factors in the soil classification system. In the soil classification system of the USA, there are many diagnostic horizons, all of which involve organic carbon content and distribution. The isohumic property is utilized in the Chinese system of soil classification; i.e., the ratio of the SOC content at 0–20 and 0–100 cm is used as a classification index. SOC is an important component of the terrestrial ecosystem carbon pool and has a profound impact on the physical, chemical, and biological properties of the soil.

1.1.3 Healthy growth of livestock and poultry

This is a hotspot in agricultural bioengineering and veterinary medicine involving in-depth traditional research. Healthy growth refers to creating a suitable environment for livestock and poultry, providing adequate feed, protecting the health of livestock and poultry, reducing disease incidences, ensuring the product quality and safety, decreasing pollution, achieving ecological balance, and reflecting a high degree of unity of the economical, ecological, and social benefits of modern animal husbandry. Healthy growth mainly focuses on the health of livestock and poultry, product safety, and environmental protection. It can ensure product safety by effective regulation of the production process.

1.1.4 *In vitro* antibacterial activity

This is an emerging research hotspot in animal medicine. Antibiotic activity refers to the ability of antibiotics to inhibit or kill pathogenic microorganisms, and it can be determined using *in vitro* antibacterial tests and *in vivo* experimental treatments. *In vitro* antibacterial experiments are important references for clinical medication. The minimum inhibitory concentration (MIC) is the minimum concentration that can inhibit the growth of bacteria in the culture medium. When the proportion of bacteria killed are used as assessment criteria, the concentration that can decrease the total number of viable bacteria by 99.0% or more than 99.5% is known as the minimum bactericidal concentration (MBC). In a batch of experiments, the MICs that can inhibit 50.0% or 90.0% of the test bacteria are known as MIC50 and MIC90, respectively. The bacteriostatic and bac-

tericidal activities of antibiotics are relative, and some antibiotics show bacteriostatic activity at low concentrations, but bactericidal activity at high concentrations.

1.1.5 Vegetation diversity and classification

Vegetation diversity and classification, which is a hotspot in agricultural resource science, involves in-depth traditional research. Vegetation diversity includes species, habitat, nutritional, life cycle, and genetic diversity. Among them, species diversity is determined by the genetic diversity in different ecological environments. The complexity of gene expression in vegetation growth and development on the spatial and temporal scale determines the diversities of vegetable external morphology, physiological metabolism, and the DNA molecular level.

1.1.6 Reduction of methane emission

This is an emerging research hotspot in agricultural resource science. Methane is the hydrocarbon with the simplest structure. In recent years, a rapid growth in methane emissions has occurred, and its reduction is the key for avoiding the exacerbation of global warming. Several studies have indicated that anthropogenic methane emissions account for 60% of global methane emissions, and approximately one-third of anthropogenic methane emissions come from agricultural production. Rice cultivation and animal husbandry are its largest sources.

1.1.7 Soil fungal communities

This is a hotspot in agricultural resource science, involving in-depth traditional research. Soil fungi refer to the unicellular or multicellular branching filamentous eukaryotic organisms live in the soil. They use the soil as their habitat for completing all or a part of their life history. Fungal hyphae have the ability to decompose organic matter, have a lower soil pH requirement than actinomycetes and bacteria have, and they are the main decomposers of organic matter in acidic soils, particularly in forests.

1.1.8 Grazing and lactating dairy cows

This is a hotspot in animal husbandry science and involves in-depth traditional research. Milk production in cows used in the dairy industry can be improved by breeding programs. Cows have poor heat resistance and high requirements for grazing and feed management. Breeding high-quality beef cattle and high quality lactating dairy cows with high and stable yield is the only method of enhancing the development of this industry. The performance determination system of cows, i.e., dairy herd improvement (DHI), is the main method of determining the improvement of dairy herds.

1.1.9 Soil moisture data assimilation

This is an emerging research hotspot in agricultural resource science. Soil moisture is an important physical factor in land-air interaction affecting the surface evapotranspiration, runoff, surface albedo, surface emissivity, and surface heat and latent heat fluxes. Land surface data assimilation is based on land surface model and hydrological model. Different data assimilation algorithms are used for assimilating surface observation data as well as satellite and radar data, and optimizing the estimations of soil moisture, temperature, and surface energy flux on the surface and root zone.

1.1.10 Behavior among wild animals

Animal behavior is a hotspot in applied ecology that requires in-depth traditional research. The behaviors of wild animals are complex and diverse. According to the different behaviors displayed, they can be divided into foraging behavior, storage behavior, aggressive behavior (within the same species), defensive behavior (among species), territorial behavior, reproductive behavior, rhythmic behavior (migratory behavior), social behavior, directed behavior, and communication behaviors. All kinds of behavior are adaptive responses of wild animals to the complex environment. Based on their learning process, behaviors of wild animals can be divided into innate behavior and learned behavior.

1.2 Understanding of engineering research focus

1.2.1 Conservation farming systems

Conservation farming systems ensure crop yield and quality improvement based on comprehensive considerations from the levels of soil, crop, and environmental stress. It includes conservation tillage techniques, crop genetic improvement techniques, and environmental stress prevention techniques. A number of international funds have conducted long-term surveys on soil fertility status and studies on conservation farming systems in African countries, such as Zimbabwe. These studies have

proposed new systematic methods for crop rotation, straw mulching, weed control, and pest management to ensure high and stable crop yields.

The major countries publishing the core papers are Zimbabwe, the Netherlands, France, Kenya, and Brazil (Table 1.2.1). The consistently cited papers are from Zimbabwe, Kenya, and the USA. Based on the distribution of research papers among institutions (Table 1.2.2), the papers are mainly published by the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, Wageningen University in the Netherlands, and the French Agricultural Research Centre for International Development (CIRAD). The cooperation network diagram indicates that Zimbabwe, the Netherlands, France, Kenya, and Brazil have a close cross-citation relationship (Figure 1.2.1). For institutions, a close cooperation exists among CIMMYT in Mexico, Wageningen University in the Netherlands, and CIRAD (Figure 1.2.2). A wide range of international cooperations has formed among countries, regions, and institutions. In this focus, the countries or regions with a large proportion of cited papers are Zimbabwe, the Netherlands, and France (Table 1.2.3), and the major research institutions are CIMMYT, the CIRAD, and Wageningen University (Table 1.2.4). The paper titled "Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management in African reproductive systems to support innovation and development", which was published in the journal *Agricultural Systems* on 2011, has been cited 78 times. This paper and two other highly cited papers published in *Field Crops* are examples of international collaborative research

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "Conservation farming systems"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Zimbabwe	30	68.18%	919	73.93%	30.63	6	0
2	The Netherlands	16	36.36%	562	45.21%	35.13	2	0
3	France	11	25.00%	322	25.91%	29.27	1	0
4	Kenya	10	22.73%	393	31.62%	39.30	4	0
5	Brazil	7	15.91%	197	15.85%	28.14	1	0
6	Ethiopia	7	15.91%	161	12.95%	23.00	2	0
7	Italy	5	11.36%	207	16.65%	41.40	2	0
8	USA	5	11.36%	146	11.75%	29.20	4	0
9	Mexico	5	11.36%	99	7.96%	19.80	1	0
10	Malawi	4	9.09%	196	15.77%	49.00	1	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "Conservation farming systems"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	CIMMYT	25	56.82%	609	48.99%	24.36	7	0
2	Wageningen Univ	16	36.36%	562	45.21%	35.13	2	0
3	CIRAD	15	34.09%	478	38.46%	31.87	2	0
4	Int Ctr Trop Agr	10	22.73%	319	25.66%	31.90	2	0
5	Int Livestock Res Inst	8	18.18%	318	25.58%	39.75	2	0
6	Int Crops Res Inst Semi Arid Trop	7	15.91%	294	23.65%	42.00	0	0
7	Univ Zimbabwe	6	13.64%	212	17.06%	35.33	2	0
8	Embrapa Cerrados	5	11.36%	81	6.52%	16.20	1	0
9	Int Inst Trop Agr	3	6.82%	105	8.45%	35.00	0	0
10	Food & Agr Org United Nations	3	6.82%	73	5.87%	24.33	1	0

Note: CIMMYT stands for International Maize and Wheat Improvement Center in Mexico; CIRAD stands for French Agricultural Research Center for International Development.

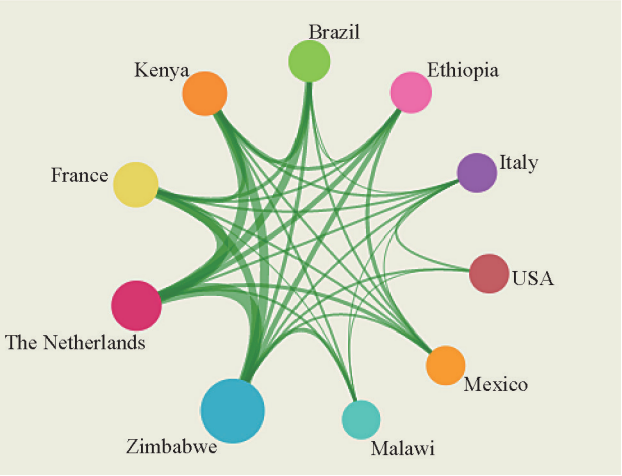

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Conservation farming system" [1]

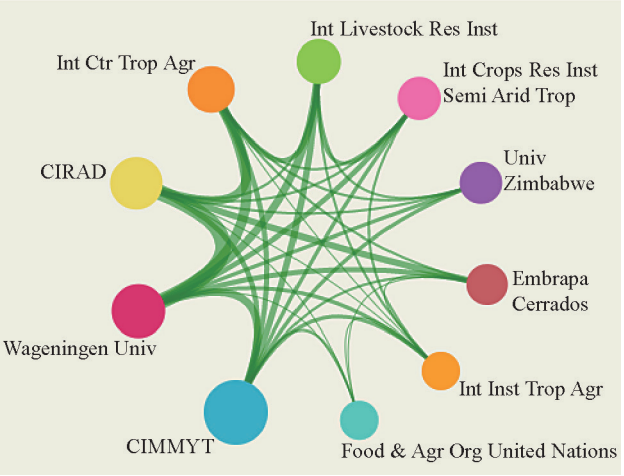

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Conservation farming system"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Conservation farming systems"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Zimbabwe	23	19.66%	2013.13
2	The Netherlands	13	11.11%	2013.38
3	France	10	8.55%	2013.70
4	Kenya	8	6.84%	2013.25
5	Ethiopia	7	5.98%	2014.29
6	Brazil	6	5.13%	2013.83
7	Mexico	5	4.27%	2014.40
8	USA	4	3.42%	2013.50
9	Italy	3	2.56%	2013.00
10	Norway	3	2.56%	2013.33

at the University of Wageningen in the Netherlands. The contributions from China to this discipline are insufficient, with only a few core or consistently cited papers. The possible reasons may be that this discipline is regionally focused, the relevant researchers have mainly focused on the existing problems of agricultural development in China, and the number of relevant scientific studies in internationally relevant institutions is still low.

1.2.2 Soil organic carbon mapping

SOM refers to the collection of humus, plant and animal residues, and microbiome, and the carbon in SOM is referred to as SOC. SOC has a profound effect on the physical, chemical, and biological properties of the soil, and its content and distribution are important in the soil classification system. To date, seven global workshops on soil mapping have been held.

The USA, Australia, France, India, and Germany are the major countries publishing the core papers (Table 1.2.5), and the countries publishing consistently cited papers are the USA and Australia. The University of Sydney, the French National Institution for Agricultural Research (INRA), and the Louisiana State University are the main contributors of core papers (Table 1.2.6). The cooperation

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Conservation farming systems"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	CIMMYT	20	14.60%	2013.65
2	CIRAD	13	9.49%	2013.54
3	Wageningen Univ	13	9.49%	2013.38
4	Int Ctr Trop Agr	8	5.84%	2013.50
5	Int Livestock Res Inst	6	4.38%	2013.67
6	Embrapa Cerrados	5	3.65%	2014.20
7	Univ Zimbabwe	4	2.92%	2012.75
8	Int Crops Res Inst Semi Arid Trop	4	2.92%	2012.75
9	Univ Life Sci	3	2.19%	2013.33
10	Int Inst Trop Agr	3	2.19%	2013.67

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Soil organic carbon mapping"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	19	38.78%	466	39.86%	24.53	3	0
2	Australia	15	30.61%	314	26.86%	20.93	2	0
3	France	8	16.33%	239	20.44%	29.88	0	0
4	India	6	12.24%	114	9.75%	19.00	1	0
5	Germany	5	10.20%	209	17.88%	41.80	1	0
6	Italy	4	8.16%	89	7.61%	22.25	0	0
7	England	4	8.16%	72	6.16%	18.00	0	0
8	Belgium	4	8.16%	69	5.90%	17.25	1	0
9	China	4	8.16%	61	5.22%	15.25	0	0
10	Canada	3	6.12%	95	8.13%	31.67	1	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Soil organic carbon mapping"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Sydney	15	30.61%	314	26.86%	20.93	2	0
2	INRA	6	12.24%	178	15.23%	29.67	0	0
3	Louisiana State Univ	6	12.24%	131	11.21%	21.83	0	0
4	Ramakrishna Mission Vivekananda Univ	5	10.20%	88	7.53%	17.60	1	0
5	Texas Tech Univ	5	10.20%	80	6.84%	16.00	1	0
6	Inst Environm & Sustainabil	4	8.16%	89	7.61%	22.25	0	0
7	Joint Res Ctr	4	8.16%	89	7.61%	22.25	0	0
8	Catholic Univ Louvain	4	8.16%	69	5.90%	17.25	1	0
9	Tech Univ Munich	3	6.12%	106	9.07%	35.33	1	0
10	W Virginia Univ	3	6.12%	105	8.98%	35.00	0	0

Note: INRA stands for the French National Institution for Agricultural Research.

network diagram suggests that the USA plays a leading role among all the countries or regions (Figure 1.2.3) and works closely with India. Although the University of Sydney has produced the largest number of core papers, the cooperation among the universities in the USA is more extensive (Figure 1.2.4). Based on the cited core papers, the USA and Australia are dominant among all the countries or regions (Table 1.2.7), the University of Sydney being the most dominant institution (Table 1.2.8). China is among the top 10 countries in this research focus, but it is in a relatively backward state in terms of the number of core papers, average citation frequency, and consistently cited papers.

Among the 49 core papers in this focus, 33 have been published in *Geoderma*. The most cited paper, "Spatial distribution of soil organic carbon stocks in France," published in *Biogeosciences* by INRA, has been cited 75 times. It is based on a regional research project on SOC. "SoilGrids1km—Global soil information based on automated mapping," published later in *Plos One* in 2014, is a highly cited paper on digital mapping of SOC of different regions or different types.

1.2.3 Healthy growth of livestock and poultry

The key to healthy growth of livestock and poultry is to ensure their healthy growth during the nursing and production processes. Porcine epidemic diarrhea virus and avian brood parasites are two major threats to safe livestock and poultry products. The healthy growth of livestock and poultry can ensure product safety from the source.

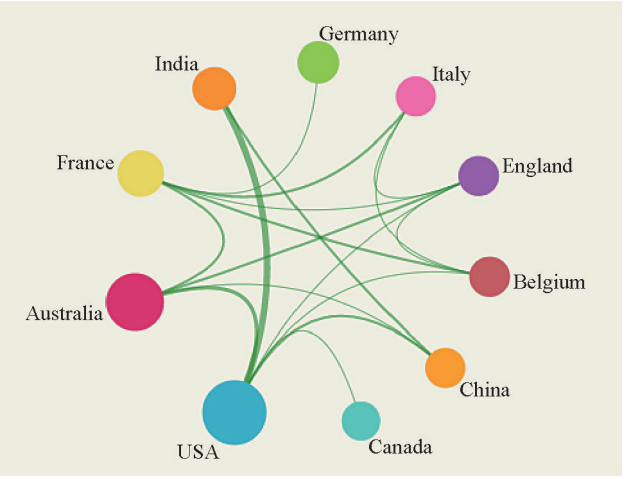

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Soil organic carbon mapping"

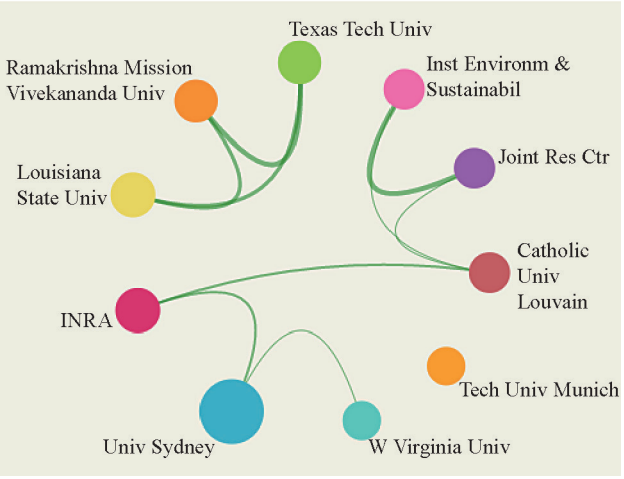

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus "Soil organic carbon mapping"

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Soil organic carbon mapping"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	14	19.44%	2014.07
2	Australia	13	18.06%	2014.31
3	France	6	8.33%	2013.33
4	India	5	6.94%	2014.20
5	England	4	5.56%	2014.00
6	Italy	4	5.56%	2014.75
7	Belgium	4	5.56%	2013.25
8	Egypt	3	4.17%	2014.00
9	China	3	4.17%	2014.67
10	Denmark	3	4.17%	2013.67

In terms of core paper publication by country or region, the USA produces the largest number of publications (Table 1.2.9), and the countries with consistently cited papers are the USA and the UK. The Iowa State University, the City University New York (CUNY), and Ohio State University are the dominant institutions (Table 1.2.10). The USA, Czech Republic, China, and Australia have a close cooperation (Figure 1.2.5). The Iowa State University has lesser number of cooperations, whereas the CUNY, Palacký University in Czech Republic, Hungarian Natural History Museum, and Hungarian Academy of Sciences have close cooperation (Figure 1.2.6). The top 3 countries producing the largest number of cited papers are the USA, China, and the Czech Republic (Table 1.2.11). Three universities in the USA—Ohio State University, Iowa State University, and CUNY—and the Palacký University in Czech Republic constitute the group of institutions with the highest number of cited core papers (Table 1.2.12). China is ranked third in the terms of the number of core papers on this research direction, but the total number of citation frequency is still at a low level. In terms of development potential, China has been ranked second for the number of cited core papers; although the publication of follow-up core papers can be expected, a core research institution has not yet been formed.

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Soil organic carbon mapping"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Sydney	13	12.38%	2014.31
2	Louisiana State Univ	5	4.76%	2013.40
3	Ramakrishna Mission Vivekananda Univ	5	4.76%	2014.20
4	Texas Tech Univ	5	4.76%	2014.40
5	Inst Environm & Sustainabil	4	3.81%	2014.75
6	Joint Res Ctr	4	3.81%	2014.75
7	Catholic Univ Louvain	4	3.81%	2013.25
8	INRA	4	3.81%	2013.00
9	Univ Wisconsin	3	2.86%	2014.67
10	Aarhus Univ	3	2.86%	2013.67

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Healthy growth of livestock and poultry"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	50	55.56%	1017	49.44%	20.34	6	0
2	Czech	14	15.56%	283	13.76%	20.21	1	0
3	China	13	14.44%	184	8.95%	14.15	1	0
4	England	12	13.33%	472	22.95%	39.33	4	0
5	Australia	11	12.22%	356	17.31%	32.36	1	0
6	Hungary	7	7.78%	163	7.92%	23.29	1	0
7	Scotland	5	5.56%	124	6.03%	24.80	1	0
8	New Zealand	5	5.56%	105	5.10%	21.00	0	0
9	France	5	5.56%	68	3.31%	13.60	0	0
10	Norway	4	4.44%	132	6.42%	33.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Healthy growth of livestock and poultry"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Iowa State Univ	14	15.56%	473	22.99%	33.79	2	0
2	CUNY	14	15.56%	237	11.52%	16.93	2	0
3	Ohio State Univ	14	15.56%	193	9.38%	13.79	1	0
4	Palacky Univ	13	14.44%	265	12.88%	20.38	1	0
5	Univ Cambridge	9	10.00%	417	20.27%	46.33	3	0
6	Australian Natl Univ	6	6.67%	251	12.20%	41.83	1	0
7	Hungarian Nat Hist Museum	6	6.67%	133	6.47%	22.17	1	0
8	Univ Minnesota	6	6.67%	107	5.20%	17.83	0	0
9	Hungarian Acad Sci	5	5.56%	142	6.90%	28.40	1	0
10	Univ Edinburgh	5	5.56%	124	6.03%	24.80	1	0

Note: CUNY stands for the City University of New York.



Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Healthy growth of livestock and poultry"

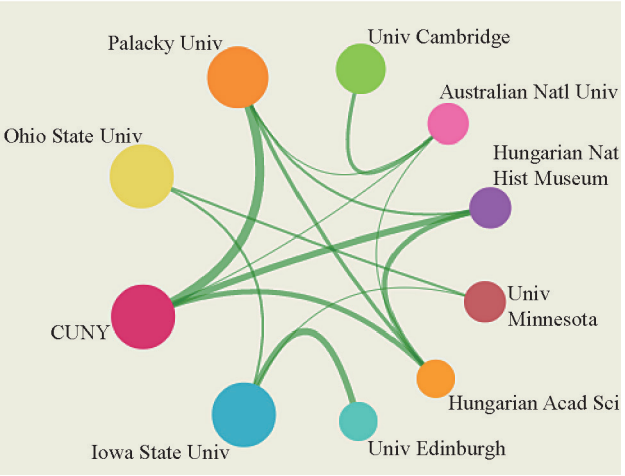

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Healthy growth of livestock and poultry"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Healthy growth of livestock and poultry"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	45	33.09%	2014.56
2	China	13	9.56%	2014.77
3	Czech	12	8.82%	2013.42
4	Australia	9	6.62%	2012.67
5	England	8	5.88%	2012.13
6	Hungary	6	4.41%	2013.67
7	Scotland	5	3.68%	2014.20
8	France	4	2.94%	2014.50
9	New Zealand	4	2.94%	2013.50
10	Slovakia	4	2.94%	2012.75

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Healthy growth of livestock and poultry"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Ohio State Univ	13	6.57%	2015.23
2	Iowa State Univ	13	6.57%	2014.77
3	CUNY	13	6.57%	2013.54
4	Palacky Univ	11	5.56%	2013.36
5	Univ Minnesota	6	3.03%	2015.17
6	Hungarian Nat Hist Museum	5	2.53%	2014.00
7	Univ Cambridge	5	2.53%	2011.60
8	Univ Debrecen	5	2.53%	2014.00
9	Australian Natl Univ	5	2.53%	2012.00
10	Eotvos Lorand Univ	5	2.53%	2014.00

Based on supporting data, the researchers of Iowa State University studying porcine epidemic diarrhea virus published a paper titled "Emergence of porcine epidemic diarrhea virus in the USA: clinical signs, lesions, and viral genomic sequences" in 2013 in the *Journal of Veterinary Diagnostic Investigation*, which has been cited 158 times and shown a profound impact. In 2011, the researchers at the Palacký University in Czech Republic published "Constraints on host choice: why do parasitic birds have no exploit some common potential hosts?" in the *Journal of Animal Ecology*" and it is a representative research paper on avian brood parasites.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 agricultural engineering development hotspots are classified into three categories.

• *Ground-breaking development hotspots.* They include "Precision irrigation" in agricultural engineering, "Animal stem cells" in veterinary medicine, and "New genetically modified varieties" in agricultural bioengineering.

• *Hotspots involving in-depth traditional research.* They include "Pesticide pollution and prevention" of plant protection, "Facility agriculture" and "Agricultural machinery improvement" of agricultural engineering, "Animal viral vaccine" in veterinary medicine, "Microbial fertilizer" in agricultural resource science, and "Biomass energy and materials" in forestry engineering.

• *Emerging development hotspots.* They include "Intelligent agricultural equipment" in agricultural engineering.

The hotspot "Agricultural machinery improvement" has produced a relatively high number of patents (> 600). However, the highest patent citation frequency is found in the hot topic "Animal stem cells" in veterinary medicine (up to 3651 times). The average citation frequency of all hotspots are approximately five times. Among them, the highest and the lowest average citation frequency of patents are in "Pesticide pollution and prevention" (approximately 10 times) and "New genetically modified species" (less than twice), respectively. The mean year (average publication year) of patents is mainly concentrated from 2012–2013 (Table 2.1.1). The number of patents in the hotspots "Pesticide pollution and prevention" and "New genetically modified varieties" in plant protection has shown a regular downward trend (Table 2.1.2).

Brief descriptions of the top 10 engineering development hotspots are as follows.

2.1.1 Intelligent agricultural equipment

This is a emerging development hotspots in agricultural engineering. Intelligent agricultural equipment combines the advanced manufacturing, information, and artificial intelligence technologies. It is an important tool for upgrading traditional agricultural machinery manufacturing with the aim of achieving intelligent automation of agricultural production processes. Moreover, it has become an important direction for the development of international high-end agricultural equipment manufacturing industry.

Table 2.1.1 Top 10 engineering development hotspots in agriculture

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Intelligent agricultural equipment	142	685	4.82	2013.37
2	Precision irrigation	261	842	3.23	2013.37
3	Pesticide pollution and prevention	160	1481	9.26	2012.11
4	Facility agriculture	226	634	2.81	2012.99
5	Agricultural machinery improvement	606	1326	2.19	2013.49
6	Animal stem cells	473	3651	7.72	2012.26
7	Animal viral vaccine	264	1232	4.67	2012.29
8	Microbial fertilizer	315	1908	6.06	2012.59
9	New genetically modified varieties	105	154	1.47	2012.11
10	Biomass energy and materials	154	806	5.23	2012.75

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in agriculture

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Intelligent agricultural equipment	23	19	27	34	33	6
2	Precision irrigation	32	52	44	71	45	17
3	Pesticide pollution and prevention	46	66	36	9	3	0
4	Facility agriculture	48	45	44	44	40	5
5	Agricultural machinery improvement	58	99	134	139	155	21
6	Animal stem cells	151	162	72	67	18	3
7	Animal viral vaccine	81	80	62	30	9	2
8	Microbial fertilizer	61	88	100	51	14	1
9	New genetically modified varieties	30	37	35	2	1	0
10	Biomass energy and materials	36	37	28	35	18	0

At present, the intelligent control of agricultural equipment focuses on the in-depth exploration of various sensors, communication systems, image processing, computer vision, and other information technologies, including the sensors used in vehicle steering control, the level control for the lifting and lowering of ground working parts of vehicles, and the electro-hydraulic control of vehicle position with pressure and depth. Furthermore, the focus includes the image sensor monitoring system for plant/crop characteristics, such as the maturity of fruits, vegetables, and other agricultural products in addition to equipment integrating image processing and visualizing sensing function (automatic visual monitoring system) for thinning out seedlings and weeding. Further, the focus includes the collaborative control of vision and image processing technology (e.g., stereoscopic vision system) on harvesters and transport trucks in a coordinated multi-machine system, the radio load control of harvester grain silos, the improvements in the grain push controllers with controllable pushing speed, the threshing mechanism combine harvester, and the performance of grain storage container. Intelligent agricultural equipment can meet the different levels of demand. They can be integrated with advanced technologies and information, including intelligent equipment, digital design and simulation systems, intelligent equipment testing platform, micro-electromechanical system agricultural sensors, agricultural robots, intelligent navigation control technology, the internet of things, big data, and cloud computing, and cloud service is the main direction of intelligent agricultural equipment research in the future.

2.1.2 Precision irrigation

This is a ground-breaking development hotspot in

agricultural engineering. At present, water shortages have become the most important limiting factor in global agricultural production. In accordance with the crop growth needs, precision irrigation achieves the intelligent monitoring of water, fertilizer, gas, heat, light, and other crop growth factors, and uses water-saving irrigation facilities to provide the most appropriate amount of water supply to crops for achieving the optimal growth status. The application of precision irrigation can significantly improve the yield and quality of agricultural products, and contribute to achieving the water-saving, fertilizer-saving, labor-saving, high yield, and environmental protection goals. In the agricultural productions of Africa, the Middle East, Central Asia, and other arid and semi-arid areas, efficient use of water resources is the primary research topic. Based on the previous technical integration and the degree of mechanization, the performance of the irrigation controller in agricultural precision irrigation technology is more accurate (e.g., on-demand water input, which can be detected and controlled precisely), and the water-saving effect is more significant. E.g., an irrigation controller that automatically adjusts the progress of irrigation water according to the budget, the irrigation controller that automatically adjusts the water outflow according to the progress of irrigation and the irrigation system based on the theory of evapotranspiration (i.e., control of irrigation water outflow through the information transmitted by evapotranspiration units).

2.1.3 Pesticide pollution and prevention

Pesticide pollution and prevention is a hotspot in the discipline of plant protection, which involves in in-depth traditional research. Pesticide pollution refers to the excessive use of pesticides and improper selection of pesticide type and application time, which lead to excessive pesticide residues in agricultural products, thereby causing serious harm to human health. Some natural enemies (predators and parasites) of pests are killed, thereby disrupting the balance between pests and their natural enemies, and a rapid pest population growth. Meanwhile, the pollinating insects are killed, which affects the crop yield. Excessive pesticides enter the soil and water owing to rainfall, farmland percolation, and drainage, thereby damaging the ecosystem. The integrated prevention and control technology includes agricultural, biological, chemical, physical, and other methods of control. Low toxicity and biological control are the preferred research and development directions of plant protection.

2.1.4 Facility agriculture

Facility agriculture is a hotspot in agricultural engineering involving in-depth traditional research. Facility agriculture refers to a modern agricultural approach that uses engineering techniques for efficient production of animals and plants under a relatively controllable condition. Facility agriculture covers facility cultivation, facility breeding, facility-produced edible fungi, etc. Modern greenhouse and plant factory are two important areas of the research on facility agriculture intelligence. Compared with the modern greenhouse, a plant factory that can avoid the field production environment is a higher level of development of facility agriculture. Among them, the collection and monitoring of environmental and biological information, intelligent system control platform, biologically standardized and pipelined production management model, and the development of the quality traceability system of agricultural products based on the internet of things will be the core hotspots in future.

2.1.5 Agricultural machinery improvement

This is a hotspot in agricultural engineering involving in-depth traditional research. The focus includes the continuous improvement and manufacturing of advanced agricultural machinery and equipment, with the ultimate aim of improving agricultural production and management, and continuously enhancing the level of agricultural production technology, economic benefits, and ecological benefits. In addition, the comprehensive integration of the specialization, automation, information technology, and other core technologies of agricultural machinery is an important direction for development.

2.1.6 Animal stem cells

It is a disruptive development hotspot in veterinary medicine. Animal stem cells are cells with an ability of self-replication under certain conditions. They can differentiate into a variety of functional cells. According to their developmental stages, the stem cells are divided into embryonic stem cells and adult stem cells. According to their developmental potential, stem cells are divided into three categories: totipotent stem cells, pluripotent stem cells, and unipotent stem cells (monopotent stem cells). Stem cells are

cells that are immature and not fully differentiated, possessing the potential to regenerate living organisms, various tissues, and organs. The animal models that have a close genetic relationship with human, such as cloned pigs, can grow organs and tissues suitable for humans, and cloned macaques can be used to test diabetes and other illnesses.

2.1.7 Animal viral vaccine

This is a hotspot belonging to the discipline of animal husbandry and involving in-depth traditional research. Vaccine refers to a biological agent that is used to inoculate living organisms, displays antigenicity, and is used to prevent and control the occurrence of infectious diseases. The types of viral vaccines include: (1) traditional vaccines, such as inactivated vaccines, attenuated live vaccines, and subunit vaccines, and (2) new viral vaccines, such as gene-deficient live vaccines, virus-like particles, nucleic acid vaccines, and live viral vectors. The new viruses that are constantly emerging pose a huge challenge for researchers to develop drugs or vaccines.

2.1.8 Microbial fertilizer

This is a hotspot in agricultural resource science involving in-depth traditional research. Microbial fertilizers refer to a type of biological products that use microbial activities for allowing crops to access a specific fertilizer. There are three categories: microbial agents, composite microbial fertilizer, and bioorganic fertilizer. They are used to inhibit the crop pests and diseases effectively or to provide nutrients and other growth-promoting substances to crops, to adjust and control the growth, enhance disease resistance, and increase the crop yield or crop quality. With the development of organic ecological agriculture, increasing attention will be paid to the use of microbial fertilizers.

2.1.9 New genetically modified varieties

This is a disruptive development hotspot in agricultural bioengineering. To obtain new genetically modified varieties, the useful target gene is isolated from donor organisms and introduced into the recipient animals and plants directly or through DNA recombination and genetic transformation. After screening, the genetically modified organism with a stable expression is obtained, and it can be produced by testing and selective breeding. In recent years, the genetic characteristics of organisms have been altered by processes such as gene knockout, and silence of genes to obtain the desired traits and breed new varieties. A large number of new cotton, corn, soybeans, and other crop varieties are reported from abroad; in addition, transgenic research on pigs, cattle, sheep, and other animals has been reported. The application of transgenic technology and the breeding of new varieties are the most popular and advanced research and development fields in the world.

2.1.10 Biomass energy and materials

This is a hotspot in forestry engineering involving in-depth traditional research. Biomass energy is the form of energy, in which the solar energy is stored as chemical energy, i.e., the biomass acts as the energy carrier. It is derived directly or indirectly from the photosynthesis of green plants and can be converted into conventional solid, liquid, and gaseous fuel. Biomass energy development technology is currently focusing on gasification, compressed fuel, combustion power generation, and the production of fuel ethanol and biodiesel. Among them, biomass gasification fuel and biomass compression molding techniques have matured from the traditional research content. In terms of combustion power generation, high-efficiency direct-fired power generation is considered the most viable way of biomass utilization and is an important future development direction. The current conversion efficiency in the production of fuel ethanol with forest waste as raw material is still low; this technique is still in the experimental stage, and the development of ethanol production technique using lignocellulose as raw material will be the focus of future research and development. The extraction of biodiesel from tree seeds with high oil content is still in the exploratory stage, and it is too early for industrial production. However, it is one of the key directions of future research and development.

2.2 Understanding of engineering development focus

2.2.1 Intelligent agricultural equipment

The focus of intelligent control technology for agricultural equipment is the in-depth explorations of various sensors, communication systems, image processing, computer vision, and other information technologies.

The countries or regions producing the core patents are China and the USA (Table 2.2.1). The number of core patents of China and the USA account for approximately 75%

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Intelligent agricultural equipment"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	107	75.35%	456	66.57%	4.26
2	USA	28	19.72%	210	30.66%	7.50
3	Korea	3	2.11%	14	2.04%	4.67
4	Canada	1	0.70%	3	0.44%	3.00
5	UK	1	0.70%	2	0.29%	2.00
6	Israel	1	0.70%	1	0.15%	1.00
7	Italy	1	0.70%	0	0%	0
8	New Zealand	1	0.70%	2	0.29%	2.00

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Intelligent agricultural equipment"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Hunter Ind	5	3.52%	51	7.45%	10.20
2	Skydrop LLC	3	2.11%	5	0.73%	1.67
3	China Agric Univ	3	2.11%	18	2.63%	6.00
4	Kunming Univ Sci & Technol	3	2.11%	6	0.88%	2.00
5	Shandong Agric Univ	3	2.11%	8	1.17%	2.67
6	Valmont Ind Inc.	3	2.11%	7	1.02%	2.33
7	Beijing Res Cent Intelligent Equip Agric	2	1.41%	7	1.02%	3.50
8	Jiangsu Guanjia Water Conservancy Technology Co., Ltd.	2	1.41%	6	0.88%	3.00
9	Nat Diversified Sales Inc.	2	1.41%	9	1.31%	4.50
10	Rain Bird Corp	2	1.41%	24	3.50%	12.00

and less than 20%, respectively. However, the opposite situation is observed in the average citation frequency of core patents, with the USA and China accounting for 7.50 and 4.26, respectively. These findings indicate that the patents of the USA are low in a number, but influential. Hunter Ind. and Rain Bird Corp. in the USA, and China Agricultural University have a high core patent citation frequency and show a significant impact (Table 2.2.2). The USA and Canada have some cooperation, but no cooperation is observed among the top 10 research institutions (Figure 2.2.1 and Figure 2.2.2).

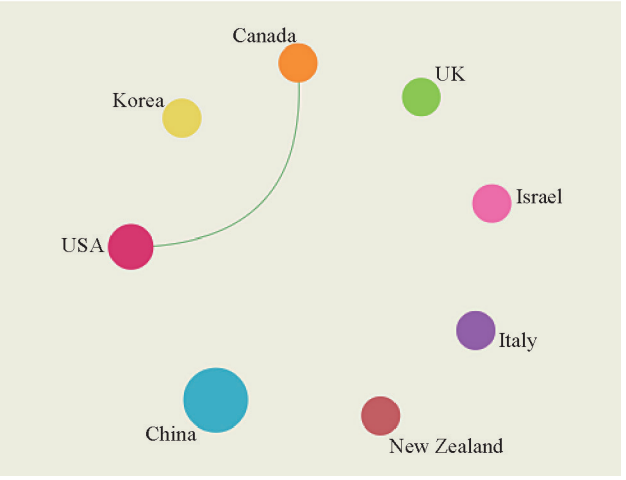

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Intelligent agricultural equipment"

2.2.2 Precision irrigation

Owing to previous technical integration and the degree of mechanization, the performance of the irrigation

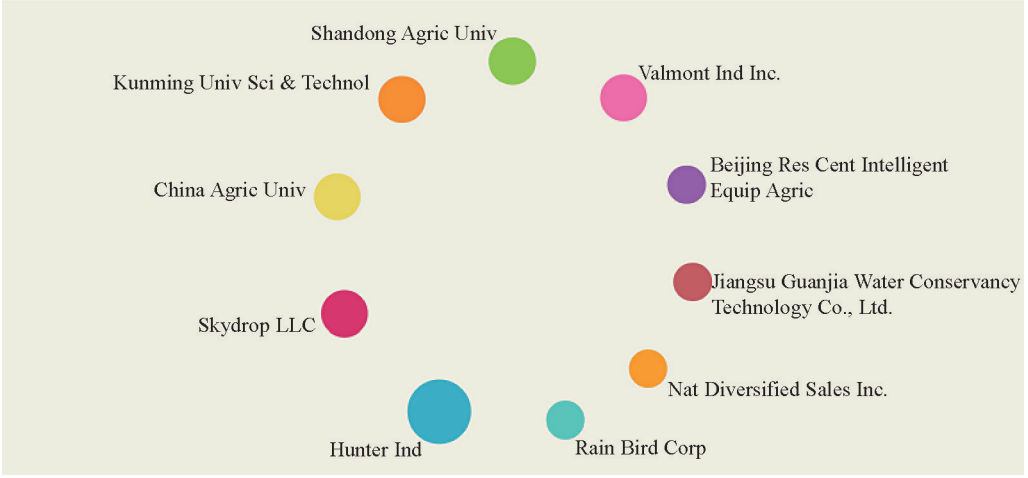

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Intelligent agricultural equipment"

controller in agricultural precision irrigation technology (e.g., on-demand water input is more accurate, and the water-saving effect is more significant. Examples include the irrigation controller that automatically adjusts the progress of irrigation water according to the budget, the irrigation controller that automatically adjusts the water outflow according to the progress of irrigation, and the irrigation system based on the theory of evapotranspiration (i.e., control of irrigation water outflow based on the information transmitted by evapotranspiration units).

In this research area, China has the highest number of core patents and is dominant (Table 2.2.3). Japan, Germany, and the USA have only a few patents, but a high average citation frequency. The average citation frequency of the Japanese patents is 4.79 times, whereas that of the Chinese patents is 3.17 times. The Nanjing Research Institution for Agricultural Mechanization (NRIAM) of the National Ministry of Agriculture and seven other Chinese institutions are among the top 10 organizations, and the other two organizations are a Japanese and an Austrian company (Table 2.2.4). Among the top 10 countries or regions, only Germany and Denmark have cooperation; among institutions, only Qingdao Agricultural University and a company in Qingdao (Qingdao Hongsheng Auto Fittings Co. Ltd.) have some cooperation (Figure 2.2.3 and Figure 2.2.4).

2.2.3 Pesticide pollution and prevention

The prevention and control techniques for pesticide

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Precision irrigation"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	208	79.69%	659	78.27%	3.17
2	Japan	19	7.28%	91	10.81%	4.79
3	Germany	6	2.30%	18	2.14%	3.00
4	USA	6	2.30%	22	2.61%	3.67
5	Korea	5	1.92%	10	1.19%	2.00
6	Austria	4	1.53%	10	1.19%	2.50
7	Russia	4	1.53%	5	0.59%	1.25
8	France	2	0.77%	7	0.83%	3.50
9	Belgium	1	0.38%	5	0.59%	5.00
10	Denmark	1	0.38%	2	0.24%	2.00

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Precision irrigation"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Min Agric Nanjing Res Inst Agric Machinery	6	2.30%	18	2.14%	3.00
2	Qinghai Agric & Husbandry Machinery Mfg	6	2.30%	19	2.26%	3.17
3	Kubota Corp	5	1.92%	21	2.49%	4.20
4	Shandong Changlin Agric Equip Co., Ltd.	5	1.92%	19	2.26%	3.80
5	Qingdao Agric Univ	5	1.92%	11	1.31%	2.20
6	Alois Pöttinger Maschinenfabrik GmbH	4	1.53%	10	1.19%	2.50
7	Qingdao Hongsheng Auto Fittings Co., Ltd.	4	1.53%	21	2.49%	5.25
8	Henan Univ Sci & Technol	4	1.53%	13	1.54%	3.25
9	Chery Heavy Industry Co., Ltd.	3	1.15%	6	0.71%	2.00
10	Chongqing Standard Machinery Mfr Co., Ltd.	3	1.15%	6	0.71%	2.00

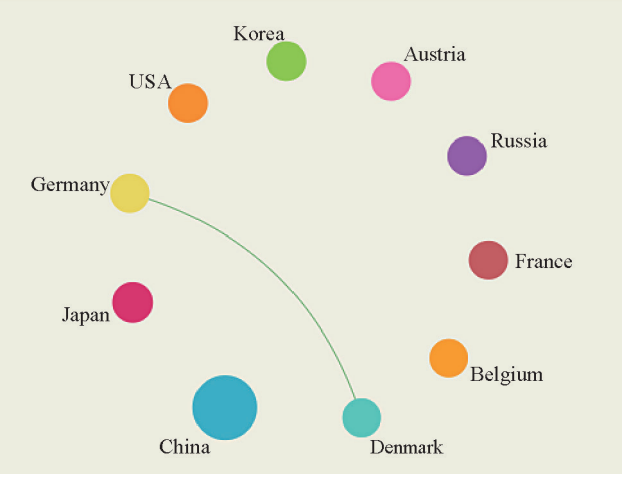

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Precision irrigation"

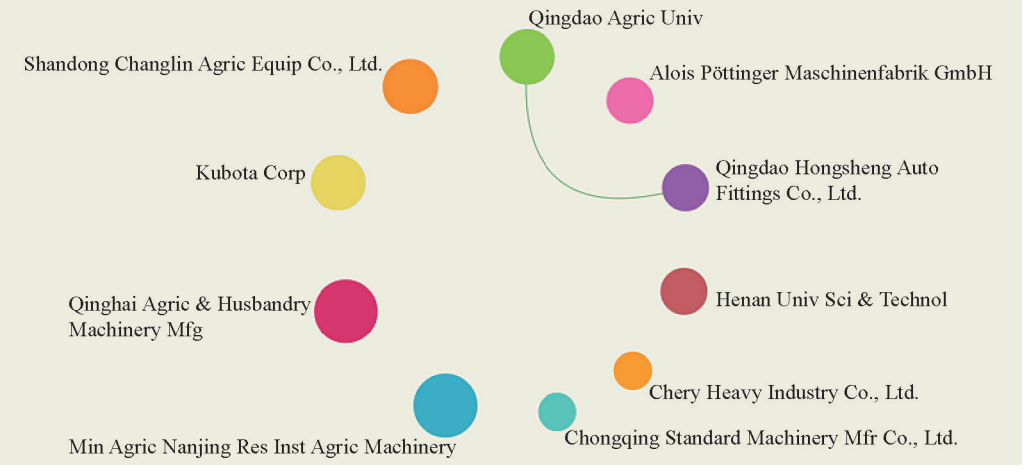

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Precision irrigation"

pollution include the following aspects: (1) Agricultural control—the use of crop rotation, selection of new pest and disease resistant varieties, and reasonable control of fertilizer and water to improve crop resistance to pests and diseases; (2) Biological control—the use of natural enemies for pest control, the use of insects, bacteria, animals and plants, and other organisms for weed control, and the use of biological pesticides for pest control; (3) Chemical control—the disease, insect, and weed forecasts, achieving timely control, and reasonable mix and alternate use of less-persistent pesticides; (4) Physical control—the use of mechanical or hand control, syrup and light trapping, manual weeding, mechanical weeding, etc. At present, the use of low toxicity and less-persistent pesticides is the dominant control technique.

The countries mainly producing the core patents on this focus are China, the USA, and Germany (Table 2.2.5). China has the largest proportion of published patents and has approximately the same average citation frequency as other countries have. Among the major organizations owning the core patents (Table 2.2.6), six institutions in Guangxi and Guangdong of China have a high number of patents, and one institution each from Germany, the USA, France, and Switzerland is among the top 10 organizations. The USA and France remain the main cooperating countries, and China mainly cooperates with Germany (Figure 2.2.5). However, there is no cooperation mechanism among the top 10 research institutions (Figure 2.2.6).

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Pesticide pollution and prevention"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	121	75.63%	1148	77.52%	9.49
2	USA	22	13.75%	177	11.95%	8.05
3	Germany	15	9.38%	153	10.33%	10.20
4	Switzerland	6	3.75%	60	4.05%	10.00
5	France	6	3.75%	46	3.11%	7.67
6	Canada	3	1.88%	24	1.62%	8.00
7	UK	3	1.88%	29	1.96%	9.67
8	Italy	2	1.25%	7	0.47%	3.50
9	Belgium	1	0.63%	6	0.41%	6.00
10	Finland	1	0.63%	12	0.81%	12.00

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Pesticide pollution and prevention"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Guangxi Idyllic Biochemistry Co., Ltd.	20	12.50%	277	18.70%	13.85
2	BASF SE	13	8.13%	122	8.24%	9.38
3	Guangdong Zhongxun Agric Sci Co., Ltd.	7	4.38%	55	3.71%	7.86
4	Dow Agrosciences LLC	6	3.75%	57	3.85%	9.50
5	Nanning Defengfu Chem Co., Ltd.	5	3.13%	42	2.84%	8.40
6	HSP Crop Technology Co., Ltd.	4	2.50%	27	1.82%	6.75
7	Nantong Liannong Pesticide Preparation	4	2.50%	45	3.04%	11.25
8	Hebei Bojia Agric Co., Ltd.	3	1.88%	45	3.04%	15.00
9	Rhodia Operations	3	1.88%	12	0.81%	4.00
10	Syngenta Participations AG	3	1.88%	36	2.43%	12.00

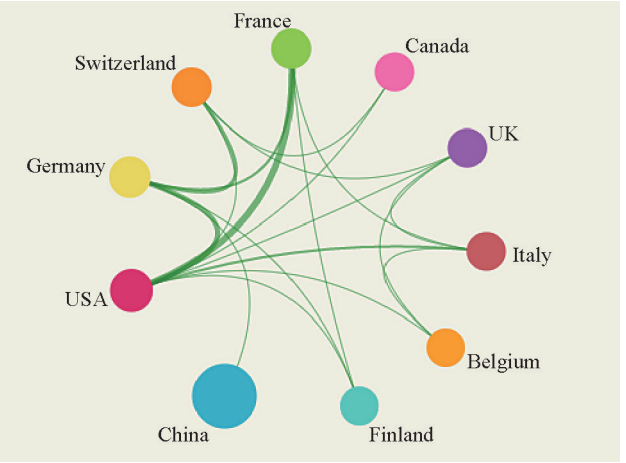

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Pesticide pollution and prevention"

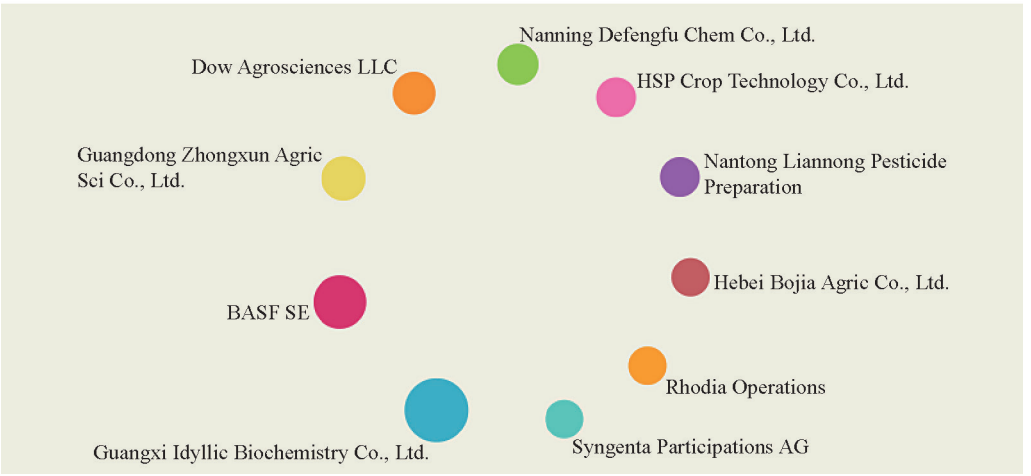

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Pesticide pollution and prevention"

Project Participants

Members of the Field Group

Leaders of the Field Group:

KANG Shaozhong, LI Zhaohu, DENG Xiuxin

Other Members:

LIU Xu, ZHAO Yaofeng, HUANG Haitao, ZHANG Wentao, WANG Qing, WEN Danyan, XU Jianxiang, YUAN Wenye, LI Chenying, SHI Lijuan, YANG Aidong, WANG Yan, XING Lu

Report Writers

KANG Shaozhong, YUAN Wenye, SHI Lijuan, XU Jianxiang, YANG Aidong, WANG Yan, XING Lu

Acknowledgments

This report was completed with the support from the project "Strategic Consulting and Research of Global Engineering Focus" in the Chinese Academy of Engineering, under the guidance and help of the project integration group. The data were processed and provided by Clarivate Analytics (Beijing). QIAN Xuhong, ZHENG Wenjiang, and MU Zhirui from the project integration group, and JIANG Zhiqiang, ZHOU Weixing, JI Jiuming, and other teachers from the East China University of Science and Technology helped in report writing, chart plotting, etc. Further, we thank the members from the Standing Committee of Agriculture Faculty of Chinese Academy of Engineering, and the academicians and experts of the relevant fields in the selection of hotspots and focus.

VIII. Medicine & Health

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 9 engineering research hotspots in medicine and health include basic medicine, clinical medicine, medical informatics and biomedical engineering, pharmacy, imaging and nuclear medicine, public health and preventive medicine, and other subjects (Table 1.1.1). Traditional research has focused on "Stem cells and regenerative medicine," "Molecular imaging technology," "Target therapy for chronic myeloid leukemia," "Sudden cardiac death," "Potential new tactics for preventing type 2 diabetes," "Robot-assisted surgery," "Femtosecond laser-assisted cataract surgery," and "Cerebral arteriovenous malformations." Currently, "Chimeric antigen receptor T-cell immunotherapy" is an emerging hotspots. All core papers regarding these topics published between 2011 and 2016 are listed in Table 1.1.2.

(1) Stem cells and regenerative medicine

Stem cells and regenerative medicine is aimed at boosting wound healing and treatment of diseases through transplantation, differentiation of stem cells, or tissue regeneration, which have enormous potential for clinical applications. Stem cells are rare populations of cells capable of differentiating into multiple types of specialized cells while maintaining their own numbers and identities via self-renewal mechanisms. In mammals, stem cells include: ① Embryonic stem cells (ESCs), which are derived from embryos and can differentiate into any of the three germ layers (i.e., endoderm, mesoderm or ectoderm), and are therefore referred to as pluripotent stem cells (PSCs). Induced pluripotent stem cells (iPSCs) are PSCs that are derived from somatic cells by "reprogramming" (including introduction of specific genes and treatment with chemicals). It is noteworthy that iPSCs allow generation of patient-specific stem cells for therapeutic purpose, thereby bypassing the requirement of embryos. Therefore, iPSCs represent a promising source of cells that may solve for immune rejection in allogenic transplantation. ② Adult stem cells, which are found in various tissues and act as repairing systems of the body by differentiating into specialized cells, e.g., neural stem cells. Presently, stem cells and regenerative medicine have been used widely for treating critical illnesses, including diabetes, stroke, cancer, etc., and have significantly improved health status and quality of life.

(2) Molecular imaging technology

Molecular imaging technology differs from conventional anatomical imaging modalities (including X-ray, ultrasound, CT, and MRI), since a specific molecular imaging agent (tracer or imaging biomarker) is administered via a local injection, intravenously, or via other routes into the living organism or human body, followed by data acquisition using a dedicated

Table 1.1.1 Top 9 engineering research hotspots in medicine and health

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Stem cells and regenerative medicine	50	2850	57.00	2013.96	30.00%	0
2	Molecular imaging technology	49	4124	84.16	2012.82	30.60%	0
3	Target therapy for chronic myeloid leukemia	49	4472	91.27	2013.12	38.80%	1
4	Chimeric antigen receptor T-cell immunotherapy	49	7880	160.82	2014.06	51.00%	2
5	Sudden cardiac death	48	2381	49.60	2013.00	14.60%	0
6	Potential new tactics for preventing type 2 diabetes	49	3463	70.67	2013.35	24.50%	0
7	Robot-assisted surgery	49	1932	39.43	2013.14	24.50%	0
8	Femtosecond laser-assisted cataract surgery	50	1958	39.16	2013.06	18.00%	1
9	Cerebral arteriovenous malformations	49	1769	36.10	2013.71	26.50%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 9 engineering research hotspots in medicine and health

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Stem cells and regenerative medicine	4	8	5	10	15	8
2	Molecular imaging technology	8	14	11	11	5	0
3	Target therapy for chronic myeloid leukemia	7	12	7	14	9	0
4	Chimeric antigen receptor T-cell immunotherapy	5	3	11	5	15	10
5	Sudden cardiac death	12	6	10	12	6	2
6	Potential new tactics for preventing type 2 diabetes	9	6	7	18	4	5
7	Robot-assisted surgery	7	10	15	6	8	3
8	Femtosecond laser-assisted cataract surgery	7	8	16	13	6	0
9	Cerebral arteriovenous malformations	2	9	6	18	12	2

single imaging modality (including PET, SPECT, MRI, ultrasound, optics, photoacoustics, Cherenkov, Raman, or quantum dot imaging, etc.) or a multi-modality fused imaging system, image reconstruction, and processing. Molecular imaging is an integrated research discipline that enables visualization, characterization, and quantification of biochemical processes such as distribution, metabolic changes, target receptor binding, and biological behaviors in vivo at the cellular and subcellular levels through tracking of specific imaging agents. Molecular imaging, which emerged in the late 1990s, is the modern biomedical imaging technology. Industries related to molecular imaging have developed gradually over the past 15 years and have expanded rapidly in recent years. Molecular imaging is a new, interdisciplinary, and highly integrated research and application field, which integrates biological medicine, chemistry, optoelectronics, material science, mathematics, informatics, intelligent manufacturing, and many other disciplines; its application areas initially included mechanistic studies of major human diseases, such as brain science, brain cognition, cancer, cardiovascular diseases, neuropsychiatric disorders etc, later extended to clinical application of individualized diagnosis and treatment as well as precision medicine, which greatly accelerated the development progress of basic and clinical medicine. In addition, it has significantly shortened the research and testing cycles of drug development. For example, the molecule-targeted drug Imatinib Gleevec® was approved by the FDA for application in patients with gastrointestinal stromal tumor (GIST) in 6 years due to the successful application of FDG-PET molecular imaging technique for monitoring the therapeutic responses in the early phase of clinical trials. Innovation and development of molecular imaging technology would enable precise prediction and theranostics for major diseases (including Alzheimer's disease, cancer, etc.). Therefore, it is important to promote molecular imaging-related research that would significantly reduce the cost of medical care and disrupt the foreign technology monopoly in the high-end medical field.

(3) Target therapy for chronic myeloid leukemia

Target therapy for chronic myeloid leukemia (CML) is an integrated process that comprises synthesis and identification of molecules targeting the BCR-ABL fusion protein based on molecular mechanism of CML, clinical follow-up, and prognosis evaluation. The key obstacles for target therapy of CML include the screening of target molecules, sequential use of tyrosine kinase inhibitors or other molecules, disease monitoring, overcoming resistance, and identifying a path to the cure. Since the late 1990s, the availability of imatinib, a first generation tyrosine kinase inhibitor used for target therapy of CML, has significantly changed long-term survival and quality of life for patients with CML. The aim for CML treatment has changed from achieving a complete cytogenetic response in the past to obtaining a deep molecular response, and finally to develop treatment-free remission and cure for the disease. The techniques for CML monitoring have evolved from cell morphology and chromosome detection to immunophenotype analysis by flow cytometry or minimal residual disease monitoring at the molecular level. The technique for minimal residual disease monitoring has evolved from qualitative PCR

to real-time quantitative PCR, and finally to digital PCR, whereas that for detecting the ABL mutation has developed from first to third generation sequencing. Currently, CML has become a chronic controlled disease from a neoplasm, and finally will be a curable disease.

(4) Chimeric antigen receptor T-cell immunotherapy

Immunotherapy has shown a great potential for cancer treatment, and was named among "the world's top ten scientific and technological breakthroughs" by the Journal of Science in 2013. The chimeric antigen receptor T-cell immunotherapy (CAR-T) has developed rapidly in recent years as a new type of cellular immunotherapy. By using gene recombination techniques, T cells derived from the peripheral blood of patients are modified by CAR to specially recognize tumor-associated antigens. The CAR-T cells are then expanded in vitro and infused back into the patients, where they precisely identify and attack the targeted tumor cells. Compared to conventional T cells, CAR-T cells show better targeting, killing activity, and durability, providing a broad prospect for clinical applications. Selection of the target antigen is a critical determinant for the specificity, effectiveness, and safety of CAR. Currently, only few tumor-specific targets are available, among which CD19 is the most effective and well-studied for the treatment of hematological cancers. CAR-T technology has undergone four generations of optimization and innovation, presenting a promising clinical efficacy in the treatment of various tumors, especially hematological malignancies. Currently, CAR-T is one of the most interesting topics in cancer therapy.

(5) Sudden cardiac death

Sudden cardiac death (SCD) is natural death caused by cardiac problems and is characterized by sudden loss of consciousness within one hour after acute symptomatic outbreak. The key scientific problems are that SCD is paroxysmal and unpredictable, with no aura before its occurrence, and therefore, the survival rate is very low. Methods to prevent the occurrence of SCD, detect early symptoms of SCD, and perform effective cardiopulmonary resuscitation (CPR) for reducing mortality are some of the critical issues to be solved in cardiovascular and emergency medicine. SCD is a disease with multiple causes and risk factors, with 2 out of 3 cases occurring outside hospitals. Globally, SCD is the primary cause of cardiovascular death outside the hospital, with average survival rate in USA being 5% and the global average survival rate < 2%. In addition, it has become the most common cause of death in adults less than 65 years of age. More than 450 000 people experience SCD every year in America. In recent years, the incidence of SCD has also increased significantly with rise in the incidence of cardiovascular disease in China. At present, the main problems are lack of prehospital treatment and basic rescue skills, and insufficient emergency transportation system in urban and rural areas. Even though remarkable progress has been made in determining the pathogenesis, risk factors, prevention, treatment, and patient management of SCD, it is still a significant global health issue with life threatening repercussions. Since the risk factors of SCD lack specific indexes, it is necessary to explore and establish an effective multivariate cooperative model to predict, identify, and control the high-risk population. Prevention and treatment of SCD would require equipping and training the community with the use of automated external defibrillators (AED). Extensive efforts are required to control SCD and reduce its health hazards for the society.

(6) Potential new tactics for preventing type 2 diabetes

Potential new tactics for preventing type 2 diabetes (T2D) include developing novel preventive and therapeutic strategies for controlling the epidemic tendency of T2D. In addition, the responsive efficiency of clinical therapies based on existing preventive measures for T2D plus current epidemiological trends of T2D and new findings in this field have to be reinforced. Key scientific questions include: ① how to achieve precise analytical expressions for the commonalities and heterogeneities of the diabetic population, ② how to develop individualized treatment with lifestyle interventions and medications assisted by deep phenotyping and artificial intelligence, and ③ to identify novel therapeutic approaches for treating overweight and obesity, which are major causes of T2D. In the last 30 years, the increase in the prevalence rate of T2D has paralleled the growth of national economies and significantly increased the risk of cardiovascular diseases, severely threatening public health. However, a low awareness rate, poor control rate, and limited treatment options for T2D are the common difficulties. In the past 5 years, large-scale epidemiological cohorts have been set up. Deep phenotyping and deep sequencing, combined with multi-omics analytical techniques, have been developed and made affordable; genetic structures from population

to individual level and interaction patterns between intestinal flora composition and environment have been revealed; controlled clinical trials to prove therapeutic efficacy for multiple novel treatments have been released successively. All these advances suggest that the strategy for prevention and control of T2D needs readjustment and improvement. Predictably, the direction of this strategic revolution in the future will focus on promoting precise prevention and treatment targeted at both the population and individuals to postpone and reverse the progression of T2D. To achieve this goal, it is crucial to adopt case-controlled research model and artificial intelligence-assisted diagnosis and treatment, and proactively combine deep phenotyping, basic research of gene-environment interactions, and efficacy analysis for lifestyle and medication interventions.

(7) Robot-assisted surgery

Robot-assisted surgery refers to surgeons completing various types of surgery with a special robotic surgery system. It involves many crucial scientific issues, which mainly consist of two aspects, namely, medical engineering and clinical application. The former includes power feedback system, semi-rigid surgical instruments, reality enhancement, and systemic miniaturization. The latter includes efficacy advantages, indication development, training and learning curve, as well as cost-effective investigation. Since the 1980s, robot-assisted surgery has gradually developed to be the forefront of minimally invasive surgery. By the end of 2016, more than 3000 robotic-surgical systems were installed worldwide, and 40 896 cases were completed in China, with more domestic robot-assisted surgery system being clinically tested. Currently, the fundamental concept of robot-assisted surgery is long-distance operation, which implies that the surgeon controls the surgical system through the stereoscopic vision and action calibration systems to complete the operation using surgical instruments. Its main advantages include three-dimensional high-definition vision, intuitive motion control, and simulation of multi-degree freedom of a surgical arm. This method allows flexibility and clear vision even in a small cavity. Its safety and short-term feasibility have been confirmed in thoracic surgery, urology, gynecology and abdominal surgery, and other areas; however, its bottlenecks include its large size, poor mobility, lack of tactile feedback, long preparation time, and high expenditure. With the development of real-time image transmission technology such as big data, artificial intelligence, high-speed internet and fiber optic cable signals, we believe that robot-assisted surgery will gradually move towards an era of intelligent and remote surgery.

(8) Femtosecond laser-assisted cataract surgery

Femtosecond laser-assisted cataract surgery is a surgical approach that utilizes a pulsed near-infrared laser of 1030 nm wavelength as an aid for completing cataract phacoemulsification. Its key scientific features include construction of multilayered corneal self-sealing incisions and limbal relaxing incisions, creating precise and complete lens capsule openings, and pre-dissecting the lens nucleus. Surgical intervention is effective in the treatment of cataract. When the lens opacity affects the patient's life and work, surgery can be performed to replace the opaque lens with an artificial intraocular lens. Since the 1980s, extracapsular cataract extraction and cataract phacoemulsification have become developed surgical methods. The 21st century has seen the wide use of phacoemulsification for its small damage and rapid recovery. In recent years, with the emergence of refractive cataract surgery, precisely intellectualized surgical treatment is becoming a trend. Corneal incision creation, continuous circular capsulorhexis, and nuclear fragmentation are important factors that affect the safety and postoperative outcomes of phacoemulsification. Femtosecond laser, as an ultrashort pulse laser with large instantaneous power, precise focusing, and strong penetration, offers a new choice for addressing this problem. The superiority of femtosecond laser-assisted cataract surgery lies in the programing and standardization of procedures with increased safety, accuracy, and predictability. However, with respect to postoperative visual acuity, refraction, and complications, femto phacoemulsification is not more advantageous than manual phacoemulsification. Integration of the femtosecond laser system with the phacoemulsification system can be expected to reduce the cost of equipment and assist in developing techniques that are superior to conventional phacoemulsification.

(9) Cerebral arteriovenous malformations

Cerebral arteriovenous malformations (AVMs) are direct, abnormal connections between arteries and veins, and are considered congenital lesions arising from aberrant vascular development during the intrauterine period. AVMs occur more often in youth and can cause

cerebral hemorrhage and seizures, which incur high lethality and morbidity. The key issues for AVMs include the mechanistic study of its occurrence and progression by targeting therapy to alter its biological behavior and brain function (including neurological and cognitive function) protection during the surgical treatment. Based on the present research status both in domestic and overseas, AVMs develop dynamically, initiated and modulated by a series of congenital and postnatal factors such as genetic variation, abnormal angiogenesis factors, and epigenetic and microenvironmental changes. The reversal or inhibition of these factors could cause degeneration of AVM behavior, thereby reducing bleeding. However, the nature of the specific factors and their spatial and temporal expression, as well as cross-interactions, remains unknown. With the development of radiological and surgical techniques, multimode radiological methods could be used for pre-operative evaluation and construction of personalized brain images by fusing the structural, functional, and hemodynamic images. Simultaneously, hybrid operation combined by vascular intervention and surgery could be used as a minimally invasive technique. A combination of these methods could be used to achieve personalized treatment and protection of brain function. The developmental trends include clarification of the congenital and postnatal factors contributing to AVM pathogenesis and progression based on large numbers of samples, development of targeting therapy for bleeding prevention, and evolution of multimode radiological imaging and hybrid operation techniques for protecting brain function during treatment of AVMs.

1.2 Understanding of engineering research focus

1.2.1 Stem cells and regenerative medicine

The concept descriptions of stem cells and regenerative has been mentioned in section 1.1 (1).

Although considerable progress has been made in stem cell research and regenerative medicine in recent years, many issues remain unsolved and require attention as mentioned below: ① accurate identification of certain types of stem cells is still difficult, largely owing to the heterogeneity of stem cells and ambiguity of stem cell markers; ② the molecular mechanisms of stem cell fate decisions, including both the intrinsic cellular mechanisms and the niche-mediated regulation of stem cells, are not fully understood; ③ robust methods for generating stem cells for clinical applications under well-defined conditions are required; ④ the functional deficiency (e.g., impaired self-renewal or lineage bias) of the cultured and reprogrammed stem cells, and the low efficiency of differentiation into cells of interest, render obtaining enough cells for clinical applications difficult; ⑤ serious concern about potential immune rejection and oncogenic risks for cells derived from PSCs exists; ⑥ methods for boosting endogenous stem cell production or in situ trans-differentiation for tissue regeneration and repair have to be established to bypass transplantation; and ⑦ methods and the underlying mechanism for derivation of complex structures and organs in vitro should be explored for allogenic and autologous organ transplantation in the future.

Advanced technologies have enabled rapid progress in stem cell research. In particular, several new technologies would be instrumental for solving the issues mentioned above: ① tracing of stem cells in vivo by reporter genes or molecular barcodes, in combination with high-resolution imaging techniques, would facilitate better characterization of various stem cells, as well as their interactions with the surrounding environment; ② single cell technologies for isolation and characterization of stem cell populations at the "omics" level (i.e., genomics, epigenomics, transcriptomics, and proteomics) can delineate the heterogeneity of stem cells and clarify the underlying mechanisms; ③ the recently developed genome-editing approaches are powerful tools for manipulating stem cells for both research and clinical applications; ④ robust, clinical-scale cell culture and expansion methods for certain stem cells (e.g., hematopoietic stem cells) are important but remain challenging; and ⑤ novel materials such as biomimetics and three-dimensional culture methods. Stem cells and regenerative medicine have always been the hotspots for international biomedical research. China has also made several exciting contributions towards stem cell research in recent years while developed countries like the USA and Japan remain the leaders in this area.

The top three countries with the maximum number of core papers on "Stem cells and regenerative medicine" are the USA, Switzerland, and Canada (Table 1.2.1). The top three countries or regions with the average citation frequency are Scotland, Italy, and Japan (Table 1.2.1). The

cooperative network of the top 10 countries with the most core publications output (Figure 1.2.1) show that the USA, Australia, Japan, and Scotland are comparatively more cooperative.

The top three institutions according to the number of publications are the Johns Hopkins University, École Polytechnique Fédérale de Lausanne, and the Harvard University (Table 1.2.2). The top three institutions with average citation frequency are The University of Edinburgh, Brigham and Women's Hospital, and then Harvard University (Table 1.2.2). The cooperative network of the top ten institutions with the most core publications output (Figure 1.2.2) show that the Harvard University, Brigham and Women's Hospital, University of Queensland, and The University of Edinburgh share a more connective tie.

The top 10 institutions producing core papers cited by core papers mainly include Johns Hopkins University, Harvard University and Brigham and Women's Hospital in the USA, École Polytechnique Fédérale de Lausanne in Switzerland, the University of Queensland in Australia, and the University of British Columbia in Canada, etc,

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "Stem cells and regenerative medicine"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	35	70%	1932	77.22%	55.20	7	0
2	Switzerland	8	16%	300	11.99%	37.50	2	0
3	Canada	7	14%	272	10.87%	38.86	0	0
4	Australia	6	12%	514	20.54%	85.67	1	0
5	Japan	5	10%	515	20.58%	103.00	1	0
6	England	4	8%	185	7.39%	46.25	0	0
7	Germany	4	8%	164	6.55%	41.00	0	0
8	Scotland	3	6%	392	15.67%	130.67	1	0
9	Italy	3	6%	382	15.27%	127.33	2	0
10	The Netherlands	3	6%	299	11.95%	99.67	1	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus "Stem cells and regenerative medicine"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Johns Hopkins University	7	14%	399	15.95%	57.00	2	0
2	École Polytechnique Fédérale de Lausanne	7	14%	249	9.95%	35.57	2	0
3	Harvard University	6	12%	560	22.38%	93.33	2	0
4	University of Queensland	6	12%	514	20.54%	85.67	1	0
5	University of British Columbia	5	10%	88	3.52%	17.60	0	0
6	Brigham and Women's Hospital	4	8%	413	16.51%	103.25	0	0
7	The Eunice Kennedy Shriver National Institute of Child Health and Human Development	4	8%	51	2.04%	12.75	0	0
8	The University of Edinburgh	3	6%	459	18.35%	153.00	1	0
9	RIKEN	3	6%	424	16.95%	141.33	1	0
10	Western General Hospital	3	6%	392	15.67%	130.67	1	0

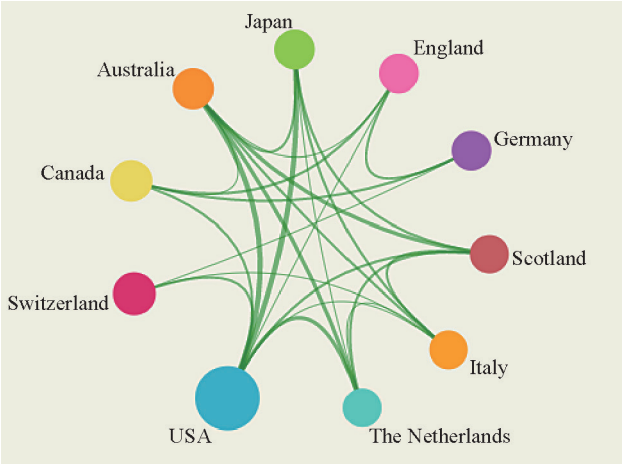

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Stem cells and regenerative medicine"[1]

whereas none of the institutions from China is included in the top 10 list (Table 1.2.3 and Table 1.2.4).

1.2.2 Molecular imaging technology

The concept descriptions of Molecular imaging technology has been mentioned in section 1.1 (2).

The current key scientific questions and investigations in the field of molecular imaging (domestic and international) are: ① How to improve the imaging specificity of a specific single molecule or multiple molecules in vivo? ② How to improve the imaging sensitivity of molecules with low concentration? ③ How to improve the imaging resolution for the spatial distribution or dynamic changes of molecules? ④ How to accurately link the computational learning and analysis

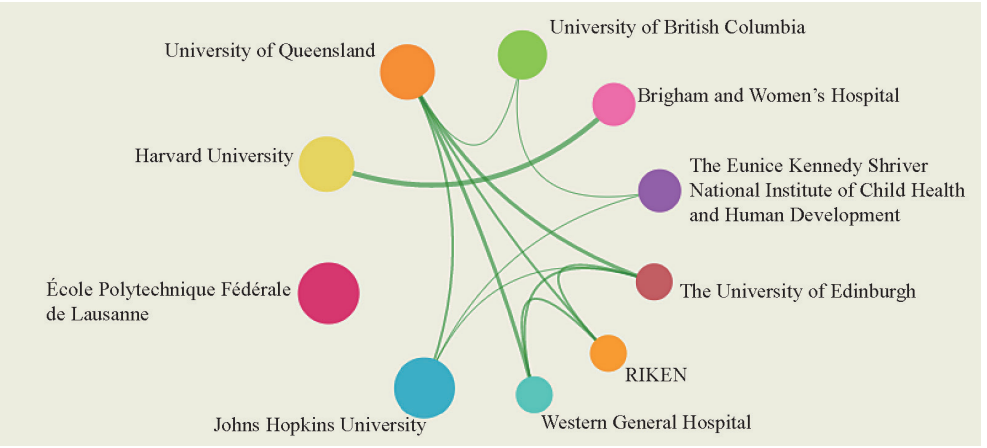

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Stem cells and regenerative medicine"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Stem cells and regenerative medicine"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	28	37.33%	2014.25
2	Canada	6	8.00%	2014.83
3	Switzerland	6	8.00%	2013.83
4	Australia	5	6.67%	2014.20
5	England	4	5.33%	2014.25
6	Germany	4	5.33%	2013.75
7	Japan	4	5.33%	2013.50
8	France	3	4.00%	2013.67
9	The Netherlands	2	2.67%	2015.00
10	Denmark	2	2.67%	2014.50

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Stem cells and regenerative medicine"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	École Polytechnique Fédérale de Lausanne	6	4.20%	2013.83
2	Johns Hopkins University	6	4.20%	2013.83
3	University of Queensland	5	3.50%	2014.20
4	Harvard University	5	3.50%	2013.60
5	Brigham and Women's Hospital	4	2.80%	2013.25
6	The University of British Columbia	4	2.80%	2015.50
7	Childrens Hosp	3	2.10%	2013.00
8	The Eunice Kennedy Shriver National Institute of Child Health and Human Development	3	2.10%	2015.33
9	Johns Hopkins Med Inst	3	2.10%	2014.67
10	University of Maryland	3	2.10%	2015.00

of medical imaging informatics to the diagnosis and prognosis of diseases?

Internationally, the trends in development of molecular imaging address questions related to translation of new imaging technology and/or molecular probes from preclinical animal model studies to clinical diagnosis and treatment, transformation of the medical applications of molecular imaging from diagnosis to precise therapeutics, early prediction and efficacy evaluation, and other comprehensive, integrated developments.

The research focus on molecular imaging technology includes:

(1) Hardware (including key components and the whole imaging system/instrumentation): Research and development (R & D) on sensing, imaging signal processing; imaging key components and equipment for converting raw data to images.

(2) Software (imaging processing and analysis): Computer processing and deep learning analysis of large image datasets, accurately linking the imaging data to the theranostics and prognosis of diseases; to establish mathematical models and reverse reconstructive algorithms based on investigations on in vivo propagation of light, sound, magnetism, radioactivity, and other physical phenomena, for improving image quality.

(3) Molecular imaging agents (single or multi-modality): Use of small organic molecules, peptides, polymers, nanoparticles, etc. to achieve real-time, rapid image detection at the molecular level. Recently, integrated therapeutic nano-composite has been introduced for imaging corresponding pathological information and targeted therapy via sensing, controlling, and targeting the biological microenvironment of diseases.

(4) Applications: Early diagnosis and detection of malignant tumors, accurate screening of the therapeutic targeted patient population, assessment of various treatment approaches (molecular targeted therapy, radiotherapy, chemotherapy, surgery, etc.) at an early stage; in vivo spatiotemporal dynamic imaging of stem cells or T cell trafficking, evaluation of therapeutic efficacy; early prediction and evaluation of cognitive function and treatment efficacy (aβ and tau protein PET imaging technologies) of Alzheimer's disease; pre-surgery functional localization of epileptic foci (PET and functional MRI); brain function and biochemical map (by PET and functional MRI) generation; neuro-function and neuro-biochemical mapping (PET and functional MRI, etc.).

(5) Studying novel principles and phenomenon-based multimodality imaging methods using multi-modality, multi-functional, multi-target smart molecular probes, and integrated multi-scale, multi-parameter, multi-functional image acquisition and processing; achieve multi-functional fused imaging and early and accurate detection of lesions using real-time multidimensional image trafficking and quantitative analysis of cells or molecules; apply multi-scale fused imaging for lesion localization and complete evaluation; use multi-time point fused imaging for transient imaging and dynamic analysis to achieve

multi-modality molecular imaging for early diagnosis; promote precise prediction, early diagnosis, and treatment of major diseases. China has a large market demand for molecular imaging technology, and its application covers all aspects of the diagnosis, treatment, and prognosis of major diseases. In addition, molecular imaging can be widely used for new drug development and in vivo evaluation. Since molecular imaging is at a critical stage for translating basic science to clinical application both in China and abroad, this is a key opportunity for China to develop molecular imaging technology. The estimated global research and application market for molecular imaging will surpass $100 billion by 2020.

The top 3 countries publishing core papers in the engineering research related to "Molecular imaging technology" are China, Singapore, and Korea (Table 1.2.5), and the top 3 countries or regions with average citation frequency are Taiwan of China, Korea, and Canada (Table 1.2.5). According to the international collaboration network (Figure 1.2.3), the USA, China, Taiwan of China, and Singapore have the maximum number of collaborations.

The top 3 institutions with core patent output are the Fudan University, Chinese Academy of Sciences, and Peking University (Table 1.2.6). The top 3 institutions with average citation frequency are the East China Normal University, Beijing Normal University, and National University of Singapore (Table 1.2.6). According to the collaboration network between major institutions (Figure 1.2.4), collaborations between the Peking University and the Harbin Institute of Technology, and the Jilin University and the Chinese Academy of Sciences are relatively strong.

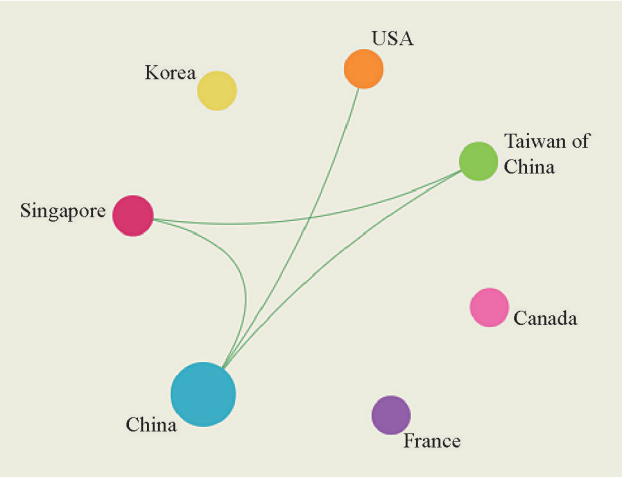

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Molecular imaging technology"

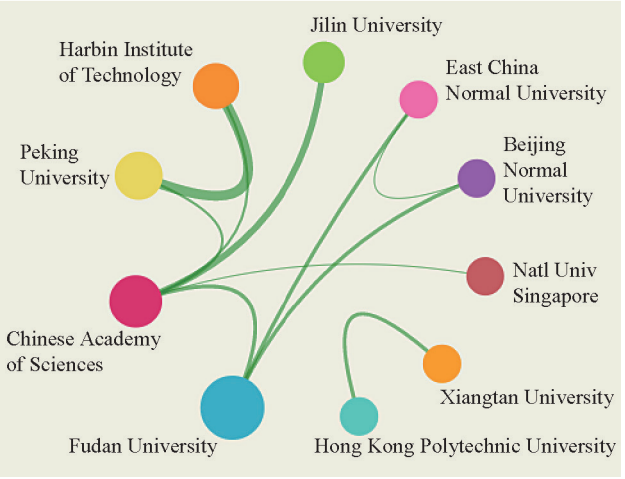

Figure 1.2.4 Collaboration network of the major producing institutes of core papers on the engineering research focus "Molecular imaging technology"

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Molecular imaging technology"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	41	83.67%	3077	81.14%	75.05	3	0
2	Singapore	4	8.16%	408	10.76%	102.00	0	0
3	Korea	2	4.08%	240	6.33%	120.00	0	0
4	USA	2	4.08%	67	1.77%	33.50	0	0
5	Taiwan of China	1	2.04%	134	3.53%	134.00	0	0
6	Canada	1	2.04%	119	3.14%	119.00	0	0
7	France	1	2.04%	56	1.48%	56.00	0	0

Fort-one core patents on molecular imaging technology have been applied from 2011 to 2016 in China, and institutions such as the Fudan University, Chinese Academy of Sciences, and Peking University have the most core patents, which indicate that China has become the leader in this research area.

The top 10 countries or regions or institutions producing core papers cited by core papers are mainly distributed in the Fudan University, Chinese Academy of Sciences, and Peking University, which shows that China is now a leader in this field (Table 1.2.7 and Table 1.2.8).

1.2.3 Chimeric antigen receptor T-cell immunotherapy

The concept descriptions of chimeric antigen receptor T-cell immunotherapy has been mentioned in section 1.1 (4).

The USA is the first country to start clinical trials of CAR-T. The global registered CAR-T clinical trials were concentrated in the USA before 2010. Europe started to register in 2011, and China in 2013. In 2014, CAR-T was designated a breakthrough therapy by the Food and Drug Administration (FDA) in the USA. There are currently 241 CAR-T clinical trials registered on clinicaltrials.gov worldwide, among which the top three countries are the USA (113), China (99), and Europe (24), respectively. In addition to the conventional therapies, CAR-T will be the most promising therapeutic approach, and is expected to change the landscape of cancer treatment. Although potential risks associated with the clinical use of CAR-T such as off-target effects, cytokine storm and other deficiencies to be improved further, and the anti-tumor effects require further validation for clinical application, it is beyond doubt that this new treatment would bring hope for cancer patients resistant to conventional treatment and is expected to become a novel anti-tumor therapeutic tool. The clinical efficacy of CAR-T therapy will achieve a greater breakthrough by screening of ideal target antigens, exploring the best CAR signal combinations, optimizing host conditions, combining other treatment options, as well as establishing standard operating procedures and

Table 1.2.6 Major producing institutions of core papers on the engineering research focus "Molecular imaging technology"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Fudan University	19	38.78%	2068	54.54%	108.84	3	0
2	Chinese Academy of Sciences	12	24.49%	751	19.80%	62.58	0	0
3	Peking University	9	18.37%	345	9.10%	38.33	0	0
4	Harbin Institute Of Technology	8	16.33%	212	5.59%	26.50	0	0
5	Jilin University	5	10.20%	220	5.80%	44.00	0	0
6	East China Normal University	3	6.12%	472	12.45%	157.33	0	0
7	Beijing Normal University	3	6.12%	400	10.55%	133.33	1	0
8	Natl Univ Singapore	3	6.12%	396	10.44%	132.00	0	0
9	Xiangtan University	3	6.12%	214	5.64%	71.33	0	0
10	Hong Kong Polytechnic University	3	6.12%	214	5.64%	71.33	0	0

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Molecular imaging technology"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	35	83.33%	2012.66
2	Singapore	4	9.52%	2013.25
3	France	1	2.38%	2012.00
4	Taiwan of China	1	2.38%	2012.00
5	Korea	1	2.38%	2012.00

quality control system. Recently, companies such as Novartis and Kite submitted applications to the FDA of the USA for approving the commercialization of CAR-T therapies. With accumulation of clinical experience and expansion of scientific research, we expect this novel cellular immunotherapy to be more effective, safe, and widely used for cancer treatment, and to contribute to the development of medicine and human health.

The top 3 countries or regions ranked by core publications related to "chimeric antigen receptor T-cell immunotherapy" research are the USA, Germany, and the UK, respectively (Table 1.2.9), and the top 3 countries ranked by average citation frequency of a paper are Canada, the USA, and Greece, respectively (Table 1.2.9). Germany, the USA, the UK, and Canada collaborate more according to the collaborative network (Figure 1.2.5) of the countries with core paper output. The top 3 institutions ranked by core publications are the University of Pennsylvania, National Cancer Institute, Children's Hospital of Philadelphia, and Memorial Sloan Cancer Center, respectively (Table 1.2.10), and the top 3 institutions ranked by average citation frequency of a paper are the Children's Hospital of Philadelphia, University of Pennsylvania and National Institutes of Health, respectively. According to the cooperation network of the top 10 institutions ranked by core publication output (Figure 1.2.6), there has been greater cooperation between the National Cancer Institute and the National Institutes of Health, between the Children's Hospital of Philadelphia and the University of Pennsylvania.

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Molecular imaging technology"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Fudan University	18	21.95%	2012.06
2	Chinese Academy of Sciences	11	13.41%	2012.91
3	Peking University	6	7.32%	2013.67
4	Harbin Institute Of Technology	5	6.10%	2014.20
5	Jilin University	5	6.10%	2013.00
6	Xiangtan University	3	3.66%	2013.33
7	Hong Kong Polytechnic University	3	3.66%	2013.33
8	National University of Singapore	3	3.66%	2012.67
9	Beijing Normal University	2	2.44%	2011.00
10	East China Normal University	2	2.44%	2011.50

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	44	89.80%	6578	98.50%	149.50	3	2
2	Germany	6	12.24%	148	2.22%	24.67	0	0
3	England	3	6.12%	134	2.01%	44.67	0	0
4	Canada	2	4.08%	611	9.15%	305.50	0	0
5	China	2	4.08%	17	0.25%	8.50	1	0
6	Greece	1	2.04%	49	0.73%	49.00	0	0
7	Qatar	1	2.04%	12	0.18%	12.00	0	0
8	Italy	1	2.04%	8	0.12%	8.00	0	0

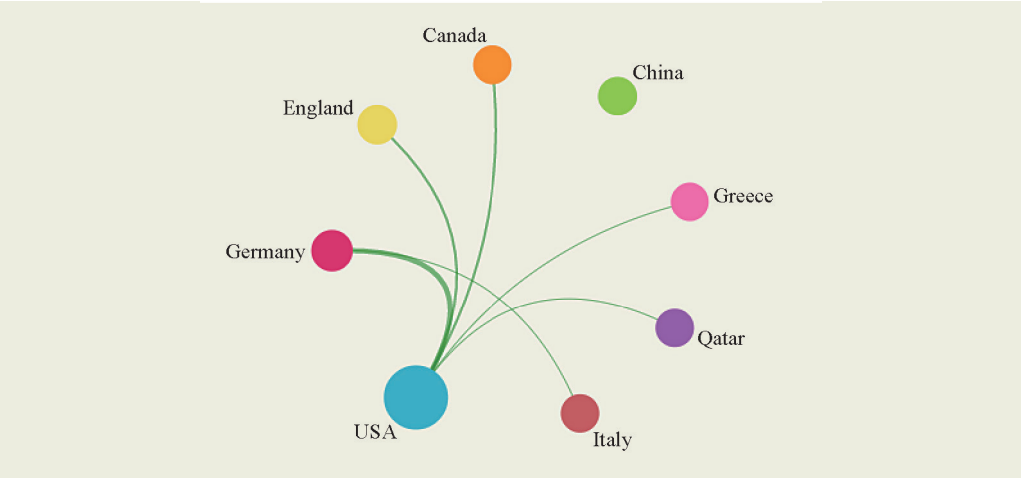

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

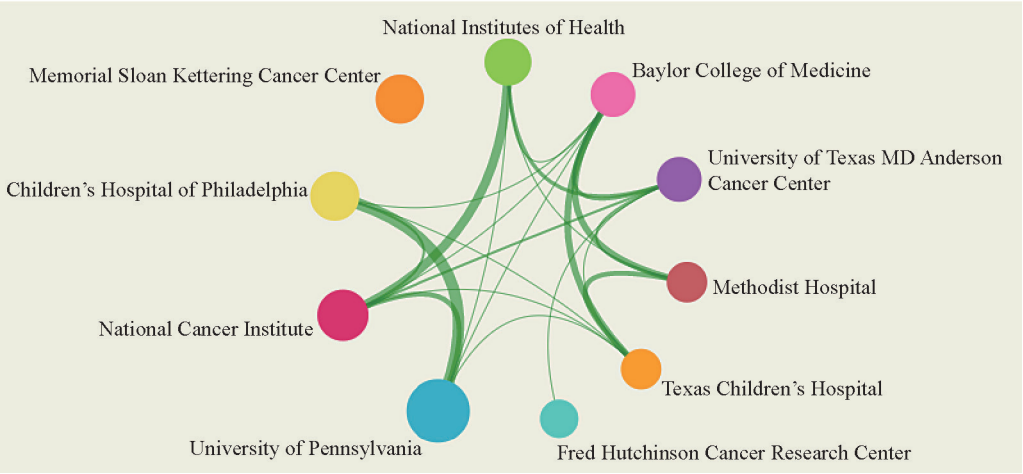

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

The top 10 countries or regions and research institutions ranked by core papers cited by core papers are mainly concentrated in the university of Pennsylvania, the National Cancer Institute, the Children's Hospital of Philadelphia and the National Institutes of Health (Table 1.2.11 and Table 1.2.12). In general, the USA takes the lead in this field.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 hotspots related to engineering development in medicine and health include basic medicine, clinical medicine, pharmacy, medical informatics and biomedical engineering, public health and preventive medicine, and other subjects (Table 2.1.1). "Genome editing" is an emerging hotspot. Conventional research has focused on "Immune cell therapy technology," "Stem cell technologies," "Biomedical materials," "Wearable medical sensors," "DNA sequencing technologies," "Telemedicine," "Precision drugs," "Vaccine preparation," and "Medical imaging techniques." All core patents related to these hotspots published between 2011 and 2016 are listed in Table 2.1.2.

(1) Genome editing

Genome editing originated from genetic engineering

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	University of Pennsylvania	16	32.65%	3272	49.00%	204.50	2	1
2	National Cancer Institute	10	20.41%	1224	18.33%	122.40	2	1
3	Children's Hospital of Philadelphia	9	18.37%	2133	31.94%	237.00	1	0
4	Memorial Sloan Kettering Cancer Center	9	18.37%	1177	17.63%	130.78	0	0
5	National Institutes of Health	8	16.33%	1193	17.86%	149.13	1	0
6	Baylor College of Medicine	7	14.29%	882	13.21%	126.00	0	0
7	University of Texas MD Anderson Cancer Center	7	14.29%	789	11.81%	112.71	0	1
8	Methodist Hospital	5	10.20%	721	10.80%	144.20	0	0
9	Texas Children's Hospital	5	10.20%	720	10.78%	144.00	0	0
10	Fred Hutchinson Cancer Research Center	4	8.16%	173	2.59%	43.25	0	1

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	34	70.83%	2014.26
2	Germany	5	10.42%	2015.00
3	Canada	2	4.17%	2013.50
4	England	2	4.17%	2013.50
5	China	2	4.17%	2015.50
6	Greece	1	2.08%	2013.00
7	Qatar	1	2.08%	2016.00
8	Italy	1	2.08%	2015.00

in the late 1970s, and since 2000, the discovery of engineered nucleases has advanced the technology. In the past five years, genome editing has become a research hotspot in various fields ranging from basic research to practical applications. Genome editing technology employs programmable nucleases for inducing precise cleavages at specific genome loci. The induced double-strand DNA breaks are fixed via endogenous DNA repair mechanisms, including non-homologous end joining (NHEJ), or, homology-directed recombination (HDR) once a template provided. Currently, three major classes of nucleases have been widely utilized to enable site-specific genome editing including zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and clustered regularly interspaced short palindromic repeat (CRISPR)/Cas9. Particularly, CRISPR/Cas9 is more precise and efficient, although it is based on relatively simple design principles. Therefore, it has broadened the potential of genome editing and has proven to be extraordinarily valuable for high-throughput genome

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Chimeric antigen receptor T-cell immunotherapy"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	University of Pennsylvania	14	11.48%	2014.21
2	National Cancer Institute	9	7.38%	2014.67
3	Children's Hospital of Philadelphia	7	5.74%	2014.00
4	National Institutes of Health	7	5.74%	2014.29
5	University of Texas MD Anderson Cancer Center	6	4.92%	2014.17
6	Memorial Sloan Kettering Cancer Center	6	4.92%	2014.33
7	Fred Hutchinson Cancer Research Center	4	3.28%	2015.00
8	University of Washington	4	3.28%	2015.00
9	Baylor College of Medicine	4	3.28%	2013.25
10	Hackensack University	3	2.46%	2014.67

Table 2.1.1 Top 10 engineering development hotspots in medicine and health

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Genome editing	231	5 430	23.51	2014.13
2	Immune cell therapy technology	654	16 090	24.60	2012.49
3	Stem cell technologies	1 173	21 013	17.91	2012.31
4	Biomedical materials	191	3 125	16.36	2012.19
5	Wearable medical sensors	527	36 151	68.60	2012.66
6	DNA sequencing technologies	480	9 633	20.07	2013.07
7	Telemedicine	31	380	12.26	2012.77
8	Precision drugs	270	7 368	27.29	2012.45
9	Vaccine preparation	765	17 392	22.73	2012.32
10	Medical imaging techniques	179	3 990	22.29	2012.13

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in medicine and health

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Genome editing	19	3	10	108	79	12
2	Immune cell therapy technology	201	147	149	103	47	7
3	Stem cell technologies	425	281	239	156	56	16
4	Biomedical materials	68	54	38	27	4	0
5	Wearable medical sensors	148	116	95	108	56	4
6	DNA sequencing technologies	102	80	76	137	74	11
7	Telemedicine	9	4	6	9	3	0
8	Precision drugs	80	71	53	51	14	1
9	Vaccine preparation	241	214	176	98	33	3
10	Medical imaging techniques	76	41	37	15	7	3

engineering, attracting great enthusiasm and investments from biomedical research institutes and pharmaceutical companies. The market is expected to surpass $5 billion by 2021.

(2) Immune cell therapy

Immune cell therapy is an immunotherapy-based strategy used for cancer treatment, in which the immune cells collected from the patient's blood are modified and expanded in vitro, and later infused back into the patient. It not only directly kills tumor cells, but also activates the immune system against tumors. Immune cell therapy has a history of more than three decades. With the rapid development in biological technology, the regimens of immune cell therapy have shown notable curative effect on advanced tumors that are resistant to conventional therapies, thus drawing increased attention in the areas of science and medicine. In 2011, Nature reported that immune cell therapy would cause a new round of research upsurge, and might play an important role in cancer therapy in the future. Cancer immunotherapy was first in the list of "the world's top ten scientific and technological breakthroughs" according to Science in 2013, and became the focus of the Science Frontier. In 2016, the USA government launched the "Cancer MoonShot" project, in which immune cell therapy is highly expected to become one of the main approaches for dramatically increasing the therapeutic efficacy of cancer treatment and a practice of precision medicine. This technology is considered one of the most revolutionary technologies, which opens up new ideas for a variety of intractable diseases (tumors, cardiovascular diseases, nervous system diseases, etc.) and brings new hope for conventional incurable diseases, indicating a great potential for application. Immunotherapy has become the fourth cornerstone of cancer treatment along with the other three standard treatments, namely, surgery, chemotherapy, and radiotherapy.

(3) Stem cell technology

Stem cell technology involves harnessing the multipotency of stem cells for remedying, healing or replacing damaged tissues or organs in organisms. Stem cells can be classified into pluripotent stem cells (PSCs) and adult stem cells. PSCs can be then further classified into embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs). ESCs are derived from embryos, and can differentiate to any cell type within the three germ layers (i.e. ectoderm, mesoderm, endoderm). iPSCs are pluripotent stem cells genetically reprogrammed from mature somatic cells to embryonic stem cell-like state. With the advent of iPSCs and reprogramming technologies, researchers can circumvent ethical issues of using embryos, while also generating patient-specific PSCs, which may avoid immune rejection in allogenic transplantations. Adult stem cells are undifferentiated cells found in multiple tissues throughout the body, which act as a repair system and replenishes dying cells or damaged tissues by differentiating to various cell types within a specialized tissue, e.g. neural stem cells. Owing to the repairing nature of stem cells, they are widely used in the treatment of several diseases including neurological, hematological, cardiovascular, hepatic, and renal diseases. It is of noteworthy that hematopoietic stem cells transplantation, a paradigm for stem cell therapies, has been broadly used for treating hematological malignancies, which have greatly improved the survival and health status of the patients. With the recent development of reprogramming technologies, pluripotent stem cell-based clinical trials for age-related macular degeneration have already been initiated in Japan. Preliminary reports of the iPSCs-derived retinal transplant in patients showed promising results; however, further clinical investigations are required.

(4) Biomedical materials

Biomedical materials are used for the diagnosis, treatment, repair, or replacement of damaged tissues and organs, or for enhancement of organ functions. In accordance with international practice, its management belongs to the scope of medical devices, accounting for about 40% of the market share of medical devices. According to the composition and properties, these materials are divided into medical metal materials, medical polymer materials, bioceramic materials, and biomedical composite materials. Biomedical materials originated in the mid-40s of last century, and the industry was formed in the 80s of last century. The application of biomedical materials not only saved a large number of lives of critically ill patients, but significantly reduced mortality associated with cardiovascular diseases, cancer, trauma and other major diseases and improved people's health level and quality of life. Thus, it has played a leading role in reforming contemporary medical technology and health care system, and has significantly reduced the cost of medical care.

(5) Wearable medical sensors

Medical sensors and transducers are important devices that transform the parameters and vital signals of the human body into measurable targets. Medical sensors are widely used in medical devices and medical research, from bedside monitors for human physiological parameters (heart rate, blood oxygen, breathing, body temperature, blood pressure, and so on) to the operation room monitors, which require continuous blood pressure monitoring, body temperature monitoring and intensive care unit monitors for measuring blood oxygenation level and intracranial pressure. Medical sensors are also the core components of large medical equipment such as ultrasound, endoscopic surgery robotics, rehabilitation robotics, etc., some of which are used for feedback control. They also find applications in optogenetics, miniature confocal microscopy, traditional Chinese medicine (the so-called "watch-listen-inquiry-touch" diagnostics), as well as in vitro diagnostics. The latest miniature molecular imaging microscope can distinguish tumor cells and normal cells in real time during operation. With the development of semiconductor and material technology, medical sensors are advancing towards miniaturization, implantation, and becoming wireless. Non-invasive wearable medical sensors are increasingly used in daily life for continuous monitoring of blood glucose, ECG, blood pressure, etc. Some of the sensors are be embedded in a variety of clothing, such as sports shoes, underwear, helmets and so on. Wearable medical sensors with various measurement parameters are becoming ubiquitous and transparent to the users. Today's novel electrochemical sensors can detect the human health status by measuring human breath and can determine the resection of benign and malignant cells by detecting smoke from minimally invasive surgery. Researchers are also working on developing point-of-care in vitro diagnostic (IVD) chip, where the electrochemical sensor with high sensitivity can detect small changes of dielectric constants scanned at low or high frequency in different cells, bacteria, and viruses. Implantable medical "wet interface" sensors have entered the mainstream, such as implanted electrode sensors for the brain wet interface, image sensor for the optic nerve and auditory nerve interface, sound sensor for vision and hearing repair, and implanted neural interface for paralyzed patients. Simultaneously, the study of biomimetic extrinsic implant sensors based on synaptic discharge and membrane ion channels is also developing rapidly. With the popularity of sensors, active wearable medical sensors that can take measurements and provide real-time feedback to the receiver have entered the market. For example, brainwave sensors are used to provide meditation feedback and facilitate people to meditate or provide brain wave measurements and stimulation to improve athletes' performance and rehabilitation. Ubiquitous medical sensors have spawned a huge industry of big health data, which has immeasurable social significance for the maintenance of human health.

(6) DNA sequencing technologies

DNA sequencing is the process of determining the precise order of nucleotides (adenine, guanine, cytosine, and thymine) in a particular region of DNA. DNA sequencing technologies have evolved through at least three or four generations from the first-generation Sanger sequencing in 1977. Sequencing technologies now permit genome, epigenome, transcriptome, or protein profiling of single cells sampled from various cell types, as well single cell multi-omics measurements. Decoding of the genome sequence provided a powerful tool for unlocking the mysteries of life, understanding medical genetics, uncovering disease mechanisms, identifying new mutations, diagnosing diseases in prenatal testing, and developing drugs for target therapy of cancer. The advent of single cell sequencing (SCS) enabled understanding of biological heterogeneity, study of the molecular mechanisms of embryo development and gametogenesis, determination of the cause of unexplained infertility, and accurate diagnosis of genetic diseases in pre-implantation embryos. Use of blood samples to examine DNA from tumor cells (liquid biopsy) can detect diseases at an early stage and circumvent the pain of surgery, monitor disease development, and custom-design treatment. Additionally, as a safe and reliable method for identifying affected fetuses before birth, non-invasive prenatal diagnosis (NIPD) is becoming increasingly popular for clinical and research applications. With rapid development, simplification of sample treatment procedures, improvement of data analysis protocol, and reduction in cost, genome sequencing technology will soon be available for common use in the laboratory and clinic. Sequencing technology will undoubtedly accelerate the progress of biomedical research, deepen the understanding of the pathogenesis of disease, promote the application of

personalized therapy, facilitate diagnosis and treatment of rare diseases, increase the opportunities for healthy birth, and improve the efficiency of disease diagnosis, prevention and treatment.

(7) Telemedicine

Telemedicine refers to the combination of medical science with the technology of remote communication, multimedia, data exchange and internet, which makes the remote acquisition, transmission, processing, storage and query of the various medical and health information possible, so as to realize detection, monitoring, diagnosis, information transmission and management of the remote object, and so on. Since the 1950s, telemedicine has developed from the initial voice communications realized at large medical centers for providing long distance medical information and services to poor and underdeveloped areas, into real-time interaction of interagency information, and significantly improved the accessibility and fairness of medical service. With the development of technology, the scope, form, efficiency and quality of telemedicine service continually improved. The key technical problems of telemedicine research in the current and upcoming period include those related to telemedicine information collection technology such as remote real-time rendering, intelligent speech recognition, use of remote check terminal and remote medical monitoring robots, safe reliable high-speed medical information transmission technology, data security technology of multi-source heterogeneous data interaction and integration, service platform, data processing and image reconstruction, management support technology of specialist processes, and quality specification. Telemedicine will continue to deepen the innovation and application in the areas of remote specialized diagnosis (e.g., ECG, imaging, pathology, and medical examination), clinical auxiliary diagnosis and treatment (e.g., remote consultation, outpatient service, operation guidance, medical services, etc.), health emergencies and disease emergency rescue, remote care, health management, intelligent decision support, remote medical education, remote medical surgery, information system, and platform construction, to usher in a profound technological revolution in traditional medical services.

(8) Precision drugs

Precision drugs refer to the small molecule drugs and biological drugs targeting specific molecules associated with a disease. With the development of omics technologies and bioinformatic tools, many biomarkers for specific diseases are identified based on analysis of big omics data from large samples. Some of them have been further evaluated as potential drug targets by investigating disease pathogenesis. Currently, small molecule inhibitors targeting intracellular kinases and monoclonal antibodies binding to cell membrane/extracellular proteins are widely used in clinical practice. With the development of technologies in drug discovery, application of machine learning and artificial intelligence would provide breakthrough tools for screening and designing small molecule drugs in addition to traditional methods such as virtual screening, structure-based drug design, and DNA-encoded compound library screening technology. Likewise, intelligent design and optimization platform based on antigen-antibody interaction patterns will promote the discovery of therapeutic antibodies compared to the current technologies used for antibody screening, humanization, and affinity maturation. In addition, establishment of animal models for human disease will also be essential for precision drug development. Collectively, application of rapid and efficient technologies will greatly improve the discovery of precision drugs for critical diseases such as cancer, autoimmune diseases, and inflammatory diseases, which would be of great significance for human health.

(9) Vaccine preparation

Vaccines are biological products used for preventing the occurrence and controlling the prevalence of infectious diseases via human-specific immune responses, namely, active immunity in terms of response to new antigens and passive immunity based on the presence of antibodies against "seen" antigens. The incidence rate of several infectious diseases have declined significantly due to the direct contribution of broad vaccination worldwide, e.g. vaccines for smallpox, poliomyelitis, measles, diphtheria, pertussis, hepatitis B, etc. Vaccine research and development in China made some critical breakthroughs during the past decade. Japanese encephalitis vaccine developed in China received WHO pre-certification in 2013, and the product has been exported to many developing countries in Asia. The comprehensive clinical trial of the Chinese recombinant Ebola vaccine was conducted in Africa in 2015, which marks a historic breakthrough for the Chinese vaccine industry. Nowadays,

the most challenging issue of global vaccine research and development is that the traditional methodology used in the development of inactivated vaccines, attenuated live vaccines, and other traditional vaccine, cannot be successfully used for generating vaccines against many infectious diseases, such as acquired immunodeficiency syndrome (AIDS) and dengue. Another issue is that the current processing methodologies for pathogen culture, separation, and purification cannot meet the needs of emergency vaccine manufacture. With the emergence of certain innovative vaccines such as subunit vaccines, viral vector vaccines, virus-like particle vaccines, and nucleic acid vaccines, and development of other cutting-edge technologies in vaccine development such as gene editing, synthetic biology, single-use bioreactors, advanced bio-manufacturing platform with process modularization and flexible factory, highly effective vaccine adjuvant, novel drug delivery system, and thermal stability technology, the efficiency of vaccine research and the manufacturing capacity of vaccines will improve significantly. Meanwhile all other sectors of global biopharmaceutical industry will also benefit from these technology progresses.

(10) Medical imaging techniques

With the development in informatics and medical imaging techniques, the importance of image analysis in clinical and scientific research has increased, which has led to immense progress in medical research and clinical treatment. Using serial digital image analysis and process techniques such as image enhancement, segmentation, registration, fusion and three-dimensional reconstruction, anatomic structures and diseased regions can now be localized, acquired, displayed in three dimensions, and quantified, which ensures the maximal utilization of medical imaging datasets. Certain developing perspectives include tomography image data analysis, 3-dimensional reconstruction model, tissue imaging techniques, holographic radiology diagnosis systems, big-data cloud process for medical images, magnetic interaction imaging devices, and so on. The above techniques are used in many fields, such as guided disease treatment (assisted surgery and imaging-guided radiotherapy) through rapid imaging process, establishment of radiomic or radio-genomic model, multi-modality molecular imaging and integrated traditional anatomic imaging, and new functional molecular imaging for extensively exploring the correlations between image information and disease biology information and prognosis, which would ensure accuracy in disease diagnosis and treatment.

2.2 Understanding of engineering development focus

2.2.1 Genome editing

The concept descriptions of genome editing has been mentioned in section 2.1 (1).

Genome editing applications take advantages of DNA repair mechanism triggered by site-specific double strand breaks (DSBs) to engineer a wide variety of genomic modifications as mentioned below: ① Gene knockout/deletion. This form of gene editing utilizes the error-prone nature of NHEJ to introduce small insertion-deletions (indels) at the target site, inducing frame-shift mutations in genes. It can be employed for disruption of disease-related genes or for establishment of disease models, etc. For example, generation of the CCR5 knockout via gene editing was employed to treat HIV infection. Gene editing at dual or multiple sites can simultaneously remove a designated fragment in order to activate or deactivate a gene of interest, such as excision of exons to restore the correct reading frame for a gene involved in Duchenne muscular dystrophy (DMD), or deletion of enhancer regions to treat hemoglobinopathies. ② Gene correction. This is used to correct disease-causing mutations in situ by promoting homology-directed recombination with an exogenous donor template. It has great potential in gene therapy of inherited diseases such as hemophilia. ③ Gene insertion. Exogenous genes are incorporated into the desired genomic site by genome editing, bypassing or alleviating risks of insertional mutagenesis due to random integration of viral vectors. In addition, targeted insertion of a normal copy of the defective gene into the endogenous locus theoretically enables physiological levels of expression. The capability of manipulating genomic sequences by genome editing has created numerous opportunities in medicine, agriculture, and the pharmaceutical industry. Gene editing strategies used for therapeutic purposes in clinical or preclinical applications are listed below: ① Anti-infectious diseases. The most common application is partially knocking out the genome of pathogens such as viruses, bacteria, etc. ② Cancer immunotherapy. Combining the CRISPR technology with CAR-T cell immunotherapy promises

to broaden the application of T-cell immunotherapy for diverse cancer types, and improve its safety aspects. Knockout of *PD-1* in T cells via gene editing increased T-cell effector function. ③ Treatment of hematological diseases. β-thalassemia was recovered at the molecular level by correcting the mutations in the hemoglobin-encoding sequence via gene editing-mediated ex vivo therapy. ④ Ocular disorders. Proof-of-principle studies suggest that deletion of an intronic region in *CEP290* via Cas9 gene editing restored substantial *CEP290* expression for the treatment of Leber congenital amaurosis (LCA). ⑤ Neuromuscular disorders. Recent studies demonstrated that deletion of one or more exons by CRISPR/Cas9 editing restored the expression of the dystrophin protein products in treatment of DMD. ⑥ Treatment of other disorders such as skin disorders, respiratory disorders, etc. In addition, genome editing technologies have exhibited extensive potentials in other fields. Genome editing-mediated genetic alteration in crops and animals may lead to remarkable increase in agricultural productivity and/or improve resistance to pathogens. In industry, numerous disease models can be established with high efficiency and less time using gene editing as the drug screening and evaluation platform. Genetically modified tools can be used competitively to augment industrial productivity. Based on the delivery methods, therapeutic genome editing strategies include ex vivo and in vivo therapy. In ex vivo therapy the target cells, such as somatic cells or hematopoietic stem cells (HSCs), are isolated from the patient, modified with the genome editing system, and subsequently returned to the host. This mode of treatment is likely to achieve higher editing efficiency with more flexible delivery methods under positive selection. Up till now, a number of clinical trials utilizing gene editing strategy have made breakthrough achievements, such as anti-HIV therapy. Moreover, combining the induced pluripotent stem cell (iPSC) technology with genome editing is very likely to have broader clinical applications. In vivo genome editing directly delivers the system into the host to target organs or tissues. The success of the in vivo therapy largely relies on the efficiency of the delivery vehicles. The main technical barrier is the divisional status of cells, which has an important effect on the system intake and editing efficiency. Lack of in vivo selection methods is also a drawback of the editing rate. So far, adeno-associated virus (AAV)-mediated Cas9 delivery has been demonstrated to be successful with specific tissue tropisms, such as to the liver and brain. Preclinical studies are currently under investigation using these methods.

At present, the primary challenges regarding clinical translation of genome editing are the safety concerns related to its off-target effects and the efficacy of the treatment. To address the safety issue, investigators optimize available systems to enhance targeting specificity; on the other hand, novel editing nucleases have been explored as alternative tools. The challenge to achieve efficient delivery needs to be solved by developing more accessible systems. Among a variety of viral vectors, the advantages of AAV vectors have gained remarkable attention and investments. In addition, non-biological vehicles such as nanoparticles might be a potent tool for delivering the editing system and should be optimized further. Genome editing has also attracted tremendous research interest in China. So far, the total number of the papers in this field published between 2011 and 2016 by Chinese investigators rank second worldwide. Therefore, further development should focus on discovering innovative technologies and promoting practical applications. In addition, ethical scrutiny and regulatory management are urgently required for appropriate application of the technology. The future of genome editing technology will depend on understanding of the current experience combined with systematic optimization and scientific planning.

In total, 231 core patents have been applied on genome editing methods within the past 5 years. The USA, Germany, France, Switzerland, and Japan rank as the top 5 countries with the most patents, and the USA is indeed in the leading according to the international collaboration network (Figure 2.2.1). Chinese authors have applied for 1.30% of the patents with an average citation frequency of 5 (Table 2.2.1).

The top 3 institutions with the maximum number of core patent inventors are the Broad Institute Inc., Massachusetts Institute of Technology, and Harvard College(Table 2.2.2), with the latter two institutions being the most productive. Furthermore, the collaboration network among international institutions(Figure 2.2.2) shows that there are active collaborations among various institutions, especially within the top three institutes.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Genome editing"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	217	93.94%	5277	97.18%	24.32
2	Germany	10	4.33%	212	3.90%	21.20
3	France	5	2.16%	38	0.70%	7.60
4	Switzerland	4	1.73%	40	0.74%	10.00
5	Japan	4	1.73%	60	1.10%	15.00
6	China	3	1.30%	15	0.28%	5.00
7	Canada	2	0.87%	4	0.07%	2.00
8	Denmark	2	0.87%	20	0.37%	10.00
9	Hungary	1	0.43%	9	0.17%	9.00

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Genome editing"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Broad Inst Inc	102	44.16%	2946	54.25%	28.88
2	Massachusetts Inst Technology	102	44.16%	2946	54.25%	28.88
3	Harvard College	62	26.84%	1941	35.75%	31.31
4	Sangamo Biosciences Inc	32	13.85%	794	14.62%	24.81
5	Sigma-Aldrich Co Llc	14	6.06%	447	8.23%	31.93
6	Factor Bioscience Inc	8	3.46%	352	6.48%	44.00
7	Univ Rockefeller	8	3.46%	425	7.83%	53.13
8	Pioneer Hi-Bred Int Inc	7	3.03%	37	0.68%	5.29
9	Editas Medicine Inc	7	3.03%	118	2.17%	16.86
10	Pioneer Int Co Ltd	6	2.60%	36	0.66%	6.00

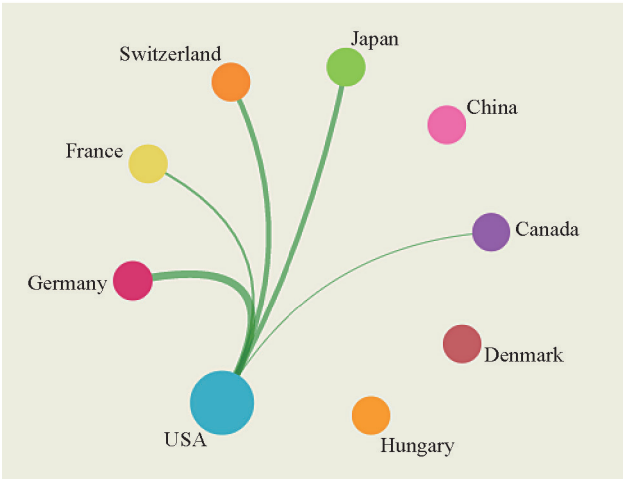

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Genome editing"

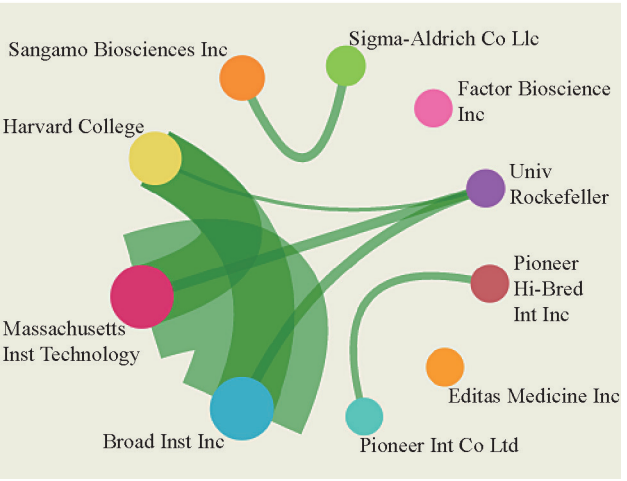

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Genome editing"

2.2.2 Immune cell therapy

The concept descriptions of immune cell therapy has been mentioned in section 2.1 (2).

The key technical problems of immune cell therapy include: ① Enhanced targeting to guide lymphocytes to tumor tissues precisely and efficiently. Developing more accurate and efficient living cell genetic modification techniques based on chimeric antigen receptor (CAR) γ δ T cells or natural killer cells (NK cells) (e.g., by using genetic engineering technique, we can produce T cells modified with monoclonal antibody against tumor-specific antigen linked to TCR receptor, CAR-T, or NK cells modified with tumor-specific monoclonal antibody linked to NK cell receptor NKG2D, CAR-NK) and antibody-arming technique (a technique that conjugates the monoclonal antibody with the toxins, which can direct the toxins to tumor cells through specific identification of tumor antigen by antibody and kill them). Currently, there are still a handful of tumor-specific targets and their corresponding targeting approaches available, which becomes the global focused competition. ② Large-scale expansion of lymphocytes. Owing to the limited number and short shelf-life of lymphocytes isolated from patient blood, obtaining a sufficient amount of effective lymphocytes is a key problem of this technology. So far, using an ordered combination of cytokines and co-stimulatory factors, sufficient amounts of immune cells such as cytokine-induced killer cells (CIK), cytotoxic T lymphocytes (CTL), NK cells, γ δ T cells, and dendritic cells (DC) can be obtained for clinical applications, which could be applied to different tumor types or patients. These immune cells can not only be directly infused into cancer patients, but also be genetically modified for developing cancer killer cells with precise targeting capabilities. However, limitations in several technical aspects, including the expansion efficiency of different types of immune cells in vitro, the amount of specific effector cells required, and the survival states of these cells in the human body after the infusion, still exist. Therefore, more systematic and standard specifications for researches in this field are needed. The most notable CAR-T technology involves the combination of the two above-mentioned techniques (large-scale expansion and CAR genetic modification), which presents encouraging efficacy in the treatment of hematological malignancies in clinical trials. CAR-T cells targeting various solid tumors have also entered clinical trials. In 2014, CAR-T was designated a "breakthrough therapy" by the FDA of USA. Currently, there are 241 CAR-T clinical trials registered on clinicaltrials.gov in the world, and among them, the top three contributing countries are the USA (113), China (99), and Europe (24), respectively. ③ Establish standard operating procedures of cellular immunotherapy. Owing to the individualization of operation, this technology has not been applied in large-scale production and used as conventional drugs. Therefore, it is necessary to establish a unified operating standard and a quality control system for effective use of this technology. Cell immune therapy in China started relatively late compared to other countries; however, it is now an emerging industry, and has been listed as one of the key research projects supported by the national policy. With the gradual standardization and improvement of China's industrial policy on immune cell therapy, as well as the entry of well-known international enterprises, the potential for the development of the industry will be released, and research and development regarding the clinical applications of this industry will develop faster.

There are 654 core patents for "Immune cell therapy technology" (Table 2.1.1) and the top five contributing countries are the USA, Germany, China, Switzerland, and France. Among them, the patents applied by Chinese authors accounted for 10.09%, and the proportion of the number of patents is large. China has become one of the key research countries of this focus of engineering development with the average citation frequency of 28.06(Table 2.2.3). As shown in the cooperation network of patent-producing countries (Figure 2.2.3), the United States, China and Switzerland cooperate more closely.

The top three institutions of the core patent output are Moderna Therapeutics, Atyr Pharma Inc and the University of Pennsylvania (Table 2.2.4), which are mainly biotech companies and universities. According to the cooperation network (Figure 2.2.4) between the major institutions, there is more collaboration between major output institutions developing the focused patent technology.

The closest cooperation is mainly between Atyr Pharma Inc and Pangu Biopharma Ltd companies, Novartis and the University of Pennsylvania, drug companies and research institutions of university, as well as Bayer and Curevac Gmbh companies.

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Immune cell therapy technology"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	487	74.46%	12 342	76.71%	25.34
2	Germany	73	11.16%	2 471	15.36%	33.85
3	China	66	10.09%	1 852	11.51%	28.06
4	Switzerland	50	7.65%	1 296	8.05%	25.92
5	France	30	4.59%	440	2.73%	14.67
6	Canada	10	1.53%	141	0.88%	14.10
7	UK	10	1.53%	86	0.53%	8.60
8	India	10	1.53%	73	0.45%	7.30
9	Sweden	7	1.07%	154	0.96%	22.00
10	Belgium	6	0.92%	147	0.91%	24.50

Table 2.2.4 Major producing institutions of core patents on the engineering development focus "Immune cell therapy technology"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Moderna Therapeutics	55	8.41%	1646	10.23%	29.93
2	Atyr Pharma Inc	48	7.34%	1992	12.38%	41.50
3	Univ Pennsylvania	43	6.57%	1213	7.54%	28.21
4	Pangu Biopharma Ltd	40	6.12%	1544	9.60%	38.60
5	Hutchinson Cancer Res Cent Fred	35	5.35%	537	3.34%	15.34
6	Novartis Ag	34	5.20%	1052	6.54%	30.94
7	Curevac Gmbh	29	4.43%	1520	9.45%	52.41
8	Bayer Intellectual Property Gmbh	26	3.98%	709	4.41%	27.27
9	Cellectis	22	3.36%	397	2.47%	18.05
10	Ibc Pharm Inc	22	3.36%	506	3.14%	23.00

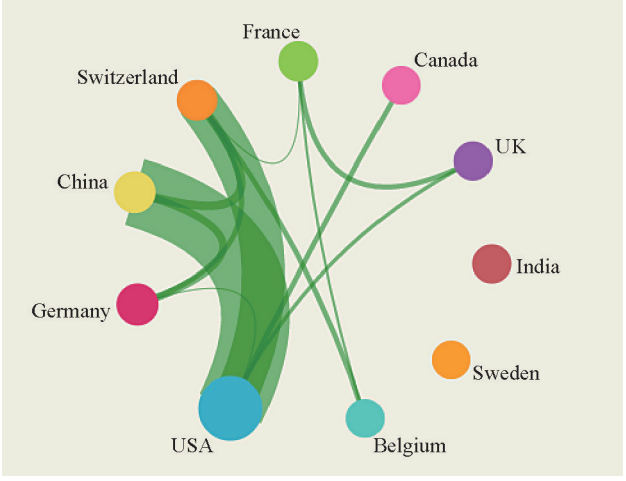

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Immune cell therapy technology"

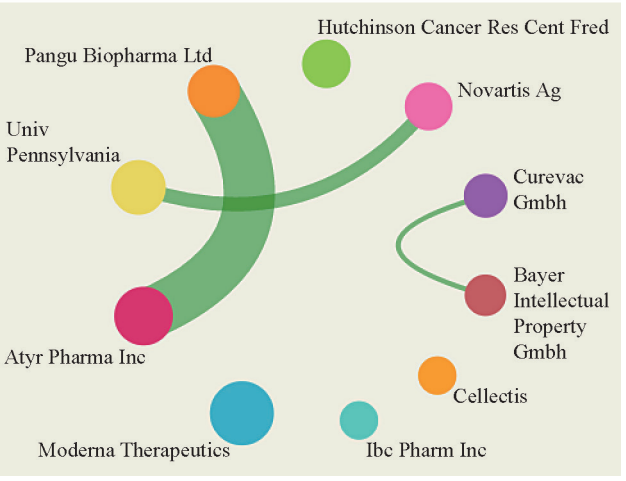

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Immune cell therapy technology"

2.2.3 Stem cell technology

The concept descriptions of stem cell technology has been mentioned in section 2.1 (3).

Although stem cell research has progressed immensely in recent years, certain critical technologies should be further developed for better understanding and clinical applications of stem cells: ① Establishment of robust, clinical-grade culture methods for culturing stem cells in vitro, methods for maintenance of pluripotency, especially the ground state of pluripotent stem cells, and deciphering the underlying mechanisms, optimization of in vitro reprogramming methods, identification of pluripotent stem cell-specific surface antigens and transcription factors, exploration of mechanisms underlying exit from pluripotency, lineage differentiation, and potential risks of tumor formation. ② Clinical-grade methods for isolation and culture of the adult (tissue) stem cells. Since the adult stem cells are heterogeneous in nature and their surface markers are not fully defined, current methods for long-term growth and expansion of self-renewing adult stem cells remain largely unsuccessful. ③ Directed differentiation of pluripotent stem cells. Specific tissues or cells can be derived from PSCs by addition of growth factors or drugs, which harness their pluripotency, e.g. islet β cells, endothelial cells, and hematopoietic stem cells, etc. ④ Transdifferentiation. Mature somatic cells can be converted into other cell types by ectopic expression of certain genes or induction by certain small molecules. Latest reports also show that transdifferentiation can occur in situ by converting cells within the damaged tissues into cells of interest for further treatment. ⑤ Engineering of complex structures in vitro. Stem cells can self-organize into organoid structures supported by certain biomaterials in three-dimensional culture. These organoids can recapitulate functions and structures of normal tissues and organs, which lay the foundation for future transplantation of artificial tissues and organs. ⑥ Methods for genetic and epigenetic manipulations of stem cells. Stem cells are characterized by unique biological traits. Cutting-edge methods such as genome editing and stem cell transfection can be adopted for manipulation of stem cell fate and gene therapy, which have enormous potential for clinical applications. China has demonstrated steady growth in stem cell research and development in the past few years, while western countries like the USA remain the major players in the global stem cell industry. Stem cell industry in China is still at the incipient stage, with most of the companies focused on the upstream industry, mainly on biobanking.

The core patents related to engineering and research focus in stem cell technologies amount to 1173 (Table 2.1.1), and the top 5 countries are the USA, China, Germany, Switzerland, and Japan. Among all countries, China contributes 12.45% authors applying for patents; China also occupies a comparatively large proportion in the sheer volume of patents, and it has become one of the most important countries in this area, with an average citation frequency of 14.14 (Table 2.2.5). The cooperative network among countries with patent output in this area (Figure 2.2.5) show the USA and China to be most cooperative.

The top three institutions with core patent output are Anthrogenesis Corp., Atyr Pharma Inc., and the Massachusetts Institute of Technology (MIT) (Table 2.2.6). Institutions with core patent output are mainly biotechnology corporations and universities. China is less industrialized compared to the innovative pattern of patent output driven by corporations. The cooperative network among major institutions (Figure 2.2.6) shows that the connections between major institutions in this focus area are relatively weak, whereas among all, the MIT, the General Hospital Corporation, and the Massachusetts General Hospital show cooperative ties in research and development.

2.2.4 Biomedical materials

The concept descriptions of biomedical materials has been mentioned in section 2.1 (4).

The current hotspots in the field of international medical materials research include the following: ① Biodegradable materials that can be gradually degraded or metabolized after being implanted in the human body with time. The foreign body implanted will automatically degrade into non-toxic, harmless substances that can be expelled from the body after completion of the mission. ② Tissue engineering materials and artificial organs to construct biological devices by using engineering principles and methods. These would to replace the damaged tissues or organs, and include the use of biological scaffolds, seed cells, and growth factors to establish complex three-dimensional spaces composed of cells and biological materials. It is imperative to develop biological materials with good biocompatibility and ability to gradually degrade and be assimilated by

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Stem cell technologies"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	764	65.13%	15 846	75.41%	20.74
2	China	146	12.45%	2 064	9.82%	14.14
3	Germany	63	5.37%	1 070	5.09%	16.98
4	Switzerland	52	4.43%	1 394	6.63%	26.81
5	Japan	46	3.92%	567	2.70%	12.33
6	Korea	42	3.58%	501	2.38%	11.93
7	Canada	32	2.73%	641	3.05%	20.03
8	Singapore	25	2.13%	490	2.33%	19.60
9	France	20	1.71%	289	1.38%	14.45
10	UK	16	1.36%	276	1.31%	17.25

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Stem cell technologies"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Anthrogenesis Corp	33	2.81%	419	1.99%	12.70
2	Atyr Pharma Inc	32	2.73%	1248	5.94%	39.00
3	Massachusetts Inst Technology	29	2.47%	454	2.16%	15.66
4	Pangu Biopharma Ltd	28	2.39%	1096	5.22%	39.14
5	Harvard College	25	2.13%	585	2.78%	23.40
6	Moderna Therapeutics	20	1.71%	912	4.34%	45.60
7	Sangamo Biosciences Inc	19	1.62%	486	2.31%	25.58
8	The General Hospital Corporation Dba Massachusetts General Hospita	17	1.45%	258	1.23%	15.18
9	Hoffmann La Roche Inc	17	1.45%	335	1.59%	19.71
10	Oncomed Pharm Inc	14	1.19%	192	0.91%	13.71

human bodies. These are used mainly to develop artificial blood, liver, heart, kidney, pancreas, blood vessel, cornea cerebrovascular stents, etc. ③ Materials for tissue engineering bones and cartilages to repair defective bones and joints using engineering principles. Electrospinning technology is used on bones, cartilages, and adipose tissue stem cells to develop artificial bone, cartilage knee joints, hip joints, meniscus, ligament, muscles, etc. ④ Dental restorative materials for developing biomaterials for the restoration of maxillofacial, mandibular, and tooth defects. ⑤ Controlled release materials for the release of drugs at a constant rate over a certain period of time. Materials are divided into natural and synthetic polymer materials. ⑥ Bionic intelligent materials: These materials are designed on the principle of synergistic interaction among biological macromolecules to produce intelligent materials with the desired host response. They imitate the cooperative behavior of biomedical materials. ⑦ Antibacterial membrane biomaterials form a biofilm on the surface of implant materials to prevent bacterial growth in postoperative infections. Since post-operative clinical bacterial film infections occur in 2%-3% cases, there is a huge market for these materials. ⑧ Nano biomedical materials, is a new interdisciplinary field regarding the structure and function of genes and proteins, including their identification, integration, transformation, special factor release, bioelectrochemical signal generation and conduction, and biomechanical and thermodynamic

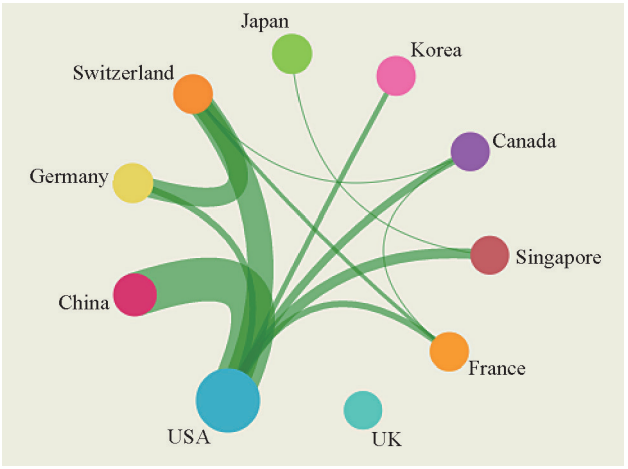

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Stem cell technologies"

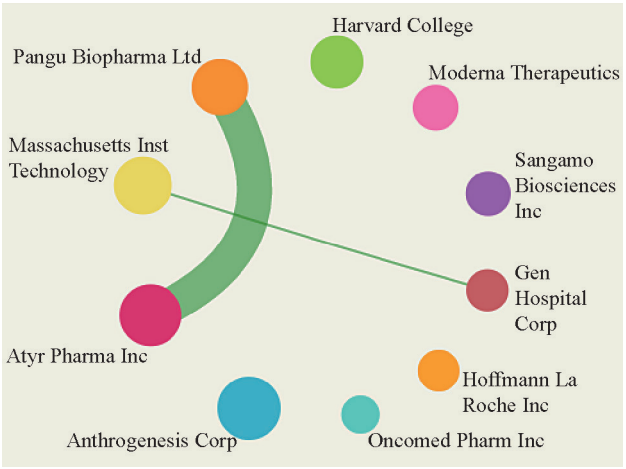

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Stem cell technologies"

properties. It also involves the development of new technical tools using multidisciplinary research.

The market demand for biomedical materials is enormous. In the past 10 years, it has been increasing at an annual rate of 20%, reaching $130 billion in 2013 and $220 billion in 2016. The USA and other western countries occupy the high end market of biomedical materials, whereas the biomedical materials market share of China is 6.5% of its domestic market. Thus, biomedical materials constitute products of the low-end market.

In total, 191 core patents have been applied on biomedical materials in the past 5 years. The USA, China, Korea, the UK, and Italy are ranked as the top 5 countries with the most patents in force (Table 2.2.7). The patents applied by Chinese authors accounted for 21.99% of the total patents and the proportion of the number of patents is large (Table 2.2.7). China has become one of the key countries researching on this aspect of engineering development with an average cited frequency of 10.02. As shown in the cooperation network of patent-producing countries (Figure 2.2.7), the United States and Italy, UK and France cooperate more closely.

The top 3 institutions with the most inventors of the core patents in force are Tufts College, Optotrace Technologies, and Ajou University (Table 2.2.8). Besides, the collaboration network among international institutions shows that the cooperation of biomedical materials is few (Figure 2.2.8).

Table 2.2.7 Major producing countries or regions of core patents on the engineering development focus "Biomedical materials"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	104	54.45%	2128	68.10%	20.46
2	China	42	21.99%	421	13.47%	10.02
3	Korea	13	6.81%	229	7.33%	17.62
4	UK	10	5.24%	132	4.22%	13.20
5	Italy	5	2.62%	86	2.75%	17.20
6	Australia	4	2.09%	80	2.56%	20.00
7	Switzerland	4	2.09%	90	2.88%	22.50
8	France	4	2.09%	38	1.22%	9.50
9	Canada	3	1.57%	5	0.16%	1.67
10	Germany	3	1.57%	5	0.16%	1.67

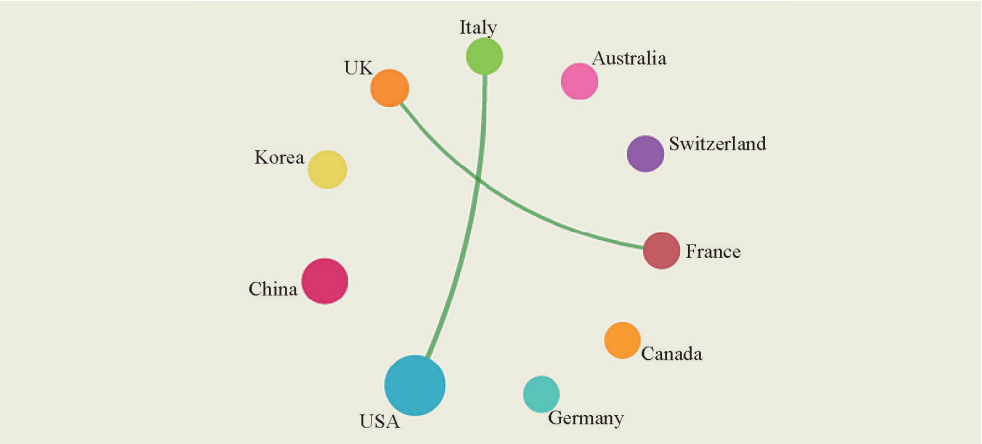

Figure 2.2.7 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Biomedical materials"

Table 2.2.8 Major producing institutions of core patents on the engineering development focus "Biomedical materials"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Tufts College	18	9.42%	384	12.29%	21.33
2	Optotrace Technologies	10	5.24%	225	7.20%	22.50
3	Ajou University	9	4.71%	145	4.64%	16.11
4	Allergan Inc	8	4.19%	261	8.35%	32.63
5	Massachusetts Inst Technology	6	3.14%	82	2.62%	13.67
6	Smith & Nephew Plc	6	3.14%	63	2.02%	10.50
7	Univ Johns Hopkins	5	2.62%	190	6.08%	38.00
8	Depuy Prod Inc	4	2.09%	107	3.42%	26.75
9	Univ Monash	4	2.09%	80	2.56%	20.00
10	Univ Kyungpook Nat Ind Acad Coop	4	2.09%	84	2.69%	21.00

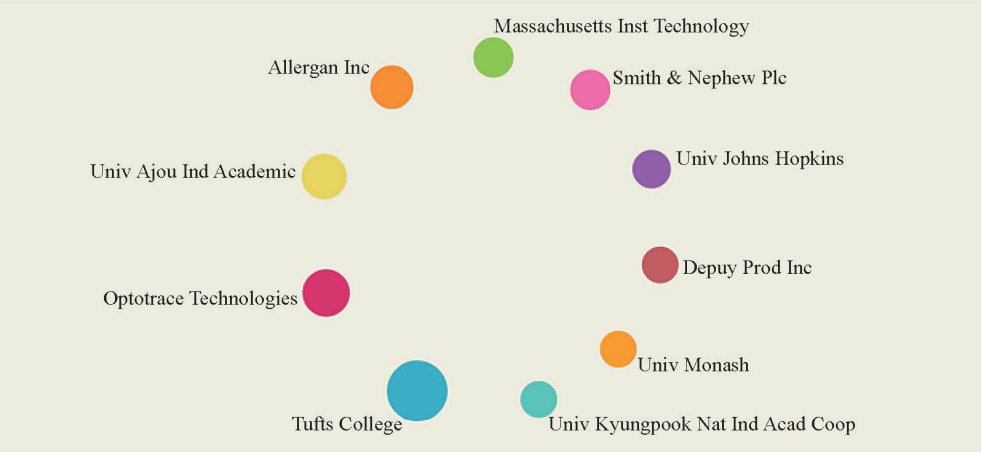

Figure 2.2.8 Collaboration network of the major producing institutions of core patents on the engineering development focus "Biomedical materials"

Project Participants

Leaders of the Field Group:
CHEN Saijuan, YANG Baofeng

Members of the Field Group:
LI Lanjuan, QIU Guixing, CAO Xuetao, HAO Xishan, FU Xiaobing, GAO Runlin, ZHANG Yun, LIU Zhihong, CHEN Xiangmei, CHEN Zhinan, DING Jian, SHEN Beifen, XU Jianguo, YANG Shengli, GU Jianren, CHEN Yazhu, WANG Weiqi, HOU Huimin, WANG Hongyang, SUN Yinghao, NING Guang, JIA Weiping, MA Ding, LUO Xiaoping, ZHOU Guangbiao, YAN Jianqun, KONG Weijia, PENG Daizhi, HU Sanyuan, GU Jin, LIU Baoyan, LI Dongmei, ZHAO Xilu, XI Xiaodong, MO Jiesheng, YAN Xiaoyu, HUANG Jinyan, CHEN Yinyin, DAI Yuting

Report Writers

SUN Xiaojian, TIAN Mei, WANG Yueying, ZHANG Lin, CUI Daxiang, ZHOU Li, BI Yufang, JI Jiafu, HUANG Yusen, WANG Shuo, CAO Yong, CAO Zhentao, QIAN Dahong, QIAO Jie, ZHAO Jie, YANG Guang, CHEN Wei, XING Ligang

Revision

CHEN Saijuan, GU Xiaosong, LU Guangmin, DONG Chen, WANG Haoyi, TIAN Zhigang, CHEN Tao, NING Guang, HAN Yaling, XIE Lixin, WANG Yongjun

IX. Engineering Management

1 Development trends of engineering research hotspots

In engineering management, engineering research hotspots, globally, are mainly focused in the following 10 fields: fuzzy group decision method, business model dynamics and innovation, service platform and enterprise information system based on the Internet of Things, human resources: influences of organizational performance and competitiveness, container allocation and liner transport network, simulation-based medical teaching, optimum status-based maintenance strategy, multi-objective particle swarm optimization, bicycle sharing system, and tradable electronic right-of-way mechanism. The respective situations of the core papers in each of these fields are shown in Table 1.1 and Table 1.2. The abovementioned 10 engineering research hotspots centrally cover mathematics, economy, industry, computer science, information and automation, and other disciplines. Of these research hotspots, four are included in the emerging frontier category: service platform and enterprise information system based on the Internet of Things, optimum status-based maintenance strategy, multi-objective particle swarm optimization, and bicycle sharing system; six of the research hotspots are included in the traditional profound research category: fuzzy group decision method, business model dynamics and innovation, human resources: influences of organizational performance and competitiveness, container allocation and liner transport network, simulation-based medical teaching, and tradable electronic right-of-way mechanism; there is no hotspot that is subject to the subversive frontier category.

1.1 Fuzzy group decision method

Along with the development of science, technology, and production, issues geared to an individual decision maker have been on the decrease; there have been more and more group decision issues geared to multiple decision makers. Furthermore, owing to the limitations and fuzziness of human understanding, during evaluation of these issues, we shall apply the concept of fuzziness, which is more objective and more suitable to handle certain complicated decision issues. Fuzzy group decision refers to behaviors of several individuals in making a unified decision on a certain issue by using fuzzy mathematics tools while considering multiple influencing factors; it requires the aggregation of group member preferences under a fuzzy environment and the formation of a group preference, followed by sorting out decision schemes according to the

Table 1.1 Top 10 engineering research hotspots in engineering management

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Fuzzy group decision method	40	2146	53.65	2011.80	35.0%	2
2	Business model dynamics and innovation	48	2584	53.83	2011.92	10.4%	0
3	Service platform and enterprise information system based on the Internet of Things	50	2227	44.54	2013.02	36.0%	0
4	Human resources: influences of organizational performance and competitiveness	36	1764	49.00	2012.47	22.2%	1
5	Container allocation and liner transport network	33	1227	37.18	2012.64	24.2%	0
6	Simulation-based medical teaching	34	1166	34.29	2012.88	20.6%	1
7	Optimum status-based maintenance strategy	38	1260	33.16	2013.66	13.2%	0
8	Multi-objective particle swarm optimization	39	1114	28.56	2013.92	41.0%	0
9	Bicycle sharing system	43	1165	27.09	2013.51	20.9%	0
10	Tradable electronic right-of-way mechanism	36	844	23.44	2013.03	5.6%	1

Table 1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in engineering management

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Fuzzy group decision method	19	14	4	2	1	0
2	Business model dynamics and innovation	21	16	7	2	2	0
3	Service platform and enterprise information system based on the Internet of Things	7	11	6	26	0	0
4	Human resources: influences of organizational performance and competitiveness	10	7	11	8	0	0
5	Container allocation and liner transport network	7	9	9	5	3	0
6	Simulation-based medical teaching	6	8	8	8	4	0
7	Optimum status-based maintenance strategy	7	1	7	8	13	2
8	Multi-objective particle swarm optimization	0	3	12	10	13	1
9	Bicycle sharing system	5	3	12	13	8	2
10	Tradable electronic right-of-way mechanism	6	7	11	5	6	1

group preference or selecting the most favorable scheme for the group. Presently, the key issues of fuzzy group decision research hotspots include fuzzy information aggregation method, fuzzy decision information measure theory, fuzzy preference relation, and the respective sorting methods. Based on fuzzy information, it is of great significance for exerting the role of experts in making group decisions to the largest extent and eliminating irrational factors to research how to aggregate preferences of various subjects and form a group preference, as well as sorting alternative schemes according to the respective attributes in the group decision process.

1.2 Business model dynamics and innovation

The concept of a business model was first proposed by Bellman et al. A business model is subject to an operation theory for organizations or enterprises; it is an expression of strategic thinking. A business model refers to the basic logic of an enterprise creating value, namely the method an enterprise applies to provide customers with products and services and earn profits in a certain value chain or value network. It is a system that consists of various constituents, the corresponding connections, and "dynamic mechanism" of the system. Business model innovation refers to the creative changes of basic logic generated by value creation of the enterprise, namely the introduction of a new business model to the social production system to create value for the customer and the enterprise itself. Along with variations of business environment and information technologies, business model conversion and innovation have become new research hotspots.

This research subject mainly concentrates on four aspects: the dynamic evolution, innovation, and conversion of the business model of the enterprise; business model innovation of SMEs; business model innovation and technical innovation; the essence, classification, and key abilities of the business model, and other theoretical research. Among these, innovation and conversion of the enterprise business model under new environments have drawn the attention of many scholars, and exerted great influence on theoretical research on the essence of the business model.

Research on business model innovation mainly covers management, psychology, finance, sociology, and other disciplines; it has interdisciplinary features and has already accumulated a large sum of studies. It is a profound hotspot of traditional research.

1.3 Service platform and enterprise information system based on the Internet of Things

In modern business, frequent variation of customization demand and specialization of operation flow requires the enterprise to collect real-time data and have an effective and highly efficient operation flow. A service platform is capable of managing the product life cycle and offering information support for data integration and intelligent interaction. While an enterprise information system is capable of combining technologies of operation

flow management, work flow management, enterprise application integration, service-oriented architecture, and network computing. Meanwhile, the Internet of Things is capable of processing real-time and heterogeneous data, and realizes the real-time sharing and intelligent collection, transmission, processing, and execution of status information among objects. Applications of the Internet of Things include applications of a great variety of equipment and heterogeneous networks of diversified specifications; it aims at establishing a formalized and systematic service platform and an enterprise information system that supports data collection, communication, and all decision activities. Current research areas within the hotspot of service platform and enterprise information system based on the Internet of Things mainly include five aspects: cloud manufacturing service system based on the Internet of Things, enterprise cloud service architecture, enterprise information system architecture analysis, framework of emergency response decision support system, and configurable information service platform based on the Internet of Things.

1.4 Human resources: influences of organizational performance and competitiveness

With the arrival of the knowledge economy age, the competition for talent has been increasingly fierce. Human resources are the most important resources for an organization to obtain competitive advantages. Human resource management is an organizational factor that is conducive for improving the total performance level of an enterprise; it has been deemed as a "potential contributor that establishes and realizes the mission, vision, strategy, and target of an organization." Enterprise human resource research mainly carries out fundamental analysis in three areas: human capital, organizational routines, and turnover intention. First, in terms of human capital, the research is mainly based on resource base theory and deems human capital as a core resource of an enterprise; in addition, it indicates that the corresponding competitive advantages could help the enterprise to improve its organizational performance during long-term development; meanwhile, by integrating itself with specific research scenarios, the appearance and functions of human capital are analyzed on the macroscopic and microscopic levels. Second, in terms of organizational routines, on one hand, by being based on the perspective of organizational learning and focusing on analyzing the formation and variation process of organizational routines from the individual and organizational levels, the research has demonstrated through analysis on the time sequence that updates of organizational routines could improve organizational performance and increase the innovative power of the enterprise; on the other hand, the research points out that organizational routines could be deemed as one of the countermeasures of the enterprise when dealing with external environment changes; by actively searching for changes in organizational routines, it could help the enterprise to develop in a more sustainable and steady manner. Finally, in terms of turnover intention, on one hand, the research has analyzed the influences of turnover on enterprise performance by using the long-term data, and discussed different turnover types (voluntary resignation and dismissal), enterprise scales, and industrial background in detail; on the other hand, the research has paid attention to the new phenomenon of group resignation, deeply discussed causes and consequences of group resignation, and analyzed the phenomenon from two aspects: theory construction and empirical analysis. In recent years, an opinion that has been universally agreed by scholars has been that human resource management serves as a strategic contributor to organizational performance, that is, strategic human resource management will gradually replace the traditional human resource management; this is becoming a guiding ideology for organizations, especially knowledge-based organizations, in conducting human resource management practices.

Research on human resources: influences of organizational performance and competitiveness mainly covers economics, management, the science of personnel, and other disciplines; it has interdisciplinary features and has already accumulated a large sum of studies. It is a profound hotspot of traditional research.

1.5 Container allocation and liner transport network

Container transport is a highly efficient transport mode with high benefits in the modern circulation field; it is convenient for conducting handling operations

and completing transport tasks by using large handling machinery and large carrier vehicles. As container transport has more advantages than other ocean shipping modes, container technology has become an integral part of the ocean shipping field.

Container liner transport is an operation mode in which the container liner company provides standardized and iterative container cargo transport services for non-fixed shippers based on specified operation rules between fixed affiliated ports on fixed routes according to the pre-determined schedule, and calculates freight based on "container freight rates." Therefore, a container liner transport network consists of the container port, container route network, and vessels running on the route network. Presently, research hotspots mainly include liner transport route network design and optimization, container transport in the liner network, fleet deployment in the liner transport network, and container vessel scheduling optimization. Among these, the key technology applied in the liner transport network design is the approximation solution of the mixed integer planning model. Most of the current research has focused on expanding various constraint details of the route network, such that the parameter conditions of the mixed integer model could more comprehensively and better approach the actual transport conditions. Various complex mathematics tools are used to search for creative solutions, so that the model solution could better reflect the real case. Furthermore, complex network theory is used as the basic theory of global linkage transport networks, but research on the theory in this hotspot is still in the explorative basic research stage. In the future, it will be necessary to continue carrying out further exploration and research.

Research on container allocation and liner transport network mainly covers transportation, economics, automation, computer science, railway transportation, and other disciplines; it has interdisciplinary features and is a profound hotspot of traditional research.

1.6 Simulation-based medical teaching

Along with the continuous development of the medical care field, computer science hardware technologies, and information technologies, the traditional medical care teaching and training mode is not able to satisfy patient requirements for medical care services any longer. Simulation-based medical teaching is an advanced training method; it develops a simulation system by applying virtual simulation technologies centered on computing technology, and uses it for assisting medical clinical teaching, doctor training, practical skill testing, technology learning, surgery planning and the like, so as to improve the accuracy of doctors in clinical diagnoses, safety, controllability, and timeliness of surgeries, and ensure the quality of medical care. Research on simulation-based medical teaching covers simulation technologies, design of methods and conceptual frameworks, research on task reports, design and application of teaching practices, practice effect analysis, and mechanism research, as well as clinical conversion of training achievements and many other issues; it comprehensively utilizes medical simulation, training theory, empirical research, as well as theories and methods of translational science. The current research hotspots are computer graphics, artificial intelligence, deep learning, man–machine interface technology, biofeedback, sensor technology, and parallel real-time computer science technology; furthermore, it also includes research on human behaviors and applications of other key technologies in the medical care profession. In the future, the research and development of intelligent and self-adaptive simulated patients with high simulation degree will be key factors in the medical care industry for patient services.

1.7 Optimum status-based maintenance strategy

Modern production equipment features high-technology contents, complex structures, and strong system characteristics. Their faults feature a very high level of randomness; in addition, these may cause severe losses, or even disasters. Thus, a reasonable maintenance strategy is of great importance. Developing from pure fault maintenance before the 1950s to preventive maintenance on a regular basis, the concept of equipment maintenance is now transforming towards optimum status-based maintenance.

An optimum status-based maintenance strategy is an advanced maintenance method. It obtains relevant information that reflects the equipment state through status monitoring technology, judges the equipment state, and identifies early signs of defect states through signal anal-

ysis, fault diagnosis, reliability assessment, service life prediction and the like, with the aim of analyzing and predicting defect conditions and the development trends of defect states, and recommending the best maintenance strategy based on equipment defect state diagnosis and predictable results.

Early identification of defect states, defect state diagnosis and prediction of degradation degree, as well as decision optimization modeling are three key technological issues in the process. Early identification of defect state relies on status monitoring on the basis of sensor technology and defect occurrence time identification technologies modeling using Hidden Markov Model, stochastic filtering, and other theories. Defect state diagnosis and degradation degree prediction can serve as a scientific reference for preparing specific maintenance schemes, the solutions of which mainly include Short-time Fourier Transform, wavelet transform, and analysis and processing of other status monitoring data, as well as artificial neural network methods, expert system, finite element methods, and other equipment status prediction modeling methods. Decision optimization modeling is the core section of status maintenance decision. By integrating maintenance expenses and other economic factors, according to certain optimization targets, such as minimum expectation value of shutdown time, minimum expectation value of maintenance expenses within unit time, and maximum expectation value of system availability etc., the respective decision optimization models can be established.

Research on optimum status-based maintenance strategy mainly covers mechanics, management, mathematics, automation, computer science, and other disciplines; it is an emerging frontier hotspot.

1.8 Multi-objective particle swarm optimization

The particle swarm optimization algorithm was derived from detailed research on the foraging behaviors of birds; by utilizing an information sharing mechanism, it enables individuals to learn about each other's experiences in order to promote the development of the population. The particle swarm optimization algorithm is a method that applies evolutionary algorithms to obtain a group of candidate solutions and uses them to solve problems; its advantages include simple concepts, low optimization requirement, high solving speed, and strong global searching ability; it is a relatively new heuristic algorithm. The particle swarm optimization algorithm can be divided into three research directions: convergence analysis, practical application, and theoretical optimization. Multi-objective particle swarm optimization is subject to theoretical optimization. The improvement of a subtarget may cause degradation in the performance of another or several other subtargets. Thus, multi-objective optimization aims at coordinating and searching for a compromise among various subtargets in order to obtain a group of optimum solutions without pros and cons; then, a choice can be made artificially. In reality, multi-objective optimization corresponds more to decision-making activities; by utilizing the particle swarm optimization algorithm, it can clearly, simply, and efficiently solve multi-objective optimization issues. Presently, the research on multi-objective the particle swarm optimization algorithm is mainly concentrated on the efficiency of the particle swarm optimization algorithm, multi-objective optimization technology, and improvement of special issues. In terms of the algorithm mechanism improvement, the research is mainly focused on solving the self-adaptive particle swarm algorithm with evolving and changing algorithm parameters, solving a discrete particle swarm algorithm of discretization issues, and solving a fuzzy particle swarm algorithm of fuzzy optimization issues; in terms of the multi-objective optimization mechanism, the research is mainly focused on the selection of non-dominated solutions, trimming of external file sets, maintaining the diversity of non-inferior solution sets, as well as reasonable selection of the globally optimal solution, gbest, and individually optimal solution, pbest.

1.9 Bicycle sharing system

The concept of a bicycle sharing system was proposed in the 1960s. However, until the end of the 1990s, there were only a few cities that had offered bicycle sharing services. Along with global warming, more and more serious environmental pollutions, and the sharp rise of traffic pressure brought by rapid development of automotive transportation in the city, sustainable development has been gradually emphasized by various countries. As a green and environmentally friendly travelling mode, sharing bicycles has become more and more popular.

Sharing bicycles means to provide bicycles for people to use and park at stop points under self-service. It features flexibility and mobility, and can extend the capacity of public transit, alleviate traffic jams, and reduce fuel usage and pollutant emission. The reasons for individuals to use shared bicycles, service conditions of shared bicycles, user preferences, and the influences of shared bicycle usage on individuals and the society have already aroused broad concerns. The key issues in current research include operational management, vehicle allocation, vehicle maintenance and care, rental point layout and scheduling, route carrying capacity, system scale, and other scientific issues. On the basis of multiple integrated algorithms, such as static scheduling optimization algorithm, NP-hard and heuristic algorithms (such as taboo search algorithm, genetic algorithm, simulated annealing, and Ant Colony algorithm, among others), researchers and administrators verify optimization models that are established by the multi-objective dynamic layout and adapt them to urban features through the simulation platform. This research aims to solve mixed integer linear programming issues on the basis of logistics representation and branch cutting methods, and finding feasible solutions in the original grid plan; it aims at intensifying the slackness of linear programming issues on the basis of Benders decomposition, and solving capacity issues on the basis of routes of vehicles. The future development trend is to enhance public transit integration by combining the global positioning system (GPS), E-Bike platforms, Dockless systems, and other sharing systems, while driving statistical analyses of user quantities and research on targets such as frequency and routes.

Research on bicycle sharing systems mainly covers economics, transportation, information technology, automobile industry, and other disciplines; it has interdisciplinary features and is an emerging frontier hotspot.

1.10 Tradable electronic right-of-way mechanism

Tradable electronic right-of-way mechanism is a new scheme of urban congestion governance that draws lessons from the emission exchange mechanism in the environmental field, under which, the government distributes the right-of-way in the form of electronic waybills to all qualified citizens at the beginning of each period free of charge, and collects diversified electronic waybills on vehicles travelling on different road sections at different periods of time according to congestion levels of the road. Citizens are allowed to freely decide their travelling mode and route according to the deduction standard of waybills, and sell excessive electronic waybills to other road users in need through a government-supervised transaction platform. Under such a tradable electronic right-of-way mechanism, based on the scientific summarization of waybills and deduction scheme design according to different road sections and periods of time, the government is capable of effectively managing and controlling overall traffic, guiding travelers in their selection of travelling hours and routes, and achieving congestion governance effects that are the equivalent to the optimum congestion charging scheme. Nowadays, with the gradual perfection of mobile internet technology, GPS, wireless telecommunication technology, as well as information and transaction platform management technology, this scheme has a high level of feasibility.

Current research has discussed static equilibrium and evolutionary processes of dynamic flow and price under the specified tradable electronic right-of-way mechanism; tradable electronic right-of-way mechanism design under the premises of homogenous and heterogeneous users, demand function information shortage and transaction costs; mixed scheme design of tradable electronic right-of-way mechanism, road tolling, and other mechanisms; and extended applications in parking space allocation and other fields similar to the tradable right mechanism. In order to further propel the implementation of the mechanism, it will be necessary to solve other issues in the future, such as how to ensure fairness of the initial allocation of electronic waybills, how to determine the distribution and usage period of electronic waybills in a reasonable manner, and how to more precisely define the prices of electronic waybills and the dynamic evolutionary process of road traffic flow through simulation.

2 Understanding of engineering research focus

2.1 Fuzzy group decision method

Decisions can be universally found in various economic,

political, and social fields. With the rapid development of science and technology, knowledge and information have exploded, prompting the emergence of various kinds of intricate and complex decision issues. More and more decision issues simultaneously contain quantitative and qualitative indicators, which contribute to the formation of complicated multi-attribute decision issues. With the development of decision theories in recent years, fuzzy group decision has become the new hotspot that arouses people's concerns. It has extensive theoretical research significance and actual background in terms of military affairs, economy, management, and system engineering. Although the research on fuzzy group decision has already obtained certain achievements, in terms of theoretical and practical applications, it still urgently requires further profound research.

A deeper analysis is carried out below by mainly focusing on how to aggregate the preferences of various subjects and form group preferences, how to sort out alternative schemes according to their attributes, and the fuzzy decision information measure theory in group decision processes.

2.1.1 Fuzzy information aggregation method research

As for the decision of fuzzy information, researchers normally apply aggregation operators, and aggregate multi-dimensional fuzzy decision information into an individual value; then, decision information aggregation values of alternative schemes are sorted out, so that the decision maker could analyze the decision. Thus, aggregation operators play an important role in the decision process of fuzzy information.

The most mature aggregation operator in current research is the ordered weighted averaging operator proposed by Yager in 1988, the function of which is to sort out evaluation information, then weight and aggregate the information according to the sorting position. Research hotspots in fuzzy information aggregation methods mainly include: the respective aggregation operators based on expression means of different fuzzy information, such as intuitionistic fuzzy set, hesitant fuzzy set, and fuzzy language; extending the existing ordered weighted averaging operator into more generalized aggregation operators; and the research on exchangeability, idempotence, monotonicity, and other expected properties of these aggregation operators. Currently, the research on intuitionistic fuzzy set aggregation operators is more mature; while research on hesitant fuzzy sets and semantics fuzzy information have been rarely seen. These areas have greater scope for further research and development.

2.1.2 Fuzzy decision information measure theoretical research

The important role of measure theory in fuzzy decision methods is mainly embodied in distance and similarity measurement of fuzzy information; it serves as the foundation of numerous decision methods. Distance and similarity indicators are mainly used for measuring the distance and similarity of data.

This research can be generally divided into distance measurement on the basis of the traditional Euclidean distance and Hamming distance, and distance measure on the basis of ordered weighted distance, mixed weighted distance, and weighted distance operator measurement of fuzzy ordered weighted distance, as well as information entropy theory. Theoretical research hotspots in fuzzy decision information measure mainly include the research on expanding distance measurement to fuzzy decision, intuitionistic fuzzy decision, interval intuitionistic fuzzy decision, and hesitant fuzzy decision; the research on a series of distance and similarity measurement methods for intuitionistic fuzzy information and interval intuitionistic fuzzy information generated on the basis of weighted distance operator, Choquet integration and geometric distance model and other theories; and information measure method for relative entropy on the basis of intuitionistic fuzzy information and interval intuitionistic fuzzy information.

2.1.3 Research on fuzzy preference relation and the respective sorting method

Preference relation describes preference information on decision issues when decision makers express targets, such as attributes or principles; by comparing the relations of every pair of targets, all targets can be sorted.

Fuzzy preference relation in the existing research is relatively mature. The core principle is to hopefully use membership and non-membership functions that take arbitrary values in the unit closed interval [0,1] to express a decision maker preference relation of two different targets. The research hotspots in this field mainly

include: using interval intuitionistic fuzzy preference matrix to solve the problem of conditional information being insufficient under the background of an interval intuitionistic fuzzy set; the research on consistency of an individual preference and commonness of the group preference relation in order to solve the problem of an individual preference relation being inconsistent or the problem of group preference relation being incompatible by focusing on limited personal capabilities of the decision maker and fuzziness of the subject; the research on how to use consistency indicators of some generalized ordered weighted averaging operators to reflect the interval fuzzy preference relation; and how to characterize the preference relation with an unknown expert weight.

2.1.4 Present status of development and future development trends

When sorting alternative schemes, the decision maker mainly relies on the aggregation method to aggregate multi-dimensional fuzzy decision information into an individual value and uses it as the reference during sorting. Thus, research on the aggregation method under multiple fuzzy information forms has become a current research hotspot. Researchers extend the case on the basis of the existing ordered weighted averaging operator and obtain many generalized aggregation operators, as well as defining the algorithm and researching expected properties of aggregation operators; more and more decision issues contain quantitative indicators and qualitative indicators at the same time, which contribute to the formation of complicated multi-attribute decision issues. Based on these issues, the researchers propose an interval ladder-shaped fuzzy number multi-attribute group decision method, triangular number, intuitionistic fuzzy number, interval intuitionistic fuzzy number, hesitant triangular fuzzy information, and fuzzy number intuitionistic fuzzy information multi-attribute group decision method, and direct fuzzy number form multi-attribute group decision method; in order to solve various problems in the decision process, such as decision information fuzziness, undetermined weight and multiple criteria, researchers have proposed multiple decision methods, such as multi-criteria interval intuitionistic fuzzy decision methods, using Hamming distance and an adequacy coefficient in the decision method to parameterize the decision maker preference information, measuring weight of the decision maker under the background of interval intuitionistic fuzzy decision information provided by the decision maker, and determining weights of decision makers based on personal decisions by applying and promoting the technique for order preference by similarity to an ideal solution (TOPSIS) method in the form of an interval number.

Chinese experts and scholars have made achievements in terms of research on fuzzy decision information aggregation methods, theoretical research on fuzzy decision information measure, fuzzy preference relations, and the respective sorting methods, proposed many kinds of fuzzy group decision methods, and made great contributions to fuzzy group decision research.

This hotspot mainly covers mathematics, economics, automation, decision-making, industry economy, computer science, and the like, and is a profound hotspot of traditional research.

2.1.5 Major countries and institutions researching fuzzy group decision methods

The top 3 countries in terms of the number of core papers on the engineering research focus "Fuzzy group decision method" were China, Spain, and USA (Table 2.1.1); the top 3 countries or regions in terms of the average citation frequency of core papers were Taiwan of China, Spain, and China (Table 2.1.1). According to the collaboration network of major producing countries or regions of core papers (Figure 2.1.1), among the top 6 countries in terms of the number of papers, China, USA, and Spain had the most cooperation.

The top 3 institutions in terms of number of core papers were University Barcelona, Chongqing University of Arts and Sciences, and Anhui University (Table 2.1.2). According to the collaboration network of the top 10 institutions producing core papers (Figure 2.1.2), Ohio State University, Anhui University, and University Barcelona had the most cooperation.

During the period from 2011 to 2016, China published 28 core papers on the engineering research focus "Fuzzy group decision method" (Table 2.1.1). The Chinese mainland institutions that published more core papers were Chongqing University of Arts and Sciences and Anhui University (Table 2.1.2).

China and Spain had the most achievements in this research hotspot, with relatively high average citations, and were both in the leading position; USA and Canada made

partial research. China had partnerships with all these countries. Different research institutions of various countries have cooperation with each other, and formed many cooperative sub-networks.

According to the analytic results, University Barcelona of Spain, Chongqing University of Arts and Sciences, and Anhui University of China made major contributions in this research hotspot. The research achievements of these three institutions accounted for 75% of total number (Table 2.1.2).

2.2 Service platform and enterprise information system based on the Internet of Things

The concept of the Internet of Things was originally derived from the network radio frequency identification system proposed by the Massachusetts Institute of Technology of USA in 1999. In 2005, the concept of the "Internet of Things" was officially defined during the World Summit on the Information Society held by the International Telecommunication Union in Tunis. The Internet of Things, in a narrow sense, refers to the network that connects different objects and is capable of realizing intelligent identification and management of objects; in a broad sense, the Internet of Things can be deemed as the integration of the information space and physical space that digitalizes and cyberizes everything, realizes highly efficient information interaction modes between objects, between objects and humans, as well as between humans and the real environment, and integrates various information technologies with social behaviors through new service modes, such that informatization can reach a higher perspective via comprehensive applications within human society. The service platform realizes encapsulation, combination, disassembly, transmission, follow-up, and interaction of information in the product life cycle management by utilizing an abstract information model, so as to offer information support for data integration and

Table 2.1.1 Major producing countries or regions of core papers on the engineering research focus "Fuzzy group decision method"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	28	70.0%	1306	66.80%	46.64	6	0
2	Spain	13	32.5%	662	33.86%	50.92	1	2
3	USA	4	10.0%	147	7.52%	36.75	1	0
4	Taiwan of China	2	5.0%	112	5.73%	56.00	0	0
5	Canada	2	5.0%	73	3.73%	36.50	1	0
6	England	1	2.5%	16	0.82%	16.00	0	0

Table 2.1.2 Major producing institutions of core papers on the engineering research focus "Fuzzy group decision method"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Barcelona	13	32.5%	662	33.86%	50.92	1	2
2	Chongqing Univ Arts & Sci	11	27.5%	572	29.26%	52.00	3	0
3	Anhui Univ	6	15.0%	231	11.82%	38.50	1	0
4	Ohio State Univ	3	7.5%	111	5.68%	37.00	1	0
5	Cent S Univ	2	5.0%	128	6.55%	64.00	1	0
6	Guangdong Ocean Univ	2	5.0%	79	4.04%	39.50	0	0
7	Tianjin Univ	2	5.0%	73	3.73%	36.50	0	0
8	Zhejiang Wanli Univ	2	5.0%	64	3.27%	32.00	0	0
9	Shandong Econ Univ	1	2.5%	80	4.09%	80.00	1	0
10	Chang Gung Univ	1	2.5%	69	3.53%	69.00	0	0

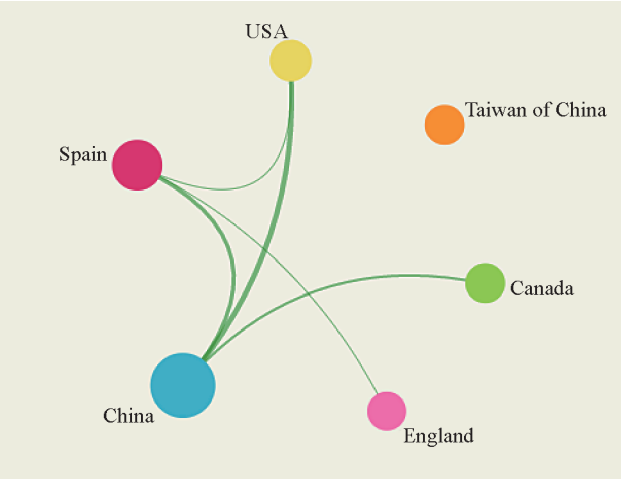

Figure 2.1.1 Collaboration network of major producing countries or regions of core papers on the engineering research focus "Fuzzy group decision method"[1]

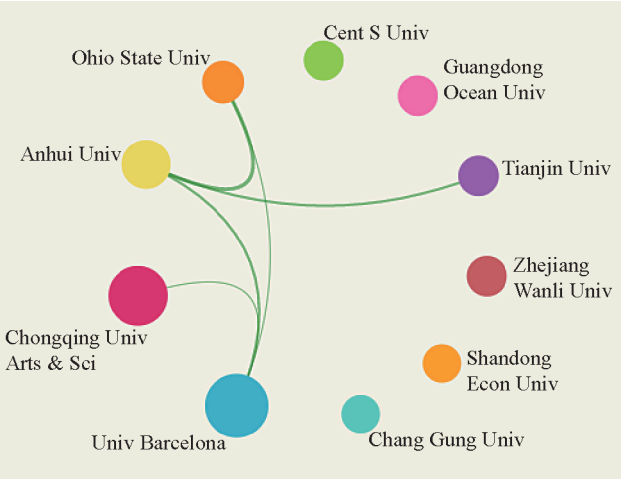

Figure 2.1.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Fuzzy group decision method"

intelligent interaction. An enterprise information system is an arbitrary information system that integrates and improves enterprise operation flow functions; it is capable of handling a large quantity of data, so as to support large and complex organizations or enterprises. The Internet of Things is deemed as a major opportunity for the development and reform of the information field. Service platforms and enterprise information systems based on the Internet of Things are capable of supporting the application of flexible and configurable modes that cover unified management of distributed and heterogeneous product data at different stages of the life cycle.

Service platform and enterprise information system based on the Internet of Things includes five frontier branch programs, namely cloud manufacturing service system based on the Internet of Things, enterprise cloud service architecture, enterprise information system architecture analysis, framework of emergency response decision support system, and configurable information service platform based on the Internet of Things.

2.2.1 Cloud manufacturing service system based on the Internet of Things

In the cyberized manufacturing period, operation mode, and manufacturing resource sharing and allocation, the intelligent access of terminal physical equipment, safety solution technologies and means are not complete. Cloud computing can change the service mode; cloud safety is able to solve safety concerns of cyberized manufacturing; by integration with the technological development of the Internet of Things, cloud manufacturing is able to solve complex manufacturing problems and carry out large-scale collaborative manufacturing. Cloud manufacturing is a service platform that utilizes network and cloud manufacturing; it is a new mode of cyberized manufacturing that organizes internet manufacturing resources (manufacturing cloud) based on user demand and offers various manufacturing services as needed. Compared with informatized manufacturing technology, there are five more prominent technical features for the integration of cloud manufacturing with the Internet of Things, including instrumentation of manufacturing resources and capabilities, virtualization, servitization, collaboration, and intelligentization; furthermore, it is capable of solving 10 major categories of key technologies, including general technology, resource awareness and access technology, resource capability virtualization and servitization technology, virtual cloud manufacturing service environment construction and management technology, virtualization cloud manufacturing service environment operation technology, virtualization cloud manufacturing service environment evaluation technology, cloud manufacturing reliability and safe manufacturing service technology, cloud manufacturing universally applicable man–machine

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

interaction technology, cloud manufacturing service platform application technology, and informatized manufacturing technology. Currently, the cloud manufacturing service system based on the Internet of Things is under construction. Various countries have also attached great importance to the cloud manufacturing industry.

2.2.2 Enterprise cloud service architecture

IT service in the modern enterprise requires a higher level of flexibility, expansibility, and cost advantage. Enterprise cloud services offer on-demand and expandable computing services. The architecture of enterprise cloud services aims at integrating IT resources in the enterprise and creating an operable standard-based service, such that it can be re-assembled and applied. Cloud services are subject to the addition, usage, and delivery mode of relevant services based on the Internet. They normally involve the provision of dynamic resources, which can easily be expanded and which are normally virtualized through the Internet. Cloud services can be divided into infrastructure service, software service, and platform service. By utilizing cloud service, it is possible to realize fast access to service, lower prophase costs and investment, and flexible payment mode. Presently, there are five trends for the development of enterprise cloud service architecture: ① develop service level agreement sensing enterprise cloud service architecture; ② develop special enterprise cloud service for SMEs; ③ develop universal cloud service interface; ④ prepare evaluation criteria and decision support tools; ⑤ conduct enterprise cloud migration factor investigation.

2.2.3 Enterprise information system architecture analysis

Information system architecture is an architecture that reflects the relationship among various components of the information system of the government, enterprise, or institution, as well as the relationship between the information system and the relevant business, and the relationship between the information system and relevant technologies, which refer to the definition of the respective choices in application programs, technologies, data, and the investment portfolio, as well as configurations of hardware, software and communications. There are many advantages for the enterprise information system architecture; for instance, it is capable of offering a more sensitive system to the enterprise; better reusing existing IT assets of the enterprise; reducing development costs and increasing reuse; offering more complete integration to the entire system; considering each application as a service, so as to promote sharing and fundamentally solving the problem of "information islands". Decision makers of the enterprise only need to prepare the flow according to management-level strategies of the enterprise; while the variation of IT system only needs to consider business applications as service modules for instant usage without putting too much thought on architectural approaches and realization details of the bottom layer. There are also certain problems for the information system architecture: ① safety cannot be fully ensured; ② purposefulness of the information system architecture is not strong; ③ research on principles of the information system architecture is insufficient. Presently, there is no book related to the research on information system architecture technologies; and dissertations are mostly related to applications of existing or mature technologies in certain fields. When selecting a software structural system for the enterprise information system, it is necessary to consider multiple quality attributes that often generate conflicts.

2.2.4 Framework of emergency response decision support system

An emergency response decision support system needs to assist decision makers to evaluate emergency plans and select an appropriate emergency plan in case of emergency, support heterogeneous emergency response data sources and offer proper emergency rescue knowledge for the decision maker. It also needs to offer differentiated services to satisfy requirements. Whether the system is effective depends on the framework it refers to. Emergency response decision support system is mainly applied in preparing the emergency early warning and emergency plan, coordinating and instructing emergency activities, managing resources, and offering relative knowledge. The framework of the emergency response decision support system mainly consists of e-government affairs, an information technical infrastructure library, and a decision feedback mechanism. The emergency response decision support system is an integral part of e-government affairs that supports government emergency response. Emergency response decisions involve organizations, departments, personnel, resources, and laws. The fundamental challenges for emergency response decisions are how to

effectively deal with emergencies by using application programs of the emergency response decision support system, and how to satisfy victims in the emergency rescue process. Research on the emergency decision system framework can be divided into four aspects: ① core module that implements the emergency response decision support system; ② learn about the knowledge warehouse operation mechanism in the emergency decision support system through internet research of emergency schemes and suggestions; ③ apply new technologies in newly established industry information integration projects and the enterprise system, and develop the existing system into a highly integrated system; ④ integrate data mining, Internet of Things, particle swarm optimization, social networks, and other new technologies or conceptual systems to improve existing performances of the system.

2.2.5 Configurable information service platform based on the Internet of Things

Internet of Things software not only needs to process real-time and heterogeneous data, but also needs to support complex business applications, and support flexible and configurable modes. It is crucial for the unified management of distributed and heterogeneous product data that cover different stages of the life cycle. The configurable information service platform can offer information support for data integration and intelligent interaction, which is conducive for developing application programs based on the Internet of Things. The configurable and open application program software platform based on the Internet of Things covers the entire product life cycle, such that heterogeneous and distributed product information can be integrated into the internal organization of product manufacturing quantity management. The configurable information service platform based on the Internet of Things consists of three dimensions, namely life cycle, product structure, and information. It is capable of designing, developing, and executing enterprise application programs in the mobile environment, and comprehensively solving the problem of multi-layered product life cycle management.

2.2.6 Present status of development and future development trends

Current research on the Internet of Things mainly concentrates on object identification or event treatment; the research emphasis has been on the design and manufacturing. Most of the research does not have high-level comprehensive intelligent interactions; they lack complete information representations at various stages of product usage, care, and maintenance. The traditional enterprise information system is mainly realized on the architecture level; they are not able to flexibly adapt to changes and uncertainties. Product information only contains certain complete parameters, and the semantic relation among components is missing in the assembly process. While in the future, information and service platforms based on the Internet of Things will not only be able to support product life cycle management and realize seamless integration of heterogeneous data from different stages, but also be able to realize seamless integration of the semantic relations among these objects in order to support intelligent interaction.

This hotspot mainly covers computer science, economy, industry, telecommunication, automation, and the like, and is an emerging frontier hotspot.

2.2.7 Major countries and institutions researching the service platform and enterprise information system based on the Internet of Things

The top 3 countries in terms of the number of core papers on the engineering research focus "Service platform and enterprise information system based on the Internet of Things" were China, USA, and Thailand (Table 2.2.1). According to the number of core papers, China was essentially in the leading position. The top 3 countries or regions in terms of average citation frequency were Wales, USA, and England (Table 2.2.1). According to the Collaboration network of the major producing countries or regions of core papers (Figure 2.2.1), among the major countries or regions in terms of the number of papers, China and USA had the most cooperation.

The top 3 institutions in terms of the number of core papers were Old Dominion University, Chinese Academy of Sciences, and Shanghai Jiao Tong University (Table 2.2.2). According to the Collaboration network of the major producing institutions of core papers (Figure 2.2.2), University of Science and Technology of China, Shanghai Jiao Tong University, Chinese Academy of Sciences, and Old Dominion University had the most cooperation.

During the period from 2011 to 2016, China published 46 core papers on the engineering research focus

"Service platform and enterprise information system based on the Internet of Things" (Table 2.2.1). The major institutions that published more core papers were Chinese Academy of Sciences, Shanghai Jiao Tong University, and University of Science and Technology of China (Table 2.2.2).

2.3 Simulation-based medical teaching

Simulation-based medical teaching refers to integrating information, demonstration, and practical learning into medical teaching activities, and conducting knowledge and skill training through simulation means. Specific research in this field mainly focuses on medical care professional teaching practice activities. Research on simulation-based medical teaching covers simulation technologies and methods, design of the conceptual framework, research on task reporting, design and application of teaching practice activities, practical effect analysis and mechanism research, and clinical conversion of training achievements; it comprehensively applies medical simulation, training theory, empirical research, as well as theories and approaches of translational sciences.

Application of simulation in medical teaching can be

Table 2.2.1 Major producing countries or regions of core papers on the engineering research focus "Service platform and enterprise information system based on the Internet of Things"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	China	46	92%	1657	81.87%	36.02	1	0
2	USA	44	88%	1864	92.09%	42.36	3	0
3	Thailand	5	10%	171	8.45%	34.20	0	0
4	England	4	8%	166	8.20%	41.50	0	0
5	Sweden	3	6%	71	3.51%	23.67	0	0
6	Wales	1	2%	86	4.25%	86.00	0	0
7	Poland	1	2%	36	1.78%	36.00	0	0
8	Taiwan of China	1	2%	26	1.28%	26.00	0	0
9	Scotland	1	2%	25	1.24%	25.00	0	0
10	Finland	1	2%	23	1.14%	23.00	0	0

Table 2.2.2 Major producing institutions of core papers on the engineering research focus "Service platform and enterprise information system based on the Internet of Things"

No.	Institution	Core papers	Proportion of Core Papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Old Dominion Univ	43	86%	1850	91.40%	43.02	3	0
2	Chinese Acad Sci	30	60%	1131	55.88%	37.70	0	0
3	Shanghai Jiao Tong Univ	22	44%	740	36.56%	33.64	0	0
4	Univ Sci & Technol China	17	34%	552	27.27%	32.47	0	0
5	Beihang Univ	7	14%	314	15.51%	44.86	0	0
6	Indiana Univ Purdue Univ	7	14%	261	12.90%	37.29	0	0
7	Chulalongkorn Univ	5	10%	171	8.45%	34.20	0	0
8	Northeastern Univ	4	8%	178	8.79%	44.50	0	0
9	Corp Res	3	6%	71	3.51%	23.67	0	0
10	ABB	3	6%	71	3.51%	23.67	0	0

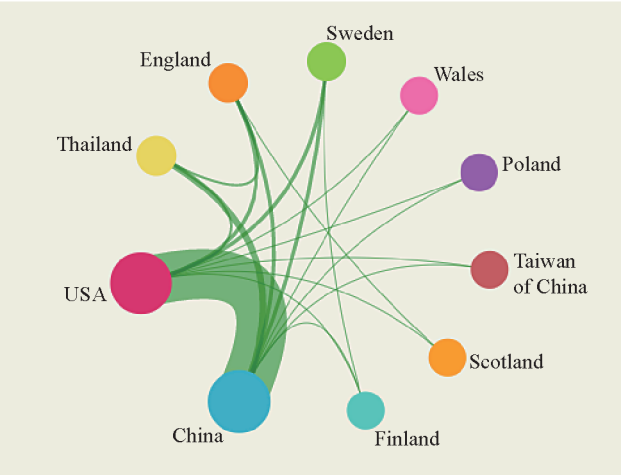

Figure 2.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Service platform and enterprise information system based on the Internet of Things"

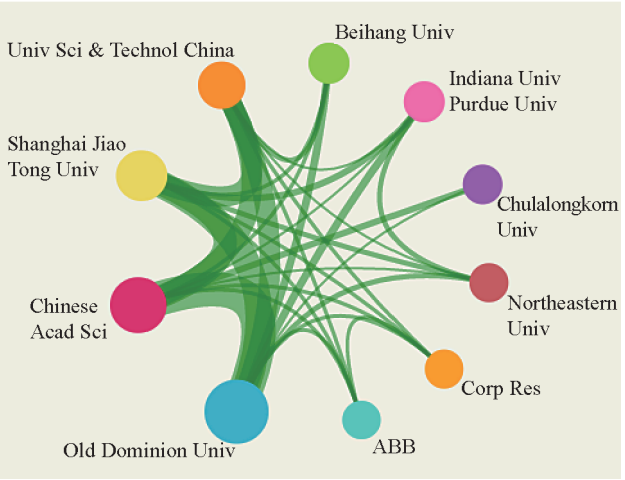

Figure 2.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Service platform and enterprise information system based on the internet of things"

deemed as having been derived from flight simulation in the aerospace field. Traditional medical teaching is similar to apprenticeship, in which apprentices are in an actual surgery operating environment with high risks at the beginning, and simulation-based medical teaching could offer apprentices a safe environment for skill training before conducting actual surgeries on patients. On the other hand, relevant research has demonstrated that, compared with classroom learning, simulation-based medical teaching has better training effects in learning clinical skills.

After decades of development, simulation-based medical teaching has already been widely applied in the medical field, covering numerous aspects from community hospitals to academic-type medical institutions, from students to medical experts, from clinical surgeries to team communications; it has been playing a significant role. A large number of works in the literature have fully demonstrated the training effects and significance of simulation-based medical teaching. As a traditional research hotspot, the current popular literature covers medical care, education, ergonomics, and psychology.

2.3.1 Mainstream of engineering science and branch engineering science

From the aspect of engineering science, the popular research on simulation-based medical teaching mainly includes medical care research and training research.

Medical care is subject to extensive disciplinary research that encompasses comprehensive care, physiotherapy, occupational therapy, health economics, and other disciplines. As an integral part of the medical care and service discipline, simulation-based medical teaching focuses on training knowledge and skills of health care personnel through simulation teaching, and finally improving their actual levels in medical care. The major concerns of the research include:

(1) Research on simulation teaching technologies and methods of medical teaching aimed at strengthening the scientific merit, flexibility, and authenticity of simulation through application of simulation tools and research on the simulation environment, so as to improve the effects of simulation-based medical teaching. This method emphasizes simulation technology innovation, and applies patient simulation using actors, physical human models, multi-media computer science systems, and standardized patients to medical teaching.

(2) With the help of idea of conversion research in medical research and development, clinical application of achievements of simulation-based medical teaching in reality is researched, including the design of teaching effect testing methods, how to improve conversion of training achievements, and how to apply simulation-based training methods in conversion research itself, and so on.

Training refers to expanding work-related knowledge, skills, and attitude of the trainee, and researching training

tools, methods, strategies, and contents by applying systematic methods. As a practical application of training research in the medical field, major concerns of the research on simulation-based medical teaching include: ① comparing and demonstrating training effects of simulation-based medical teaching through designed experiments or meta-analysis; ② research learning theories and conceptual framework that are suitable for medical teaching from the aspect of training and use them to instruct the design of simulation-based medical teaching, such as cognitive load theory, group training theory, conceptual framework of simulation-based training, task reporting, and analysis of characteristics of learners, and so on; ③ research internal mechanism and design strategies of simulation-based medical teaching, and analyze medical teaching differences generated by different applications from programmed basic skills to complex surgeries. Current research mainly includes research on teaching personnel, cost-benefit ratio of medical teaching, simulation ability allocation, and auxiliary design of means for supporting various steps of training.

2.3.2 Present status of development and future development trends

Presently, research on simulation-based medical teaching is focused on simulation technologies and methods, learning theories and methods, practical applications, and conversion of training achievements. The current status of the development of relevant research mainly includes the following aspects:

(1) It is generally agreed that research on medical technology can be divided into three stages, including the upstream stage T1 (laboratory technology research), downstream stage T2 (clinical applications to patient-care), and stage T3 (applications being able to actually improve health of patients and the public). By extending this concept to the research on simulation-based medical teaching, it can be discovered that, most of the current research focuses on teaching methods and technologies (stage T1) of simulation teaching. In recent years, a minority of research has demonstrated feasibility of effects in clinical experiments (stage T2) and the improvement of the ultimate medical level (stage T3). Research thinking in the future has been expanded from research and development of simulation systems to clinical applications, namely how to test the actual effects of the simulation system, so as to select and smoothly operate the system; how to analyze the relationship among patients, technologies, medical care professions and organizational institutions through simulation; how to transform knowledge obtained from simulation into guiding principles for practical operations or practical teaching courses. This is also the major concern of most of popular papers in this analysis.

(2) Simulation-based medical teaching uses particularly established simulation centers as main training grounds, which are different from clinical practices and thus create the problem of conversion. Some research has started to focus on in-situ simulation, while integrating the actual clinical environment with the simulation. Currently, in-situ simulation has already made certain progress, but it is still mainly restrained by description of applications in partial fields, like surgeries, and a lack of comprehensive and systematic research.

(3) Current research mainly focuses on simulation technology and innovation, while neglecting the "human" factor. In other words, the research mainly surrounds technologies and methods of medical teaching and lacks a focus on teaching personnel. As the organizer and guide of medical teaching activities, teaching personnel exert major influences on medical teaching. Future research shall pay more attention to the functions of teaching personnel, such as characteristics and behaviors of teaching personnel, influences on teaching activities, and influences on the teaching personnel excitation mechanism.

(4) In existing empirical research, in terms of demonstrating effectiveness of training, researchers pay more attention to "whether it is effective," and seldom do they explore "why it is effective"; in addition, the experimental design mode that mainly consists of volunteers also lacks verification by actual clinical effects. Meanwhile, a large body of the existing research lacks comparisons with diversified existing methods.

(5) Some important steps of simulation training, especially the task reporting process, are emphasized by current research. A task report refers to an introspective discussion carried out by learners under the instruction of teaching personnel, which aims at discovering and making up defects appearing in teaching activities through discussions and strengthening the understanding towards knowledge and skills. Task reporting is an important step in the learning cycle. Several popular papers have

separately carried out studies in terms of the effectiveness, methods, strategies, and conceptual framework of task reporting, designing auxiliary means, and analysis of key problems. Current research on task reporting of simulation-based medical teaching still lacks a definite theoretical framework, and research on the respective internal mechanism and auxiliary means are not yet complete.

This hotspot mainly covers computer science, automation, telecommunication, biology, medicine, and the like, and is a profound hotspot of traditional research.

2.3.3 Key countries and institutions researching simulation-based medical teaching

The top 3 countries or regions in terms of the number of core papers on the engineering research focus "Simulation-based medical teaching" were USA, Canada, and England (Table 2.3.1); the top 3 countries or regions in terms of the average citation frequency were Switzerland, Belgium, and England (Table 2.3.1). According to the collaboration network of the major producing countries or regions of core papers (Figure 2.3.1), among the top 9 countries or regions in terms of the number of papers, England, Canada, and USA had the most cooperation.

The top 3 institutions in terms of the number of core papers were University Calgary, Mayo Clinical, and University Toronto (Table 2.3.2). According to the collaboration network of the major producing institutions of core papers (Figure 2.3.2), University Toronto, Mayo Clinical, University Calgary, and University British Columbia had the most cooperation.

These results have further reflected that, regardless of quantity or quality of papers, USA and Canada were both in the leading position. Furthermore, the production institutions of core papers mainly consisted of universities, according to which, it is believed that, universities have been the main force of current research; other research institutions are mainly hospitals and medical centers. Meanwhile, there was significant cooperation between researchers from universities and those from hospitals, which have also proved the concerns of the current research on clinical practices, emphasized above.

During the period from 2011 to 2016, China published 0 core papers on the engineering research focus "Simulation-based medical teaching".

The existing core papers are all from foreign researchers. There are significant differences currently in simulation-based medical teaching research between China and other countries. Compared with the comprehensive research of other countries from simulation teaching technologies to clinical applications, research in China is still at the relatively basic stage in all aspects. Especially that the actual clinical applications of simulation-based medical teaching still lack of powerful analytic demonstration and further research. In future research, China shall not restrain our visions on upstream simulation teaching methods and technologies themselves; instead, we shall start from actual circumstances and pay attention to how to more effectively improve downstream clinical applications.

Major producing countries or regions of citing core papers on the engineering research focus "Simulation-based medical teaching" were USA, Canada, Denmark, England,

Table 2.3.1 Major producing countries or regions of core papers on the engineering research focus "Simulation-based medical teaching"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	USA	23	67.65%	692	68.86%	30.09	6	1
2	Canada	12	35.29%	339	33.73%	28.25	1	0
3	England	4	11.76%	141	14.03%	35.25	1	0
4	The Netherlands	3	8.82%	84	8.36%	28.00	1	0
5	Denmark	3	8.82%	63	6.27%	21.00	0	1
6	Switzerland	2	5.88%	83	8.26%	41.50	0	0
7	Belgium	1	2.94%	39	3.88%	39.00	0	0
8	Brazil	1	2.94%	23	2.29%	23.00	1	0
9	Sweden	1	2.94%	15	1.49%	15.00	0	0

Table 2.3.2 Major producing institutions of core papers on the engineering research focus "Simulation-based medical teaching"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Calgary	6	17.65%	181	18.01%	30.17	1	0
2	Mayo Clin	5	14.71%	155	15.42%	31.00	0	0
3	Univ Toronto	5	14.71%	73	7.26%	14.60	0	0
4	Northwestern Univ	4	11.76%	178	17.71%	44.50	0	0
5	Univ London Imperial Coll Sci Technol & Med	3	8.82%	69	6.87%	23.00	1	0
6	Univ British Columbia	3	8.82%	56	5.57%	18.67	0	0
7	Univ Hlth Network	3	8.82%	46	4.58%	15.33	0	0
8	McMaster Univ	2	5.88%	135	13.43%	67.50	0	0
9	Ctr Med Simulat	2	5.88%	82	8.16%	41.00	0	0
10	Harvard Univ	2	5.88%	82	8.16%	41.00	0	0

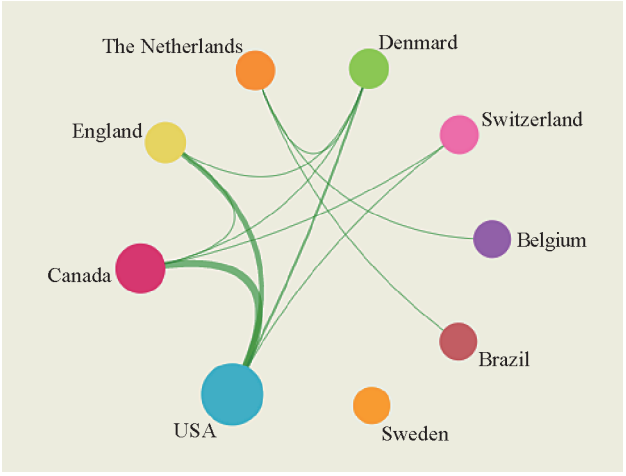

Figure 2.3.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Simulation-based medical teaching"

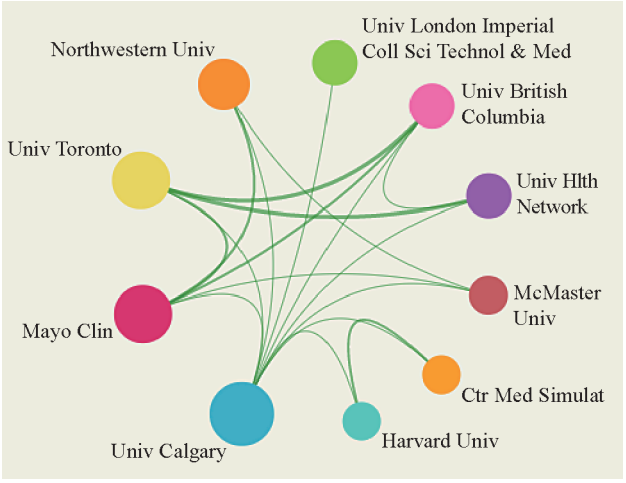

Figure 2.3.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Simulation-based medical teaching"

and Switzerland (Table 2.3.3); the major producing institutions of citing core papers were University Health Network, University Toronto, Ann & Robert H Lurie Children's Hospital Chicago, Loyola University Chicago, University Calgary, Northwestern University (Table 2.3.4). Based on the above, China was not in a leading position.

2.4 Multi-objective particle swarm optimization

Optimization issues universally exist in production and people's daily lives. In recent years, in order to solve these optimization issues, research works on optimization methods have emerged in large numbers. Although traditional optimization method theories based on mathematics planning are mature, there are multiple restrictions and shortcomings when solving optimization issues, such as curse of dimensionality, needs of a continuous and differentiable objective function and so on. Thus, in the past few decades, a swarm intelligence optimization method derived from the natural evolution process has been greatly developed, with the formation of a series of intelligent optimization algorithms. The particle swarm optimization algorithm has been widely researched and applied due to its clear definition, easy realization, and high solving efficiency. It is a global arbitrary search algorithm based on swarm intelligence,

which was proposed after being inspired by migration and aggregation behaviors of birds in their foraging process. Ever since it was proposed, it has always been a hotspot of research on intelligent optimization algorithms. In 2002, Coello et al. proposed the multi-objective particle swarm optimization algorithm; later, the algorithm received great attention from scholars of relevant fields both at home and abroad, and research achievements emerged in an endless stream. The multi-objective particle swarm optimization algorithm has been widely applied to multi-objective optimization issues in fields like energy, chemical engineering, economy, bio-information and the like, such as redundancy allocation of multi-objective reliability, and reliability optimization; the minimum cost generation expansion in the electric system field, multi-objective reactive power optimization of electric system, electric system economic environment scheduling under multi-objective restrictions of the generator; multi-objective optimization of stock exchange decision geared to the maximum interests in the economy field, and oil field multi-objective model solving; genetic multi-objective clustering in the bio-information field, and multi-objective optimization of orthogonal immune clone.

Presently, research on the multi-objective particle swarm optimization algorithm mainly concentrates on efficiency of the particle swarm optimization algorithm, multi-objective optimization technology, and research on improvement of special issues. In terms of algorithm mechanism improvement, the research mainly concentrates on self-adaptive particle swarm algorithms that change with the evolution process for solving algorithm parameters, discrete particle swarm algorithms for solving discrete issues and fuzzy particle swarm algorithm for solving fuzzy optimization issues; in terms of the multi-objective optimization mechanism, the research mainly concentrates on selection of non-dominated solutions, trimming of external file sets, maintaining the diver-

Table 2.3.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Simulation-based medical teaching"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	6	42.86%	2014.0
2	Canada	5	35.71%	2014.2
3	Denmark	1	7.14%	2015.0
4	England	1	7.14%	2015.0
5	Switzerland	1	7.14%	2013.0

Table 2.3.4 Top 10 institutions producing of core papers that are cited by core papers on the engineering research focus "Simulation-based medical teaching"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Hlth Network	3	10.71%	2013.67
2	Univ Toronto	3	10.71%	2013.67
3	Ann & Robert H Lurie Childrens Hosp Chicago	2	7.14%	2015.00
4	Loyola Univ Chicago	2	7.14%	2014.00
5	Univ Calgary	2	7.14%	2013.50
6	Northwestern Univ	2	7.14%	2014.00
7	Alberta Childrens Prov Gen Hosp	1	3.57%	2015.00
8	ETH	1	3.57%	2013.00
9	Herlev Univ Hosp	1	3.57%	2015.00
10	Hosp Sick Children	1	3.57%	2014.00

Note: ETH stands for ETH Zurich.

sity of non-inferior solution sets, as well as reasonable selection of globally optimal solution gbest and individually optimal solution pbest.

2.4.1 Mainstream of engineering science and branch engineering science

Currently, research on the multi-objective particle swarm algorithm mainly concentrates on the efficiency of the particle swarm optimization algorithm, multi-objective optimization technology, and research on improvement of special issues. ① In terms of improving the global search ability and convergence speed of the particle swarm optimization algorithm, it mainly focuses on improvement of the particle swarm optimization algorithm itself, such as using a microhabitat and multi-population mode to improve the global search ability of the algorithm, reasonably selecting pbest and gbest to balance global search ability and convergence speed of the algorithm, dynamic self-adaptive confirmation of inertia weight, and integrating with other algorithms to improve search ability of the algorithm; ② In terms of multi-objective optimization technology, it mainly includes the research on scientifically and reasonably dominating, sorting, and reducing computational complexity, and the research on new external file set trimming technologies to improve the diversity and distributivity of the non-inferior solution set; ③ In terms of integrating with actual engineering applications, it mainly includes principal-subordinate analysis and hierarchical and layering research on the target by integrating with real situations of engineering applications, reducing dimension of the optimization target, lowering the complexity of algorithm solving, introducing expert knowledge to constrain the optimization space for decision variables and improve the convergence speed of the algorithm, and researching constraint handling method of the algorithm based on practical issues to improve the efficiency of algorithm solving. Generally speaking, most of the research of scholars in various countries on the multi-objective particle swarm optimization algorithm is carried out by integrating actual engineering issues while mainly aiming to solving actual engineering issues; algorithm research works, particularly on the theoretical level, can be hardly seen. This is also the key research issue which needs to be surmounted of the multi-objective particle swarm algorithm, as well as the future development trend.

2.4.2 Present status of development and future development trends

For over a decade, the multi-objective particle swarm algorithm has received widespread attention, with the publication of a large quantity of academic research papers and highly cited papers. Currently, it is still the hotspot of research in the multi-objective optimization field. Now, research on multi-objective particle swarm algorithm mainly centers on two aspects: ① algorithm mechanism improvement, such as self-adaptive particle swarm algorithm with parameters changing with the evolution process, discrete particle swarm algorithm for solving discrete issues, and fuzzy particle swarm algorithm for solving fuzzy optimization issues; ② as for the research on multi-objective optimization mechanisms, such as selection of non-dominated solutions, trimming of external file sets, maintaining the diversity of non-inferior solution sets, and reasonable selection of the globally optimal solution gbest and individually optimal solution pbest. By integrating with the current research condition analysis of the multi-objective particle swarm optimization algorithm, the future research trends include:

(1) Particle swarm topological structure research. Diversified particle swarm neighboring topological structures are simulations toward societies of different types, such as star connection, ring connection, and so on; by researching the scope of application of different topological structures, it is conducive for the extension and application of the particle swarm optimization algorithm.

(2) Theoretical research on the particle swarm algorithm. Current research on the algorithm mainly focuses on application research; parameters of the algorithm are normally selected by applying trial-and-error method based on experience, which still lacks theoretical instructions. Thus, it is necessary to further strengthen the theoretical research on the convergence speed, parameter robustness, and global convergence of the algorithm, including discussions on its characteristics under multi-objective and constrained conditions.

(3) Research on the mechanisms of the high-dimension multi-objective algorithm. While dealing with high-dimension multi-objective issues, computational complexity of the traditional multi-objective algorithm based on Pareto Sorting grows exponentially with the increase in the quantity of optimization targets, namely the Curse of Dimensionality exists. It is necessary to further develop a

more reasonable and highly efficient non-inferior solution sorting and selecting mechanism, which lowers temporal and spatial computation complexity without degrading the search performance.

This hotspot mainly covers automation, industry, computer science, telecommunication, aeronautics and astronautics, mathematics, mechanics, and the like, and is an emerging frontier hotspot.

2.4.3 Major countries and institutions researching multi-objective particle swarm optimization

The top 3 countries in terms of the number of core papers on engineering research focus of "Multi-objective particle swarm optimization" were Iran, France, and South Africa (Table 2.4.1); the top 3 countries in terms of the average citations were Mexico, South Africa, and France (Table 2.4.1). According to the collaboration network of the major producing countries or regions of core papers (Figure 2.4.1), among top 10 countries in terms of the number of papers, South Africa, France, Iran, and Mexico had the most cooperation.

The top 3 institutions in terms of the number of core papers were KN Toosi University, Islamic Azad University, and KN Toosi University of Technology (Table 2.4.2). According to the collaboration network of the top 10 producing institutions of core papers (Figure 2.4.2), KN Toosi

Table 2.4.1 Major producing countries or regions of core papers on the engineering research focus "Multi-objective particle swarm optimization"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Iran	27	69.23%	655	72.46%	24.26	1	0
2	France	9	23.08%	284	31.42%	31.56	0	0
3	South Africa	6	15.38%	210	23.23%	35.00	0	0
4	USA	5	12.82%	110	12.17%	22.00	0	0
5	China	5	12.82%	93	10.29%	18.60	0	0
6	India	4	10.26%	119	13.16%	29.75	0	0
7	Mexico	3	7.69%	127	14.05%	42.33	0	0
8	Israel	3	7.69%	64	7.08%	21.33	0	0
9	Malaysia	1	2.56%	29	3.21%	29.00	0	0
10	Turkey	1	2.56%	14	1.55%	14.00	0	0

Table 2.4.2 Major producing institutions of core papers on the engineering research focus "Multi-objective particle swarm optimization"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	KN Toosi Univ	12	30.77%	355	39.27%	29.58	0	0
2	Islamic Azad Univ	11	28.21%	245	27.10%	22.27	0	0
3	KN Toosi Univ Technol	9	23.08%	276	30.53%	30.67	0	0
4	Univ Tehran	8	20.51%	182	20.13%	22.75	0	0
5	PUT	7	17.95%	154	17.04%	22.00	0	0
6	IRGCP	6	15.38%	210	23.23%	35.00	0	0
7	Univ KwaZulu Natal	6	15.38%	210	23.23%	35.00	0	0
8	ENSEM	6	15.38%	161	17.81%	26.83	0	0
9	Univ Massachusetts	4	10.26%	79	8.74%	19.75	0	0
10	IPN	3	7.69%	127	14.05%	42.33	0	0

Note: PUT stands for Petroleum University of Technology; IRGCP stands for Institut de Recherche en Génie Chimique et Pétrolier; ENSEM stands for Ecole Nationale Supérieure d'Electricité et de Mécanique; IPN stands for Instituto Politécnico Nacional.

University, KN Toosi University of Technology, University KwaZulu Natal, and IRGCP had the most cooperation.

During the period from 2011 to 2016, China published five core papers on engineering research focus of "Multi-objective particle swarm optimization". In this research hotspot, Iran was the country with an absolute advantage in the quantity of core papers; it was a leading country. France, South Africa, China, and USA also had higher quantities of core papers.

The major producing countries or regions of citing core papers on the engineering research focus "Multi-objective particle swarm optimization" were Iran, France, South Africa, China, and India (Table 2.4.3); the major producing institutions of citing core papers were separately University Tehran, KN Toosi University, Petroleum University of Technology (PUT), and KN Toosi University of Technology (Table 2.4.4). Based on the above, China was in a leading position.

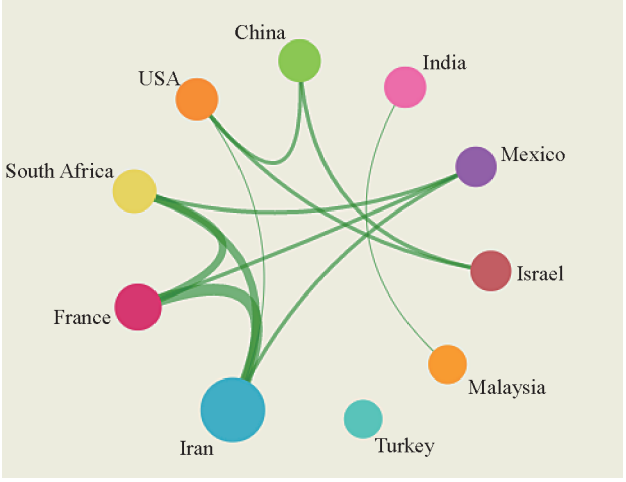

Figure 2.4.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Multi-objective particle swarm optimization"

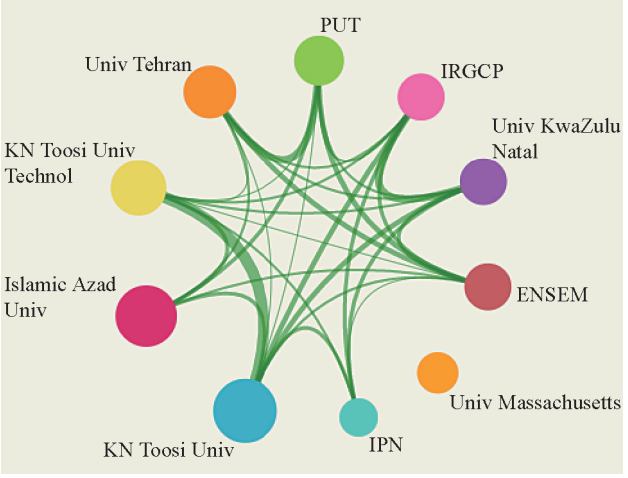

Figure 2.4.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "Multi-objective particle swarm optimization"

Table 2.4.3 Major producing countries or regions of core papers that are citied by core papers on the engineering research focus "Multi-objective particle swarm optimization"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Iran	25	45.45%	2014.60
2	France	9	16.36%	2014.11
3	South Africa	5	9.09%	2013.40
4	China	4	7.27%	2013.75
5	India	3	5.45%	2014.00
6	Israel	2	3.64%	2013.50
7	Mexico	2	3.64%	2013.00
8	USA	2	3.64%	2013.50
9	Australia	1	1.82%	2014.00
10	Malaysia	1	1.82%	2013.00

Table 2.4.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Multi-objective particle swarm optimization"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Tehran	11	11.11%	2014.91
2	KN Toosi Univ	10	10.10%	2014.10
3	PUT	9	9.09%	2014.89
4	KN Toosi Univ Technol	8	8.08%	2014.38
5	ENSEM	7	7.07%	2014.43
6	Islamic Azad Univ	7	7.07%	2015.00
7	IRGCP	5	5.05%	2013.40
8	Univ KwaZulu Natal	5	5.05%	2013.40
9	Imam Khomeini Int Univ	4	4.04%	2015.00
10	Petr Univ Technol	4	4.04%	2015.25

Project Participants

Members of the Field Group

Leaders of the Field Group:

HE Jishan, SUN Yongfu, DING Lieyun

Other members:

WANG An, ZHENG Jingchen, YANG Shanlin, ZHOU Jianping, GUO Chongqing, LING Wen, HU Wenrui, XU Qingrui, WANG Yingluo, XIANG Qiao, LI Yijun, SHENG Zhaohan, HUANG Haijun, GAO Ziyou, CHEN Xiaohong, SHI Yong, HU Xiangpei, TANG Li Xin, FANG Dongping, LI Qiming, WANG Kunsheng, LV Jianzhong, WANG Mengjun, HUANG Wei, WANG Hongwei, LUO Hanbin, YU Zehua, LI Zhichun, ZHONG Botao, LI Yong, ZHOU Ying, FANG Ji, WENG Jingbo, HU Shiqian, WANG Jin, LI Diquan

Report Writers

DING Lieyun, WANG Hongwei, LUO Hanbin, ZHONG Botao, HE Ling, WANG Xu, WU Jianzhang, MA Yeqin, ZHOU Jingyang, ZHAO Ling, QIN Hui, TAO Chanjuan, FANG Weili, XU Jie, ZHANG Liangbin, LI Kaiman, SHENG Da, FANG Qi, KONG Liulin, DONG Chao, LEI Lei

Acknowledgements

LU Yaobin, ZHOU Jianzhong, YANG Hai

Chapter 3 National Performance

In Chapter 2, we deciphered and analyzed in detail the engineering research hotspots in nine fields and the engineering development hotspots in eight fields. This chapter describes the overall performance of engineering research and engineering development hotspots in different countries or regions by quantifying the contributions of leading countries or regions to these engineering research and development hotspots by the number of hotspots they dominate.

1 Overall comparison of the performance of the top 10 countries or regions in engineering research hotspots

The core papers on hotspots in engineering research are retrieved by Clarivate Analytics from the top 10% of the highly cited papers in each year in the Core Collection of Web of Science. There are 12 644 core papers, divided into 294 candidate hotspots. Based on data analysis, academicians and experts in related fields have selected about 10 engineering research hotspots for each field through professional judgment, resulting in 89 hotspots in total. The core papers in engineering research hotspots have relatively strong innovations, so to a certain extent, they reflect their leading role in engineering research. Ranking based on the first authors of the hotspot core papers can roughly be used to evaluate the leading performance of a nation or region.

Table 1.1 describes the statistical results of the top 10 countries or regions based on the number of core papers. The 10 countries or regions are ranked in accordance with the number of participating hotspots, where China's data does not include Taiwan of China, and England's data does not include Scotland and Northern Ireland. As shown, the first author core papers from the USA are distributed in all nine fields and in 78 engineering research hotspots. The leading performance of the USA is close to 88% in engineering research. It ranks first among 30 engineering research hotspots, accounting for 33.7% of hotspots, and ranks in the top 3 out of 50 hotspots, accounting for 56.2% of hotspots. The USA ranks first in all three statistical indicators. China's first author core papers are distributed in 66 hotspots, accounting for 74.2% of hotspots. It ranks first among 29 hotspots, accounting for 32.6% of the total, approaching the USA. It ranks in the top 3 out of 42 hotspots, accounting for 47.2%. China's overall performance is slightly lower than the USA, but clearly ahead of other

Table 1.1 Top 10 countries or regions based on the number of first author core papers

Country/Region	Participation			First place			Top 3		
	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields
USA	78	87.6%	9	30	33.7%	9	50	56.2%	9
China	66	74.2%	9	29	32.6%	8	42	47.2%	8
England	50	56.2%	9	0	0%	0	19	21.3%	7
Germany	43	48.3%	9	2	2.2%	2	16	18.0%	8
Australia	37	41.6%	9	3	3.4%	2	17	19.1%	6
Italy	38	42.7%	9	3	3.4%	3	8	9.0%	5
Korea	30	33.7%	8	3	3.4%	3	10	11.2%	6
Japan	30	33.7%	8	3	3.4%	3	7	7.9%	5
Iran	18	20.2%	8	4	4.5%	4	7	7.9%	6
Algeria	5	5.6%	4	2	2.2%	2	2	2.2%	2

countries or regions.

Core papers that cite other core papers can reflect how the techniques, data, and theories presented in the core papers have been further advanced after publication. Therefore, Core papers that cite other core papers track key discoveries, pay attention to cutting-edge developments, and play a potential leading role in future advances. The rank of a country or region, based on the number of hotspots covered by its first author citing core papers, can be used to identify its potential leading performance.

Table 1.2 shows the statistical results for the top 10 countries and regions determined by the number of first author citing core papers, which are ordered according to the number of participating hotspots. This table shows that citing core papers from the USA participate in the most hotspots, followed by China, Germany, Australia, and Japan. In particular, Spain, Taiwan of China, and Singapore perform well in terms of potential leading performance in engineering research hotspots, while Korea, England, and Italy are not in the top ten. From the number of participating hotspots of the core papers that cite other core papers, the number of first place hotspots and the number of top 3 hotspots, China and the USA perform comparably, and these two countries are far ahead of other countries or regions in all three indicators. Compared to Table 1.1, China has shown a very strong follow-up development capability in engineering research. Singapore and Taiwan of China also show a good trend of development, while Korea, England, and Italy rank 11, 12, and 13, respectively.

2 Overall comparison of the performance of the top 10 countries or regions in engineering development hotspots

Table 1.3 shows the statistical results for the top 10 countries or regions based on the number of first patentees of the core patents in the engineering development hotspots. Among them, China's data does not include Taiwan of China. The data demonstrates that the core patents of the first patentee in the USA, China, Japan, Korea, Germany, Canada, UK, Switzerland, France, and the Netherlands are distributed in all eight fields and involved in all 79 engineering development hotspots.

In addition, of the 79 engineering development hotspots, sixty-five are led by the USA, which are distributed in eight fields and account for 82.3% of all hotspots; fourteen are led by China, which are distributed in three fields and account for 17.7% of all hotspots; and no other countries or regions rank the first place in any hotspot. Concerning the top 5 countries or regions in any hotspot, the USA' and China's development hotspots are involved in eight fields and all 79 hotspots, while Japan's are involved in 73 hotspots belonging to eight fields, far ahead of other countries or regions.

Table 1.2 Top 10 countries or regions based on the number of core citing papers

Country/Region	Participation			First place			Top 3		
	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields
USA	65	73.0%	9	25	28.1%	8	44	49.4%	9
China	59	66.3%	9	25	28.1%	9	42	47.2%	9
Germany	32	36.0%	9	3	3.4%	3	15	16.9%	7
Australia	30	33.7%	9	4	4.5%	4	15	16.9%	7
Japan	22	24.7%	8	4	4.5%	4	10	11.2%	5
Spain	21	23.6%	7	1	1.1%	1	5	5.6%	3
Singapore	16	18.0%	7	0	0%	0	7	7.9%	5
Iran	14	15.7%	7	5	5.6%	5	10	11.2%	6
Taiwan of China	12	13.5%	7	2	2.2%	2	3	3.4%	2
Algeria	4	4.5%	4	1	1.1%	1	2	2.2%	2

Table 1.3 Top 10 countries or regions based on the number of first patentees

Country/Region	Participation			First place			Top 5		
	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields	Number of hotspots	Proportion	Number of fields
USA	79	100%	8	65	82.28%	8	79	100%	8
China	79	100%	8	14	17.72%	3	79	100%	8
Japan	79	100%	8	0	0.0%	0	73	92.41%	8
Korea	79	100%	8	0	0.0%	0	46	58.23%	8
Germany	79	100%	8	0	0.0%	0	45	56.96%	7
Canada	79	100%	8	0	0.0%	0	39	49.37%	8
UK	79	100%	8	0	0.0%	0	19	24.05%	5
Switzerland	79	100%	8	0	0.0%	0	5	6.33%	1
France	79	100%	8	0	0.0%	0	5	6.33%	3
Netherland	79	100%	8	0	0.0%	0	3	3.80%	2

3 Relationship between research hotspots

A relationship between engineering research hotspots can be characterized by mutual citations between hotspots' core papers. Figure 3.1 illustrates the citation network of the 89 engineering research hotspots, where the nodes represent hotspots, the node size represents the number of core papers in the hotspot, and hotspots with the same color belong to the same field. Two nodes are connected if there is at least one citation between the papers in two hotspots. The weight of a link is defined by the count of citations between two nodes.

We can observe two characteristics from the figure. First, the core papers in the field of medical and health do not cite the core papers in other fields, nor are they cited by other fields. Second, there are more links between hotspots than within hotspots. Intra-field connections are natural manifestations of the inner relations of various directions in the same field, and inter-field connections reflect the infiltration and integration between different fields. Based on the intrinsic linkages between hotspots, triangular structures can be observed, such as the "Reduction of methane emission" hotspot in the agriculture field and two hotspots named "Analytic techniques of atmospheric CH_4 emission and sources" and "Remote sensing inversion technique and estimation of flux for greenhouse gases" in the fields of environmental and textile engineering , all of which are related to the study of greenhouse gas emissions. Another includes the "Flow, heat/mass transfer, and combustion under extreme conditions" hotspot in the field of energy and mining engineering, and the hotspots called "Preparation of porous surfaces and their applications in enhanced heat transfer" and "construction and application of superhydrophobic surfaces" in the fields of chemical, metallurgical, and materials engineering, which are all involved in basic research on heat transfer, mass transfer, momentum transfer, and chemical reactions.

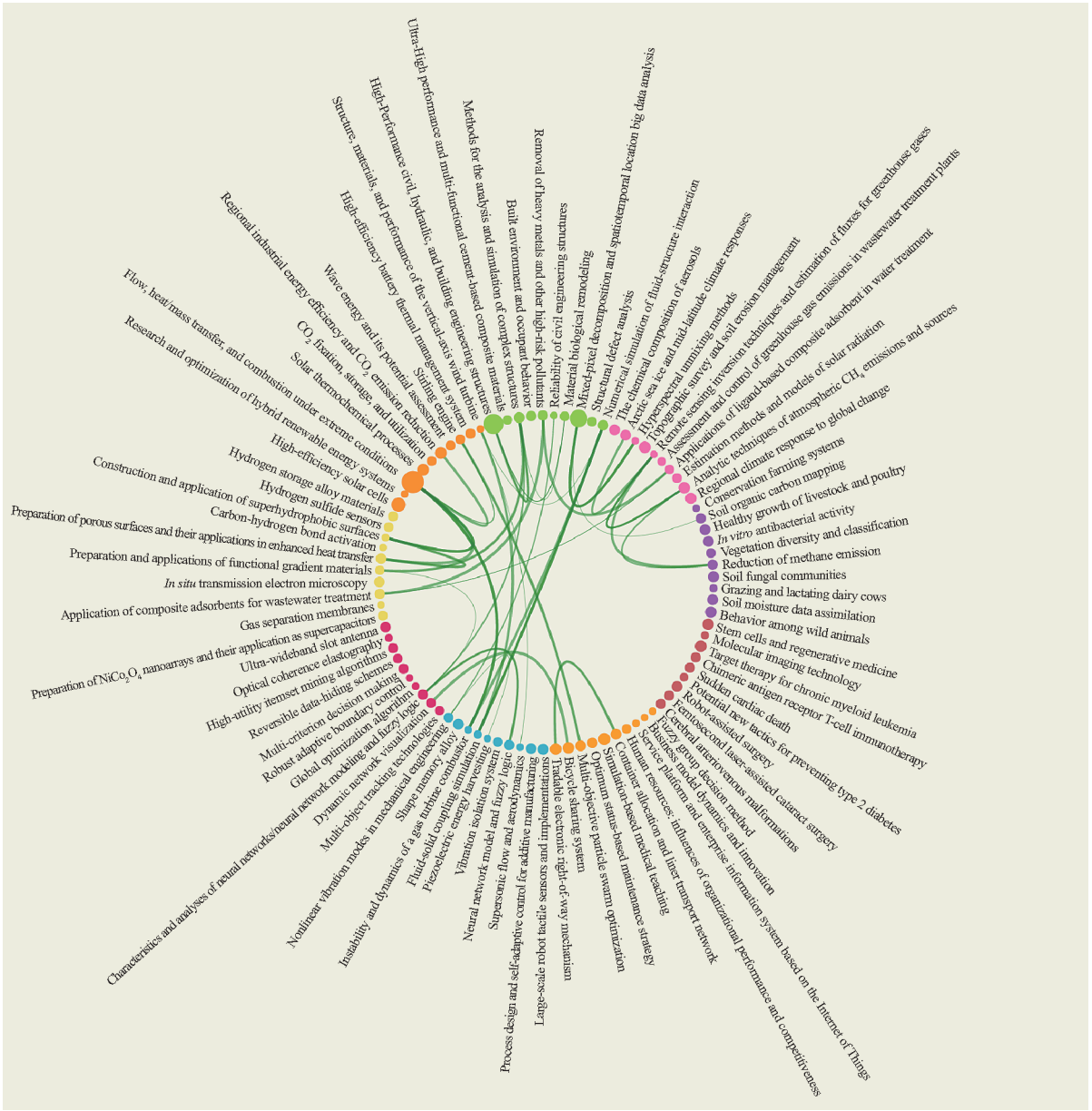

Figure 3.1 Citation network of engineering research hotspots

Project Participants

Experts of the General Plan Group

Consultants:

ZHOU Ji, FAN Daiming

Leader:

QIAN Xuhong

Members of General Plan Group (in random order)

DUAN Zhengcheng, GUO Dongming, PAN Yunhe, LU Xicheng, WANG Jingkang, XUE Qunji, WENG Shilie, NI Weidou, PENG Suping, CUI Junzhi, SHEN Zuyan, HAO Jiming, KANG Shaozhong, LI Zhaohu, DENG Xiuxin, CHEN Saijuan, YANG Baofeng, HE Jishan, SUN Yongfu, DING Lieyun, HAN Jun, WU Xiang, TU Shandong, ZHOU Weixing, MA Tieju, JI Jiuming, LIN Jiaping, CAI Fang, JIANG Zhiqiang

Writers of General Plan Report

ZHOU Weixing, JI Jiuming, JIANG Zhiqiang, ZHENG Wenjiang, MU Zhirui

Data Support Group

Clarivate Analytics

Secretary Group

Leaders:

WU Guokai, HAN Jun, AN Yaohui

Assistant Leaders:

WU Xiang, DING Ning, JI Xue, ZHOU Weixing

Members: (in random order)

WANG Xiaojun, FAN Guimei, WANG Aihong, ZONG Yusheng, TANG Haiying, ZHANG Jian, HUANG Haitao, LI Dongmei, YU Zehua, WEN Danyan, AN Qi, YAN Jianlin, CHEN Shuting, ZHENG Wenjiang, MU Zhirui

Acknowledgements

Thanks to the strong support of Higher Education Press, Clarivate Analytics, the editorial departments of nine journals of CAE, the Chinese Academy of Engineering Center for Strategic Studies, China Knowledge Center for Engineering Science and Technology, the offices of nine academic divisions of CAE, East China University of Science and Technology, Huazhong University of Science and Technology, Zhejiang University, National University of Defense Technology, Tianjin University, Shanghai Jiao Tong University, Tongji University, Tsinghua University, China Agricultural University, Young Professionals Office of "The Thousand Talents Plan," and Engineering Sciences Press.

Thank all academicians and experts who have participated in the questionnaire/survey.

Engineering Focus