Engineering Fronts

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Engineering Fronts

Contents

Foreword

Engineering science and technology are important driving forces in the development of society, and engineering fronts are important guidelines for the future development of engineering science and technology. Understanding trends and aiming to be at the forefront of global engineering technology has become a strategic choice for countries around the world. Since 2017, the Chinese Academy of Engineering (CAE), in conjunction with *Clarivate Analytics* and the Higher Education Press, has been organizing a research project named "Global Engineering Fronts," which aims to bring together talents in engineering and technology and push the fronts of global engineering research and development by reviewing papers and patent data. They also hope that the results of this project will provide a reference for people to respond to global challenges and achieve sustainable development.

The 2019 Global Engineering Fronts research continues to draw knowledge from journals and supplements in academic divisions of the CAE. By paying equal attention to the engineering research and development fronts, this project has obtained 93 global engineering research fronts and 94 global engineering development fronts through data analysis, expert review, integration of quantitative analysis and qualitative research, and combination of data mining and expert argumentation. Among these, 28 engineering research fronts and 28 engineering development fronts are listed as the focus fields.

To achieve a more scientific pre-judgment, the 2019 Global Engineering Fronts project began to nominate fronts from the perspective of the demand based on the experience of the first two years. Moreover, three rounds of deep interactions and iterative argumentation between data and experts have been conducted at each stage of data exchange, data analysis, and expert review. The aim is to improve the accuracy of data mining, research, and judgment, which can effectively maximize the utilization of papers, patents, and data indicators.

This report consists of two parts. The first chapter explains the research through data and methodology and the second chapter includes nine analysis reports, focusing on nine fields, namely mechanical and vehicle engineering; information and electronic engineering; chemical, metallurgical, and materials engineering; energy and mining engineering; civil, hydraulic, and architectural engineering; environmental and light textile engineering; agriculture; medicine and health; and engineering management. Each report describes and analyzes the engineering research and development fronts in the abovementioned fields, and explains in detail the key fronts.

Chapter 1 Methodology

Underpinned by experts' evaluation and data, the 2019 Global Engineering Fronts project adopts multi-round interactions between experts and data for iterative research and analysis, realizing a deep integration of the experts' subjective judgments and objective data analyses. This project selected 93 global engineering research fronts and 94 global engineering development fronts in 2019, with 28 engineering research fronts and 28 engineering development fronts being listed as the current focus of interpreting according to principles, such as development prospects and the degree of attention. The number distribution of engineering fronts of the nine fields is shown in Table 1.1.

The specific research methods consist of three stages, namely data exchange, data analysis, and expert review. During the data exchange stage, the interaction of domain experts and library and information experts plays a significant role in defining the scope of data mining. In the data analysis stage, research hotspots and ThemeScape maps featured by data are obtained through clustering methods, and engineering hotspots are determined through expert research. In the expert review stage, the results of fronts are obtained through methods such as expert discussions and questionnaires. In addition, to fix the problem of insufficient research data owing to algorithm limitations or lags in data mining, experts from different fields were encouraged to check the results of the data analysis to fill in the gaps and nominate the engineering fronts. The specific operation procedure is shown in Figure 1.1, in which green and purple boxes indicate data analysis and expert research steps, respectively.

1 Identification of engineering research fronts

In this report, the identification of the engineering research fronts is performed mainly in the following two ways. The first is defining the literature clustering theme through the clustering method of co-citation according to the SCI journal papers and data of conference proceedings from the *Web of Science Core Collection* of *Clarivate Analytics*. The second is defining the engineering research fronts through expert nomination. Alternative engineering research fronts that were identified through expert argumentation and refinement went through questionnaires and multiple rounds of expert discussions, yielding approximately ten engineering research fronts in each field.

1.1 Acquisition and preprocessing of paper data

Clarivate Analytics mapped the fields of *Web of Science* and the nine academic division fields of the CAE and obtained a list of journals and conferences in each field. After the correction

Table 1.1 Number distribution of engineering fronts of the nine fields

Field	Number of engineering research fronts	Number of engineering development fronts
Mechanical and Vehicle Engineering	10	10
Information and Electronic Engineering	10	10
Chemical, Metallurgical, and Materials Engineering	11	12
Energy and Mining Engineering	12	12
Civil, Hydraulic, and Architectural Engineering	10	10
Environmental and Light Textile Engineering	10	10
Agriculture	10	10
Medicine and Health	10	10
Engineering Management	11	10
Total	93	94

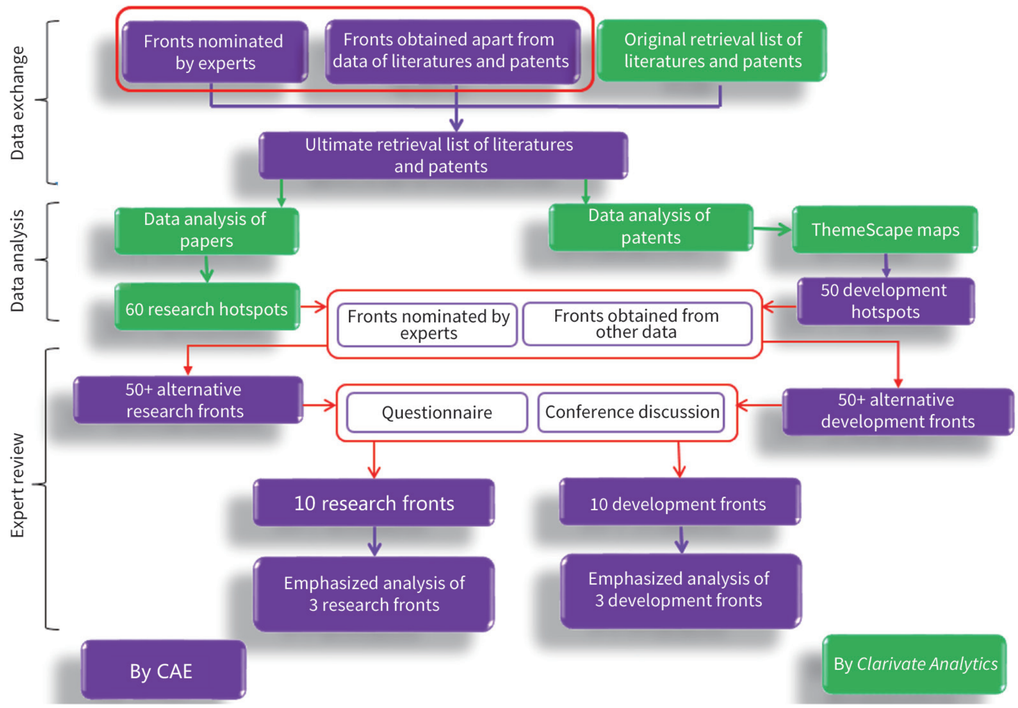

Figure 1.1 Operation procedure of Global Engineering Fronts project

and supplementation by domain experts, the sources for data analysis in the nine fields were determined to be 10 817 journals and 24 330 Conferences. In addition, for articles from 70 journals with integrative subjects (such as *Science*), the field of each article was identified according to the subjects of its references. In this way, the articles and conference papers published between 2013 and 2018 were retrieved (the cut-off date of the citations was February 2019).

For each field, *Clarivate Analytics* comprehensively considered the differences between journals and conferences, the publication year, etc. Next, the paper lists mentioned above were retrieved and extracted. By processing journals and conference proceedings separately, papers with high impact and rank among the top 10% of the citations were selected as the original data set for the analysis of the research hotspots, as shown in Table 1.1.1.

1.2 Acquisition and selection of literature clustering topics

Through the citation clustering analysis of the top 10% highly-cited papers in the above nine data sets, all the literature clustering topics in the nine fields were obtained. The topics of papers published during the year 2017–2018 were selected according to the number of core papers, the total number of citations, and the proportion of consistently cited papers. After that, 25 different literature topics were obtained. In addition to the criteria for the selection of the topics of papers published in 2017–2018, the papers published before 2017 were selected according to the mean publication year of core publications and the proportion of consistent citations. As a result, 35 different literature topics were extracted. Overlapping topics were replaced by topics that did not intersect with other fields. In addition, subjects that were not covered by clustering topics were extracted separately according to keywords. Finally, 806 literature clustering topics in the nine fields were obtained (Table 1.2.1).

1.3 Expert review

The identification of the research fronts by the experts is an important supplement to data mining. In the data exchange stage, domain experts proposed research fronts issues, and library and information experts codified these issues for data

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

No.	Field	Number of journals	Number of conferences	Number of top 10% highly-cited papers
1	Mechanical and Vehicle Engineering	457	1 768	38 676
2	Information and Electronic Engineering	986	9 632	109 507
3	Chemical, Metallurgical, and Materials Engineering	1 128	2 313	219 081
4	Energy and Mining Engineering	226	785	440 641
5	Civil, Hydraulic, and Architecture Engineering	359	512	28 384
6	Environmental and Light Textile Engineering	1 003	605	93 524
7	Agriculture	1 575	975	105 523
8	Medicine and Health	4 328	7 059	392 142
9	Engineering Management	755	681	32 927

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

No.	Field	Number of topics	Number of top 10% highly-cited papers	Number of alternative engineering research hotspots
1	Mechanical and Vehicle Engineering	6 720	29 960	138
2	Information and Electronic Engineering	16 816	76 015	67
3	Chemical, Metallurgical, and Materials Engineering	26 563	116 361	68
4	Energy and Mining Engineering	10 624	47 860	100
5	Civil, Hydraulic, and Architectural Engineering	5 594	25 867	115
6	Environmental and Light Textile Engineering	18 486	80 850	90
7	Agriculture	7 663	33 909	81
8	Medicine and Health	46 264	203 487	63
9	Engineering Management	4 240	18 321	84

mining, which was an important part of the data sources analysis. In the data analysis stage, domain experts provided keywords, representing papers or journals for the subjects that did not belong to the clustering topics, which were used to support the *Clarivate Analytics*' search. In the expert review stage, the domain experts compared and checked the literature clustering results provided by *Clarivate Analytics*. Clustering topics that did not appear in the results of data mining but were considered important by experts underwent a second round of nomination and were supported by data provided by the library and information experts. Finally, domain experts merged, revised, and refined the engineering research front topics obtained through data mining and expert nomination and selected 93 engineering research fronts through network questionnaires, academic questionnaires, and multiple rounds of discussion.

2 Identification of engineering development fronts

2.1 Selection of engineering development hotspots

The identification of the engineering development fronts is performed mainly in the following two ways. In the first method, the *Derwent Innovation* patent database of *Clarivate Analytics* was considered as the original data source. The matching relation between the patent classification of *Derwent* and the specialty division criteria system of the CAE's academic divisions was used to obtain the primary data for the analysis. Then, 53 subjects of the nine fields with at least 10 000 citations were clustered, and 53 ThemeScape maps were obtained. The domain experts interpreted the alternative engineering development fronts from these maps, while analyzing the field of engineering management as a separate subject group. The second approach involved nomination by expert or patent analysis by small peer. The alternative development fronts obtained through the above two methods went through questionnaire surveys and several special seminars. As a result, approximately ten engineering development fronts in each field were identified.

2.2 Acquisition and interpretation of the ThemeScape maps

Clarivate Analytics established the matching relation between the Derwent Manual Codes and the specialty division criteria system of the CAE's divisions. Then, the scope of the patent data retrieval and search strategies in the nine fields was determined. Domain experts deleted, supplemented, and improved the Derwent Manual Codes to determine the patent retrieval criteria of the 53 specialty groups. The retrieved patents were published between 2013 and 2018, and the cut-off date of the citations was February 2019.

Based on the *Derwent Innovation* patent platform retrieval, the annual average of the citation number and technical coverage width indicators were considered comprehensively, and the topics of the top 10 000 highly-cited patents, corresponding to each specialty group, were selected. Fifty-three patents from the ThemeScape maps were obtained by considering the semantic similarity of the patents' text, which is effective in displaying the distribution of the engineering development techniques.

Experts from various fields, with the assistance of library and information experts, selected the engineering development fronts from ThemeScape maps, merged similar fronts, and determined the final development fronts. Finally, they decided the alternative engineering development fronts of each specialty group. In addition, to avoid assessing the patent data mining merely by figures and facts, field group experts interpreted the data from patents with few citations and poor correlation in the ThemeScape maps.

2.3 Nomination of development fronts by experts

To compensate for the limitations of the algorithms or the lags in data mining, which might extract inappropriate development fronts, domain experts were encouraged to check the result and identify new development fronts. In the data exchange stage, domain experts proposed keywords and descriptions of development fronts, and library and information experts codified these fronts for patent retrieval, which formed an important part of the data source. In the data analysis stage, the results were double-checked and the ThemeScape map deviation was corrected to identify the fronts that were unpopular or marginal, which were then overlooked by the statistical data. In the expert review stage, domain experts made necessary further nominations for the fronts that were not listed in the data mining results but were considered to be important. This procedure was supported by the data provided by the library and information experts. In the end, domain experts merged, revised, and refined the data for the identification of the engineering development fronts obtained from data mining and expert nomination and acquired 351 candidate development fronts. Through network and academic questionnaires and multiple rounds of discussion, 94 engineering development fronts were selected.

3 Terminologies

Fronts: "Fronts" in global engineering research fronts refers to the main directions that should be followed for the development of future engineering technology. The front is an important guideline for cultivating innovation in engineering disciplines.

Literature (Papers): This includes peer-reviewed and published journal articles, reviews, and conference papers retrieved from *Web of Science*.

High-impact papers: The top 10% papers in terms of the number of citations, published in the same year and belonging to the same subject.

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

Core papers: High-impact papers related to the engineering research fronts.

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

Mean publication year: Average publication years for all papers in the literature clustering themes.

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

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

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

Technical coverage width: It is measured by the number of Derwent Manual Codes to which each patent family belongs. This indicator can reflect the breadth of technology coverage of each patent.

Specialty division criteria system of the CAE's academic divisions: This includes 53 specialized fields covered by nine academic divisions of engineering science and technology. It is determined in accordance with the *Academic Divisions and Specialty Division Criteria of the Chinese Academy of Engineering for the Election of Academicians (for Trial Implementation)*.

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The ten most-researched engineering topics in the field of mechanical and vehicle engineering (hereafter referred to as mechanical field) include mechanical, transportation, ship and marine engineering; weapon science and technology; aeronautical and astronautical science and technology, and power and electrical equipment engineering and technology (as listed in Table 1.1.1). Among these, "high-energy density solid-state lithium batteries," "drag/heat reduction in supersonic flow," "high-performance nano-biosensors," "information security and privacy protection in the Internet of Vehicles (IoV)," "self-adaptive target capture by tethered space robots," and "hybrid power systems with renewable energy and fuel cells" are extensively studied traditional topics. "Intelligent manufacturing based on the industrial Internet of Things (IIoT)," "cooperative control of multirobot systems," "integration of design and manufacturing based on topology optimization and additive manufacturing," and "resource scheduling and risk assessment of smart grids" are considered as emerging topics. The annual publication of papers during the years 2013–2018 is listed in Table 1.1.2. "Hybrid power systems with renewable energy and fuel cells" and "cooperative control of multirobot systems" are the most rapidly growing topics in terms of paper publications in recent years.

(1) Intelligent manufacturing based on the industrial IIoT

The IIoT can achieve rational allocation of manufacturing resources, on-demand execution and continuous optimization of manufacturing processes, and rapid adaptation of manufacturing environments through network interconnections, data exchange, and system interoperation of manufacturing systems. As a result, intelligent manufacturing systems driven by innovative manufacturing services are developed. Relevant studies are currently categorized in three main areas: 1) intellisense (i.e., intelligent perception) and iterative optimization of smart products in their entire life cycle that includes the perception and handling of large amounts of data in the industrial value chains of design, production, logistics, sales, and services; 2) universal interconnection and accurate control of manufacturing systems that include sensing devices, distributed control systems, manufacturing execution systems, enterprise resource planning systems, and supply chain management systems at the equipment, control, shop floor, enterprise, and enterprise collaboration layers; 3) modeling, simulation, and real-time analysis of intelligent functions of manufacturing systems including entity coordination, system

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Intelligent manufacturing based on the IIoT	21	460	21.90	2017.1
2	High-energy density solid-state lithium batteries	26	828	31.85	2015.4
3	Drag/heat reduction in supersonic flow	48	983	20.48	2016.3
4	Cooperative control of multirobot systems	23	764	33.22	2017.1
5	High-performance nano-biosensors	45	1478	32.84	2016.6
6	Information security and privacy protection in the IoV	17	617	36.29	2015.6
7	Integration of design and manufacturing based on topology optimization and additive manufacturing	5	86	17.20	2017.0
8	Self-adaptive target capture by tethered space robots	34	779	22.91	2015.5
9	Hybrid power systems with renewable energy and fuel cells	47	1179	25.09	2016.7
10	Resource scheduling and risk assessment for smart grids	18	689	38.28	2016.5

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

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Intelligent manufacturing based on the IIoT	0	0	0	3	13	5
2	High-energy density solid-state lithium batteries	3	7	2	8	4	2
3	Drag/heat reduction in supersonic flow	3	5	5	10	14	11
4	Cooperative control of multirobot systems	0	2	1	0	10	10
5	High-performance nano-biosensors	2	2	5	4	23	9
6	Information security and privacy protection in the IoV	2	2	2	6	5	0
7	Integration of design and manufacturing based on topology optimization and additive manufacturing	0	0	1	0	2	2
8	Self-adaptive target capture by tethered space robots	2	6	5	14	7	0
9	Hybrid power systems with renewable energy and fuel cells	0	1	3	16	17	10
10	Resource scheduling and risk assessment for smart grids	0	0	3	5	8	2

integration, information fusion, and new business patterns such as customization and predictive maintenance of smart products. Research in these areas faces the challenges of the complexity and diversity of interconnection technologies and protocols, a wide range of applications, numerous hidden issues of cyber security and data safety. Therefore, new 5G mobile networks, human–cyber–physical systems (HCPSs), software-defined networks, edge computing, digital twins, and so on have emerged as frontiers in the research and development trends of intelligent manufacturing based on the industrial Internet of Things.

(2) High-energy density solid-state lithium batteries

Liquid-state lithium batteries are in widespread use, but they have already reached their theoretical or engineering limits in the key metrics of energy density and safety. Therefore, new methods of energy storage must be developed to satisfy future needs. Solid-state batteries use solid instead of liquid electrolytes containing small organic molecules. Thus, these batteries possess advantages over liquid batteries in terms of energy density, safety, and life cycle and are believed to be the next-generation electrochemical power sources. Surface/interface mass transfer, key materials compatibility, low interfacial impedance technology, evolution mechanism during the entire life cycle, and other frontier science challenges are mainly addressed in the emerging technology of solid-state batteries. In future, in situ analysis and characterization techniques will be developed for interface impedance problems such as the following. 1) Matching of key materials with high specific energy include cathode materials with high capacity/high voltage, high-performance solid electrolytes, and high capacity lithium anodes with high capacity metals. These challenges require considerable attention at present. 2) Preparation techniques for low impedance micro-interfaces that include design and material matching are vital for mass production. 3) The attenuation in the battery performance and the evolutionary route of the materials in the system during the entire life cycle are key factors in the assessment and prediction of health status of solid-state batteries. Further development of solid-state metal–air batteries based on solid electrolytes with long lifetimes will become the ultimate goal of research on electrochemical power components.

(3) Drag/heat reduction in supersonic flow

Drag/heat reduction in supersonic flow studies the flow of gas or plasma on solid surfaces with a relative speed above Mach 3. Such a supersonic flow occurs in nozzles on hypersonic vehicles, around spacecrafts re-entering the atmosphere, and in high-altitude, high-speed scouting planes or nozzle internal flow in jet engines. Strong aerodynamic heating, air ionization, impact waves, burning, and other problems accompany such rapid motion. Theoretically, problems in plasma flow, impact wave, rarefied air dynamics, and heat transfer under complex flow can be barely simulated through the currently applied Navier–Stokes equation-based numerical simulation method. The direct Monte Carlo simulation and Fokker–Planck equation methods must be improved. Real experimental methods should further develop sensors that are resistant to the high temperatures and impact forces found in supersonic systems and wind tunnels. Drag/heat reduction techniques under investigation include the use of needles, reverse and internal jets, plasma boundary layer control, laser energy deposition, bottomward direction of aircraft exhaust, sacrificial surface layers for ablation, and internal insulation at the front end of an aircraft. The manufacture of jet orifices and gas supply systems, experimental techniques, and numerical simulation techniques for complex curved surfaces should have increased capabilities.

(4) Cooperative control of multirobot systems

As the cross development in artificial intelligence (AI), automation, and computer science, the interactions of multiple robots have become an important subject of study in engineering control. Communication, coordination, scheduling, cooperation, and control among robots have all been studied, and highly coordinated collective dynamic actions have been observed; multirobot cooperation can be applied to accomplishing substantial complex work that no single robot can complete. Multirobot control methods are known to be robust and can reliably solve actual problems. Traditional multirobot production systems employ a centralized control structure and ignore the possibility of cooperative behavior. Such systems cannot adjust to production patterns involving small quantities and numerous varieties of products, and lack smart manufacturing ability. As the manufacturing industry develops toward ever larger and more complex operations, there is a pressing need for cooperative multirobot systems with improved compliance, consistency, and optimization performance.

(5) High-performance nano-biosensors

Nano-biosensors are very important for modern biotechnology. The trend in this area is toward small, portable, fast, highly sensitive, integrated, and inexpensive devices. High-performance nano-biosensors of current interest include immunosensors, surface plasma resonance biosensors, mycotoxin ultratrace sensors, and tumor biomarker sensors. Ultratrace and highly selective nano-biosensors are an imminent requirement because conventional biosensors lack sensitivity and selectivity in the detection of mycotoxins and tumor cells. Such devices, based on novel biocompatible nanomaterials such as metal sulfide quantum dots, nanocomposites, graphene oxide, and two-dimensional nanomaterials, could greatly improve the sensitivity, response rate, and selectivity of biosensors, and is likely to become a dominant research topic in the field.

(6) Information security and privacy protection in the IoV

The IoV is a new intelligent system that integrates wireless communication technology into the modern automobile industry. It incorporates advanced technologies, such as big data, cloud computing, and AI, substantially contributing to road planning, resource scheduling, and traffic improvement. However, because of its large network scale, open communication environment, and predictable mobile track, the IoV is extremely vulnerable to attacks, system crashes, and privacy leaks. Safeguarding the IoV is therefore a major goal of academics and automotive industry researchers. Proposed secure communication methods, such as aggregate signatures and periodic certificate ignoring, have improved verification and communication efficiency, which can solve the problem of the high communication overhead of digital signature communication based on Public Key Infrastructure (PKI). Privacy protection proposals such as anonymous authentication, shared certificates, and group signatures can reduce the number of vehicles using unique certificates, thereby enhancing user privacy. Location privacy protection schemes such as *k*-anonymity, mixed zones, and group navigation can prevent the location server from knowing the actual place from which a location request originates. Such research can effectively improve the communication efficiency and safety of the IoV. However, as driverless technology rapidly develops, the IoV will face an increasingly complex network environment and ever greater data-processing demands. IoV information security and privacy protection will be a long and arduous task.

(7) Integration of design and manufacturing based on topology optimization and additive manufacturing

Both topology optimization and additive manufacturing are major innovations in design and manufacturing. The integration of the two has become a leading priority in the development of China’s high-end equipment industry. Currently, it is mostly implemented by a serial method that attempts to fabricate the optimized designs through additive manufacturing. Research on more sophisticated topology optimization methods for additive manufacturing remains limited. On the one hand, many additive manufacturing components must still meet the requirements of traditional processes, such as casting, sheet metal, and machining. Consequently, the advantages and potentials of additive manufacturing are difficult to maximize. On the other hand, existing topology optimization methods do not consider the design of the structure from the perspective of multi-material, multi-scale, and multi-component integration, and the special constraints of the additive manufacturing process are hardly considered at all. Such circumstances inevitably result in structural performance being sacrificed, given the current serial mode of design and manufacturing. Although existing research has achieved initial results, it cannot reveal its design principles from the depth of material–structure–process integration. Structural models of mechanical behavior, influencing mechanisms of process constraints, topology optimization design with a complex overall structure, design tool development, and material applications of additive manufacturing constitute a bottleneck for additive manufacturing and structural innovation design.

(8) Self-adaptive target capture by tethered space robots

As human activity in space increases, the number of lost or retired spacecraft and the amount of orbital debris increase as well. The use of robots to remove unwanted materials in space is thus gradually becoming a prevalent research topic in the aerospace industry. Tethered robots are an effective solution for capturing and dragging large targets with complex motion, but they can easily collide, oscillate, or roll in microgravity or vacuum environments. Tethered space-robot technology requires advances in attitude measurement techniques and coordinated control systems based on vision. Collision analysis, real-time dynamics, and control design should be improved to ensure the reliability of tethered space robots in the target-capture process.

(9) Hybrid power systems with renewable energy and fuel cells

Internal combustion vehicles bring people convenience and comfort, but also cause serious environmental pollution and consume fossil fuels. Almost all countries are therefore researching green and renewable energy. Hybrid power systems based on renewable energy and fuel cells have become attractive particularly to the automotive industry due to their lack of emissions. Hybrid systems also have high power density, high stability, and a wide range of operating temperature. These advantages make them preferred power sources for solving energy and environmental problems in the future. Currently, the main and auxiliary energy sources are commonly used to simultaneously supply energy to the multi-energy power system structure. Research on the structure and optimization of hybrid systems, and selection of reasonable control strategies for the proper distribution of power between the various energy sources, are the core issues of current hybrid power system research, which is complicated by the diversity of hybrid power systems, the complexity of their control systems, and their weak dynamic performance.

(10) Resource scheduling and risk assessment for smart grids

Smart grids are grids of a new type closely integrating modern sensing, communication, information, and control technologies into the traditional framework. Seamless connection and real-time interaction between the elements of a smart grid can be ensured through the application of distributed intelligence, broadband communication, and automatic control, resulting in a more reliable, safer, cheaper, and more environmentally friendly grid. The keys to building a smart grid are the establishment of a strong and flexible grid structure, access to renewable and distributed energy, integration of open power–information communication systems, and construction of an efficient network of emergency centers. Because the scale of power systems is continually expanding, the risks of grid operation are increasing, and resource scheduling tasks are becoming increasingly complicated and arduous. Thus the development of new resource-scheduling and risk-assessment methods for smart grids is necessary to improve the flexibility, security, and reliability of power systems.

1.2 Interpretations for three key engineering research fronts

1.2.1 Intelligent manufacturing based on the IIoT

We are currently in an era of intense global competition, sometimes called a new industrial revolution. In the national development strategies of many countries, including German Industry 4.0, American Advanced Manufacturing, Made in China 2025, British Industry 2050, and the Japan Revitalization Strategy, intelligent manufacturing is ranked as an important direction for the future development of industry. Research on the IIoT, a crucial enabling technology for intelligent manufacturing, has become widespread. This includes research on the interconnection of entities in the manufacturing field; information modeling and fusion; innovative application modes; and optimization of manufacturing resources allocation. Current research and development in intelligent manufacturing based on the IIoT proceeds in three dimensions (life cycle, system level, and intelligence) and six directions (intellisense, ubiquitous connectivity, precision control, digital modeling, real-time analysis, and iterative optimization).

The life cycle dimension includes the application of the IIoT to chained sets of interrelated activities (such as design, production, logistics, sales, and services) that focus on collaboration and interconnection between enterprises. The system level dimension focuses on the application of the IIoT at the equipment, control, shop floor, enterprise, and supply chain coordination levels, that is, on interconnections mostly within a single enterprise. The intelligence dimension concentrates on entity collaboration, system integration, information fusion, and emerging business patterns including the transformation from manufacturing to services and product predictive maintenance. Intellisense research explores the effective use of sensors, including radio-frequency identification (RFID) systems, as a means to obtain information on different aspects of a product's life cycle. Ubiquitous connectivity research investigates methods of interconnecting machines with each other, with people, and with the environment. Digital modeling studies the mapping of manufacturing resources to digital spaces, including the abstract modeling of the full elements of the production. Real-time analysis studies visualization and conducts visual analysis of manufacturing resource data, exploring the intrinsic link between industrial resource states in virtual and real spaces. Precision control studies the precise information interaction and seamless cooperation of manufacturing resources in the IIoT. Iterative optimization studies self-learning and improvement methods, and explores the optimal configuration of manufacturing resources, processes, and environments in the IIoT.

Although some important progress has been made in the three dimensions and six directions of intelligent manufacturing research based on the Internet of Things, such research faces the usual problems posed by the complexity and diversity of interconnected technologies and protocols, different depths and widths of applications, cyber security and data safety, as well as other issues. In recent years, HCPS, new 5G mobile networks, software-defined networks, edge computing, and digital twins have attracted a lot of attention. Ternary systems and frameworks, large-bandwidth communication, low latency and superior connection, automated and programmable networks, device-side edge computing, and virtual digital and physical device spaces mapping are all important topics in this field.

The four countries/regions producing the most core papers in intelligent manufacturing based on the IIoT are China (7), Germany (6), Sweden (6), and Italy (6). The three countries/regions with the greatest average number of citations are Germany (38), Brazil (28), and France (23.75), as shown in Table 1.2.1. Among the 10 countries/regions with the most core papers, substantial collaboration is initiated between China, Switzerland, and Sweden, as shown in Figure 1.2.1. The four institutions with the most core papers are ABB Corporate Research Center (4), Beijing University of Posts and Telecommunications (3), Tsinghua University (3), and University of Padua (3). The three institutions with the highest average number of citations are Asea Brown Boveri Corporate Research Center (34), Cisco Systems (34), and Center Communication Systems Research (34), as shown in Table 1.2.2. Among the ten institutions with the most core papers, substantial collaboration is initiated between the ABB Corporate Research Center, Beijing University of Posts and Telecommunications, and Tsinghua University, as shown in Figure 1.2.2. The three countries or regions with the most citing papers are China (71), Italy (61), and the USA (52), as shown in Table 1.2.3. The institutions with the greatest number of citing papers are ABB Corporate Research Center (12), National Research Council (Italy) (11), Federal University of Santa Catarina (7), and University of Padua (7), as shown in Table 1.2.4.

1.2.2 High-energy density solid-state lithium batteries

Liquid electrolyte lithium batteries, limited by material and device structure constraints, have reached their theoretical engineering limits for several key indicators, including energy density, safety, and cycle life. Further improvements in materials or processes cannot easily be translated into major improvements in performance. Therefore, new energy-storage materials and matching device structures must be developed to meet the future need for high specific energy. Liquid electrolyte batteries use a small-molecule organic solvent, which is flammable and easily degraded, initiating a series of chain reactions that reduce battery performance. Solid-state batteries use solid electrolytes instead of liquid, and possess potential advantages in energy density, safety, and cycle life.

Table 1.2.1 Countries or regions with the greatest output of core papers on "intelligent manufacturing based on the IIoT

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	7	33.33%	97	21.09%	13.86
2	Germany	6	28.57%	228	49.57%	38.00
3	Sweden	6	28.57%	106	23.04%	17.67
4	Italy	6	28.57%	76	16.52%	12.67
5	USA	5	23.81%	70	15.22%	14.00
6	Switzerland	4	19.05%	68	14.78%	17.00
7	France	4	19.05%	95	20.65%	23.75
8	Canada	3	14.29%	66	14.35%	22.00
9	Brazil	2	9.52%	56	12.17%	28.00
10	South Korea	2	9.52%	22	4.78%	11.00

Table 1.2.2 Institutions with the greatest output of core papers on "intelligent manufacturing based on the IIoT"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	ABB Corp Res	4	19.05%	39	8.48%	9.75
2	Beijing Univ Posts & Telecommun	3	14.29%	49	10.65%	16.33
3	Tsinghua Univ	3	14.29%	49	10.65%	16.33
4	Univ Padua	3	14.29%	43	9.35%	14.33
5	City Univ Hong Kong	2	9.52%	39	8.48%	19.50
6	KTH Royal Inst Technol	2	9.52%	44	9.57%	22.00
7	Royal Inst Technol	2	9.52%	14	3.04%	7.00
8	Asea Brown Boveri Corp Res	1	4.76%	34	7.39%	34.00
9	Cisco Syst	1	4.76%	34	7.39%	34.00
10	Ctr Commun Syst Res	1	4.76%	34	7.39%	34.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "intelligent manufacturing based on the IIoT"

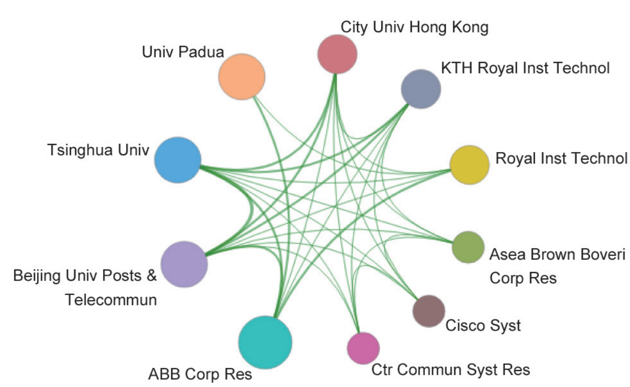

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "intelligent manufacturing based on the IIoT"

Table 1.2.3 Countries or regions with the greatest output of citing papers on “intelligent manufacturing based on the IIoT”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	71	18.88%	2017.8
2	Italy	61	16.22%	2017.6
3	USA	52	13.83%	2018.0
4	Germany	47	12.50%	2017.7
5	Sweden	27	7.18%	2017.7
6	UK	22	5.85%	2017.9
7	Brazil	22	5.85%	2017.9
8	South Korea	20	5.32%	2017.7
9	Spain	20	5.32%	2017.8
10	France	19	5.05%	2017.6

Table 1.2.4 Institutions with the greatest output of citing papers on “intelligent manufacturing based on the IIoT”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	ABB Corp Res	12	15.79%	2017.7
2	Natl Res Council Italy	11	14.47%	2017.4
3	Univ Fed Santa Catarina	7	9.21%	2017.9
4	Univ Padua	7	9.21%	2017.3
5	KTH Royal Inst Technol	6	7.89%	2017.8
6	Beijing Univ Posts & Telecommun	6	7.89%	2017.8
7	Berlin Sch Econ & Law	6	7.89%	2017.3
8	Old Dominion Univ	6	7.89%	2018.2
9	Natl Inst Stand & Technol	5	6.58%	2017.6
10	Univ Texas Dallas	5	6.58%	2018.4

By matching the high-voltage positive electrodes and selecting compact structure modes, they effectively avoid the side reactions caused by small organic molecules. Therefore, solid-state batteries are believed to be the most promising generation of high-specific-energy electrochemical power sources.

Despite the great advantages that solid-state batteries potentially afford, several major challenges hinder their adoption for large-scale usage. The first is that of exploring a practical high-performance solid electrolyte exhibiting high ionic conductivity under the condition of various rates and establishing suitable manufactory processes to avoid damaging the desired interface microstructures. Materials genomics, which uses cutting-edge technology such as AI and machine learning to discover and optimize new materials, provides a more efficient way to design and develop high-performance solid electrolyte materials than the traditional trial-and-error method. This emerging approach will undoubtedly accelerate the evolution of solid-state batteries. Another challenge involves material-matched preparation technology and techniques that are based on surface/interface mass transfer and interface impedance. Material systems and structural processes certainly need to be changed systematically to match the changing manufacturing processes. Integrated roll-to-roll preparation is currently considered a promising direction for research. Another bottleneck is that the performance life cycle of solid-state batteries remains unclear. Life cycle monitoring can take as long as ten years; understanding changes in performance over such a long time is very challenging. Big data analysis, including AI and deep learning, will be required to address the performance attenuation of batteries over their entire life cycle.

Solid-state batteries can meet the need for high energy density to a certain extent, but the ultimate goal of research on electrochemical power devices is to match that of conventional fuels. Metal–air batteries based on solid electrolyte materials can, in theory, come close to achieving this, with specific energy densities near 11 430 W·h/kg. Such batteries are currently the focus of intense research and development, but there are serious challenges yet to be overcome on ways to deal with side effects caused by air anodes, stabilization of metal cathodes, and improvement in cyclic performance. Important science and engineering topics will involve research on catalytic mechanisms, structural design, and module packing and power management. In the future, research will give way to development, and the focus will shift to material systems, engineering, and processes.

The four countries or regions that have produced the most core papers on high-energy density solid-state lithium battery engineering are India (20), Slovenia (5), the USA (2), and Hungary (2). The countries or regions producing the highest average number of citations are Slovenia (39.2), India (30.35), and the USA (28), as shown in Table 1.2.5. There is extensive research cooperation between India and Hungary, as shown in Figure 1.2.3. The institutions with the most core papers are Institute of Chemical Technology (17), University of Ljubljana (5), and Jozef Stefan Institute (3). The institutions with the highest average citation numbers are Jozef Stefan International Postgraduate School (55.5), Jozef Stefan Institute (49.67), and University of Ljubljana (39.2), as shown in Table 1.2.6. More cooperation transpires between the University of Ljubljana, the Jozef Stefan Institute, and the Jozef Stefan International Postgraduate School than with other institutions, as shown in Figure 1.2.4.

The countries or regions with the most citing papers are China (113), India (100), Malaysia (30), and Italy (30), as shown in Table 1.2.7. The institutions that have produced the most citing papers are Institute of Chemical Technology (50), University of Ljubljana (16), Chinese Academy of Sciences (13), and University of Malaya (13), as shown in Table 1.2.8.

Table 1.2.5 Countries or regions with the greatest output of core papers on “high-energy density solid-state lithium batteries”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	India	20	76.92%	607	73.31%	30.35
2	Slovenia	5	19.23%	196	23.67%	39.20
3	USA	2	7.69%	56	6.76%	28.00
4	Hungary	2	7.69%	48	5.80%	24.00
5	China	1	3.85%	25	3.02%	25.00

Table 1.2.6 Institutions with the greatest output of core papers on “high-energy density solid-state lithium batteries”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Inst Chem Technol	17	65.38%	528	63.77%	31.06
2	Univ Ljubljana	5	19.23%	196	23.67%	39.20
3	Jozef Stefan Inst	3	11.54%	149	18.00%	49.67
4	Jozef Stefan Int Postgrad Sch	2	7.69%	111	13.41%	55.50
5	Univ West Hungary	2	7.69%	48	5.80%	24.00
6	Malaviya Natl Inst Technol	2	7.69%	39	4.71%	19.50
7	Ecol Engn Inst Ltd	1	3.85%	29	3.50%	29.00
8	FJP CCN Domzale Kamnik Doo	1	3.85%	29	3.50%	29.00
9	Clarkson Univ	1	3.85%	31	3.74%	31.00
10	Ecosphere Energy Serv LLC	1	3.85%	31	3.74%	31.00

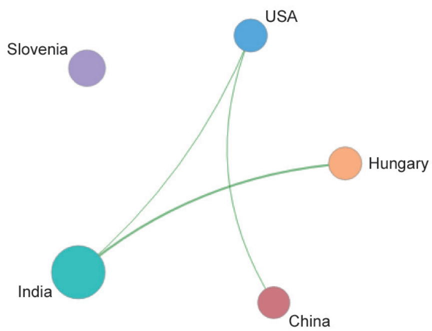

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "high-energy density solid-state lithium batteries"

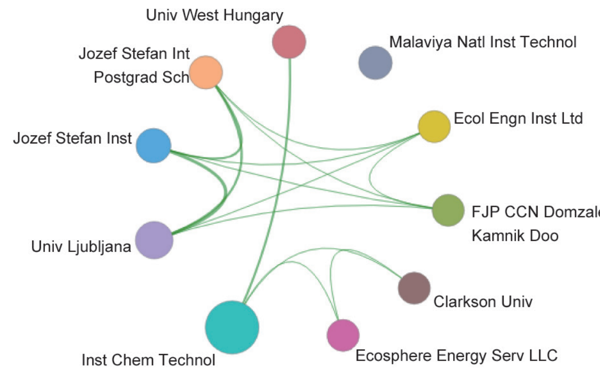

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "high-energy density solid-state lithium batteries"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "high-energy density solid-state lithium batteries"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	113	27.49%	2017.0
2	India	100	24.33%	2016.7
3	Malaysia	30	7.30%	2016.7
4	Italy	30	7.30%	2016.6
5	Iran	29	7.06%	2016.9
6	Slovenia	22	5.35%	2016.2
7	USA	19	4.62%	2017.1
8	South Korea	19	4.62%	2016.6
9	Spain	18	4.38%	2016.4
10	Poland	16	3.89%	2017.6

Table 1.2.8 Institutions with the greatest output of citing papers on "high-energy density solid-state lithium batteries"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Inst Chem Technol	50	33.56%	2016.5
2	Univ Ljubljana	16	10.74%	2016.1
3	Chinese Acad Sci	13	8.72%	2017.4
4	Univ Malaya	13	8.72%	2016.5
5	Jozef Stefan Inst	10	6.71%	2015.7
6	Univ Chinese Acad Sci	9	6.04%	2017.1
7	Natl Res Council Italy	8	5.37%	2017.6
8	Harbin Inst Technol	8	5.37%	2016.6
9	Natl Inst Technol	8	5.37%	2017.3
10	Korea Adv Inst Sci & Technol	7	4.70%	2016.3

1.2.3 Drag/heat reduction in supersonic flow

At present, most of the problems in supersonic flow are theoretically studied by numerical simulations based on the Navier–Stokes equations. The Monte Carlo direct simulation method and the Fokker–Planck equation, which can simulate thin air conditions, shock waves, and plasma, are rarely used, due to a lack of sophisticated software. Existing hypersonic wind tunnels can be used to perform experiments in this area, and provide mature noncontact testing techniques. However, the lack of sensors that can withstand temperatures of 1000 °C and high impact forces leads to difficulties in effectively contact testing many heat flow and heat transfer details. Research on high-temperature-resistant sensors based on silicon nitride, sapphire, platinum alloys, and other materials is expected to solve such problems, although substantial requirements will still be placed on the insulation and refrigeration technologies of sensing systems.

When hypersonic vehicles and spacecraft re-enter the atmosphere, the airflow can reach speeds in excess of Mach 6 and be accompanied by strong aerodynamic heating, air ionization, and aerodynamic load. Moreover, the air is thin at high altitudes and in near-earth space. Therefore, using the Navier–Stokes equations for numerical simulations is inherently difficult. The once-promising idea of adding a needle to the front end of the hypersonic aircraft has largely been abandoned because of the ease of ablation. At present, heat insulation for a spacecraft is mainly achieved by optimizing the aerodynamic shape, preparing a sacrificial layer on the outer surface that will be lost to ablation, and preparing a heat insulation layer on the inner surface. Research has been conducted on drag reduction (or even incidental heat reduction) achievable by the use of reverse jets, plasma boundary-layer control, laser energy deposition, and direction of aircraft exhaust at the bottom of an aircraft.

For high-altitude and high-speed scouting planes, the airflow speed is generally between Mach 2.5 and 6 that leads to strong aerodynamic heating, but generally not to an extensive ionization of the air. These planes ordinarily fly at altitudes of less than 30 000 m in an environment satisfying the conditions of a continuous medium, and therefore they can be analyzed by numerical simulation methods based on the Navier–Stokes equations. The drag can be reduced by adding a needle at the front end of the aircraft, and the heat can be reduced by preparing an insulating layer on the inner surface.

When the problem of nozzle internal flow occurs in jet engines, especially in turbojets and ramjets, the airflow velocity after nozzle expansion is generally above Mach 2.5, and the temperature is often above 1400 °C so that the air is largely a plasma, and the heat exchange is intense. Theoretical analysis based on the Fokker–Planck equation is needed in these circumstances. Research addressing this situation has mainly focused on heat reduction, whether by an ablation sacrificial layer on the outer surface, thermal insulation on the inner surface, or thermally protective jet flow in the boundary layer. A few studies have also explored drag reduction and improvements in engine efficiency, using surface microstructures and jet flow control.

The countries or regions producing the most core papers in engineering development focusing on drag/heat reduction in supersonic flow are China (34), Iran (10), the UK (3), and Azerbaijan (3). The countries or regions with the greatest average number of citations are Iran (29.5), Australia (20), and China (19.15), as shown in Table 1.2.9. Among the top 10 countries or regions, China, the UK, and Azerbaijan display the most cooperation, as shown in Figure 1.2.5. The institutions producing the most core papers are National University of Defence Technology (29), Babol University of Technology (5), and Islamic Azad University (5). The institutions with the highest average number of citations are Babol University of Technology (40), Islamic Azad University (35.8), and Isfahan University of Technology (35.5), as shown in Table 1.2.10. Among the top 10 institutions, Islamic Azad University and Babol Noshirvani University of Technology display the most cooperation, as shown in Figure 1.2.6. The countries or regions with the most citing papers are China (174), Iran (36), and India (22), as shown in Table 1.2.11. The institutions producing the most citing papers are National University of Defence Technology (89), Harbin Institute of Technology (27), and Khazar University (15), as shown in Table 1.2.12.

Table 1.2.9 Countries or regions with the greatest output of core papers on “drag/heat reduction in supersonic flow”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	34	70.83%	651	66.23%	19.15
2	Iran	10	20.83%	295	30.01%	29.50
3	UK	3	6.25%	30	3.05%	10.00
4	Azerbaijan	3	6.25%	29	2.95%	9.67
5	India	1	2.08%	15	1.53%	15.00
6	Japan	1	2.08%	7	0.71%	7.00
7	Australia	1	2.08%	20	2.03%	20.00
8	Pakistan	1	2.08%	8	0.81%	8.00
9	USA	1	2.08%	10	1.02%	10.00
10	Russia	1	2.08%	7	0.71%	7.00

Table 1.2.10 Institutions with the greatest output of core papers on “drag/heat reduction in supersonic flow”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Natl Univ Def Technol	29	60.42%	601	61.14%	20.72
2	Babol Noshirvani Univ Technol	5	10.42%	170	17.29%	34.00
3	Islamic Azad Univ	5	10.42%	179	18.21%	35.80
4	Khazar Univ	3	6.25%	29	2.95%	9.67
5	Babol Univ Technol	2	4.17%	80	8.14%	40.00
6	Isfahan Univ Technol	2	4.17%	71	7.22%	35.50
7	Nanjing Univ Aeronaut & Astronaut	2	4.17%	21	2.14%	10.50
8	Chinese Aerodynam Res & Dev Ctr	2	4.17%	13	1.32%	6.50
9	Amirkabir Univ Technol	2	4.17%	15	1.53%	7.50
10	Indian Inst Space Sci & Technol	1	2.08%	15	1.53%	15.00

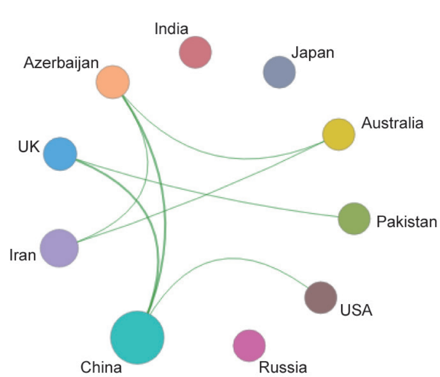

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “drag/heat reduction in supersonic flow”

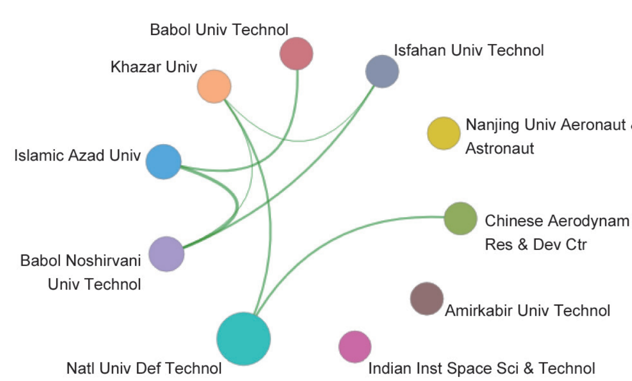

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “drag/heat reduction in supersonic flow”

Table 1.2.11 Countries or regions with the greatest output of citing papers on "drag/heat reduction in supersonic flow"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	174	62.37%	2017.1
2	Iran	36	12.90%	2017.0
3	India	22	7.89%	2017.3
4	Azerbaijan	15	5.38%	2018.0
5	UK	9	3.23%	2017.4
6	France	7	2.51%	2018.0
7	Russia	4	1.43%	2017.3
8	USA	4	1.43%	2017.8
9	Sweden	3	1.08%	2017.7
10	Australia	3	1.08%	2017.7

Table 1.2.12 Institutions with the greatest output of citing papers on "drag/heat reduction in supersonic flow"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Natl Univ Def Technol	89	39.73%	2016.6
2	Harbin Inst Technol	27	12.05%	2017.5
3	Khazar Univ	15	6.70%	2018.0
4	Babol Noshirvani Univ Technol	14	6.25%	2016.7
5	Beihang Univ	13	5.80%	2017.5
6	Nanjing Univ Aeronaut & Astronaut	13	5.80%	2017.8
7	Islamic Azad Univ	12	5.36%	2016.8
8	Northwestern Polytech Univ	11	4.91%	2017.9
9	Isfahan Univ Technol	11	4.91%	2017.0
10	Babol Univ Technol	10	4.46%	2017.3

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

In the previous section, we examined the top ten engineering research fronts in mechanical engineering (broadly defined). In this section, we will examine the top ten development (as opposed to research) fronts in the field (Table 2.1.1). Six of these fronts are characterized by in-depth traditional research: "propulsion systems for near-space hypersonic vehicles," "design and manufacturing technology of high-efficiency gas turbine engines," "wave-energy power generation and collection," "novel high-efficiency hydrogen fuel cells," "marine electric propulsion systems," and "development and application of electromagnetic stealth metamaterials for aircraft". There are also four other fronts that are newly emerging: "human–computer interaction systems based on deep learning," "3D bio-printing technology," "visual sensing and recognition for driverless vehicles, and "interception of unmanned aerial vehicles (UAVs)." Table 2.1.2 shows the annual number of core patents published from 2013 to 2018. "Human–computer interaction systems based on deep learning" and "visual sensing and recognition for driverless vehicles" are the most significant directions of patent disclosure in recent years.

(1) Propulsion systems for near-space hypersonic vehicles

A near-space hypersonic vehicle is a high-speed aircraft that is intended to be flown mainly at altitudes in the range of 20–100 km and at speeds above Mach 5. In addition, this

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

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Propulsion systems for near-space hypersonic vehicles	217	338	1.56	2015.8
2	Human–computer interaction systems based on deep learning	603	1214	2.01	2017.3
3	3D bio-printing technology	195	363	1.86	2016.7
4	Design and manufacturing technology of high-efficiency gas turbine engines	765	2878	3.76	2015.4
5	Visual sensing and recognition for driverless vehicles	348	1745	5.01	2016.8
6	Wave-energy power generation and collection	147	214	1.46	2015.6
7	Interception of UAVs	121	523	4.32	2016.8
8	Novel high-efficiency hydrogen fuel cells	1464	1918	1.31	2015.5
9	Marine electric propulsion systems	141	176	1.25	2015.7
10	Development and application of electromagnetic stealth metamaterials for aircraft	242	348	1.44	2015.9

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

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Propulsion systems for near-space hypersonic vehicle	25	42	25	43	33	49
2	Human–computer interaction systems based on deep learning	16	14	23	48	130	372
3	3D bio-printing technology	3	6	29	41	55	61
4	Design and manufacturing technology of high-efficiency gas turbine engines	123	160	112	148	112	110
5	Visual sensing and recognition for driverless vehicles	8	15	33	57	112	123
6	Wave-energy power generation and collection	28	26	15	20	21	37
7	Interception of UAVs	4	7	11	11	43	45
8	Novel high-efficiency hydrogen fuel cells	253	257	216	208	263	267
9	Marine electric propulsion systems	21	24	16	21	39	20
10	Development and application of electromagnetic stealth metamaterials for aircraft	26	40	32	34	53	57

vehicle possesses fast response, strong defense penetration, and flexible maneuvering, all of which belong to a strategic field of competitive development among great countries. Current development work focuses mainly on three types of hypersonic vehicles: cruise vehicles, horizontal take-off and landing vehicles, and reusable space vehicles. Basic technical problems that need to be addressed include the overall design of the aircraft and multidisciplinary optimization; aerodynamic layout taking into account the wide speed and high lift-resistance ratio; hypersonic propulsion; integration of the aircraft/propulsion system; structural thermal protection and energy management; optimization of multifunctional structure design; and advanced highly dynamic control. Of all these, propulsion technology plays a decisive role and is a frontier development field. Ultra-high-speed air-breathing propulsion technology based on hypersonic combustion and expansion of the working boundary is expected to solve the problem of combustion issue and energy conversion in the presence of extremely high air flow. Much work is focused on multi thermal cycle combination and match optimization, as well as cycle work mode conversion, which are the key and premise for promoting the combined aerospace propulsion technology into practical research. The working capability of wide-range efficient combination is the basic support that requires the integration of thermal cycle optimization, advanced combustion organization, flow control, lightweight structure, and residual control to improve the comprehensive efficiency of the full-speed domain.

(2) Human–computer interaction systems based on deep learning

Human–computer interaction (where the "computer" can be either hardware or software) has increasingly been studied using AI technology such as deep learning. This leads to the development of the new generation of intelligent interactive systems that are able to receive and process peripheral instructions, text, speech, gestures, expressions, and other inputs from human users and to output information in the ways that humans perceive as natural. Deep learning has achieved more significant results in speech recognition, image recognition and segmentation, and machine translation than any previous technology. However, it still faces many issues, such as the syntax ambiguity in speech, boundaries definition of word, and semantics ambiguity. Similarly, there are multiple objects and targets, and the dependencies between the foreground and its background in image recognition. There are many different training methods for deep learning, e.g., single- and multi-node multi-graphics processing units (GPUs). But the training of deep learning involves very high energy consumption. Nevertheless, in future human–computer interaction systems, deep learning seems certain to retain its dominant position, and it is still the most challenging point.

(3) 3D bio-printing technology

In recent years, the manufacturing and regeneration of live tissues and even organisms have become feasible. The integration of manufacturing technology with biology demonstrates the extraordinary advance of modern science and technology, and is certain to have even greater industrial value in the future. One area in which great technical progress has been made is the use of 3D printing to manufacture or repair living biological tissues and organs. Research has been largely moved forward in the following directions. 1) Manufacture of complex biological structures. The focus is on further studying human functional organs (e.g., heart tissue). This involves understanding the nerve signal regulation; converting simple mechanical support tissues into functional tissues through neuroregulation; analyzing the symbiotic fusion of 3D printed and human host tissues, and realizing the regeneration and functional recovery of human organs. 2) Brain tissue manufacturing *in vitro* with the assistance of 3D printing. This involves the bionic design and precision manufacture of various types of neuron, and the ability to print neuron combinations corresponding to the targeting functional site. 3) Bioenergy transformation organization, i.e., building and efficiently controlling devices such as artificial muscles and bio-batteries that convert or release energy more efficiently, and develop efficient devices for energy storage and release for soft tissue. 4) Biomechanical symbiosis that involves the development of manufacturing technology of multi-cell types and multi-materials to build hybrid robots with living tissues or organs with flexible motion, to provide an innovative manufacturing foundation for such lifelike soft robots.

(4) Design and manufacturing technology of high-efficiency gas turbine engines

Gas turbine engines, especially aircraft engines, have been at the forefront of engineering development as technological progress imposes ever more stringent requirements for materials, design, and manufacturing. These engines have been called the "jewels in the crown of the industry." To improve the performance of gas turbine engines, the following lines of development are being actively pursued: 1) design and manufacturing of blades, including the development of low aspect-ratio, hollow, resin- and ceramic-based composite, single crystal, cast cool, and super-cooling blades; 2) design and manufacturing of bladed disks and rings, including powder-metallurgical superalloy turbine, titanium alloy, hollow double-spoke turbine, hot isostatic pressed and molded, superplastic isothermally forged, and counter-rotating disks and rings; 3) low-emission combustion technologies, including lean oil direct mixing, lean premixed pre-evaporation, partial evaporation with rapid mixing, lean direct injection (LDI), and multipoint LDI (MP-LDI); 4) design and manufacturing of coatings, including thermal-barrier ceramic and wear-resistant coatings; and 5) complex structure additive manufacturing and design integration, including complex shell structures for the control and injection of fuel.

(5) Visual sensing and recognition for driverless vehicles

Driverless technology can be divided into three modules: perception, decision-making, and control. Environmental awareness is both the key to achieving completely driverless vehicles and the main factor limiting the development of such vehicles today. At present, driverless vehicles rely on cameras and laser radar for recognition of their surroundings. Vision-based environmental perception systems contain more image information than radars. Monocular cameras have fast operating speeds but can only capture single images and miss scene-depth information. Binocular stereo-vision is favored by many researchers because it is relatively simple, is only slightly influenced by lighting, and provides abundant information that can be used to identify road conditions. In recent years, 3D vision reconstruction using real-time stereo-matching has been rendered practical by improvements in computer hardware. The analysis and processing of images for visual recognition are usually implemented with convolutional neural networks. From the collected image information, the traffic scene can be intelligently identified and predicted, thereby reducing the occurrence of traffic accidents and injuries. An increasing number of research institutions and universities are now working on such vision-based assisted-driving and driverless systems.

(6) Wave-energy power generation and collection

Wave energy, a type of renewable clean energy, has a high density and wide distribution surface. The development and utilization of such energy could be important in addressing the energy crisis, environmental pollution, and climate change. Scientific research on wave energy mainly aims at two goals. The first is to evaluate reserves of wave energy and their temporal–spatial distribution, thereby providing effective guidance for the design of wave energy power stations and conversion devices. The second is the design, development, and experimental operation of wave energy power conversion and generation devices. At present, the main methods of wave energy power generation are the oscillating float, cross-wave, oscillating water column, and soft bladder methods. Compared with the other possibilities, the offshore oscillating float has a simpler structure, lower cost, more flexible location, more convenient transportation and maintenance, and higher efficiency, making it the mainstream technology of wave energy power generation at present. However, offshore devices can easily be affected by catastrophic events in the complex and variable marine environment. Moreover, ocean waves possess many challenging features, such as their instability, huge reserve, wide distribution, and difficult utilization. Many difficult tasks regarding the use of wave energy resources in power conversion and power collection still remain to be undertaken. These include deepening the understanding of nonlinear waves, optimizing the design of wave energy devices, improving their response speed and conversion efficiency, enhancing their stability and reliability, and reducing the manufacturing, installation and maintenance costs.

(7) Interception of UAVs

With advances in information, control, communication, and other fields of technology, UAVs have come into widespread use in the civil and military fields. The problem of illegally flown UAVs poses a serious threat to public safety and even national security. Therefore, countermeasures should be developed as soon as possible. At present, anti-UAV technology mainly involves direct detection and interception. The former utilizes ground-view reconnaissance, radar detection and tracking, aerial early warning, and satellite reconnaissance technologies to detect and track UAVs accurately. The latter includes electronic countermeasures (interference blocking); ground fire and high-energy laser weapons (damage capture); and monitoring and control technology based on photoelectric, radar, and other monitoring systems with data-chain interference technology. Although interference blocking is simple, low-cost, and utilizes easy-to-carry systems, the electronic countermeasure signals are highly demanding on the environment and susceptible to the influence of other electromagnetic signals in space. Moreover, this technology is ineffective against UAVs which are not controlled externally. Damage capture is suitable for complex environments, but it is complex and expensive, and it causes permanent damage to the UAVs, interfering with evidence collection. To enable the efficient identification and capture of UAVs in complex environments, an anti-UAV technology should be developed that is portable, uses intelligent tracking, and incorporates a multi-means multilevel defense system.

(8) Novel high-efficiency hydrogen fuel cells

To address both energy shortage and environmental pollution, increasing attention has been paid throughout the world to the development of green and efficient energy technology. Hydrogen fuel cells convert the chemical energy in hydrogen into electrical energy through chemical reactions. This technology has attracted increasing attention owing to its freedom from pollution, high energy-conversion efficiency, and other advantages. However, it has several shortcomings, such as the high cost of hydrogen production, the immaturity of hydrogen storage technology, and the incompleteness of the hydrogen transmission system. Novel high-efficiency hydrogen fuel cells technology is a core cutting-edge technology in the new-energy field. Development focuses on the core materials of hydrogen fuel cells; design of advanced and high-performance hydrogen fuel cell reactors and key auxiliary system components; hybrid fuel cell power systems; hydrogen production, transportation, and storage; and construction of a refueling infrastructure. The transition from carbon energy to hydrogen energy will be ongoing, and hydrogen fuel cells will realize their value in new-energy vehicles, distributed power generators, and other applications.

(9) Marine electric propulsion systems

Propulsion system is generally composed of a power station, power station management system, power distribution system, speed control system, propulsion motor, monitoring system, and propeller. The ship is propelled by the propulsion motor that drives the propeller or other actuators. This system is widely used on large tankers, surface warships, engineering ships, submarines, and other types of ships. Power generation, propulsion motor improvements, harmonic suppression, electronic automation, high-power energy storage, power supply and distribution, and motor control technologies are all subjects of active current development. Modeling and simulation will also play an important role in improving the performance of electric propulsion systems on ships. Particularly important goals of current development work include the following: 1) replacing the DC electric propellant and AC/DC electric propulsion system with an AC electric propulsion system; 2) developing superconducting power propulsion; 3) developing a submarine fuel cell propulsion system to replace lead-acid batteries; 4) meeting high-power requirements with magnetic fluid propellants, water-spraying thrusters, and other high-efficiency thrusters; and 5) developing integrated all-electric propulsion systems.

(10) Development and application of electromagnetic stealth metamaterials for aircraft

Electromagnetic metamaterials are artificially structured materials containing sub-wavelength arrays of plasmonic resonators engineered to present optical properties that are usually either difficult or impossible to obtain in naturally occurring materials and composites. The traditional principle of aircraft stealth is to reduce detectability either by changing how the radar wave is reflected or by absorbing it. Metamaterials, however, can actually change the propagation route of the wave (i.e., bend it) to achieve orbiting and stealth, thereby providing a new research perspective for radar stealth absorption materials. Aircraft electromagnetic stealth metamaterials need to be thin and light, with an absorption bandwidth sufficient to cover the lightning and infrared bands, strong enough to resist impact and corrosion, and easy to maintain. Although some significant progress has been made, several problems, such as limited bandwidth, significant increase, complexity, and difficultly in large-scale manufacture, remain to be solved. In view of these problems, research on the electromagnetic stealth metamaterials of aircraft mainly focuses on the following topics: 1) broadband metamaterials with good absorption properties; 2) tunable active metamaterials; 3) flexible electromagnetic stealth metamaterials, and 4) 3D printing of electromagnetic stealth metamaterials.

2.2 Interpretations for three key engineering development fronts

2.2.1 Propulsion systems for near-space hypersonic vehicles

(1) Ultra-high-speed air-breathing propulsion systems

Dynamic propulsion at relatively low speeds (subsonic and supersonic) is already a mature technology; hypersonic air-breathing (ramjet) propulsion with Mach numbers < 6–7 is a developing and maturing one. Therefore, the frontier of development is ultra-high-speed air-breathing propulsion technology at even greater Mach numbers. Such a technology is an inevitable choice for the space industry that now requires a higher and wider speed domain than ever before. When the flying Mach number exceeds 10, the Mach number in the combustion chamber after the compression of the air-in channel correspondingly increases, even reaching the hypersonic combustion regime ($Ma \geq 5$). Therefore, combustion issue and energy release under extremely high-speed conditions have become the primary technical difficulties in this field, which the USA and Australia have been particularly interested in exploring. The second flight test of the X-43A, conducted by NASA in 2004, was the first time that combustion was observed in an ultra-high-speed air-breathing super-combustion stamping engine with flight Ma = 10, as well as the first occasion that the propulsion system was shown to work in practice. Afterwards, the USA and Australia jointly executed the HyShot, HyFire, HyCAUSE, and other flight test verification programs, which focused on reaching a flying Ma of 8–12 (ultra-high-speed flow). They also conducted basic research on combustion and achieved outstanding progress in ultra-high-speed air-breathing propulsion system verification. To solve the difficulty of fuel-air mixing and utilize the advantages of premixed, shock wave-induced combustion, engine precursor fuel injection was emphasized, and the shock induced combustion ramjet (SHC ramjet) has become the subject of intensive research.

(2) Wide-area combined cycle propulsion systems

The outstanding feature of the proposed horizontal take-off and landing hypersonic aircraft (other than its flying Mach number) is its broad flight range, with working stages ranging from the subsonic to the hypersonic. This greatly exceeds the working capability of existing traditional power propulsion systems, so combined cycle propulsion has becomes possible choice. It solves the problem of wide-area working capability, and it also achieves high-performance across the wide speed domain. At present, two types of combined cycle propulsion schemes based on traditional power have been developed, namely, rocket-based and turbo-based combined cycles. However, challenges in terms of performance, engineering implementation, and task suitability still exist. Even so, combined cycle propulsion schemes with wide adaptability and high performance remain at the cutting edge so far as optimization of power composition and the thermal cycle are concerned. Combined cycle propulsion systems based on turbine, ramjet, and rocket represent an important development direction. In recent years, the former US aerospace company Aerojet has experimented with a “TriJet” three-way cycle propulsion scheme in which the pilot rocket ramjet channel is used to solve the problems of wide-speed range and modal conversion relay. The British company Reaction Engines, Ltd., has proposed a combined cycle synergistic air-breathing rocket engine that integrates turbine, rocket, and ramjet features with deep pre-cooling technology. Considering the needs of practical research and development, engineers should focus on solving the key problems of thermal cycle matching optimization, system integration, and dynamic mode conversion.

(3) Detonative propulsion technology

The release and conversion of chemical energy through fuel combustion is critical for propulsion systems; two processes are involved, namely, deflagration and detonation. Traditional aerospace power propulsion devices based on deflagration have developed to a mature stage, but can hardly improve their performance and propulsion efficiency. Detonation features an ultrasonic combustion wave closely coupled with a shock wave, and it is a self-compressed combustion mode described by similarity equations. The thermal efficiency of detonation is higher than that of isobaric combustion. Detonation is expected to break through the existing energy cycle efficiency bottleneck and become an inevitable choice for propulsion technology due to its high performance. At present, the research in this area mainly focuses on the detonating combustion organization mode. Pulse, continuous, and stationary detonation engines have been introduced and investigated. Detonative combustion is gradually changing from a theoretical research topic into one with practical applications. Among the varieties of detonation engine, the continuous rotating mode has the most potential and is expected to trigger a major transformation of spaceflight. At present, mastering the propagation mechanism of controlled continuous detonation is the core problem to be solved. The integration of the detonative combustion mode with traditional power types (turbine, stamping, and rocket) in a combined cycle is also critical for future progress.

The top three countries in this field in terms of core patent disclosure volume are China (100), the USA (51), and Russia (40), whereas the top three countries in terms of the average number of citations are the USA (3.43), Canada (2.75), and China (1.53) (Table 2.2.1). Cooperation exists among the USA, China, and Canada, as displayed in Figure 2.2.1. The three institutions with the most core patent disclosures are Nanjing University of Aeronautics and Astronautics (15), Xiamen University (8), and Boeing Co. (7) (Table 2.2.2). From the current sample data, little cooperation is present among the major patent-producing institutions (Figure 2.2.2).

2.2.2 Human–computer interaction systems based on deep learning

In modern world, it is increasingly important that computers are able to naturally interact with humans by receiving and processing text, voice, gestures, expressions, gaze,

Table 2.2.1 Countries or regions with the greatest output of core patents on "propulsion systems for near-space hypersonic vehicles"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	100	46.08%	153	45.27%	1.53
2	USA	51	23.50%	175	51.78%	3.43
3	Russia	40	18.43%	8	2.37%	0.20
4	South Korea	6	2.76%	1	0.30%	0.17
5	Canada	4	1.84%	11	3.25%	2.75
6	India	4	1.84%	0	0.00%	0.00
7	France	3	1.38%	2	0.59%	0.67
8	Germany	3	1.38%	1	0.30%	0.33
9	Brazil	2	0.92%	1	0.30%	0.50
10	Japan	2	0.92%	1	0.30%	0.50

Table 2.2.2 Institutions with the greatest output of core patents on "propulsion systems for near-space hypersonic vehicles"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UNUA	15	6.91%	40	11.83%	2.67
2	UYXI	8	3.69%	16	4.73%	2.00
3	BOEI	7	3.23%	20	5.92%	2.86
4	UNBA	5	2.30%	7	2.07%	1.40
5	UNDT	5	2.30%	6	1.78%	1.20
6	BEIT	5	2.30%	2	0.59%	0.40
7	ACFL	4	1.84%	13	3.85%	3.25
8	CAMH	4	1.84%	8	2.37%	2.00
9	UNAC	4	1.84%	5	1.48%	1.25
10	CAER	4	1.84%	3	0.89%	0.75

UNUA: Nanjing University of Aeronautics and Astronautics; UYXI: Xiamen University; BOEI: Boeing Co.; UNBA: Beihang University; UNDT: National Defence University of People's Liberation Army; BEIT: Beijing Institute of Technology; ACFL: Advanced Ceramic Fibers LLC; CAMH: Institute of Mechanics, Chinese Academy of Sciences; UNAC: United Technologies Corp.; CAER: Beijing Institute of Near Space Vehicles System Engineering.

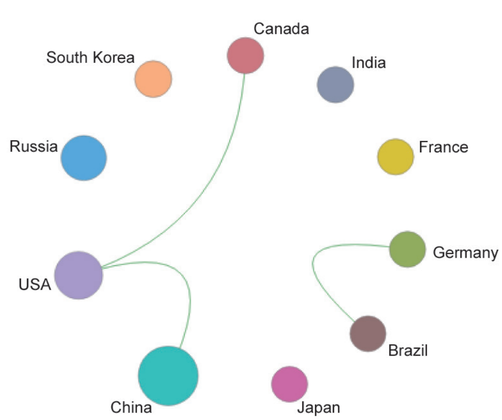

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "propulsion systems for near-space hypersonic vehicles"

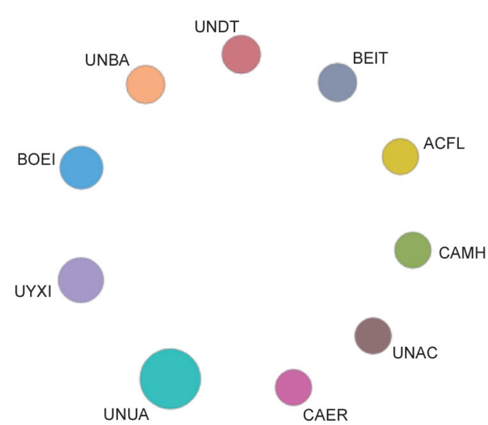

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "propulsion systems for near-space hypersonic vehicles"

and peripheral instructions as input, and ideally providing output in these forms when possible. In recent years, human–computer interaction systems have been gradually implemented into many real applications, such as the speech recognition in car navigation system; the motion recognition in wearable computers, stealth technology, and immersive games; haptic interaction technology in virtual reality; remotely controlled robots and telemedicine; the speech recognition in call routing, home automation and speech dialing; the silent speech recognition technology, for people with language impairments; the eye tracking technology for advertising and other websites; and brain-wave based human–computer interface systems for people with language and mobility impairments. However, many problems are yet to be addressed in these systems, including low rates and high time delay of vision-based gesture recognition, the low accuracy of the image-based multi-target recognition and segmentation as well as the high time and energy consumption for dealing with large amounts of data. New algorithms are urgently needed to improve accuracy and efficiency.

The research on human–computer interaction system has naturally focused on deep learning for complex pattern recognition that has achieved remarkable results in data mining, image recognition and segmentation, machine translation, natural language processing, multimedia learning, speech recognition, recommendation and personalization technology. However, deep learning-based human–computer intelligent interaction systems still have many issues, such as the syntax ambiguity in speech, boundaries definition of word, and semantics ambiguity. Similarly, there are multiple objects and targets, and the dependencies between the foreground and its background in image recognition. There are many different training methods for deep learning, e.g., single- and multi-node multi-GPUs. But the training of deep learning involves very high energy consumption. Nevertheless, the further study should be based on the real applications, investigate the new deep learning models to increase the final accuracy and recognition speed, and eventually enable machines with analytical learning capabilities to process text, images, sound, and other data accurately in real time in human level.

The top three countries in this field in terms of core patent disclosure volume are the USA (231), China (225), and South Korea (57), whereas the top three countries or regions in terms of the average amount of citations are Canada (4.9), the USA (4.31), and India (2.45) (Table 2.2.3). Cooperation exists between the USA and Canada, as well as the USA and China, as illustrated in Figure 2.2.3. The top three institutions in terms of core patent disclosures are International Business Machines Corporation (28), Sichuan Yonglian Information Technology (13), and Samsung Electronics Co., Ltd. (10) (Table 2.2.4). From the current sample data, little cooperation is present among the major patent-disclosing institutions (Figure 2.2.4).

2.2.3 3D bio-printing technology

Further to the usage of traditional materials such as wood, metal and silicon, the manufacturing technology has been progressed to build living matters. During this still-incomplete transition, the function-driven innovation in the new products should be encouraged, which could be carried out in the following directions.

(1) Design and manufacture of the function-based living organ structure

To develop the cell/gene based structural and functional design theory, one should fully understand the progressing characteristics of self-growth for the living organisms. The existing mechanical design theory, which was solely based on structural design and mechanical function, needs to be transformed to focus on the integration of structure, stimulator, function and progressing. Future design methods should incorporate such characteristics of life as biological stimulators, functional symbiosis, and evolution. The laws governing the self-reproduction and self-replication of cells and genes should be better understood, so that the designed artificial structures can better emulate the behavior and life cycle of natural ones. The manufacture and engineering control of biodegradable, activatable, and growable structures should also be studied.

(2) Regulation and maintenance of 3D printed life units

In 3D cell printing, the living organ unit is the basis for tissue growth and development. The organic combination of organic cells or genes is the core of late functional presentation, and the accumulation of living organ units of single cell and gene at micro-/nano-scale is normally required during the manufacturing process. The principle of accumulation and the relationship between its effects should be comprehended, in order to maintain the adjustable probability in terms of the 3D

Table 2.2.3 Countries or regions with the greatest output of core patents on "human–computer interaction system based on deep learning"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	231	38.31%	995	81.96%	4.31
2	China	225	37.31%	91	7.50%	0.40
3	South Korea	57	9.45%	19	1.57%	0.33
4	Japan	26	4.31%	7	0.58%	0.27
5	India	20	3.32%	49	4.04%	2.45
6	Canada	10	1.66%	49	4.04%	4.90
7	Germany	5	0.83%	0	0.00%	0.00
8	Israel	4	0.66%	3	0.25%	0.75
9	Ireland	4	0.66%	0	0.00%	0.00
10	Australia	3	0.50%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "human–computer interaction system based on deep learning"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	IBMC	28	4.64%	67	5.52%	2.39
2	SYIT	13	2.16%	0	0.00%	0.00
3	SMSU	10	1.66%	10	0.82%	1.00
4	MICT	8	1.33%	8	0.66%	1.00
5	EBAY	6	1.00%	1	0.08%	0.17
6	INEI	6	1.00%	1	0.08%	0.17
7	AMAZ	5	0.83%	68	5.60%	13.60
8	PURS	5	0.83%	6	0.49%	1.20
9	BAI	5	0.83%	3	0.25%	0.60
10	DRTC	5	0.83%	0	0.00%	0.00

IBMC: International Business Machines Corp.; SYIT: Sichuan Yonglian Information Technology; SMSU: Samsung Electronics Co., Ltd.; MICT: Microsoft Corp.; EBAY: Ebay Inc.; INEI: Jinan Inspur High & New Technology Investment; AMAZ: Amazon Technologies Inc.; PURS: Pure Storage Inc.; BAI: Bonsai AI Inc.; DRTC: Dalian Roiland Technology Co., Ltd.

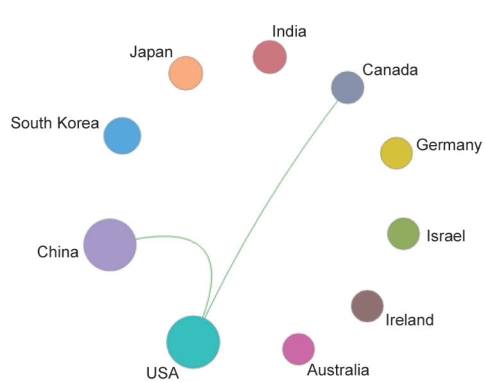

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "human–computer interaction system based on deep learning"

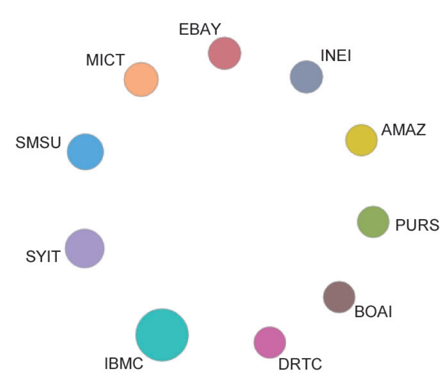

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "human–computer interaction system based on deep learning"

structure and time-dependent function. The most important feature of 3D printing is the application of living organs, and the activity of the living organs is essential. Therefore, the physiological and biological environment needs to be adopted in the printing process, including the supplement of nutrients and the necessary gases, etc.

(3) Function formation mechanisms and component function formation

It is not enough to simply print an exact copy of a biological structure, since the structure's eventual function must also be considered, and the relationship between function formation and the design and manufacturing process should be understood and developed. Multicellular systems especially change their functions over time, even on short time scales, for example by releasing energy (as muscle cells do), or by transferring information through intercellular interaction (as neurons do). These time-dependent patterns of functionality and change must be understood and emulated for the development of multi-functional devices.

(4) Manufacturing and functional evaluation of multifunctional devices or organizations

Based on the understanding of the development, functional growth, and structure of living organ units from an engineering point of view, to design a living organ with the prerequisite structure and functional growth characteristics, the following problems should be tackled: 1) how to adjust the cell or gene combinations via 3D printing technology, 2) how to control the printing process to reduce the damage for cells, and 3) how to regulate or stimulate the function of the formed organ or device. Moreover, the effects of 3D printing on function formation should be investigated; biological functions should be evaluated and measured; systematic research should be developed starting from the life units, functional design, undamaged printing to the forming of function, to provide technology for the manufacturing of life organ or devices.

(5) Brain-inspired design and manufacture

Deep learning of AI is based on model hypothesis, data training, accumulative learning, and even by the use of bio-inspired genetic algorithms to evolve, for example, airplanes instead of birds. Brain-inspired technology includes implanting chips into re-created or artificial brains using 3D printing methods, building powerful biochips by learning the interconnection of neurons, or using genes to imitate a living brain. Moreover, how to connect the manmade brain with the host tissue for information collection, decision making or motion actuating remains an innovative research field.

The top countries or regions in terms of core patent disclosure volume in this field are China (143), the USA (28), and South Korea (6), whereas the top three countries or regions in terms of the average number of citations are Sweden (21.5), the USA (3.11), and Japan (1.25) (Table 2.2.5). Collaboration exists between the USA and Sweden as well as the UK and Italy, as shown in Figure 2.2.5. The top three institutions with core patent disclosures are Xi'an Jiaotong University (6), Tsinghua University (5), and Jilin University (4) (Table 2.2.6). From the current sample data, no cooperation is present among the major patents output institutions (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents in the engineering development front of "3D bio-printing technology"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	143	73.33%	177	48.76%	1.24
2	USA	28	14.36%	87	23.97%	3.11
3	South Korea	6	3.08%	0	0.00%	0.00
4	Japan	4	2.05%	5	1.38%	1.25
5	Taiwan of China	3	1.54%	3	0.83%	1.00
6	Sweden	2	1.03%	43	11.85%	21.50
7	Germany	2	1.03%	3	0.83%	1.50
8	Italy	2	1.03%	1	0.28%	0.50
9	UK	2	1.03%	0	0.00%	0.00
10	India	2	1.03%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of "3D bio-printing technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYXJ	6	3.08%	11	3.03%	1.83
2	UYQI	5	2.56%	3	0.83%	0.60
3	UYJI	4	2.05%	40	11.02%	10.00
4	EBAY	4	2.05%	26	7.16%	6.50
5	CAAT	4	2.05%	6	1.65%	1.50
6	UYZH	4	2.05%	6	1.65%	1.50
7	XPCB	4	2.05%	5	1.38%	1.25
8	USWCH	4	2.05%	4	1.10%	1.00
9	UYPO	4	2.05%	0	0.00%	0.00
10	UYBC	3	1.54%	6	1.65%	2.00

UYXJ: Xi'an Jiaotong University; UYQI: Tsinghua University; UYJI: Jilin University; EBAY: Ebay Inc.; CAAT: Shenzhen Institute of Advanced Technology; UYZH: Zhejiang University; XPCB: Xi'an Particle Cloud Biotechnology Co., Ltd.; USWCH: West China Hospital, Sichuan University; UYPO: Postech Acad-Ind Found; UYBC: Beijing University of Chemical Technology.

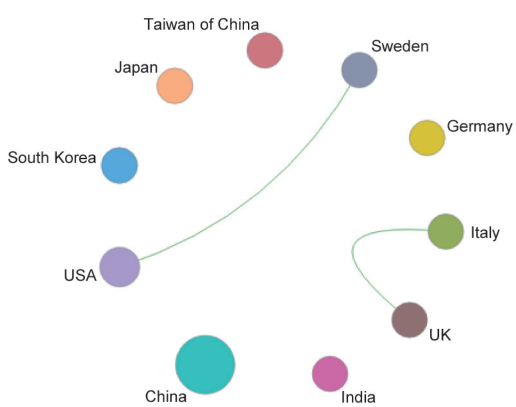

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "3D bio-printing technology"

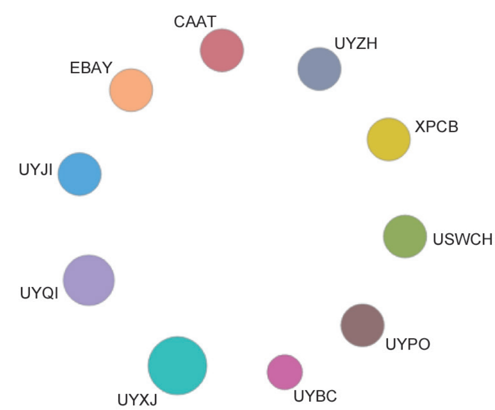

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "3D bio-printing technology"

Participants of the Field Group

Leaders

DUAN Zhencheng, GUO Dongming

Members

CHEN Maozhang, FAN Huitao, GU Guobiao, GUAN Jie, GU Songfen, HUANG Xianxiang, JIN Donghan, LI Jun, LIU Youmei, QIAN Qingquan, QIU Zhiming, SUN Fengchun, TAN Jianrong, TANG Renyuan, WANG Jun, WANG Zhenguo, YANG Huayong, ZHANG Litong, SHI Tielin, JI Xue, LI Miaoxin

Report Writers

SHEN Weiming, SHI Yanjun, CAO Yuancheng, YUAN Weizheng, HE Yang, LI Renfu, GAO Liang, LI Dichen, XIA Qi, XIA Liang, CHEN Xiuguo, ZHAN Xiaobin, CHEN Xixi, GONG Bo, TAN Xianhua, LI Junjie, GONG Bo, WANG Meng, LIU Zhiyong, SUN Bo, GU Honggang, SHI Yating

II. Information and Electronic Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the field of information and electronic engineering are summarized in Table 1.1.1, including the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science and technology. Among them, "silicon-based integrated photonic devices for optical interconnects, optical computing, and optical sensing," "5G large-scale antenna array wireless transmission theories and technologies," and "artificial micro/nanostructures and their manipulation of the optics and electromagnetic fields" are among the popular topics published by *Clarivate Analytics*; "brain-inspired intelligence" is a product of the clustering analysis from the projects supported by the governments of eight countries or regions, including China, the USA, EU, Canada, and Russia, during the period 2016–2018; "new-generation neural networks and their applications" is a result of the analysis of the topics of prominence from 2015 to 2018 in the field of artificial intelligence (AI) in SciVal; the five other fronts are recommended by researchers.

The number of core papers published from 2013 to 2018 related to each front is listed in Table 1.1.2. Among them, "new-generation neural networks and their applications" is the most significant front based on the rapid increase in the number of core papers published in recent years.

(1) Brain-inspired intelligence

AI has become the core driving force in the new round of technological revolution and industrial transformation. Varying from the current algorithm-centered AI, the brain-inspired intelligence attempts to imitate, learn, and surpass the perceptive and cognitive functions of the biological brain, which is one of the important technical approaches for achieving the ultimate goal of AI, the artificial general intelligence.

Generally, there are two technical approaches for achieving brain-inspired intelligence, top-down functional analogy and bottom-up structural imitation, which are both opposing

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Brain-inspired intelligence	337	19 232	57.07	2014.3
2	Space-terrestrial integrated network	122	6 424	52.66	2015.0
3	Brain imaging technologies	941	64 743	68.80	2014.2
4	Synergetic sensing–communication–computation–control network: theory and methodologies	26	2 057	79.12	2014.7
5	Hybrid-augmented intelligence	472	20 783	44.03	2014.5
6	Silicon-based integrated photonic devices for optical interconnects, optical computing, and optical sensing	45	4 020	89.33	2014.9
7	5G large-scale antenna array wireless transmission theories and technologies	655	49 476	75.54	2015.7
8	Artificial micro/nanostructures and their manipulation of the optics and electromagnetic fields	51	5 602	109.84	2014.6
9	Quantized precise metering/measurement and related theory	30	2 973	99.10	2014.6
10	New-generation neural networks and their applications	679	38 644	56.91	2016.0

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

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Brain-inspired intelligence	119	102	56	40	14	6
2	Space-terrestrial integrated network	25	26	25	24	14	8
3	Brain imaging technologies	337	266	192	99	41	6
4	Synergetic sensing–communication–computation–control network: theory and methodologies	6	8	5	2	4	1
5	Hybrid-augmented intelligence	136	129	98	66	34	9
6	Silicon-based integrated photonic devices for optical interconnects, optical computing, and optical sensing	6	14	13	6	3	3
7	5G large-scale antenna array wireless transmission theories and technologies	38	88	138	202	157	32
8	Artificial micro/nanostructures and their manipulation of the optics and electromagnetic fields	13	13	11	9	5	0
9	Quantized precise metering/measurement and related theory	10	5	7	5	0	3
10	New-generation neural networks and their applications	56	47	126	169	203	78

and inseparable. The functional analogy based on cognitive science refers to the cognitive mechanism of the brain in designing new AI models. However, because it is significantly difficult to comprehend the cognitive mechanism, it is difficult to determine when it will make a breakthrough. The structural imitation based on neuroscience attempts to construct devices similar to the biological nervous system by accurate simulation of biological neurons, synapses, and neural circuits, and then produces similar functions through stimulation training. It is expected to achieve a breakthrough in a few decades.

In recent years, with the rapid progress of brain observation, analytic techniques and instruments, neuroscience, and cognitive science, several countries have launched the “Brain Project.” If breakthrough can be achieved in the analysis of drosophila brain, the fine analysis of the human brain is expected to be completed within about 20 years. Neuromorphic devices for fine simulation of biological neurons and synapses have emerged at the same time. The first machine capable of fine simulation of the human brain is expected to be completed by 2022. The structural imitation and functional analogy techniques are expected to achieve rapid docking and interaction, which will significantly accelerate the development of brain-inspired intelligence.

(2) Space-terrestrial integrated network

The space-terrestrial integrated network is an infrastructure based on the terrestrial network, which extends the space network to provide information service for the activities of various users, such as space-, land-, and sea-based users. It is a network system that uses network technology to achieve the interconnection of the Internet, mobile communication networks, and space networks, and provides various types of network services. Considering the large scale, the three-dimensional multilayered topology, a high degree of heterogeneity, and a wide variety of services of the space-terrestrial integrated network, the challenge in networking is to design a network architecture with clear structure, simple functions, and easy and efficient implementation. The network can adapt to the rapid developments and changes in communication technology and can support new applications that are emerging endlessly.

At present, certain foreign countries are focusing on the research of satellite-terrestrial network in the field of space-terrestrial integrated network, emerging trends including modifying the mode of development from traditional high-orbit constellation to medium/low orbit constellation, establishing new investment and financing modes, market operation modes, and building new satellite manufacturing factories for mass production. The research on the space-terrestrial integrated network in China was initiated only a few years ago. Owing to the limitations in global station construction and availability of orbital resources, the research is facing considerable challenges in networking technology. It is essential to use the technological infrastructure of China in the aerospace and Internet industries to actively explore this huge market.

When combined with the development status of the space-terrestrial integrated network of China, the primary research directions are: 1) land, sea, air, and space integration network architecture design; 2) protocol research for large-scale, highly heterogeneous space network; 3) lightweight handover mechanism research for highly dynamic mobility; 4) research on multi-dimensional network resource joint management technology.

(3) Brain imaging technologies

The brain is intricate and complicated. There are not only hundreds of billions of neurons, but also millions of connections between them. Till now, the core functions of the brain, such as mood and emotions, are still unsolved problems. It is the key to overcome major diseases of the nervous systems, which seriously endanger the physical and mental health of people. It will also provide an important basis for the development of brain-like computing systems and devices, overcoming the limitations of traditional computer architecture, and determining the future developmental directions of AI.

Since the invention of the microscope at the end of the 16th century, every breakthrough in microscopic imaging technology has provided a developmental milestone to life science research. In recent years, several brain imaging technologies have been developed; moreover, significant progress has been achieved in imaging resolution, imaging speed, imaging depth, and imaging field-of-view. The new brain imaging technology focusing on the multiscale characteristics of the brain loop will provide key guidance and support for the task of the National Brain Plan in analyzing the structure and function of the brain loop on multiple levels. The primary research directions include: development of a high-throughput three-dimensional structure and function imaging and new sample processing technologies, as well as new methods for image data processing and analysis for the application of cell resolution to different biological whole brain nerves; rapid quantitative analysis of metatypes, connections, and activities; development of in vivo high-resolution optical imaging, and other new technologies with a wide range and deep penetration depth to achieve high spatial-temporal resolution of nerve activities in conscious and free-moving animals; development of new technologies of ultrafine imaging, such as photoelectric correlation to achieve ultrafine analysis and quantitative characterization of subcellular structures, such as synapses. In the future, further improvement of the imaging depth of living brain imaging, achieving high-speed and high-resolution three-dimensional reconstruction of neural loop, and exploring accurate brain structure and function imaging are the expected development trends in brain imaging technology.

(4) Synergetic sensing–communication–computation–control network: theory and methodologies

In future, the nodes of large-scale Internet of Things (IoT) have to be equipped with highly integrated sensing, communication, and computation capabilities. All the nodes participate in the processes of data acquisition, manipulation, transmission, and feedback, which are usually tightly coupled. This results in essential changes of the node model, traffic model, and control model, as well as the way of information evolvement in future networks, which further boosts the revolution of network architecture and finally results in a synergetic sensing–communication–computation–control (SSCCC) network. However, the theoretical foundation of such a network is rather weak and there is an urgent requirement for further research.

The primary research topics in this area include, but are not limited to, the following: 1) establishing new essential information metrics and key performance indicators that can satisfactorily reflect the performances of future large-scale networks; 2) developing the information-theoretic model and the analytical tools for the SSCCC networks; 3) investigating the rationale of information evolvement and the fundamental performance limits of the SSCCC networks with tightly coupled sensing, communication, computation, and control processes in addition to a varying large network state space under certain resource constraints. The goal is to reveal the origin of the information bottleneck in an SSCCC network and to achieve its network intelligence, moreover, to create a foundation for future large-scale IoT by developing the post-Shannon information theory.

(5) Hybrid-augmented intelligence

The long-term goal of AI is to create machines that learn and think like human beings. Intelligent machines have become companions of human beings. The interaction between and hybrid of humans and machines are expected to become significantly common in our life. Owing to the high levels of uncertainty and vulnerability in human life and the openended nature of problems that humans are facing, no matter how intelligent machines are, they are unable to completely replace humans. Therefore, it is necessary to introduce human cognitive capabilities or human-like cognitive models into AI systems to develop a new form of AI, that is, hybrid-augmented intelligence. This form is a feasible and important development model for AI or machine intelligence.

Driven by the new round of science and technology revolution and grand changes in industry, AI has been rapidly used in industries, deeply involved with organizing and managing procedures, leading to disruptive changes to social organizations. Efficient collaborations between humans and intelligent systems for value co-creating and sharing are thought as the optimal pattern of AI being merged into the human society. Hybrid-augmented intelligence thus becomes the key supporting technology.

Hybrid-augmented intelligence is developing along two directions, human-in-the-loop hybrid-enhanced intelligence and brain and neuroscience inspired hybrid-augmented intelligence. These two directions share some common theoretical basis, while their research focuses are quite different. For human-in-the-loop hybrid-augmented intelligence, efforts are put on adopting human role in the computing pipeline of machine intelligence, to enhance the intelligence level of the machine. In contrast, the research on brain and neuroscience inspired hybrid-augmented intelligence focuses on how to build brain-inspired computational models and self-learning.

Currently, rapid progress has been made in hybrid-augmented intelligence. Human-centered AI, a good example of human-in-the-loop hybrid-augmented intelligence, has been wildly applied in finance, medical treatment, management, etc. Meanwhile, intersection of brain science, neuroscience, and AI has been mutually promoted. More and more new cognitive computing models and computing architectures have been proposed. Hybrid-augmented intelligence has become the main feature of the new generation AI and is playing the leading role.

(6) Silicon-based integrated photonic devices for optical interconnects, optical computing, and optical sensing

Silicon photonics is a technology for developing and integrating photonic and optoelectronic devices based on silicon or using silicon as the substrate (e.g., SiGe/Si, silicon-on-insulator), using existing complementary metal-oxide semiconductor compatible processes, which can process and manipulate photons for effective optical interconnects, optical computing, and optical sensing. This technology shares the characteristics of integrated electronic circuit, such as ultra-large-scale integration and ultra-high-precision manufacturing, as well as the advantages of photonic technology, such as ultra-high-rate operation and ultralow power consumption. Among them, different kinds of silicon-based integrated photonic devices are the core foundation and premise of this technology, including silicon-based optical transmitters, optical detectors, optical modulators, and waveguide devices.

Silicon-based optical transmitters are used to generate light waves as information carriers, such as silicon-based light-emitting diodes and silicon-based lasers; moreover, the current research focuses on efficient light-emitting mechanisms based on silicon doping and defect regulation, and the integration and regulation of new light-emitting nanomaterials. Silicon-based optical detectors are used to receive optical signals and convert them to electrical signals, which are then transmitted to computing cells; further, the current research focuses on improving detection sensitivity, reducing dark currents, and increasing bandwidth. Silicon-based modulators are used to load electrical signals from computing units onto optical waves; further, the current research focuses on increasing the modulation rate, reducing insertion loss, and increasing the modulation depth. Silicon-based waveguide devices are the channels for optical transmission, including routers, wavelength-division multiplexers, and polarization multiplexers; the current research primarily focuses on designing and fabricating new structures to improve the capacity of information transmission.

(7) 5G large-scale antenna array wireless transmission theories and technologies

The large-scale antenna array (LSAA) based wireless transmission technology is one of the key 5G technologies. It is different from other existing wireless communication systems. In this system, the base station (BS) is equipped with an LSAA and provides services for multiple users using the same time-frequency resources. The number of antennas usually ranges from dozens to hundreds and is one to two orders of magnitude higher than that in existing wireless communication systems. Under the circumstances of multiple cells, time division multiplexing, and infinite antennas in every BS, the LSAA-based system has different characteristics when compared to other systems in a single cell and with finite antennas. While considering the antenna configuration, on one hand, these antennas can be collocated in a single BS to form a collocated LSAA-based system; on the other hand, these antennas can be distributed in multiple nodes to form a distributed LSAA-based system.

The LSAA-based wireless transmission technology has four advantages. First, the LSAA-based system has higher spatial resolution than the existing multiple-input multiple-output (MIMO) system, which implies that it can further explore resources in the space domain. Using the degree of spatial freedom from LSAA-based wireless transmission, more users can simultaneously communicate with the BS using the same time-frequency resources. Thus, the spectrum efficiency can be significantly improved without increasing the BS density. Second, the LSAA-based system can provide a narrower beam; thus, the co-channel interference can be significantly reduced. Third, its transmitted power can be reduced by a wide margin; consequently, the power efficiency is improved. Fourth, if the number of antennas is sufficiently large, the detection performance is optimal even when the simple linear precoder and detector are used. Additionally, noise and uncorrelated interference can be omitted.

To explore the potential advantages provided by the LSAA-based wireless transmission technology, a channel model that is suitable for practical 5G application scenarios was proposed. Its effect on the capacity was also analyzed. Under the circumstances of the practical channel model, appropriate pilot overhead, and acceptable implementation complexities, the spectrum efficiency and power efficiency were investigated; moreover, the optimal wireless transmission scheme, estimation methods of channel state information, and joint resource scheduling methods for multiuser spatial resource sharing were intensely investigated. There are 64 antennas in commercially deployed sub-6 GHz BSs. To further improve efficiency and coverage, the evolving 5G and 5G millimeter wave (mmWave) systems are expected to be equipped with more than 256 antennas.

(8) Artificial micro/nanostructures and their manipulation of the optics and electromagnetic fields

Electromagnetic metamaterials are artificial materials created by homogenizing a series of subwavelength unit cells, whose local electromagnetic response can be manipulated. In infrared and visible frequencies, such metamaterials are composed of micro/nanostructures. The exotic properties of the artificial materials and their strong capability to efficiently control the electromagnetic waves have enabled a broad spectrum of applications, such as meta-hologram, metalens, and carpet cloaking. In the past ten years, the studies on metamaterials and micro/nanostructures for engineering of electromagnetic wave-based applications were selected twice among the annual top 10 scientific breakthroughs by *Science*.

The past decade has also witnessed continuous advancements in novel design and fabrication techniques of micro/nanostructures. This has become a growingly important scientific frontier and inter-disciplinary research area, with the strong connections of solid-state physics, materials science, mechanics, applied electromagnetics, optoelectronics, etc. As a key platform of electromagnetic wave technology, the artificial micro/nanostructures is positively expected to lead the revolution of modern information technologies, secure national defense industry, emerging energy-harvesting technology, high-end semiconductor/chip nano-fabrications, etc. Currently, the policy makers, academia, and industries world-wide have paid remarkable attention to research, development, and fabrication of such artificial micro/nanostructures. For example, the USA Department of Defense has focused on artificial micro/nanostructures, under the branches of “Metamaterials and Plasmonics” and “Nanoscience and Nanoengineering,” from among their officially deemed six disruptive basic research areas. In Europe, more than 50 leading scientists and laboratories have received tremendous and highly selective funds for their related research. Even in Japan, despite the economic downturn and significant downscaling of research funds, at least two technical research projects on artificial micro/nanostructures have been generously funded. In the industry, top-notch semiconductor manufacturers, such as Intel, Advanced Micro Devices, and International Business Machines Corporation (IBM), have established a joint fund to support the research and development of artificial micro/nanostructures to control light and electromagnetic fields.

(9) Quantized precise metering/measurement and related theory

Since May 20, 2019, the seven units of the International System of Units (SI) were redefined in terms of constants that describe the natural world. The units, second, meter, kilogram, ampere, kelvin, mole, and candela, are correspondingly defined by the following constants: unperturbed ground-state hyperfine transition frequency of the cesium 133 atom (Δv_{Cs}), speed of light in vacuum (*c*), the Planck constant (*h*), elementary charge (*e*), the Boltzmann constant (*k*), the Avogadro constant (N_A), and the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz (K_{cd}). This indicates that an era of quantum metrology has originated. The new definitions will assure the future stability of SI and build a firm foundation for the use of new technologies, including quantum technologies.

The precise quantum measurement technologies are increasing based on the new SI definitions. These technologies employ quantum systems, quantum properties, or quantum phenomena to measure a physical quantity, which demonstrate the advantages of significantly high sensitivity and precision. A different class of applications has emerged with quantum measurements for various physical quantities ranging from magnetic and electric fields to time, frequency, and temperature. In the future, with the development of the quantum theory and technology, the quantum metrology/measurement is expected to advance toward metrology democratization, considerably low noise, and significantly high accuracy. This technology will gradually change the traditional measurement capabilities, enabling higher sensitivity and precision, including atomic observations up to macroscopic length scales.

(10) New-generation neural networks and their applications

Inspired by brain research in biology and neuroscience, artificial neural networks use nonlinear mapping functions to model the input-output transformation process of neurons and grow into a category of machine learning methods. The rapid development of new-generation neural networks is attributed to the breakthrough of deep learning based neural networks. Studies on deep neural networks primarily include learning theory of neural networks (such as generalization ability and regularization methods), supervised/unsupervised deep neural networks, convolution neural networks, sequential neural networks, attention model, compression and acceleration of neural networks, neural architecture search, and new models of neural networks (such as memory networks, generative adversarial networks, and deep reinforcement neural networks). Deep neural networks have been successfully applied in various fields of AI, such as representation learning, computer vision, pattern recognition, speech recognition and synthesis, natural language processing, and robotics. Owing to its significant performance improvement in image classification, speech recognition, and machine translation, deep neural networks are widely deployed in different industrial applications. The challenges of current research on neural networks include certain basic defects, such as the lack of learning autonomy, high cost of the training process, poor adaptability to the open dynamic environment, and the low level of privacy protection. The efforts that boost the research of neural networks may involve: 1) developing new models of neural networks based on the research on brain cognition; 2) interpretability of deep neural networks; 3) small sample size and meta-learning for deep neural networks; 4) adversarial game and security of neural networks.

1.2 Interpretations for three key engineering research fronts

1.2.1 Brain-inspired intelligence

The research and development of brain-inspired intelligence can be traced back to a series of brain-based devices proposed and developed by the Nobel Prize winner, Gerald Edman, in the 1980s, and to Neuromorphic Engineering initiated by Professor Carver Mead at the California Institute of Technology. Since the start of the new century, developed countries have launched the development of neuromorphic computing systems. On October 29–30, 2015, the US Department of Energy convened a forum for experts on the topic of “Neuromorphic Computing: From Materials to System Architecture.” In 2016, three large-scale neuromorphological computing systems were implemented one by one: the BrainScaleS system of the Heidelberg University in Germany, the SpiNNaker system of the University of Manchester, and the TrueNorth based chip system from IBM. There are other neuromorphic systems, including the Neurogrid of Stanford University, Si elegans of the University of Ulster, UK, and the neuromorphic chip and Loihi-based systems developed by Intel in recent years. According to the article *A*

Survey of Neuromorphic Computing and Neural Networks in Hardware published in May 2017, the number of papers on neuromorphology technology has increased rapidly since 1985 with a total of 2682 papers, indicating that the implementation of brain-like systems technology is the predominant force in the development of brain-inspired intelligence.

The related research on brain-inspired intelligence in China was conducted over a period of ten years. In September 2015, Beijing launched the "Brain Science Research" project, for two major tasks, "brain cognition and brain-like computing," which considered nine tasks at three levels, i.e., theoretical basic research, brain-like computer development, and brain-like intelligence application, including the brain structure analysis platform, cognitive function simulation platform, neuromorphic devices, brain-like processors, machine learning chips, brain-like computers, audiovisual perception, autonomous learning, and natural conversation. Researchers in Beijing worked together to challenge the major common technologies and have achieved important results. For example, Shi Luping and his colleagues at Tsinghua University proposed a paradigm framework for brain-like hybrid computing and developed a brain-like chip called "Tianjic." The results were published as the cover paper of *Nature* in 2019. Huang Tiejun and his team at Peking University proposed a bionic visual spike coding model for simulating the mechanism of the retina; moreover, in 2018, they developed a full-time and ultra-fast retina-like chip that was thousands of times faster than the human eye. At the national level, the implementation plan of the major scientific and technological projects of "brain science and brain-like intelligence" presented since 2016, was formally compiled and is expected to start soon. In 2018, the Ministry of Science and Technology of China issued a national plan, i.e., Science and Technology Innovation 2030—New-Generation AI, which clearly considers neuromorphic technology and chips as an important research direction.

Neuroscience research in the USA has a strong foundation. Brain-inspired intelligence research is also conducted in academic institutions and enterprises. The numbers of core papers and citations in the USA account for more than half of the global total. UK accounts for nearly 20% of the core papers globally. Germany, Canada, and the Netherlands each account for about 10%, and China, Sweden, Spain, and Italy each account for about 5% (Table 1.2.1). The international cooperation targets of China are primarily the USA and Canada. The cooperation among other countries is the same (Figure 1.2.1). The production institutions of core papers are relatively centralized (Table 1.2.2 and Figure 1.2.2). Among the institutions which published no less than 10 core papers, beside the Swedish Karolinska College, a major brain science center, all others are well-known universities in the field of brain science and AI, including Harvard University, Yale University, McGill University, Oxford University, Stanford University, Edinburgh University, Cambridge University, and Toronto University (Table 1.2.2). The number of citing papers in the USA accounts for more than one-third, UK and China both account for more than 10%, and the distribution of other countries is basically the same as that of the producing countries, indicating that China is obviously on par with the top countries in the field of brain-inspired intelligence (Table 1.2.3).

Table 1.2.1 Countries or regions with the greatest output of core papers on "brain-inspired intelligence"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	169	50.15%	10 431	54.24%	61.72
2	UK	64	18.99%	4 337	22.55%	67.77
3	Germany	40	11.87%	1 871	9.73%	46.78
4	Canada	39	11.57%	2 568	13.35%	65.85
5	Netherlands	30	8.90%	2 313	12.03%	77.10
6	Australia	21	6.23%	1 553	8.08%	73.95
7	China	21	6.23%	1 133	5.89%	53.95
8	Sweden	17	5.04%	837	4.35%	49.24
9	Spain	17	5.04%	765	3.98%	45.00
10	Italy	16	4.75%	1 398	7.27%	87.38

Table 1.2.2 Institutions with the greatest output of core papers on “brain-inspired intelligence”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	17	5.04%	1037	5.39%	61.00
2	Yale Univ	13	3.86%	1099	5.71%	84.54
3	McGill Univ	13	3.86%	834	4.34%	64.15
4	Univ Oxford	13	3.86%	1316	6.84%	101.23
5	Stanford Univ	13	3.86%	918	4.77%	70.62
6	Univ Edinburgh	13	3.86%	588	3.06%	45.23
7	Univ Toronto	10	2.97%	767	3.99%	76.70
8	Univ Cambridge	10	2.97%	623	3.24%	62.30
9	Karolinska Inst	10	2.97%	487	2.53%	48.70
10	Univ Minnesota	9	2.67%	1010	5.25%	112.22

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “brain-inspired intelligence”

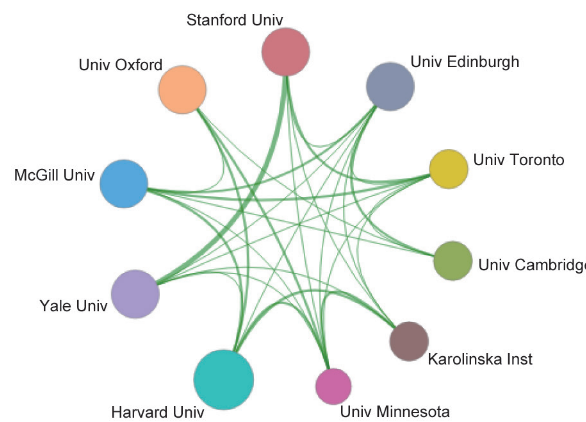

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “brain-inspired intelligence”

Table 1.2.3 Countries or regions with the greatest output of citing papers on “brain-inspired intelligence”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	6725	35.51%	2016.8
2	UK	2382	12.58%	2016.9
3	China	1899	10.03%	2017.2
4	Germany	1680	8.87%	2016.8
5	Canada	1344	7.10%	2017.0
6	Australia	1017	5.37%	2017.0
7	Netherlands	983	5.19%	2016.9
8	Italy	909	4.80%	2017.0
9	France	735	3.88%	2016.8
10	Spain	679	3.59%	2016.9

Among the top 10 institutions with the greatest output of citing papers, six come from the USA (Table 1.2.4).

1.2.2 Space-terrestrial integrated network

Considering the large scale of the space-terrestrial integrated network, three-dimensional multi-layered topology, high degree of heterogeneity, and the wide variety of services, networking focuses on designing a network architecture with a clear structure, simple functions, and easy and efficient implementation. This is the primary problem that the space-terrestrial integrated network is required to solve.

At present, the development priorities of major countries and regions in the world are as follows: (1) The USA is committed to the large-scale construction of a commercial integrated network, such as the large-scale manufacturing and launch of low-cost low-orbit satellites by Starlink, and the promotion of the Google Loon project for commercialization. (2) The EU is committed to the integration of the satellite-terrestrial network and the 5G network architecture, focusing on the combination of software defined networking (SDN)/network functions virtualization (NFV). There are several projects under the Horizon 2020 plan that have launched demos. (3) China has established a major project on space-terrestrial integrated information network and a low-orbital satellite network construction plan.

At present, research on the integration technology of the space-terrestrial network is conducted primarily in the following directions:

(1) Integrated network architecture design for land, sea, air, and space

The infrastructure of the space-terrestrial integrated network is divided primarily into high-, medium-, and low-orbit satellites, high-altitude aircraft, marine mobile equipment, and ground equipment. The advantages and disadvantages of different facilities in terms of coverage, transmission delay, bandwidth cost, capacity, frequency, etc. are different. To efficiently carry various types of service, determining the characteristics of various types of equipment to form a composite collaborative network and fully utilizing the new technologies in the network field, such as SDN, to improve system controllability, are key issues in the design of the space-terrestrial integrated network architecture.

(2) Protocol research for large-scale, highly heterogeneous space network

At present, various network protocols, such as the Consultative Committee for Space Data Systems (CCSDS), Delay Tolerant Network (DTN), Snapshot, and Internet Protocol (IP), have been proposed in the field of space-terrestrial integration. A spacecraft can adopt the CCSDS protocol. In the case of intermittent connection, the DTN protocol can be used. In the case of regular motion, the Snapshot protocol can be used. The terrestrial users can use the IP protocol to support broadband networking applications. Recently, researchers also proposed the use of a content centric networking (CCN) in this area. This protocol family requires further enrichment and adaptation for the specific scenarios of the space-terrestrial integrated network, which is a key challenge that requires further research.

Table 1.2.4 Institutions with the greatest output of citing papers on “brain-inspired intelligence”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Harvard Med Sch	396	11.79%	2017.6
2	Univ Toronto	362	10.78%	2016.9
3	UCL	314	9.35%	2016.8
4	Stanford Univ	313	9.32%	2016.7
5	Kings Coll London	307	9.14%	2016.8
6	Univ Oxford	306	9.11%	2016.8
7	Univ Penn	300	8.93%	2017.1
8	Harvard Univ	298	8.87%	2015.9
9	Yale Univ	264	7.86%	2016.9
10	Univ Cambridge	249	7.42%	2017.0

(3) Lightweight handover mechanism research for highly dynamic mobility

Considering the characteristics of the constructed network nodes, especially low-orbit satellites with highly dynamic motion, user-oriented multi-satellite, and multibeam frequent switching, it is necessary to focus on highly dynamic motion and light-weight mobility handover mechanisms to effectively reduce the delays and data loss during the handover between networks, which can improve network mobility performance when space network resources are limited.

(4) Research on multi-dimensional network resource joint management technology

For the integration of space-based networks and terrestrial networks, technologies such as SDN/NFV have to be applied to the integrated network to achieve the key technologies of multidimensional network resource virtualization slicing and service quality assurance, application-driven network control, on-demand network resource scheduling, and safe and reliable network management, which can achieve efficient control and interconnection of satellite Internet and terrestrial Internet.

The top three countries with the greatest output of core papers on the research front of “space-terrestrial integrated network” are the USA, China, and Germany (Table 1.2.5). According to the main production institutions of the core papers (Table 1.2.6), the top three institutions are Southeast University, California Institute of Technology, and Tsinghua University. From the cooperation network of major countries or regions (Figure 1.2.3), it can be observed that all the concerned countries demonstrate close cooperation. From the cooperation network between the main institutions (Figure 1.2.4), it can be observed that the major cooperation is between Southeast University and the PLA University of Science and Technology. From the statistical results of the primary output countries and regions that cite the core papers (Table 1.2.7), China, the USA, and Germany were ranked the top three. Among them, China was ranked first with 1753 papers, accounting for 26.93%. From the list of primary institutions that cite core papers (Table 1.2.8), the top three institutions are Chinese Academy of Sciences, the National Aeronautics and Space Administration, and Beijing University of Posts and Telecommunications.

1.2.3 Brain imaging technologies

In the second decade of the 21st century, we are witnessing and experiencing a revolutionary change in the concept of brain intelligence. Because of the significant value of brain science research in the scientific, economic, social, and military fields, each developed country is attempting to become the global strategic command center for brain and cognitive technology. In recent years, the USA, the EU, and Japan have each successively issued a “brain plan,” expecting a major breakthrough in brain science, thereby providing a basis for the in-depth development of AI in the future and promoting the innovative development of emerging industries based on the integration of brain-like intelligence and the brain computer.

Table 1.2.5 Countries or regions with the greatest output of core papers on “space-terrestrial integrated network”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	47	38.52%	2141	33.33%	45.55
2	China	27	22.13%	1256	19.55%	46.52
3	Germany	27	22.13%	994	15.47%	36.81
4	France	23	18.85%	1540	23.97%	66.96
5	Italy	19	15.57%	972	15.13%	51.16
6	UK	19	15.57%	768	11.96%	40.42
7	Australia	18	14.75%	801	12.47%	44.50
8	Canada	15	12.30%	770	11.99%	51.33
9	Netherlands	12	9.84%	562	8.75%	46.83
10	Switzerland	9	7.38%	413	6.43%	45.89

Table 1.2.6 Institutions with the greatest output of core papers on "space-terrestrial integrated network"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Southeast Univ	8	6.56%	309	4.81%	38.63
2	CALTECH	7	5.74%	296	4.61%	42.29
3	Tsinghua Univ	7	5.74%	274	4.27%	39.14
4	NASA	6	4.92%	435	6.77%	72.50
5	PLA Univ Sci & Technol	6	4.92%	259	4.03%	43.17
6	Max Planck Inst Biogeochem	6	4.92%	171	2.66%	28.50
7	Chinese Acad Sci	5	4.10%	380	5.92%	76.00
8	ETH	5	4.10%	232	3.61%	46.40
9	Univ Calif Berkeley	5	4.10%	237	3.69%	47.40
10	Univ Texas Austin	5	4.10%	249	3.88%	49.80

CALTECH: California Institute of Technology; NASA: National Aeronautics and Space Administration; ETH: Swiss Federal Institute of Technology Zurich

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "space-terrestrial integrated network"

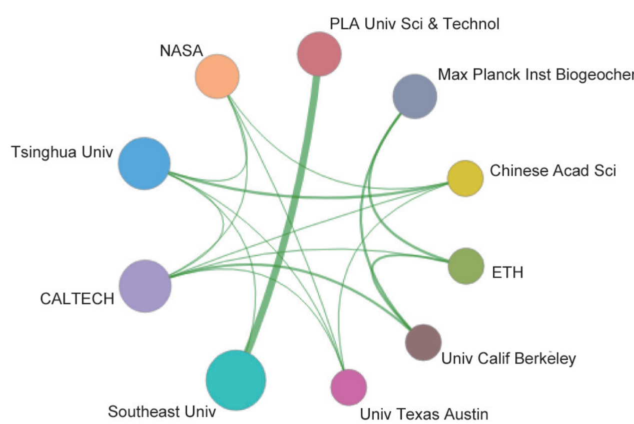

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "space-terrestrial integrated network"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "space-terrestrial integrated network"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1753	26.93%	2017.5
2	USA	1428	21.94%	2017.2
3	Germany	560	8.60%	2017.1
4	UK	536	8.23%	2017.5
5	France	431	6.62%	2017.2
6	Italy	411	6.31%	2016.9
7	Canada	398	6.11%	2017.4
8	Australia	308	4.73%	2017.3
9	Spain	260	3.99%	2017.2
10	India	217	3.33%	2017.3

Table 1.2.8 Institutions with the greatest output of citing papers on "space-terrestrial integrated network"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	367	26.14%	2017.3
2	NASA	144	10.26%	2016.9
3	Beijing Univ Posts & Telecommun	143	10.19%	2017.0
4	Univ Chinese Acad Sci	131	9.33%	2017.5
5	Tsinghua Univ	122	8.69%	2017.5
6	CALTECH	112	7.98%	2016.8
7	Univ Maryland	86	6.13%	2017.2
8	Southeast Univ	81	5.77%	2017.3
9	Beijing Normal Univ	77	5.48%	2017.3
10	Wuhan Univ	72	5.13%	2017.6

Brain science research has the dual characteristics of scientific frontier and comprehensive intersection. Brain imaging technology is an effective way to deeply analyze the brain functional connection group. Essentially, deep analysis of the brain functional connection group is a reverse engineering interpretation of the brain working principle. On this basis, this research is expected to develop a new computing system based on the brain structure and circuit principle, break the technical bottleneck of modern computers and AI while dealing with complex problems, and achieve self-organization and self-sufficiency, deep learning, and even a new type of neural AI system.

In recent years, the basic research of brain science has developed rapidly; moreover, the technology of AI and brain–computer interface is changing with each passing day. There is no doubt that brain science research has entered a golden age. With the development of brain science research, scientists have proposed higher requirements for brain imaging technology. They plan to focus on methods to integrate the macro, meso, and micro brain tissue structures, draw the brain function linkage map, seek the systematic grasp of brain tissue structure and function, and develop and optimize non-invasive tools, such as light, sound, electricity, and magnetogenetics, for treatmentment of nervous and mental diseases. The primary development directions of brain imaging technology are as follows: (1) high-resolution brain structure analysis methods and technologies, including the development of high-throughput three-dimensional structure and function imaging and new sample processing technologies, as well as new image data processing and analysis methods, to achieve rapid and quantitative analysis of the types, connections, and activities of different species of brain neurons with cell resolution; (2) large-scale *in vivo* high-resolution optical imaging with deep penetration and other new technologies that can achieve high-resolution analysis of nerve activities in conscious and free animals in space/time; (3) photoelectric correlation and other new technologies that can achieve ultrastructural analysis and quantitative characterization of subcellular structures, such as synapses.

It can be observed from the countries or regions that primarily publish core papers in the area of "brain imaging technology" (Table 1.2.9) that the top three countries are the USA, UK, and Germany. According to the primary institutions that publish core papers (Table 1.2.10), the top three institutions are Harvard University, King's College London, and Stanford University. It can be observed from the cooperation network among the major countries or regions (Figure 1.2.5) and among the major institutions (Figure 1.2.6) that a close corporation is demonstrated. According to the statistical results of the major output countries or regions (Table 1.2.11), the USA, China, and UK are ranked the top three. Among them, China is ranked second with 6423 papers, accounting for 11.77% of the total. According to the main output institutions of the citing papers (Table 1.2.12), the top three institutions are Harvard Medical School, University College London, and University of Toronto.

Table 1.2.9 Countries or regions with the greatest output of core papers on "brain imaging technologies"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	561	59.62%	41 453	64.03%	73.89
2	UK	174	18.49%	14 613	22.57%	83.98
3	Germany	117	12.43%	9 494	14.66%	81.15
4	Canada	80	8.50%	7 192	11.11%	89.90
5	Netherlands	73	7.76%	7 700	11.89%	105.48
6	China	67	7.12%	6 081	9.39%	90.76
7	France	55	5.84%	4 512	6.97%	82.04
8	Italy	46	4.89%	4 930	7.61%	107.17
9	Switzerland	42	4.46%	3 520	5.44%	83.81
10	Australia	41	4.36%	3 141	4.85%	76.61

Table 1.2.10 Institutions with the greatest output of core papers on "brain imaging technologies"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	75	7.97%	6 817	10.53%	90.89
2	Kings Coll London	42	4.46%	2 308	3.56%	54.95
3	Stanford Univ	41	4.36%	3 277	5.06%	79.93
4	Univ Penn	40	4.25%	3 235	5.00%	80.88
5	Univ Coll London	35	3.72%	4 082	6.30%	116.63
6	Yale Univ	34	3.61%	2 668	4.12%	78.47
7	Univ Calif Los Angeles	34	3.61%	3 173	4.90%	93.32
8	Univ Toronto	31	3.29%	2 661	4.11%	85.84
9	Univ Oxford	29	3.08%	3 720	5.75%	128.28
10	Massachusetts Gen Hosp	29	3.08%	2 953	4.56%	101.83

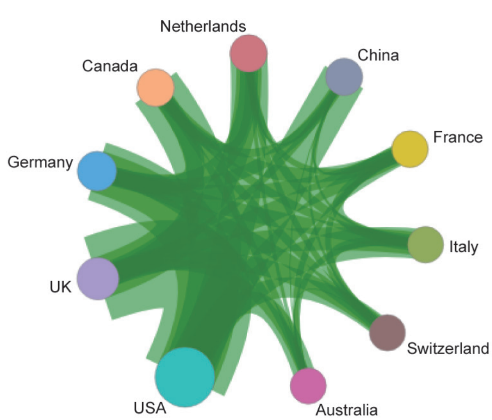

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "brain imaging technologies"

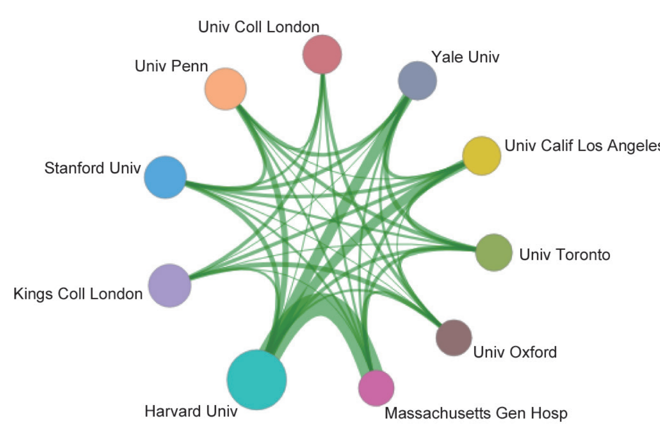

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "brain imaging technologies"

Table 1.2.11 Countries or regions with the greatest output of citing papers on “brain imaging technologies”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	20 120	36.88%	2016.8
2	China	6 423	11.77%	2017.1
3	UK	5 800	10.63%	2016.8
4	Germany	5 221	9.57%	2016.8
5	Canada	3 455	6.33%	2016.9
6	Netherlands	2 799	5.13%	2016.8
7	Italy	2 637	4.83%	2016.9
8	France	2 532	4.64%	2016.8
9	Australia	2 156	3.95%	2016.9
10	Switzerland	1 755	3.22%	2016.8

Table 1.2.12 Institutions with the greatest output of citing papers on “brain imaging technologies”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Harvard Med Sch	1300	12.68%	2017.6
2	UCL	1106	10.79%	2016.9
3	Univ Toronto	996	9.72%	2016.8
4	Kings Coll London	976	9.52%	2016.6
5	Stanford Univ	948	9.25%	2016.7
6	Harvard Univ	894	8.72%	2015.6
7	Univ Penn	873	8.52%	2017.0
8	Chinese Acad Sci	823	8.03%	2017.0
9	Univ Oxford	811	7.91%	2016.8
10	Univ Calif San Francisco	766	7.47%	2016.8

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts in the information and electronic engineering field are summarized in Table 2.1.1, including the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. Among these 10 fronts, “systems and technologies for analysis and identification of images and videos,” “development of sensors based on the micro/nanoelectronic technology,” and “surgical robot technology” are published based on the analysis of *Derwent Innovation* of *Clarivate Analytics*; the seven other fronts are recommended by researchers.

The annual disclosure of core patents involved in the top 10 development fronts from 2013 to 2018 is listed in Table 2.1.2.

(1) Millimeter wave (mmWave) ultra-high throughput technology

The mmWave ultra-high throughput technology achieves high-speed data transmission using mmWave frequency spectrum. The frequency range of the mmWave frequency band is 26.5–300 GHz, corresponding to 1–10 wavelengths. Using the spectrum resources within the above-mentioned bands, the data throughput can reach gigabits per second or even terabytes per second. It is universally acknowledged that a degradation of the performance occurs in microwave/mmWave/terahertz integrated circuits (ICs); moreover, the cost

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Millimeter-wave ultra-high throughput technology	293	4 246	14.49	2015.4
2	Ultraprecision instrument technology and intelligence	186	237	1.27	2015.7
3	Systems and technologies for analysis and identification of images and videos	227	18 350	80.84	2014.1
4	Development of sensors based on the micro/nanoelectronic technology	213	382	1.79	2015.9
5	Surgical robot technology	286	44 560	155.80	2014.5
6	Energy-efficient AI chip technology	184	256	1.39	2016.8
7	Sensor unit and measurement technology based on graphene nanomaterial	221	918	4.15	2015.3
8	Flexible and wearable optoelectronics	48	356	7.42	2016.4
9	Security detection technologies for IoT	48	36	0.75	2016.8
10	Synthetic aperture radar (SAR) image processing, target recognition, and feature learning	329	882	2.68	2016.0

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

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Millimeter-wave ultra-high throughput technology	21	18	26	40	52	90
2	Ultraprecision instrument technology and intelligence	18	20	31	34	35	38
3	Systems and technologies for analysis and identification of images and videos	89	71	35	28	4	0
4	Development of sensors based on the micro/nanoelectronic technology	35	22	28	26	49	53
5	Surgical robot technology	80	87	45	53	16	5
6	Energy-efficient AI chip technology	3	3	4	13	36	81
7	Sensor unit and measurement technology based on graphene nanomaterial	14	22	31	27	41	40
8	Flexible and wearable optoelectronics	0	2	2	14	15	13
9	Security detection technologies for IoT	1	2	4	7	18	16
10	SAR image processing, target recognition, and feature learning	15	36	70	62	63	75

increases as the frequency increases. Meanwhile, the increase in frequency will result in size reduction of the antenna and passive components to generate a similar gain. Recently, the Ministry of Industry and Information Technology of China adopted two mmWave frequency bands of 24.25–27.5 GHz and 37–42.5 GHz, as 5G trail bands. As the core enabling technology, the massive MIMO system (mMIMO) can effectively increase the system capacity and data throughput by employing an LSAA to manipulate the electromagnetic waves for beamforming. However, it will pose significant challenges to mmWave communication techniques, primarily in the architecture of the BS, user equipment (UE), multichannel chip, component packaging, and over-the-air (OTA) measurement. The advancement of mmWave technology has indicated a major trend toward the achievement of higher data throughput and system integration.

(2) Ultraprecision instrument technology and intelligence

Measuring instruments are generally third-party standards required to measure certain property values of targets, which have indictors such as accuracy and range. Ultraprecision instruments are those that have the highest level of precision in measuring instruments, which perform a leading and supporting role in scientific frontier research and technological frontier development. The primary technical directions of ultraprecision instruments include cutting-edge science exploration instrument technology (including gravitational wave detection and new-principle microscope), engineering measuring instrument technology in production (including dynamic measurement, ultraprecision laser measurement, and industrial transmission measurement), biomedical instrument technology (including high resolution biological microscope and cryo-electron microscope), metrology and measurement standard technology (ensuring the accuracy and consistency of the above-mentioned measurement process, including the redefinition of the basic SI units and various basic physical quantities and parameter measurement standards). At present, with the rapid development of information technology, technologies such as IoT, cloud computing, big data, and AI have been promoted. Ultraprecision instrument technology has developed along with the trends of integration, informationization, networking, and intelligence and with the requirements for improvements in measurement accuracy and multiparameter simultaneous measurement.

(3) Systems and technologies for analysis and identification of images and videos

Various intelligent methods are used for images and videos to accomplish complicated tasks, such as analysis, recognition, counting, and prediction. Advanced technologies and concepts of image processing, computer vision, pattern recognition, AI, automatic control, network communication, and edge computing are involved. These technologies have been successfully applied in many fields, including retailing, Internet content supervision, security, transportation, and sports. Applications in medical monitoring, autopilot, and virtual reality are also emerging.

In the era of deep learning, the development directions of systems and technologies for analysis and identification of images and videos include the following: 1) developing edge computing devices with higher computing power and lower power consumption; 2) reducing the communication cost of the terminal camera and central computer; 3) improving the resolution of various types of acquisition equipment and the quality of image acquisition, especially in the case where the lighting condition is not ideal; 4) real-time analysis of high-resolution video using hardware such as graphic processing units; 5) developing more capable AI technologies to strictly control the false alarm (i.e., false-positive) rate and to continuously improve the accuracy and efficiency of data analysis; 6) establishing an automatic framework of a cross-camera analytics system by incorporating metadata information (e.g., the geographical information system).

(4) Development of sensors based on the micro/nanoelectronic technology

A sensor is a device or equipment that responds to a stimulus and transmits a useful output signal with an affirmatory relationship. With the advent of the electronic information technology era centering on digitalization, networking, and intelligence, it requires significantly more effort to achieve high performance, multifunction, miniaturization, integration, and intelligence for these sensors while ensuring their low cost, long lifetime, and stable performance.

Owing to the utilization of IC technology, the micro/nanoelectronic technology enables the fabrication of the micro/nano-scale electronic devices. By the assembly and fusion of research in the fields of microelectronics, micromechanics, chemical and biological engineering, nanotechnology, and so on, the micro/nanoelectronic technology provides an effective solution for the miniaturization, integration, intelligence, and mass production of these sensors. Thus, there is an increasing demand for micro/nano sensors in the industrial IoT, consumer electronics, biomedicine, automotive, robotics, aerospace, and military fields.

A smart sensor constructed using system-on-chip technology in IoT, for instance, has localized computational capability to turn the raw data into actions in real time, allowing fast response and circumventing network latency issues. Tactile sensors that serve as an important interface between a human and machine can detect the mechanical properties of the human and the local environment. Their wearability, biocompatibility, and mechanical durability have been increasingly improved with the help of the micro/nanoelectronic technology. By employing the advantages of biosystems, the micro/nanoelectronic technology-based bionic sensors, such as the electronic nose, eye, tongue, and ear, are emerging. Serving as a key component of the intelligent sensing system, the gas sensors using low-dimensional nanomaterials with large specific surface areas have advantages in sensitivity, response, and recovery time. By introducing the cutting-edge nanotechnology and micro-electro-mechanical system (MEMS), the miniaturization, integration, and automation of biomedical sensors can be achieved, with molecular or atomic precision in measurement or control.

In particular, MEMS sensors can integrate mechanical, electronic, and optical functional micro/nanostructures into one system, facilitating the miniaturization, intelligence, and multifunctionalization of sensors, and have tremendous applicable value and broad market prospects. As MEMS sensors have strong coupling between fundamental scientific and engineering problems owing to the inherent interdisciplinarity and diversity, studies on application-specific integrated microinstrument, microsensor array, and multisensory integration are being conducted.

(5) Surgical robot technology

Surgical robot technology is a robotic technology for medical surgery based on modern technologies, such as spatial positioning, fast calculation, three-dimensional digital medical imaging, advanced robotics, and AI. Surgical robots usually consist of functional modules, such as human–machine interaction and display, medical images, system software, robotic devices, and positioning devices. The research directions of surgical robot technology primarily include: 1) human–machine interaction and cooperative control; 2) telepresence and virtual reality for remote operation; 3) three-dimensional digital medical imaging; 4) robotic mechanism design that can perform ingenious and fine operations; 5) multisensor information fusion for medical treatment; 6) spatial tracking and positioning, real-time calibration and registration for medical surgery.

Surgical robots demonstrate the advantages of enhanced surgical dexterity, improved operational accuracy, stability, safety, etc. They can accomplish fine surgical operations in the cavity, pelvis, and anatomical structure of the vascular system, which is conducive to the reconstruction and recovery of human organs. At present, surgical robots are applied in many medical fields, such as orthopedics, dentistry, surgery, neurology, and ophthalmology. However, they still exhibit problems, such as poor portability, high cost, lack of ability to diagnose diseases and make clinical decisions, and the requirement of a doctor to control the robots. To compensate for the deficiencies in existing surgical robots, the trend is to develop general miniaturized, light-weight, and low-cost surgical robots, and to develop surgical robots capable of autonomously treating diseases, making clinical decisions, and conducting manipulation.

(6) Energy-efficient AI chip technology

The AI chip is defined as an IC chip that can execute various AI algorithms, such as artificial neural network and machine learning. As the physical entity that enables AI, it provides powerful computing capability for intelligent information processing and is the core technology to promote the development of the AI ecosystem. With the advent of intelligent applications, such as IoT, autonomous driving, wearable devices, and mobile computing, the improvement in chip performance under Moore's law is slowing down; moreover, the von Neumann architecture is unsuitable for emerging AI algorithms. Identification of a suitable method to improve energy efficiency has become the bottleneck for further penetration of AI chips.

Currently, the general AI chips based on hardware-software co-optimization and the field-programmable gate array based on fine-grained reconfigurable technology, which supports training and inferencing, are oriented primarily to cloud scenarios. The property of high power consumption makes them unavailable for energy-efficient AI processing. The current high-efficiency AI chips primarily include: 1) Customized hardware acceleration chip for an AI algorithm, which is the most popular approach currently. According to the differences in implementation, it can be categorized into digital AI chip, mixed-signal AI chip, memristor-based AI chip, and optical AI chip. 2) A neuromorphic AI chip, inspired by biological brain mechanism, has the advantages of significant brain-like, low-power-consumption, and low-latency operations. The primary development directions of future energy-efficient AI chip technologies are: 1) near memory/in-memory computing-based AI chip; 2) software-defined-hardware-based AI chip; 3) AI chip based on emerging non-volatile memories.

(7) Sensor unit and measurement technology based on graphene nanomaterial

Nanomaterial is a general term for zero-, one-, two-, and three-dimensional materials composed of ultrasmall particles having a size of less than 100 nm, such as fullerenes, carbon nanotubes, and graphene. Nanomaterials have unique physical and chemical properties and exhibit a series of special optical, magnetic, mechanical, electrical, and catalytic properties. They have shown good application prospects in the field of sensors and have received extensive attention. While considering graphene as an example, with its unique two-dimensional crystal of hexagonal honeycomb network structure, graphene demonstrates a large surface area, superior electrical conductivity, high mechanical strength, good light transmission, and easy functionalization. As a sensing unit, each atom is in full contact with the sensing environment; moreover, the physical properties of graphene are changed by this contact to measure the magnetic field, pressure, optical signal, molecular material, etc. This technology can be applied to physical sensing, chemical sensing, biosensing, and other fields. Graphene-based electrochemical biosensing technology is a cutting-edge crossover technology that combines biology and information to measure small chemical molecules in living organisms, such as nitric oxide, hydrogen peroxide, and dopamine, and also deoxyribonucleic acid/ribonucleic acid. It can also be used to measure protein macromolecules and biological cells. The development of this technology has far-reaching effects in the fields of biological sciences and medical health. At present, the primary directions of this technology are to improve the accuracy and sensitivity of graphene sensors, optimize the size and structure of the sensor, and achieve its application in the medical market as soon as possible.

(8) Flexible and wearable optoelectronics

Flexible and wearable optoelectronics is an emerging technology for integrating electronic and photonic devices on flexible plastic substrates, with one or multiple functionalities, such as power supply, signal transmission, material sensing and detection, data recording, and imaging display. Relevant research areas include, but are not limited to, the following interdisciplinary directions: mechanical engineering design, optoelectronic device design, numerical simulation, flexible materials, semiconductor processing technology, printing technology, additive manufacturing, system integration, sensing, and signal processing. When compared to traditional optoelectronic devices, the major characteristic of flexible and wearable optoelectronics is that the flexible devices are ultralight, ultrathin, and able to exhibit and maintain their excellent optoelectronic properties under bending, folding, compression, or stretching actions. Nowadays, they are widely applied in fields such as electronic and photonic skin, intelligent robot sensing, and wearable and implantable physiological monitoring and disease treatment.

To satisfy the urgent requirements of flexible wearable devices in the current era of AI and IoT, flexible and wearable optoelectronic devices can be developed in the following areas: 1) optimizing material selection and mechanical structure design, to achieve ultra-high flexibility and stretchability of optoelectronic devices; 2) investigating large-area device array with multifunctionalities, to achieve high resolution, high sensitivity, rapid response multidimensional signal (e.g., direction, stress, temperature, humidity, and biochemicals) detection over a large area; 3) systematic integration of flexible electronic and photonic devices to achieve self-supply, self-illumination, wireless signal transmission, as well as real-time data interpretation of flexible devices; 4) studying biocompatible and biodegradable materials for flexible and implantable optoelectronic devices to explore their applications in disease diagnosis and treatment, physiotherapy rehabilitation, etc.; 5) developing new processes and technologies to fabricate high-performance flexible and wearable optoelectronic devices in large scale at low cost.

(9) Security detection technologies for IoT

The IoT is the core and key technology to achieve the Internet of Everything. Currently, IoT is extensively used in sensing and monitoring in the fields of energy, transportation, ocean, space, etc. However, the security defense mechanism of current IoT is vulnerable, which creates a significant hidden risk to the key infrastructure. The aim of IoT security detection technologies is to identify the hidden risks by obtaining and evaluating the security status of software and hardware devices and systems running on IoT, and to provide support for further security reinforcement and defense.

The primary research topics of current IoT security detection include: 1) security detection of the operating system and application software in IoT nodes; 2) vulnerability analysis on IoT protocols and communication interfaces; 3) security detection of IoT chips; 4) technologies of remote monitoring and forewarning of IoT. With the emergence of new attacks, such as advanced persistent threat, the threat to the IoT is becoming more complex and generalized. In the future, the threat intelligence sensing and sharing of IoT and the network-wide security situation perception are expected to be novel development trends in this field, which can provide strong support for resisting all kinds of new attacks. The standardization of IoT security detection is also an important research topic.

(10) SAR image processing, target recognition, and feature learning

SAR, as an active microwave imaging technique, is widely deployed in both civilian and military sectors, owing to its all-day, all-weather, multiband, and multipolarization characteristics as well as penetrating capability. With the improvement of SAR sensors, more value has been placed on the corresponding image interpretation process, and many studies were focused on SAR image processing, target recognition, and feature learning, which further promotes the development of SAR applications.

There are several steps involved in SAR image processing, including noise reduction, enhancement, correction, registration, and segmentation, so that targets are highlighted and/or background is weakened. Target feature learning is a process of extracting and refining useful information from SAR images, and finally presenting the desired feature vectors. Typical methods include principal component analysis (PCA), kernel PCA, and non-negative matrix factorization. Target recognition is to construct a classifier, and then different or similar types of targets can be distinguished using target features, such as amplitude, phase, texture, and polarization of SAR images. There are four types of methods for target recognition, i.e., based on template matching, pattern classification, sparse representation, and deep learning.

The very front of engineering development in this area includes the following four aspects: 1) Utilization of multisource images, i.e., with SAR parameter variability and multi-system collaboration, multisource images are obtained, and the performance will be improved effectively by multi-image fusion. 2) Multiscale processing, where more target features are extracted through multiscale processing, which provides more information for the following classifier to complete the target recognition task. 3) Deep learning approach, where image preprocessing and target feature extraction are integrated with an end-to-end architecture, thus achieving higher precision under the condition of sufficient training data. 4) Task-driven design, where a united data processing link for the entire target recognition process can be formed with a task-driven design from top to bottom, benefiting the SAR image interpretation process.

2.2 Interpretations for three key engineering development fronts

2.2.1 Millimeter-wave ultra-high throughput technology

The network equipment for 5G mmWave mobile commununications is composed primarily of base stations and a core network. The base station consists of an active antenna unit (AAU) and a baseband unit, among which AAU generally integrates the antenna, radio frequency (RF) circuits, and baseband preprocessing parts, and employs the mMIMO technique to minimize the large path loss, while the 5G UE architecture will adopt multiple small-scale phased arrays. Currently, 5G mmWave AAU generally implements an LSAA, e.g., 256 antenna elements, to improve the data transmission rate and to expand the system capacity. Simultaneously, the high-performance multi-channel integrated RF technique is extensively applied. As the mmWave UE is constrained by its volume, power consumption, and cost, a small-scale antenna array (e.g., four antenna elements) will be deployed, and the integration of the antenna and RF parts will take the form of the highly integrated mmWave front-end module. The development of mmWave multi-channel chips would be the key research orientation to achieve the miniaturization of mmWave BS and UE. Multiple RF transmitters and receivers will be designed in one chip to reduce the volume, cost, and power consumption. To further improve the performance of the mmWave system, a high level of packaging technology is firmly demanded, for which the technology of antenna-in-package was developed to integrate the antenna and RF circuit in the same package. Furthermore, for system performance assessment, high integration challenges the feasibility of conventional measurements. Accordingly, the OTA-based method was proposed to deal with the above challenge; however, the relevant measurement standards, equipment, and methods are still under study.

The mmWave ultra-high throughput technology is expected to become one of the key enabling technologies in 5G/6G wireless communication, next-generation WiFi, Internet of space, etc. As the essential supporting technology of the future electronic communication industry, it is widely supported and developed as a long-term strategic field by many countries globally. Global institutions focus on the research and development of spectrum resources below 50 GHz. Major countries have provided suggestions on spectrum allocation and are actively working on research and industrial distribution. Up to now, there have been 293 patents of mmWave ultra-high throughput technology (Table 2.1.1), and the number is increasing year by year (Table 2.1.2). The top three countries are the USA, China, and Japan (Table 2.2.1). In terms of the leading organizations with core patents (Table 2.2.2), the top three organizations are Intel Corporation, Qualcomm Inc., and Panasonic Corp. In addition, from the cooperation network among the major countries or regions (Figure 2.2.1), it can be observed that effective cooperation is achieved predominantly among a few countries, such as China, the USA, Russia, and Sweden. While considering the cooperation network among the major institutions (Figure 2.2.2), a closer technical cooperation is required in the future.

In summary, as the mmWave ultra-high throughput technology has developed rapidly in recent years, a relatively complete industrial chain has been formed globally, including the original equipment manufacturer, device development, chip design, packaging & measurement, and system integration. Although China has the technological capacity and the industrial base in this area, more emphasis should be placed on basic research, core technology research and development in this area from a strategic perspective, as well as advanced integration ability.

Table 2.2.1 Countries or regions with the greatest output of core patents on “millimeter-wave ultra-high throughput technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	117	39.93%	3392	79.89%	28.99
2	China	80	27.30%	100	2.36%	1.25
3	Japan	49	16.72%	288	6.78%	5.88
4	South Korea	30	10.24%	236	5.56%	7.87
5	Russia	8	2.73%	731	17.22%	91.38
6	Israel	7	2.39%	18	0.42%	2.57
7	Germany	3	1.02%	4	0.09%	1.33
8	Netherlands	2	0.68%	19	0.45%	9.50
9	Taiwan of China	2	0.68%	7	0.16%	3.50
10	Sweden	2	0.68%	4	0.09%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on “millimeter-wave ultra-high throughput technology”

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	ITLC	USA	34	11.60%	1501	35.35%	44.15
2	QCOM	USA	28	9.56%	610	14.37%	21.79
3	MATU	Japan	17	5.80%	27	0.64%	1.59
4	SMSU	South Korea	13	4.44%	185	4.36%	14.23
5	SONY	Japan	12	4.10%	296	6.97%	24.67
6	HUAW	China	12	4.10%	18	0.42%	1.50
7	BDCO	USA	8	2.73%	268	6.31%	33.50
8	GLDS	South Korea	8	2.73%	10	0.24%	1.25
9	IBMC	USA	6	2.05%	9	0.21%	1.50
10	APPY	USA	5	1.71%	160	3.77%	32.00

ITLC: Intel Corporation; QCOM: Qualcomm Inc.; MATU: Panasonic Corp.; SMSU: Samsung Electronics Co., Ltd.; SONY: Sony Corp.; HUAW: Huawei Technologies Co., Ltd.; BDCO: Broadcom Corp.; GLDS: LG Electronics Inc.; IBMC: International Business Machines Corp.; APPY: Apple Inc.

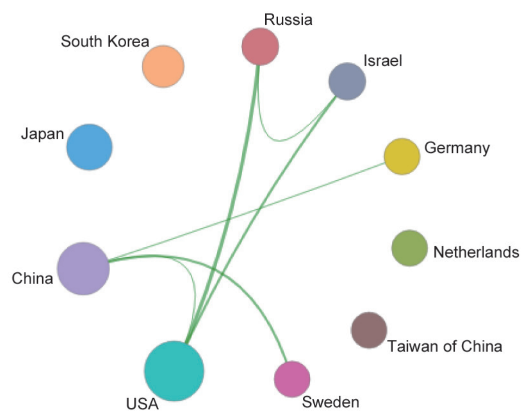

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "millimeter-wave ultra-high throughput technology"

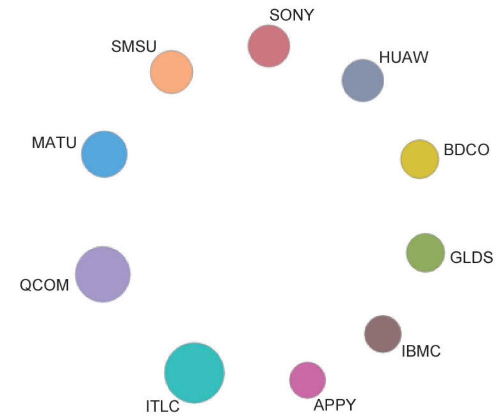

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "millimeter-wave ultra-high throughput technology"

2.2.2 Ultraprecision instrument technology and intelligence

Ultraprecision instrument technology refers to a class of high-precision instrument technology with the highest level of precision and the strongest measuring capability, which performs leading and supporting roles in the scientific frontier research and technological frontier development. The level of development of a national instrument technology often reflects the ability of innovation, the level of scientific and technological development, and the core competitiveness of a country. Currently, the countries that are advanced in science and technology are those having the most powerful instrument technology. Ultraprecision instrument technology is an essential means to build a national measurement system, to lead scientific exploration, and to achieve technological innovation. At the same time, it is an indispensable means to support the high-quality development of precision medicine and top equipment manufacturing. To summarize, ultraprecision instrument technology lies in a necessary and dominant position, which is competed for by countries with high levels of science and technology.

Ultraprecision instruments have always steered the world in scientific exploration and industrial development. Till 2018, the total number of Nobel Prizes was 374, of which about 72% of awards in physics, 81% of awards in chemistry, and 95% of awards in physiology or medicine were presented to technical innovations created using relevant cutting-edge instruments. This driving force also drives the development of ultraprecision instruments. In modern industrial manufacturing technology and scientific research, ultraprecision instruments have formed the development trend of precision, integration, networking, and intelligence, primarily including the three aspects described below.

(1) Development of new-principle instruments. The continuous improvement of instrument accuracy is the eternal goal pursued by instrument science. The development of instruments based on new principles is the key to the advancement of instrument accuracy in the future, which can not only improve the accuracy level of existing measurement parameters, but also achieve the measurement of new parameters. For example, the invention of scanning tunneling microscopy enables humans to observe the physicochemical properties of individual atoms on the surface of a substance in real time as well as the electronic behavior of the surface, raising the measurement resolution to the atomic level, which has performed a major role in the research in the fields of surface science, materials science, and life sciences. Currently, new principles of ultraprecision instruments are constantly being developed, such as X-ray three-dimensional microscope, which can achieve high-resolution imaging of its internal structure without destroying the object. Scanning electron microscopy also demonstrated the trends of high-pass quantification, femtosecond ultrafast time resolution, in-situ observation, etc.

(2) Metrology standard technology shows a quantized trend. The classic method of reproducing and preserving the basic units in the SI system is to use physical benchmarks, while the physical benchmarks are not sufficiently stable for accurate replication. At present, the seven basic units in SI have all been redefined according to physical constants,

which were officially implemented on World Metrology Day on May 20, 2018. The SI system has ushered in a historic change; moreover, this change will certainly promote the development of metrology standard technology toward quantization. The quantized metrology benchmark has the advantages of miniaturization and chip formation; further, it can be directly embedded in ultraprecision instruments and equipment. It can achieve real-time calibration for optical instrument, optimizing the accuracy of the instrument and equipment, and can significantly improve equipment manufacturing efficiency. At the same time, one of the key directions for the future development of ultraprecision instruments includes more accurate measurement of basic physical constants (such as Newton's universal gravitational constant, Planck's constant, Avogadro's constant, and Boltzmann's constant) and basic physical quantities (such as mass, voltage, and current).

(3) Measuring instruments aid in the development of networking- and intelligence-based technologies. With the improvement of AI, cloud computing, big data technology, mobile Internet technology, and industrial chain, the future development of instrument technology will change from functionalization to intelligentization, from single-parameter measuring instruments to composite multiparameter measuring instruments. These new intelligent ultraprecision instruments are expected to perform an important role in several fields, such as space development, deep sea exploration, environmental monitoring, and bioengineering.

At present, there are 186 core patents in this engineering development front (Table 2.2.3). The top three countries or regions are China, Japan, and Taiwan of China. According to the primary institutions with core patents (Table 2.2.4), the top

Table 2.2.3 Countries or regions with the greatest output of core patents on "ultra-precision instrument technology and intelligence"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	173	93.01%	206	86.92%	1.19
2	Japan	4	2.15%	6	2.53%	1.50
3	Taiwan of China	3	1.61%	1	0.42%	0.33
4	Germany	2	1.08%	3	1.27%	1.50
5	South Korea	2	1.08%	3	1.27%	1.50
6	Switzerland	1	0.54%	18	7.59%	18.00
7	USA	1	0.54%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "ultra-precision instrument technology and intelligence"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CNNU	China	6	3.23%	5	2.11%	0.83
2	BEIT	China	4	2.15%	13	5.49%	3.25
3	CHAV	China	4	2.15%	3	1.27%	0.75
4	SGCC	China	4	2.15%	1	0.42%	0.25
5	UNBA	China	3	1.61%	7	2.95%	2.33
6	HAIT	China	3	1.61%	0	0.00%	0.00
7	MITO	Japan	2	1.08%	7	2.95%	3.50
8	HUNA	China	2	1.08%	6	2.53%	3.00
9	UYBT	China	2	1.08%	5	2.11%	2.50
10	CAER	China	2	1.08%	4	1.69%	2.00

CNNU: China National Nuclear Corp.; BEIT: Beijing Institute of Technology; CHAV: China Aviation Industry Corp.; SGCC: State Grid Corporation of China; UNBA: Beihang University; HAIT: Harbin Institute of Technology; MITO: Mitsubishi Heavy Industries Co., Ltd.; HUNA: Hunan Institute of Measuring & Testing Technology; UYBT: Beijing University of Technology; CAER: China Aerospace Science and Technology Corp.

three institutions are China National Nuclear Corp., Beijing Institute of Technology, and China Aviation Industry Corp. Based on the cooperation among major countries or regions (Figure 2.2.3), the research between countries is relatively independent. It can be observed from the cooperation network between the primary institutions (Figure 2.2.4) that there is no cooperation between these institutions.

2.2.3 Systems and technologies for analysis and identification of images and videos

With the rapid growth of smartphones and high-definition cameras in recent years, as well as the outbreak of various short video applications and live-streaming platforms, more and more videos have to be analyzed and classified quickly and accurately. According to public data on the Internet, the number of smartphones in China has reached 1.3 billion, and the number of video surveillance cameras has exceeded 200 million. Such massive video data is the primary driving force of the rapid development of this technology.

The core technologies can be divided into three categories: (1) low-level feature extraction; (2) object detection, segmentation, recognition, and retrieval; (3) object tracking, scene understanding, video summarization, anomaly detection and action recognition, information fusion from multiple cameras, etc. Among them, traditional low-level feature extraction methods, such as histograms of Gaussian, scale invariant feature transform, local binary pattern, and Harr, use the handcrafted features for image representation. In recent years, with the development of deep neural networks, especially convolutional neural networks, the explicit feature extraction process has been replaced by end-to-end neural networks. The object detection, segmentation, recognition, and retrieval techniques are mostly designed for single image analysis. A well-trained classification network can be easily applied to deal with these tasks with certain alterations in the last layers of the net. Finally, object tracking, scene understanding, video summarization, anomaly detection and action recognition, and information fusion from multiple cameras require more comprehensive analysis of one or numerous videos. Spatial information, audio information, and camera positions are incorporated into the single image analysis networks to accomplish these high-level analysis and identification tasks.

According to the applications, the analysis and identification systems can be divided into three categories: (1) descriptive analytics; (2) predictive analytics; (3) retrospective analytics. Among them, descriptive analytics focuses on analyzing the current state of the key objects, persons, and scenes of the images and videos. At present, most systems are at this level; further, the higher-level analytics relies on accurate descriptive analytics. Predictive analytics is to predict the future state of the key objects, persons, and scenes according to the current images and videos. Retrospective analytics is to infer the possible cause shown in the previous videos of the present abnormal state.

The major patent output countries or regions, major output institutions, major inter-country/region cooperation

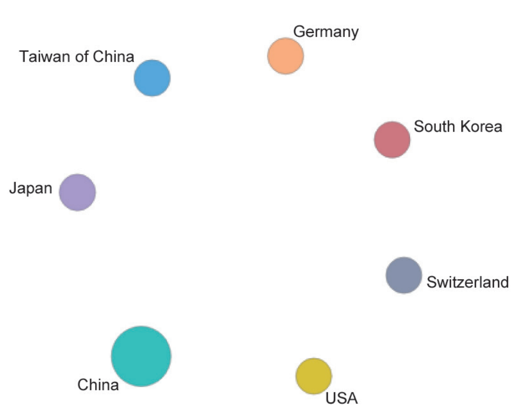

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of “ultra-precision instrument technology and intelligence”

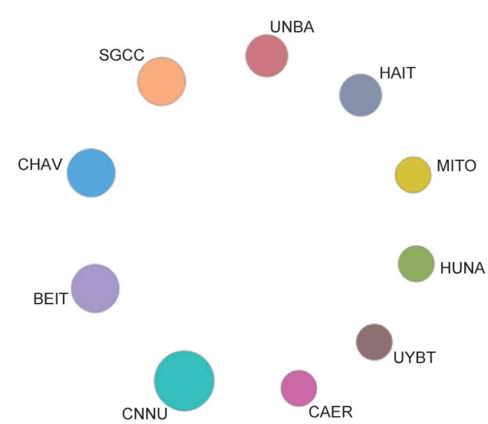

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “ultra-precision instrument technology and intelligence”

networks, and major inter-institution cooperation networks are presented in Tables 2.2.5 and 2.2.6 and Figures 2.2.5 and 2.2.6, respectively. The top three countries for core patent disclosure and citations are the USA, Japan, and Israel (Table 2.2.5). Among them, the USA is in leading position in terms of the number of patents and citations. The network of cooperation between countries or regions is also centered in the USA, with collaboration with Japan and European countries (Figure 2.2.5). China ranks eighth in the world in both core patent disclosure and citations. The top three institutions with the highest number of core patents are Honeywell International Inc., Pelican Imaging Corp., and Google Inc. (Table 2.2.6). However, there is rare cooperation among these institutions (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents on “systems and technologies for analysis and identification of images and videos”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	173	76.21%	15 338	83.59%	88.66
2	Japan	25	11.01%	1 441	7.85%	57.64
3	Israel	8	3.52%	488	2.66%	61.00
4	Netherlands	5	2.20%	282	1.54%	56.40
5	France	4	1.76%	424	2.31%	106.00
6	UK	4	1.76%	361	1.97%	90.25
7	South Korea	4	1.76%	265	1.44%	66.25
8	China	4	1.76%	200	1.09%	50.00
9	India	3	1.32%	174	0.95%	58.00
10	Germany	2	0.88%	125	0.68%	62.50

Table 2.2.6 Institutions with the greatest output of core patents on “systems and technologies for analysis and identification of images and videos”

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	HONE	USA	28	12.33%	6261	34.12%	223.61
2	PELI	USA	15	6.61%	1091	5.95%	72.73
3	GOOG	USA	9	3.96%	531	2.89%	59.00
4	FOTO	Ireland	8	3.52%	585	3.19%	73.13
5	SONY	Japan	8	3.52%	436	2.38%	54.50
6	APPY	USA	7	3.08%	428	2.33%	61.14
7	ADOB	USA	6	2.64%	595	3.24%	99.17
8	MITE	USA	6	2.64%	376	2.05%	62.67
9	MICT	USA	6	2.64%	366	1.99%	61.00
10	AMAZ	USA	6	2.64%	254	1.38%	42.33

HONE: Honeywell International Inc.; PELI: Pelican Imaging Corp.; GOOG: Google Inc.; FOTO: Fotonation Ltd.; SONY: Sony Corp.; APPY: Apple Inc.; ADOB: Adobe Systems Inc.; MITE: Mitek Systems Inc.; MICT: Microsoft Corp.; AMAZ: Amazon technologies Inc.

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "systems and technologies for analysis and identification of images and videos"

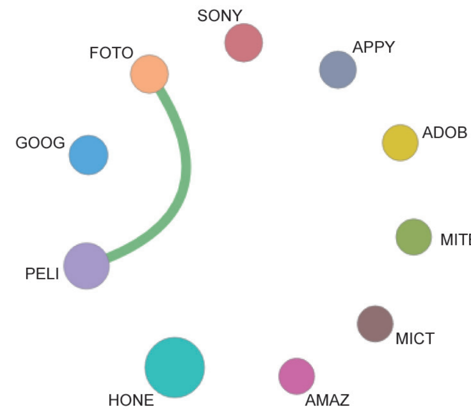

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "systems and technologies for analysis and identification of images and videos"

Participants of the Field Group

Leaders

PAN Yunhe, LU Xicheng

Co-leaders

TAN Jiubin, LYU Yueguang, CHEN Jie

Members of the Expert Group

Academicians

Group 1: TAN Jiubin, ZHUANG Songlin, LI Tianchu, ZHANG Guangjun, JIANG Huilin, LIU Zejin

Group 2: LYU Yueguang, DUAN Baoyan, WU Manqing, CHEN Zhijie, YU Shaohua, DING Wenhua

Group 3: CHEN Jie, PAN Yunhe, LU Xicheng, ZHAO Qinping, CHAI Tianyou, FEI Aiguo, WU Jianping

Deputy of Co-leaders

LU Zhengang, CHE Jibin, SUN Jian

Other Experts (in alphabetic order of the last name)

BAI Yang, CHEN Jinbao, CHEN Lin, CHEN Xiaoming, CUI Yong, FU Jun, HAN Yahong, HAO Xiang, HUANG Jin, JIANG Tian, JIN Zhonghe, LI Dongsheng, LI Tiancheng, LIU Leibo, LIU Wei, LIU Xianzhu, SI Ke, SUN Bingzhen, TAO Jin, WANG Dan, WU Jun, XU Yang, XU Zhiwei, ZHANG Chuan, ZHU Yiming, ZHU Yongwen, ZHUANG Wei

Members of the Work Group

Consultants: WU Zhaohui, LU Dongming, WU Fei

Library and Information Specialists: YANG Weiqiang, LIU Shulei, GENG Guotong, CHEN Zhenying, LIANG Jianghai, HUO Ningkun, WU Ji, YANG Xiao, LI Qian, SHI Chen, YE Wenying, LI Hong, ZHOU Yunping, WANG Kaifei

Liaisons: WANG Chengjun, WANG Bing, ZHANG Jia

Secretaries: ZHAI Ziyang, HU Xiaonv, YANG Weiqiang

Report Writers (in alphabetic order of the last name)

BAI Yang, HAN Yahong, HONG Wei, HUANG Tiejun, JIANG Tian, JIN Zhonghe, LI Haoyu, LI Tianchu, LIANG Jianghai, LIN Hongtao, LIU Jiang, LIU Leibo, PU Jian, QIU Chengwei, SI Ke, TAN Jiubin, WANG Haiming, WU Jun, XU Huaping, XUE Jianru, YU Chao, ZHANG Zhaoyang, ZHUANG Wei

III. Chemical, Metallurgical, and Materials Engineering

1 Engineering research fronts

1.1 Trends in top 11 engineering research fronts

The top 11 engineering research fronts assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering include the fields of energy, materials, chemistry, and biotechnology (Tables 1.1.1 and 1.1.2). Among these top research fronts, "renewable energy systems," "membrane bio-reactor and membrane fouling control technology," and "applications of porous organic materials for CO_2 capture" are based on the popular topics suggested by *Clarivate Analytics*. The other eight are recommended by the domain experts working in these research areas.

"Renewable energy systems," "catalyst design by artificial intelligence (AI)," and "membrane bio-reactor and membrane fouling control technology" are the more emerging research fields based on the data for the mean year of publications (Table 1.1.1). Notably, "catalyst design by AI" is a rapidly rising field according to the increasing number of core papers published annually (Table 1.1.2) even though the citation numbers are not high (Table 1.1.1). "Catalytic biomass conversion" and "applications of porous organic materials for CO_2 capture" are hot research areas as the number of citations per publication is greater than 90 citations (Table 1.1.1).

(1) Renewable energy systems

Renewable energy is the energy that is generated from natural processes that are continuously replenished. Renewable energy systems (RES) such as those utilizing wind, solar, biomass, hydropower, geothermal, and ocean energy play critical roles in realizing the energy sector that is clean, low-carbon, safe, and efficient. Although the RES have developed rapidly in recent years, they are still limited by relatively high cost, low reliability, and unsatisfactory synergy among multiple systems, resulting in challenges in terms of global energy transition.

Currently, the main goal of the studies researching RES is to utilize the energy more cleanly and efficiently, and thereafter introduce advanced coordination among a variety of RES

Table 1.1.1 Top 11 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Renewable energy systems	26	1 232	47.38	2016.2
2	High-temperature alloy	500	16 602	33.20	2014.6
3	Material life cycle engineering	240	18 703	77.93	2014.8
4	Catalyst design by AI	50	352	7.04	2016.7
5	High-performance C/C composites for aerospace and aeronautics	139	4 482	32.24	2014.7
6	Membrane bio-reactor and membrane fouling control technology	38	1 401	36.87	2015.9
7	Catalytic biomass conversion	110	10 116	91.96	2014.3
8	Chemical biotechnology	226	19 594	86.70	2014.4
9	Applications of porous organic materials for CO_2 capture	80	7 663	95.79	2014.8
10	High-performance adsorption-catalytic materials for separation and purification	84	6 539	77.85	2014.8
11	Artificial nitrogen fixation under ambient conditions	80	4 873	60.91	2014.9

Table 1.1.2 Annual number of core papers published for the top 11 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Renewable energy systems	1	3	5	4	8	5
2	High-temperature alloy	126	115	139	73	38	9
3	Material life cycle engineering	57	61	47	42	23	10
4	Catalyst design by AI	2	4	5	10	10	14
5	High-performance C/C composites for aerospace and aeronautics	36	26	35	33	7	2
6	Membrane bio-reactor and membrane fouling control technology	6	4	4	6	8	10
7	Catalytic biomass conversion	27	44	26	12	0	1
8	Chemical biotechnology	73	61	43	40	8	1
9	Applications of porous organic materials for CO_2 capture	18	22	13	14	12	1
10	High-performance adsorption-catalytic materials for separation and purification	14	23	22	15	9	1
11	Artificial nitrogen fixation under ambient conditions	21	18	16	5	10	10

for optimizing the production, transportation, distribution, conversion, storage, and consumption of energy with the life cycle view. In general, the major aspects of the research can be categorized into four points: 1) from a macroscopic point of view, the proposal of strategies and paths for the development of the RES; 2) from a microscopic point of view, the improvement of the technical performances such as economics, reliability, and effectiveness of the RES; 3) in terms of energy generation, the optimization of hybrid renewable and traditional energy systems; 4) from the perspective of energy consumption, the integration of the RES into the energy, industrial, and transport sectors.

(2) High-temperature alloy

A high-temperature alloy based on iron, nickel, and cobalt, is a metal material that can withstand the working conditions at a high temperature of 600 °C for a long time. It is also called "super alloy" and exhibits a comprehensive performance such as excellent high-temperature strength, good oxidation resistance and hot corrosion resistance, and good fatigue performance and fracture toughness, as well as high alloying characteristics. Super alloys are the key materials for the manufacture of aeroengine hot components, and are widely used in the fields of electric power generation, metallurgy, glass manufacturing, and atomic energy, as well as in ship and automobile industries. Known as the "cornerstone of advanced engines" and accounting for 40%–60% of the total engine weight, super alloys are important in the development of engine technology. Currently, the research of super alloys include the development of new alloys and the surface treatment and welding of alloy materials. In particular, the high-temperature properties, together with the demand for new aeroengines and expansion of alloy applications in recent years have accelerated the development of new super alloys.

(3) Material life cycle engineering

Material life cycle engineering (MLCE) is an eco-design-oriented applied engineering field to meet the performance requirements, protect the environment, and conserve the resources. Through the application of technological and scientific principles including hazardous substance substitution, green process planning, clean production, and resource recycling in the complete industrial supply chain, MLCE can allow a systematic optimization of material products during the entire life cycle. Material ecological design plays an important role in alleviating the issues of resource scarcity and environmental pollution as the related issues are comprehensively considered in the early product design stages. Furthermore, the application of MLCE can reduce or even eliminate the negative effects of material products on the environment in the industrial supply chain.

MLCE has developed into an international research frontier based on the multidisciplinary intersection of materials, manufacturing, and environmental sciences. MLCE studies mainly include the material ecological design theory and methods, material life cycle evaluation theory and methods, development of assessment database of material environmental impact and analysis software, and recycling technology in MLCE.

The application of life cycle engineering in the field of materials should be further strengthened in future. By means of eco-design, life cycle assessment, and life cycle optimization technologies, a green development model of eco-environment materials industry can be established, which can gradually decrease the significant imbalance between the material production and resources, thereby allowing sustainable development in the field of materials.

(4) Catalyst design by AI

AI involves establishing an artificial neural network and utilization of machine learning. Currently, machine learning is used to address the clustering and regression problems. The first step in the application of machine learning to the field of catalysis is the identification of the problem as either clustering or regression. Then, the artificial neural network is developed by executing the learning and testing processes. After the artificial neural network is trained, it can be adopted to predict the catalytic performances of some simple catalysts and reactions. The decisive factors in determining the catalytic performances under these conditions are the adsorption energy values of one or two reactants. Although machine learning has already been applied to various types of problems in catalysis, there is no publication reporting the literature mining or image recognition of catalysis data such as infrared (IR) spectra by machine learning. We expect that these gaps will be filled in future.

(5) High-performance C/C composites for aerospace and aeronautics

C/C composites consist of continuous carbon fibers (as reinforcing phase) and carbon materials (as matrix). C/C composites have excellent properties such as low specific gravity, high specific strength, high specific modulus, low thermal expansion coefficient, ablation resistance, and thermal shock resistance. For the leading edges of the wing, nose cones, rocket nozzles, re-entry vehicles, and thermal protection system applications, C/C composites have unparalleled advantages compared with other materials. In recent years, with the rapid development of the aerospace industry, there is an urgent need for the development of long-term, high-temperature-resistant, and oxidation-resistant C/C composites. Material modification and coating protection are the two effective oxidation resistant strategies for C/C composites. The pursuit of long-life, anti-oxidation coating on the C/C composites is one of the main research areas for C/C composites. However, owing to the long production cycle, high cost, and difficulties in batch production, the applications of C/C composites are limited to aerospace and military. Therefore, it is necessary to develop new processing methods for the preparation of advanced C/C composites, which can reduce the preparation time and production cost.

(6) Membrane bio-reactor and membrane fouling control technology

Membrane bio-reactor (MBR) is a new waste water treatment technology which combines membrane separation and biological treatment. Currently, the solid/liquid separation membrane bio-reactor (SLSMBR) is the most widely studied and used reactor in MBR technology. The secondary sedimentation tank in the conventional activated sludge process is replaced by a membrane, which allows the coupling of high-efficiency membrane separation and traditional activated sludge method. Owing to the retention of microorganisms and macromolecular organics by the membrane, the biological concentration and organic oxidation efficiency in the reactor are high. Compared with the conventional activated sludge method, the MBR technology has advantages such as high effluent quality, low sludge production, small floor space, and low operation cost. The MBR technology has attracted significant worldwide attention for waste water treatment. However, as the membrane in MBR is directly contacted with the mixture solution, the particles and macromolecule solutes are inevitably absorbed and deposited onto the membrane surface or into the pores under physical, chemical, or biological actions, leading to the membrane pore blocking, reduction of water flux, and increase in the transmembrane pressure. Membrane fouling is one of major issues that restricts the extensive application of MBR technology. The studies regarding the control of membrane fouling and regeneration of membrane are important, and can be mainly focused on the membrane material and properties, type of pollutant, and operation conditions.

(7) Catalytic biomass conversion

Biomass is a general term for various organisms produced by photosynthesis using atmosphere, water, and soil. It is the major organic and renewable carbon resource in nature. Owing to its widespread resources, abundance, and carbon neutrality, the biomass is extensively used to synthesize fuels and prepare a variety of fine chemicals, which are considered an alternative to petrochemical resources. Catalytic biomass conversion is an effective method to achieve efficient usage. Representative biomass resources currently studied are lignocellulose (including cellulose, hemicellulose, and lignin), oils, sugars, and microalgae. Components such as sugar and cellulose can be catalytically converted into products of higher alcohols and platform compounds. Catalytic conversion of lignin produces aromatic hydrocarbons, aromatic aldehydes (carboxylic acids), phenols, and alkane fuels. Oils and fats can be used for producing biodiesel. All these aspects are interesting research directions in the field of biomass conversion. Owing to the complexity and difficulties in pretreatment as well as the reaction and separation of the biomass components, the development of more economic and green separation processes and catalytic systems is the main goal in the near future. In addition, the complete utilization of the multiple components of biomass and the co-production of high-value-added H_2, fuels, and chemicals are also the emerging trends in the catalytic biomass conversion field.

(8) Chemical biotechnology

Chemical biotechnology employs chemical methods to regulate cellular growth, metabolism, and product formation for the production of biochemicals, biofuels, and biomedicine. To generate chemical signals, the cells reshape their metabolism, leading to a more favorable phenotype resulting in additional products, reduced by-products, and improved stress-resistance. The chemicals may affect the cellular transcription, translation, or enzyme catalysis, and consequently alter the biosynthesis of macromolecules and small metabolites. After the engineered cells are successfully constructed by genetic engineering and genome editing tools, an additional phenotype space can be explored by applying a chemical biotechnology strategy. The results are of significance in the areas of both biotechnology and biological sciences. A particularly emerging area is the implantation of abiogenic-chemicals or those from the traditional petrochemical industry into the cellular metabolism to obtain useful products that can lead to more innovations in future.

(9) Applications of porous organic materials for CO_2 capture

The rapid increase in the atmospheric CO_2 concentration in recent years has caused a serious threat to the sustainable development of human society because of the accompanying greenhouse effect. Therefore, the development of cost-effective and environmentally friendly technologies for CO_2 capture are necessary to mitigate this problem. The CO_2 capture mainly includes pre-combustion capture (H_2/CO_2 separation), post-combustion capture (CO_2/N_2 separation), and oxy-fuel combustion (H_2O/CO_2 separation). The most widely used method in industry for CO_2 capture, i.e., amine adsorption, requires a high energy penalty to regenerate the adsorbent and results in many environmental problems. Compared with amine adsorption, the porous organic materials for CO_2 adsorption and separation are more energy efficient and easier to utilize and regenerate. Porous organic materials such as metal-organic frameworks (MOFs) and porous organic polymers (POPs) are promising for CO_2 capture applications owing to their exceptional properties including high surface area, easily tunable structure, and reproducibility. The CO_2 uptake capacity, CO_2 selectivity, physical/chemical stability, and production/regeneration cost are the four commonly used indicators to evaluate the performance of porous organic materials for CO_2 capture. The CO_2 capacity or selectivity can be realized by the pre/post-synthetic modifications of MOFs/POPs to introduce CO_2-philic functionalities. Using this method, the researchers have developed MOFs/POPs with high CO_2 adsorption performance and some MOFs can even be produced on a large scale. More research should be focused on improving the stability of these porous organic materials under relevant industrial conditions (in the presence of H_2O, CO, NO_x, and SO_x) and reducing the production cost of these materials. By overcoming these issues, the porous organic materials can be considered as promising candidates for the next-generation CO_2 capture technology in industry.

(10) High-performance adsorption-catalytic materials for separation and purification

Volatile organic compounds (VOCs) cause various problems such as photochemical smog, greenhouse effect, ozone layer destruction, and adverse effects to human health, which have threatened the survival and development of human beings. In terms of VOC abatement technologies, adsorption is a mature one, with small energy consumption and high treatment efficiency. The catalytic combustion technology has many advantages including large processing capacity, no secondary pollution, and ease of dealing with flammable and explosive gases. The main factors in the development of these two efficient waste gas treatment technologies are the adsorbents and catalysts. The development of high-performance adsorption-catalytic materials for separation and purification is the key to achieve energy conservation and reduction of emissions in the chemical processes. For VOC adsorbents, the activated carbon materials and zeolites have been widely used in industry. The development target for the high-performance adsorbents is selective adsorption, large adsorption capacity, and easy desorption. Currently, the noble metal catalysts are widely used as combustion catalysts. However, the development of noble metals is limited by disadvantages such as easy sintering, poor heat resistance, and high cost. The development of universal combustion catalysts with low cost and good stability is an urgent issue that should be addressed in the field of catalytic combustion.

The following points need to be considered in the research and development of high-performance adsorption-catalytic materials for separation and purification. 1) A deep analysis of the interaction between VOCs and adsorbents/catalysts should be performed through the development of material characterization and computational simulation. 2) Research on a mixture of VOCs, involving water vapor, SO_x, and NO_x should be carried out to simulate the real conditions of VOC emission. 3) The development of dual-function materials with both high-efficiency adsorbent and catalyst functions is optimal, i.e., the VOCs with low concentration in the exhaust gas can be concentrated by selective adsorption at the adsorption site on the material and then completely removed by the catalytic oxidation activity in the same material.

(11) Artificial nitrogen fixation under ambient conditions

Niterogen fixation through the conversion of atmospheric nitrogen into ammonia is regarded as one of the most significant processes in industry as ammonia not only plays a key role in the production of fertilizers to sustain the rising global population, but also serves as a green energy carrier and an alternative fuel. Since 1913, ammonia is mainly synthesized on an industrial scale by the traditional Haber–Bosch process at a high pressure (15–20 MPa) and high temperature (300–500 °C). This process is highly energy-consuming and accounts for more than 1.4% of the world's energy consumption and 1.6% of world's CO_2 emissions. Therefore, it is necessary to develop a green, sustainable, and alternate artificial niterogen fixation process to synthesize ammonia by employing renewable resources at ambient conditions. Possessing eco-friendly and sustainable characteristics, nitrogen-to-ammonia conversion through nitrogenase enzymes, photochemical reduction, and electrochemical reduction are considered as promising candidates for artificial niterogen fixation under mild conditions. Moreover, the electrocatalytic process using water as a sustainable proton source to substitute the raw material hydrogen used in the Haber–Bosch process is feasible for lowering the energy demand and decreasing the CO_2 emissions, which can allow the sustainable development of human society and alleviate the global energy and environmental crises. As the core components of the artificial niterogen fixation system, the rational design of efficient nitrogen reduction reaction (NRR) catalysts with high activity, high selectivity, and good stability, and the development of reaction process can promote the advancement of the NRR as a green and more sustainable method with low energy consumption are needed. Research efforts directed toward the electrocatalysts designed for NRR under ambient conditions have attracted worldwide interest.

1.2 Interpretations for three key engineering research fronts

1.2.1 Renewable energy systems

One of the greatest challenges in future is the sustainable generation and utilization of energy, and the RES play the most significant role in the realization of a sustainable energy system. In recent years, there is an increasing trend toward the studies on the RES, particularly the wind, solar, and biomass energy systems, among which, four emerging trends are discussed as follows. First, from a macro perspective, the researches should aim at understanding if and how the energy sector can be decarbonized by utilizing the RES. For instance, some European countries such as Denmark have proposed long-term plans for the energy transition, which employ renewable energy resources to replace the fossil fuels.

To build a clean, low-carbon, safe, and efficient energy system for China, it is necessary to promote the utilization of the renewable energy (particularly, the wind and solar energy) in the end-use energy sectors for enhancing the energy efficiency in the end-use consumption (primarily, the industry and transport sectors) and developing the distributed RES. Second, the popularization of the renewable energy relies heavily on the technical progress of the RES. Therefore, improving the conversion/utilization efficiency, strengthening the economic competitiveness, and developing advanced energy storage systems to enhance the reliability of the RES will be crucial in future researches. Third, the energy systems in future will consist of different types of energy sources from renewable energy to fossil fuels, implying that the collaborative planning and operational optimization of the hybrid energy systems, particularly the renewable energy-based systems, will be the new trends. The methods for the creation of a hybrid energy system based on the characteristics of different energy sources and improvement of the utilization ratio of the renewable energy in the hybrid system are some areas that can be investigated. Finally, the RES offer an opportunity to utilize sustainable sources in the traditional energy, industrial, and transport sectors. Among the various research directions, the integration of renewable sources into hydrogen production will be continually pursued, to not only afford a feasible way for the utilization of renewable energy, but also realize clean hydrogen manufacturing. The renewable-based hydrogen can be applied in the fields beyond the electric power sector, i.e., (1) for linking hydrogen to cooling, heating, and electricity for synthesizing and optimizing different energy networks and sectors; (2) utilizing hydrogen as an industrial gas to promote the development of industrial sectors as low-carbon units by employing it in smelting, metallurgy, chemical engineering, and other industries as high-efficiency raw material, reducing agent, and heat source; (3) employing renewable hydrogen for decarbonizing the transport sector, where a sustainable transportation system can be built by integrating the renewable energy, hydrogen, fuel cells, and new energy vehicles from a life cycle view.

By reviewing the core papers regarding the RES published after 2013, the countries/regions and institutions that mainly focus on the studies in this area are listed in Tables 1.2.1 and 1.2.2, respectively. Denmark, Germany, and Finland are the top three countries in terms of publications, accounting for 61.54%, 42.31%, and 19.23% of the total number of the core papers, respectively, whereas Aalborg University and Aarhus University have made the most significant contributions in this research field. As shown in Figure 1.2.1, Denmark and Germany have the best collaborative relationship, and the collaboration network between Germany–Finland and Denmark–USA is also well-developed. Figure 1.2.2 exhibits that the most active collaboration is observed among Aarhus University, Frankfurt Institute for Advanced Studies, and Goethe University, Frankfurt. According to Table 1.2.3, the core papers are mostly cited by the researchers from Germany, Denmark, and the USA in the descending order, whereas the data listed in Table 1.2.4 indicates that Aalborg University, Lappeenranta University of Technology, and Aarhus University are the top three institutions that include the core literature as references.

Table 1.2.1 Countries or regions with the greatest output of core papers on "renewable energy systems"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Denmark	16	61.54%	944	76.62%	59.00
2	Germany	11	42.31%	594	48.21%	54.00
3	Finland	5	19.23%	161	13.07%	32.20
4	USA	4	15.38%	307	24.92%	76.75
5	Australia	3	11.54%	72	5.84%	24.00
6	Pakistan	1	3.85%	8	0.65%	8.00
7	Spain	1	3.85%	36	2.92%	36.00
8	Croatia	1	3.85%	11	0.89%	11.00
9	Netherlands	1	3.85%	13	1.06%	13.00
10	South Africa	1	3.85%	13	1.06%	13.00

Table 1.2.2 Institutions with the greatest output of core papers on "renewable energy systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Aalborg Univ	8	30.77%	433	35.15%	54.13
2	Aarhus Univ	7	26.92%	315	25.57%	45.00
3	Lappeenranta Univ Technol	5	19.23%	161	13.07%	32.20
4	Frankfurt Inst Adv Studies	4	15.38%	83	6.74%	20.75
5	Goethe Univ Frankfurt	3	11.54%	214	17.37%	71.33
6	Stanford Univ	2	7.69%	80	6.49%	40.00
7	Australian Natl Univ	2	7.69%	41	3.33%	20.50
8	Karlsruhe Inst Technol	2	7.69%	20	1.62%	10.00
9	Forschungszentrum Julich	1	3.85%	6	0.49%	6.00
10	Rhein Westfal TH Aachen	1	3.85%	6	0.49%	6.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "renewable energy systems"

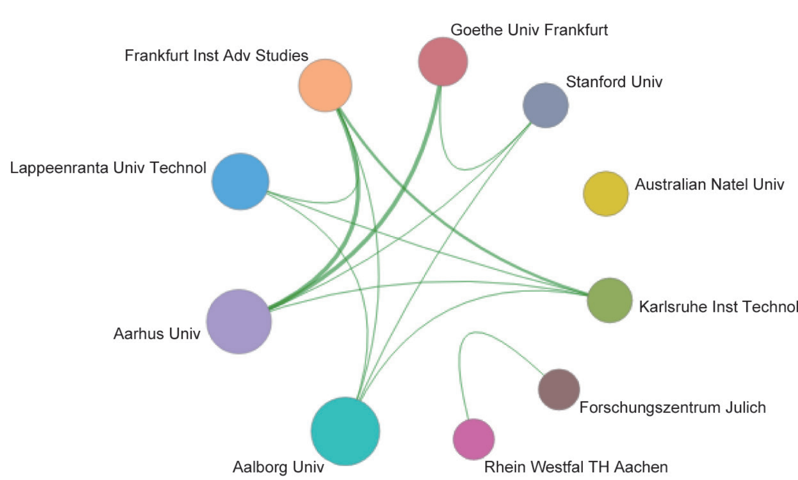

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "renewable energy systems"

Table 1.2.3 Countries or regions with the greatest output of citing papers on "renewable energy systems"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Germany	132	16.92%	2017.0
2	Denmark	121	15.51%	2017.0
3	USA	120	15.38%	2016.3
4	China	77	9.87%	2017.4
5	Finland	65	8.33%	2017.3
6	UK	57	7.31%	2017.0
7	Italy	53	6.79%	2017.4
8	Australia	47	6.03%	2016.9
9	Spain	38	4.87%	2017.1
10	Switzerland	35	4.49%	2017.1

Table 1.2.4 Institutions with the greatest output of citing papers on "renewable energy systems"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Aalborg Univ	52	19.40%	2017.3
2	Lappeenranta Univ Technol	46	17.16%	2017.3
3	Aarhus Univ	39	14.55%	2016.8
4	Stanford Univ	23	8.58%	2015.3
5	Tech Univ Denmark	21	7.84%	2016.4
6	Univ Zagreb	18	6.72%	2016.8
7	Forschungszentrum Julich	16	5.97%	2017.5
8	Univ Sydney	14	5.22%	2016.6
9	Karlsruhe Inst Technol	14	5.22%	2017.4
10	Frankfurt Inst Adv Studies	13	4.85%	2017.1

1.2.2 High-temperature alloy

Super alloy is a metal material developed in the 1930s and was first used in the aviation industry by the UK, Germany, and the USA. After the second world war, owing to the rapid development of the aviation industry and high performance of super alloys, many countries developed new high-temperature alloys. In addition to the wide use of high-temperature components, super alloys have been applied in thermal and nuclear power generation, metallurgy, and glass manufacturing, as well as in ship and chemical industries.

The composition of super alloy is complex, containing active elements such as chromium and aluminum, and is unstable under oxidation or hot corrosion environments. Additionally, the surface defects of the machined parts, caused by work hardening and residual stress, have a negative impact on its chemical performance and mechanical properties. Because of high alloying, super alloy materials are prone to the segregation of components, which has a significant impact on the micro-structure and properties of the cast super alloys and deformed super alloys. With different characteristics from those of ordinary metal materials, the preparation of super alloys includes the casting of high-temperature alloy (conventionally cast super alloy, directional solidification columnar super alloy, and single crystal super alloy), deformed super alloy, and powder super alloy.

With advances in alloy theory and production process, the performances of super alloys have been enhanced through alloy strengthening and process improvement. Alloy strengthening includes alloy solid solution strengthening and grain boundary strengthening with a second phase hardening agent. Process strengthening includes improvement in smelting, solidification, crystallization, thermal processing, heat treatment, and surface treatment to improve the microstructure. The preparation technology and process for super alloy materials are still undergoing improvement and innovation, for example, the adoption of the triple-melt process of vacuum induction melting, electroslag remelting, and vacuum arc remelting (VIM-ESR-VAR), improvement of high-temperature strength by using the directionally solidified alloy and single crystal alloy, and utilization of powder metallurgy to reduce the segregation of alloying elements and increase the material strength. In addition, the oxide dispersion-strengthened super alloys and high-temperature inter-metallic materials are also under development.

The countries/regions and institutions with the greatest output of core papers in the field of “high-temperature alloy” since 2013 are listed in Tables 1.2.5 and 1.2.6, respectively. The collaboration networks among major countries/regions and institutions are shown in Figures 1.2.3 and 1.2.4. The countries/regions and institutions with the greatest number of citing papers are included in Tables 1.2.7 and 1.2.8.

The majority of the core papers are published by the top four countries, China, the USA, Germany, and the UK. Among these, the Chinese output of the core papers accounts for 40.2% of the total, whereas the number of core papers from the USA accounts for 20.6%, and those from Germany and the UK both exceed 10%. The top four countries of average citation are Sweden, Japan, China, and the UK (Table 1.2.5). The USA and

Table 1.2.5 Countries or regions with the greatest output of core papers on “high-temperature alloy”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	201	40.20%	7174	43.21%	35.69
2	USA	103	20.60%	3269	19.69%	31.74
3	Germany	62	12.40%	1955	11.78%	31.53
4	UK	53	10.60%	1824	10.99%	34.42
5	India	30	6.00%	875	5.27%	29.17
6	France	28	5.60%	725	4.37%	25.89
7	Canada	27	5.40%	881	5.31%	32.63
8	South Korea	16	3.20%	457	2.75%	28.56
9	Sweden	14	2.80%	628	3.78%	44.86
10	Japan	13	2.60%	480	2.89%	36.92

Table 1.2.6 Institutions with the greatest output of core papers on “high-temperature alloy”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	39	7.80%	984	5.93%	25.23
2	Cent S Univ	33	6.60%	1862	11.22%	56.42
3	Northwestern Polytech Univ	28	5.60%	912	5.49%	32.57
4	State Key Lab High Performance Complex Mfg	28	5.60%	1701	10.25%	60.75
5	Univ Erlangen Nurnberg	20	4.00%	641	3.86%	32.05
6	Univ Birmingham	14	2.80%	602	3.63%	43.00
7	Harbin Inst Technol	14	2.80%	521	3.14%	37.21
8	Ruhr Univ Bochum	13	2.60%	376	2.26%	28.92
9	Univ Oxford	13	2.60%	384	2.31%	29.54
10	Max Planck Inst Eisenforsch GmbH	12	2.40%	362	2.18%	30.17

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “high-temperature alloy”

Germany have the highest level of collaboration, followed by China, France, and Canada. This shows that these countries focus more on collaboration in this field (Figure 1.2.3). The institutions that account for the highest output of the core papers in this area are the Chinese Academy of Sciences, Central South University, and Northwestern Polytechnical University (Table 1.2.6).

The percentages of citing papers from China and the USA are 46.93% and 16.54%, respectively. According to the data analysis, the highest number of core papers are cited by Chinese institutions, which indicates that the Chinese scholars are at the forefront of this research area (Table 1.2.7). The institution that accounts for the highest output of the citing papers is the Chinese Academy of Sciences, followed by Northwestern Polytechnical University and Beijing University of Science and Technology (Table 1.2.8).

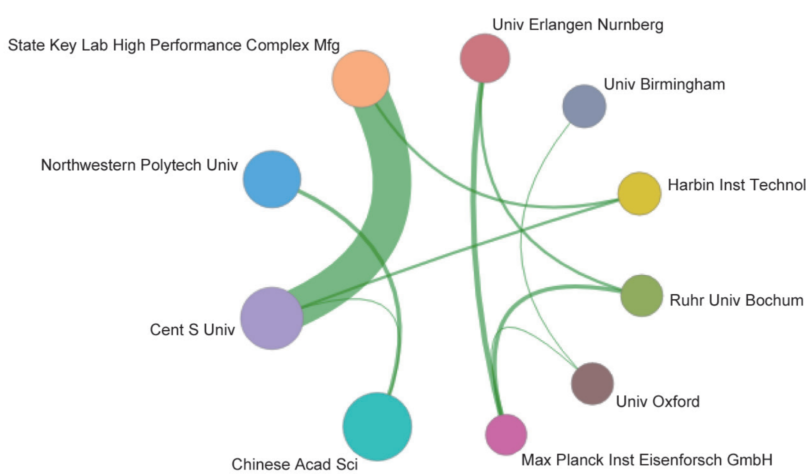

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “high-temperature alloy”

Table 1.2.7 Countries or regions with the greatest output of citing papers on “high-temperature alloy”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	4652	46.93%	2017.1
2	USA	1639	16.54%	2017.0
3	India	623	6.29%	2017.3
4	Germany	583	5.88%	2017.0
5	UK	555	5.60%	2017.0
6	South Korea	369	3.72%	2017.0
7	France	345	3.48%	2016.9
8	Japan	334	3.37%	2017.0
9	Iran	307	3.10%	2017.1

The output of core papers and citing papers in China and the USA are among the highest in the world, and the number of core papers cited by the Chinese institutions is high.

1.2.3 Material life cycle engineering

Faced with the increasing resource scarcity and environmental pollution, sustainable development through the harmonization of materials, resources, and environment has become a global consensus. MLCE is considered to be important for alleviating these issues. Therefore, the life cycle engineering research has attracted significant attention and has been extensively developed since the beginning of the 21st century. MLCE requires material design during the entire life cycle process. Systematic optimization of the complete industrial chain can be achieved through the quantitative analysis of the material performance, resource consumption, and environmental performance. Furthermore, the environmental impact of the material products during the complete life cycle can be effectively reduced by continuous technological innovation and optimization of process parameters during the manufacturing, management, and recycling processes. Currently, the research on MLCE mainly includes the material ecological design theory and methods, material life cycle evaluation theory and methods, development of assessment database of the material environmental impact and analysis software, and recycling technology in MLCE.

Table 1.2.8 Institutions with the greatest output of citing papers on “high-temperature alloy”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	591	20.61%	2017.0
2	Northwestern Polytech Univ	418	14.58%	2017.1
3	Univ Sci & Technol Beijing	307	10.71%	2017.0
4	Cent S Univ	273	9.52%	2017.1
5	Harbin Inst Technol	263	9.17%	2017.1
6	Tsinghua Univ	205	7.15%	2016.8
7	Beihang Univ	202	7.05%	2017.0
8	Shanghai Jiao Tong Univ	171	5.96%	2017.0
9	Oak Ridge Natl Lab	148	5.16%	2017.1
10	Northeastern Univ	147	5.13%	2017.4

Table 1.2.9 Countries or regions with the greatest output of core papers on “material life cycle engineering”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	46	19.17%	2923	15.63%	63.54
2	Italy	29	12.08%	2002	10.70%	69.03
3	UK	28	11.67%	3683	19.69%	131.54
4	China	22	9.17%	1623	8.68%	73.77
5	Spain	21	8.75%	1401	7.49%	66.71
6	Netherlands	12	5.00%	1478	7.90%	123.17
7	Switzerland	12	5.00%	539	2.88%	44.92
8	Belgium	11	4.58%	1415	7.57%	128.64
9	Germany	11	4.58%	1343	7.18%	122.09
10	Portugal	11	4.58%	861	4.60%	78.27

The main countries/regions and institutions with maximum number of core papers in MLCE research during the period between 2013 and 2018 are listed in Tables 1.2.9 and 1.2.10, respectively. As shown in Table 1.2.9, the USA and Italy are the two countries with the maximum output of core papers, accounting for 19.17% and 12.08% of the total output, followed by the UK with 11.67%. Among the institutions, the Technical University of Denmark has the highest percentage (3.33%) of published core papers as shown in Table 1.2.10. Figure 1.2.5 shows the collaboration network among the countries or regions with maximum output in this research field. China and the USA collaborate most frequently. The collaborations between the Chinese Academy of Sciences and the University of Nottingham as well as that between University Catania and Politecnico di Milano are relatively less frequent (Figure 1.2.6). China and the USA are ranked first and second among various countries for citing core papers, accounting for 30.08% and 16.81%, respectively, as shown in Table 1.2.11. According to Table 1.2.12, the top three institutions with maximum output of citing papers are the Chinese Academy of Sciences, Tsinghua University, and University of Chinese Academy of Sciences, with the corresponding percentages of citing papers of 26.32%, 12.42%, and 9.87%, respectively.

Table 1.2.10 Institutions with the greatest output of core papers on “material life cycle engineering”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Tech Univ Denmark	8	3.33%	512	2.74%	64.00
2	Univ Lleida	5	2.08%	516	2.76%	103.20
3	Univ Perugia	5	2.08%	368	1.97%	73.60
4	Univ Catania	5	2.08%	197	1.05%	39.40
5	Univ Nottingham	5	2.08%	195	1.04%	39.00
6	Delft Univ Technol	4	1.67%	1033	5.52%	258.25
7	Univ Coimbra	4	1.67%	492	2.63%	123.00
8	Chinese Acad Sci	4	1.67%	172	0.92%	43.00
9	Politecn Milan	4	1.67%	150	0.80%	37.50
10	Univ Pittsburgh	3	1.25%	208	1.11%	69.33

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “material life cycle engineering”

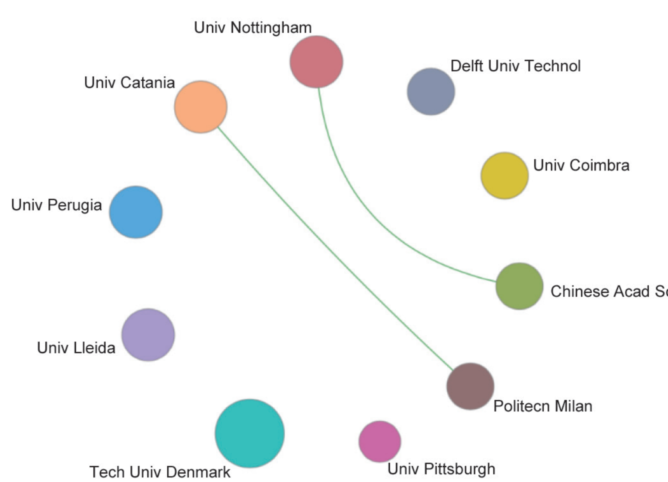

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “material life cycle engineering”

Table 1.2.11 Countries or regions with the greatest output of citing papers on "material life cycle engineering"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	3864	30.08%	2017.5
2	USA	2160	16.81%	2017.2
3	Italy	1052	8.19%	2017.2
4	UK	1004	7.82%	2017.3
5	Spain	919	7.15%	2017.3
6	Germany	852	6.63%	2017.3
7	France	677	5.27%	2017.2
8	India	631	4.91%	2017.5
9	Australia	624	4.86%	2017.5
10	South Korea	582	4.53%	2017.6

Table 1.2.12 Institutions with the greatest output of citing papers on "material life cycle engineering"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	464	26.32%	2017.5
2	Tsinghua Univ	219	12.42%	2017.3
3	Univ Chinese Acad Sci	174	9.87%	2017.6
4	Tech Univ Denmark	133	7.54%	2016.9
5	Katholieke Univ Leuven	129	7.32%	2016.9
6	Hong Kong Polytech Univ	127	7.20%	2017.6
7	Natl Univ Singapore	117	6.64%	2017.1
8	Zhejiang Univ	109	6.18%	2017.6
9	Shanghai Jiao Tong Univ	100	5.67%	2017.6
10	Univ Sci & Technol China	97	5.50%	2017.7

2 Engineering development fronts

2.1 Trends in top 12 engineering development fronts

The top 12 engineering development fronts assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. Among them, "combination of AI with chemical engineering," "biomass substitution of polymer materials," "development of microreaction system," "wearable flexible electronic devices," "biorefinery for chemical products from biomass renewable resources," "key fabrication technology for advanced structural and functional integrated ceramic materials for major national defense demands," and "intelligent bionic self-healing coating technology" are based on the published patents provided by *Clarivate Analytics*. The other five are recommended by the experts. The annual numbers of patents published from 2013 to 2018 are listed in Table 2.1.2.

"Combination of AI with chemical engineering," "targeting the function design of materials with the assistance of computer simulation technology" (Table 2.1.1), and "catalyst design by AI" (Table 1.1.1) are in development for accurate production operations, efficient and smart manufacturing processes, and system-optimized design.

(1) Combination of AI with chemical engineering

With the increasing scarcity of resources and energy supplements, the requirement for the safe and environmentally friendly chemical engineering processes and the design, production, and control of the conventional chemical

Table 2.1.1 Top 12 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Combination of AI with chemical engineering	506	1 326	2.62	2015.9
2	Biomass substitution of polymer materials	859	3 331	3.88	2014.5
3	Military refractory metal material	491	2 398	4.88	2014.3
4	Development of microreaction system	442	3 660	8.28	2014.3
5	Wearable flexible electronic devices	696	4 374	6.28	2014.9
6	Coal conversion to chemicals	669	4 655	6.96	2014.1
7	Targeting the function design of materials with the assistance of computer simulation technology	664	7 642	11.51	2014.9
8	Performance and response behavior detection and characterization technology under extremely harsh in-service environments	325	4 091	12.59	2012.7
9	Biorefinery for chemical products from biomass renewable resources	368	1 341	3.64	2014.5
10	Key fabrication technology for advanced structural and functional integrated ceramic materials for major national defense demands	1016	3 793	3.73	2014.4
11	Intelligent bionic self-healing coating technology	474	1 437	3.03	2015.7
12	Polymer materials with excellent biodegradability and multiple recyclability	947	10 767	11.37	2013.7

Table 2.1.2 Annual number of core patents published for the top 12 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Combination of AI with chemical engineering	60	79	64	93	93	117
2	Biomass substitution of polymer materials	223	210	226	138	60	2
3	Military refractory metal material	71	67	45	63	66	79
4	Development of microreaction system	146	133	85	58	17	3
5	Wearable flexible electronic devices	148	138	157	126	102	25
6	Coal conversion to chemicals	229	210	151	73	6	0
7	Targeting the function design of materials with the assistance of computer simulation technology	108	191	144	117	82	22
8	Performance and response behavior detection and characterization technology under extremely harsh in-service environments	41	32	24	23	27	39
9	Biorefinery for chemical products from biomass renewable resources	101	98	95	51	19	4
10	Key fabrication technology for advanced structural and functional integrated ceramic materials for major national defense demands	309	287	220	155	41	4
11	Intelligent bionic self-healing coating technology	75	70	66	80	91	92
12	Polymer materials with excellent biodegradability and multiple recyclability	114	135	104	110	124	107

engineering processes cannot be fully satisfied by the modern industry. Recently, the “AI + chemical engineering” approach has shown promising implications in the revolution of production, management, and marketing of the chemical industry, which can enhance the core innovation and competitiveness. The application of AI in chemical engineering in recent years can be divided into two aspects: the abstraction of the problems and the development of specific techniques in chemical engineering processes. Currently, the combination of AI with chemical engineering has already been applied in the following fields: 1) catalysts design, 2) equipment detection and fault diagnosis, 3) digital twin, 4) optimization of the controlling and warning processes, and 5) management of resources and energy.

(2) Biomass substitution of polymer materials

Polymer materials such as plastics, rubber, and fibers have extensive applications. The pace of development and application range of the polymer materials have exceeded those of the traditional metal and inorganic materials, and these have become an indispensable in industry, agriculture, national defense, science and technology, and daily life. However, most of the polymer materials are currently derived from the non-renewable petrochemical resources (oil, coal, and natural gas) and their sustainable development is challenging. The development of new polymer materials in accordance with the sustainable development goals is a common concern of researchers and industry worldwide.

The biomass substitution of polymer materials involves the use of renewable resources such as natural plants and animals as synthetic raw materials to replace the original petroleum-based raw materials. Currently, the main research will focus on the following aspects. 1) A new type of green polymerization reaction system suitable for industrial scale production will be developed from low-cost biobased monomers, which can be used to synthesize biobased polymer materials with controllable structures and excellent performances. 2) Various types of polyhydroxyalkanes will be synthesized by fermentation with microorganisms from various carbon sources. 3) Biobased polymer materials will be prepared by chemical or physical modification directly using starch, cellulose, chitin, and various agricultural and forestry wastes as raw materials. In future, the cost reduction and improvement of the comprehensive performances of biobased polymer materials will be the key issues to be addressed for their large-scale industrial applications.

(3) Military refractory metal material

Military refractory metal materials such as W, Mo, Ta, and Nb have melting points higher than 2000 °C. Owing to their high melting point, low thermal expansion coefficient, low vapor pressure, excellent corrosion resistance against liquid metals, and high-temperature strength, the refractory metal materials have been widely applied in aerospace, electrical and electronics, national defense, and nuclear sectors.

With the rapid development of the these high-tech fields, demands for refractory metal materials with high performances are increasing. A significant amount of research has been carried out on the methods for strengthening and toughening of refractory metal materials together with high performance. Because of the highest melting point of 3420 °C and small thermal neutron capture cross section, W and its alloys were selected as the most promising candidate materials for first wall and divertor of International Thermonuclear Experimental Reactor (ITER). However, limitations including low-temperature brittleness and high-temperature oxidation have hindered the engineering applications of W. Therefore, the strengthening and toughening of refractory metal materials in combination with their high performance in extreme servicing environment is a critical research issue to be resolved. In addition, the combination of powder preparation of refractory metal materials and additive manufacturing is another research field with significant potential. Refractory metal products with complex shapes for applications in extreme servicing environments can be fabricated using 3D printing technology, which has considerable advantages compared to the traditional powder metallurgy. Moreover, these 3D refractory metal products with high performances can satisfy the strategic demands in manufacturing, aerospace, and national defense sectors.

(4) Development of microreaction system

Microchemical engineering and technology is a new discipline and frontier in the field of chemical engineering. It focuses on the study of the behaviors and principles of the chemical engineering process with characteristic scales in the microscale range (within submillimeter scale).

Owing to the small channel characteristic scale, low reactant holdings, and modular structure of the microreactor system, it possesses excellent heat and mass transfer performance, good safety, easy control, and direct amplification (numbering-up) of the process, which can significantly improve the safety and production efficiency of the rapid and highly exothermic reaction process, and accelerate the practical applications of the laboratory results. This system has broad application prospects in fine chemicals such as medicine, pesticides, and energetic materials, as well as in the fields of polymers, petrochemicals, biochemicals, medical detection, and synthesis of micro and nanomaterials. The optimization design of the microreaction process and the development of engineering system equipment are urgently needed including the optimization design of microreactor structure, development of reaction process, process intelligent control, system integration, and manufacture of microreaction equipment. This involves the transfer process mechanism, transfer–reaction coupling mechanism, optimization of microstructural components, process safety control strategy, parallel scaling-up law, and system integration and optimization.

It is important to upgrade the traditional chemical industry and improve the chemical process safety and environmental protection. Microreactor technology can realize chemical process intensification, process safety, energy conservation, and reduction of emission.

(5) Wearable flexible electronic devices

Wearable flexible electronic devices are the electronic devices that are in direct or indirect contact with the skin and are mechanically flexible. To adapt to different working environments and human body requirements for device deformation, flexible wearable electronic devices often require good mechanical flexibility, but high technical difficulty limits the development of wearable flexible electronic devices. First, the wearable flexible electronic devices require good stretchability and flexibility without damaging the electronic properties, which puts higher demands on the circuit materials. Second, the preparation conditions and performances of the flexible electronics currently show a gap from the traditional electronics. The applications of flexible wearable electronics are observed in all aspects of human life. The research in this area mainly focuses on electronic skin, wearable physiological monitoring and treatment devices, flexible conductive fabrics, thin film transistors, and flexible gate circuits with transparent film.

(6) Coal conversion to chemicals

In terms of the petroleum resources, crude oil refining and petrochemical industry are very important for the rapid development of the national economy. With increasing dependence on foreign oil resources, the energy security can be severely challenged. Based on China’s natural endowment of energy resources, the clean and efficient utilization of coal resources is important for solving environmental problems and supporting high-quality and rapid economic and social development. In the modern coal/chemical industry, significant breakthroughs have been made in the commercialization of technologies such as coal-to-olefins, coal-to-ethylene glycol, and coal-to-liquifaction oil. These successful developments have opened the pathway for producing chemicals and clean fuels from coal with syngas/methanol as intermediates. Further developments include the utilization of innovative technologies to extend the applications of coal-based chemical processes, eliminate the technical bottlenecks of coal-based olefins, coal-based aromatics, and coal-based oxygenates, and improve economical efficiency of the process. The coupled and coordinated development of coal-to-chemical conversion with petrochemicals, power generation, and biomass conversion will be significant in the further enhancement of the efficiency of resource/energy utilization and will be useful for the sustainable development of the chemical industry.

(7) Targeting the function design of materials with the assistance of computer simulation technology

The traditional materials research and development involves repeated trial and error processes that not only waste significant manpower and material resources, but are also time-consuming due to the long research and development cycle. Computer molecular simulation technology can provide a qualitative prediction and simulate the quantitative results of some structures and properties of molecular systems. With the help of computer technology and theoretical calculation methods, the approach toward materials research has gradually changed from the traditional “experience-guided experiment” to “theoretical prediction and experimental verification.” In particular, high-throughput computational screening techniques developed for a large number of samples can significantly accelerate the discovery of excellent materials. In the research and development process of new materials, high-throughput screening, big data, and high-performance computer development have afforded the possibility of designing materials with "targeted" function.

(8) Performance and response behavior detection and characterization technology under extremely harsh in-service environments

Advanced structural ceramic materials are commonly used at high temperatures, where the in-service environments are extremely harsh. To accurately reflect the practical response of the structural ceramic materials under these harsh environments, the adopted simulation method must appropriately reflect the actual in-service environment. However, the existing relevant simulating environments are generally different from the actual conditions. Hence, the simulation method and technologies need to be further improved. According to the basic properties of the advanced structural materials and the in-service response and testing in harsh conditions, it is necessary to improve the performance testing and evaluation of the components and structural parts. Promotion of the research and development processes, industrialization of major products, and provision of uniform testing standards and specifications are the important developmental trends that can facilitate the wide application of advanced structural ceramic materials.

(9) Biorefinery for chemical products from biomass renewable resources

Biorefinery is an emerging industrial model for the production of energy and chemicals from the biomass renewable resources. It is a process integration for the sustainable conversion of biomass into energy, chemicals, and materials, involving food, feed, paper, and textiles in many important industrial fields. Biorefineries can allow deep processing and recycling of renewable biomass resources. In theory, most traditional petrochemicals can be obtained from the biorefinery processes. Additionally, owing to the recyclability of the raw materials and combination with many biological processes, the biorefineries can significantly reduce the energy consumption and air and water pollution in industrial processes, and support the current green development trend. Therefore, the biorefineries for materials and chemicals have a wide scope for development.

(10) Key fabrication technology for advanced structural and functional integrated ceramic materials for major national defense demands

Due to the rapid development of the high-tech aerospace industry, there is an urgent need for advanced ceramic materials that combine specific structural and functional characteristics. However, because of limitations such as difficulty in molding and machining and low fracture toughness, the development of the processing technology is important for applications in high-tech aerospace industry. Currently, the national defense sector urgently requires high-performance advanced ceramic materials with complex shapes. In this context, the low-cost green manufacturing techniques for the near net sizes and complex shapes should be developed. To improve the preparation techniques for multi-functional ceramic fiber composite films, high-strength porous ceramics resistant to high-temperature corrosion, and ceramic substrates with high thermal conductivity, the reliable evaluation criteria and lifetime prediction model must be established. With the aim of industrial development and international cooperation, it can effectively promote the research and development of advanced ceramic materials and provide support for the national key projects and strategic new industries.

(11) Intelligent bionic self-healing coating technology

Intelligent bionic self-healing coating technology refers to the use of self-healing capabilities derived from medicine and biology in the field of materials science, which means that the coating can be automatically repaired after the generation of cracks. There are many methods to develop self-healing coatings such as the introduction of microcapsules into a polymer matrix to form a healing agent and an initiator. When cracks are generated under an external force, the embedded microcapsules are torn and the polymerization is initiated, followed by re-bonding and repairing of the crack. A hybrid organic–inorganic nanocomposition can also be assembled as a cell wall to form a microtube, and the coating can be spontaneously repaired and healed after damage. The current research focuses on polyethylene terephthalate coatings, automotive paint finishes, mobile phone back cover coatings, and some rubber materials.

(12) Polymer materials with excellent biodegradability and multiple recyclability

Polymers are widely applied materials and are irreplaceable in almost all national economic fields. Most of the polymers are chemically stable and nondegradable, which are processed mainly by incineration or land filling after abandonment, and only very few of them are recycled. Moreover, the properties of the recycled commercial polymers, which are typically obtained by physical reprocessing, inevitably deteriorate and therefore, multiple recycling of polymers cannot be performed. With increasing interdependence between the human society and polymers, the proliferation of polymer waste results in serious global problems such as environmental pollution and wastage of resources. For example, the white pollution, marine microplastic, and oil crises, which are directly related to the polymer applications, have become one of major hindrances to sustainable development of human society.

In view of these urgent challenges, the development of a new generation of polymer materials with comparable performances to those of commercial polymers, excellent biodegradability after abandonment, and multiple recyclability has attracted considerable attention from scientists and engineers. Under suitable recycling conditions, these novel polymers can be effectively pyrolyzed into monomers for further polymerization, resulting in highly efficient multiple recycling. For polymers that are unsuitable for recycling, these can be biodegraded into small molecules that are harmless to the environment, i.e. water and carbon dioxide. Therefore, this approach provides a novel, comprehensive, and effective solution for the global problems arising from the components derived from polymer applications.

2.2 Interpretations for three key engineering development fronts

2.2.1 Combination of AI with chemical engineering

Limitation of resources and energy supplements have necessitated the requirement of safe and environmentally friendly chemical engineering processes, and the design, production, and control of the conventional chemical engineering processes cannot be satisfied by the modern industry. Recently, the successful applications of AI in the fields of man–machine game and machine vision have opened a new pathway for updating the chemical engineering processes. The “AI + chemical engineering” approach is showing promising results in the production, management, and marketing of the chemical industry, which can enhance the innovation and competitiveness in these fields.

The applications of AI in chemical engineering in recent years can be divided into two aspects: the abstraction of the problems and the development of specific techniques in chemical engineering processes. The abstraction of the problems in chemical engineering is mainly focused on the generation of problems from traditional chemical processes by classical AI methods followed by the development of their solutions with well-established AI techniques. The development of specific techniques in chemical engineering processes is mainly focused on the expansion of the classical AI techniques by adding special elements from chemical engineering processes, followed by development of specific intelligent algorithms and software that satisfy the chemical processes.

These two aspects should be studied in depth for the application of AI in not only the basic research and development, but also in applied research of chemical engineering. The combination of AI with chemical engineering has been applied in the following fields.

(1) Catalyst design. The design of chemical catalysts requires large amount of experimental data and professional knowledge. Their combinations and correlations can be rapidly determined by the application of AI. As a result, the research and development cycle of the catalysts and small molecules can be shortened. By the prediction of the active binding sites of the small molecules, the synthetic route and reverse molecular design can help in improving the efficiency of catalyst design. (2) Equipment detection and fault diagnosis. Based on the big data processing and knowledge inference, AI algorithm models have been applied to the signals of vibrations, sound, images, and electricity of the operational chemical equipment, for online monitoring of the processes and predictions of the faults and errors. (3) Digital twin. By combining the big data in industry and applying the AI techniques to the mechanisms, the models for characterizing the operational state of the chemical engineering processes can be developed, the parallel of manufacturing can be realized in a visualized manner, and management and optimization of the chemical processes can be achieved. (4) Optimization of the controlling and warning processes. Big data and AI techniques show promising prospects in multi-objective collaborative optimization and control. The safety,

stability, and effectiveness in complex chemical processes can be improved by controlling and warning processes. (5) Management of resources and energy. Developing man-machine cooperation and knowledge-driven decision system for intelligent production plan, based on the industrial internet, big data, and knowledge-based work automation, can allow the optimization of a production plan that fuses the demand-driven and device operation characteristics. Then, the resources and energy demand in chemical engineering processes can be optimized.

The countries/regions with the highest output of core patents on the "combination of AI with chemical engineering" are mainly from the USA and China, followed by Japan and South Korea; some European countries, Germany, Sweden, Switzerland, and France, have also contributed significantly (Table 2.2.1). The USA and Germany have close collaboration in this front (Figure 2.2.1), but there is no collaboration from the institutions with the highest output of core patents (Table 2.2.2 and Figure 2.2.2); most of these are American institutions.

2.2.2 Biomass substitution of polymer materials

Environmental pollution, resource wastage, and strong dependence on the petrochemical resources caused by

Table 2.2.1 Countries or regions with the greatest output of core patents on "combination of AI with chemical engineering"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	165	32.61%	640	48.27%	3.88
2	China	131	25.89%	235	17.72%	1.79
3	Japan	64	12.65%	79	5.96%	1.23
4	South Korea	45	8.89%	22	1.66%	0.49
5	Germany	22	4.35%	15	1.13%	0.68
6	Sweden	14	2.77%	47	3.54%	3.36
7	Taiwan of China	14	2.77%	15	1.13%	1.07
8	Switzerland	12	2.37%	24	1.81%	2.00
9	France	9	1.78%	8	0.60%	0.89
10	Israel	8	1.58%	26	1.96%	3.25

Table 2.2.2 Institutions with the greatest output of core patents on "combination of AI with chemical engineering"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	KLAT	USA	12	2.37%	44	3.32%	3.67
2	GENE	USA	10	1.98%	37	2.79%	3.70
3	SKFK	Sweden	9	1.78%	37	2.79%	4.11
4	BOEI	USA	8	1.58%	25	1.89%	3.13
5	FICO	USA	7	1.38%	23	1.73%	3.29
6	DANH	USA	6	1.19%	52	3.92%	8.67
7	ASHF	UK	6	1.19%	19	1.43%	3.17
8	HONE	USA	5	0.99%	32	2.41%	6.40
9	UNAC	USA	5	0.99%	22	1.66%	4.40
10	SIEI	Germany	5	0.99%	4	0.30%	0.80

KLAT: KLA-Tencor Corp.; GENE: General Electric Co.; SKFK: SKF AB; BOEI: Boeing Co.; FICO: Fisher Controls International, Co., Ltd.; DANH: HACH Co.; ASHF: Ashford Tech Software Inc.; HONE: Honeywell Int. Inc.; UNAC: United Technologies Corp.; SIEI: Siemens AG.

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "combination of AI with chemical engineering"

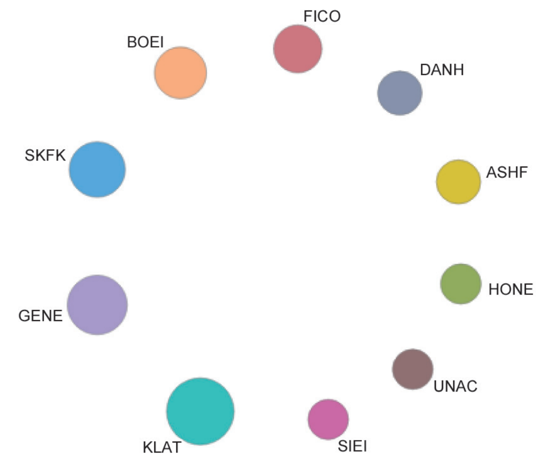

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "combination of AI with chemical engineering"

the extensive use of polymer materials have attracted the attention of researchers and industries worldwide since the 21st century. Using the renewable biomass derived from nature to prepare biobased polymer materials can not only effectively resolve the issues of resource and energy security, but also alleviate the environmental and climate problems caused by the rapid increase of carbon emissions. The key challenges in the biomass substitution of polymer materials are large-scale preparation of monomers from the biomass sources, polymerization with high efficiency, improvement of the properties of biobased polymers, and reduction in the cost of biosynthetic polymer materials. Currently, the industrial products from biobased polymer materials including polylactic acid and polyhydroxyalkanoate are available, but some limitations such as low yields, high cost, and properties that are not comparable to the petroleum-based polymers are observed. Therefore, the research and development of biobased polymer materials with high cost–performance ratio or performance reaching or exceeding those of some petroleum-based products are the important directions of development for the biobased polymers in future.

The major countries/regions and institutions with greatest core patents in biomass substitution of polymer materials since 2013 are listed in Tables 2.2.3 and 2.2.4, respectively. The collaboration networks between the major countries/regions and institutions are shown in Figures 2.2.3 and 2.2.4, respectively. The research in biobased polymer materials mainly focuses on the preparation of polymers from biomass monomers or biofermentation and the preparation of biobased polymer materials by chemical and physical modifications using starch, cellulose, chitin, and various agricultural and forestry wastes as raw materials. The top three countries with maximum core patents are China, the USA, and Japan. The percentages of core patents and citations from China are 68.34% and 59.95%, respectively, whereas those from the USA are 10.24% and 19.63%, respectively, and Japan are 10.24% and 9.07%, respectively. The USA has the most extensive collaboration with other countries including Japan, the UK, the Netherlands, and Germany. In addition, Germany collaborates with Switzerland, Japan, and the USA, but China, Austria, and France do not collaborate with other countries. The China Petrolum and Chemical Corporation, Dow Global Technologies LLC, BASF SE, Changchun Institute of Applied Chemistry of Chinese Academy of Sciences, Toray Industries, LG Chem., and other institutions have core patents on biobased polymers, among which the China Petrolum and Chemical Corporation has the greatest number of core patents.

2.2.3 Military refractory metal material

Military refractory metal materials such as W, Mo, Ta, and Nb have melting points higher than 2000 °C. Owing to their high melting points, excellent high-temperature mechanical properties, and unique physical and chemical properties, the refractory metal materials have been widely applied in aerospace, electrical and electronics, national defense,

Table 2.2.3 Countries or regions with the greatest output of core patents on “biomass substitution of polymer materials”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	587	68.34%	1997	59.95%	3.40
2	USA	88	10.24%	654	19.63%	7.43
3	Japan	88	10.24%	302	9.07%	3.43
4	South Korea	40	4.66%	140	4.20%	3.50
5	Germany	22	2.56%	96	2.88%	4.36
6	Switzerland	8	0.93%	34	1.02%	4.25
7	France	7	0.81%	32	0.96%	4.57
8	Netherlands	6	0.70%	41	1.23%	6.83
9	UK	4	0.47%	38	1.14%	9.50
10	Austria	4	0.47%	31	0.93%	7.75

Table 2.2.4 Institutions with the greatest output of core patents on “biomass substitution of polymer materials”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	SNPC	China	11	1.28%	48	1.44%	4.36
2	DOWC	USA	9	1.05%	76	2.28%	8.44
3	BADI	Germany	9	1.05%	49	1.47%	5.44
4	CAAC	China	8	0.93%	24	0.72%	3.00
5	TORA	Japan	8	0.93%	13	0.39%	1.63
6	GLDS	South Korea	7	0.81%	78	2.34%	11.14
7	ASAH	Japan	6	0.70%	32	0.96%	5.33
8	SABI	USA	5	0.58%	39	1.17%	7.80
9	CPCH	USA	5	0.58%	31	0.93%	6.20
10	ESSO	USA	5	0.58%	30	0.90%	6.00

SNPC: China Petroleum and Chemical Corporation; DOWC: Dow Global Technologies LLC; BADI: BASF SE; CAAC: Changchun Institute of Applied Chemistry of Chinese Academy of Sciences; TORA: Toray Industries, Inc.; GLDS: LG Chem. Co. Ltd.; ASAH: Asahi Kasei Chem. Co.; SABI: SABIC Global Technologies B.V.; CPCH: Chevron Phillips Chem Co. LP.; ESSO: Exxonmobil Chem Patents Co., Ltd.

and nuclear sectors. The USA, Japan, European countries, and some other countries consider the refractory metals as important strategic materials because of their vital roles in various high-tech fields. With the continuous development of high-tech fields and extreme servicing environments, the demand for refractory metal materials with high performance is rapidly increasing. Extensive research has been performed to strengthen and toughen the refractory metal materials and improve the performance. The strengthening and toughening methods mainly include elemental doping, severe plastic deformation, and dispersion strengthening. The low-temperature brittleness and high-temperature oxidation resistance can be improved by refining the grain size or introducing second nanoscale particles. With the development of 3D printing, the refractory metal products with complex shapes for applications in extreme servicing environments can be fabricated using 3D printing technology, which is a significant advantage in comparison to the traditional powder metallurgy. Moreover, these 3D refractory metal products with high performances can meet the strategic demands in manufacturing, aerospace, and national defense sectors.

Tables 2.2.5 and 2.2.6 include the countries/regions and institutions with the greatest output of core patents in the field

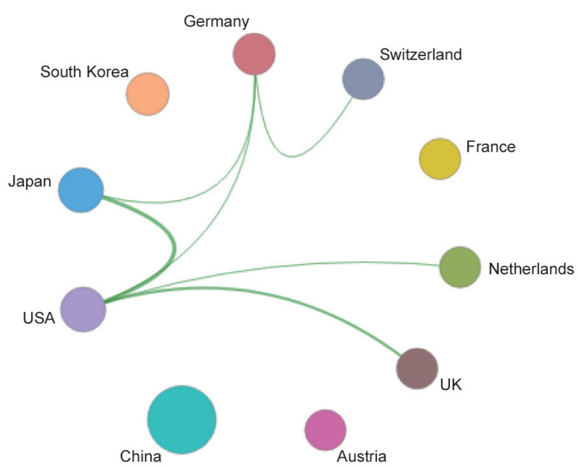

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of “biomass substitution of polymer materials”

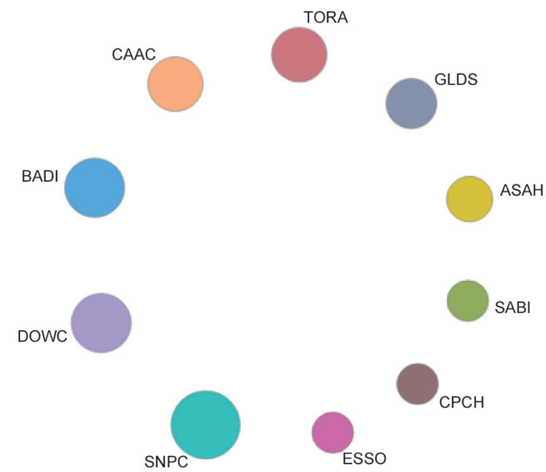

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “biomass substitution of polymer materials”

Table 2.2.5 Countries or regions with the greatest output of core patents on “military refractory metal material”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	292	59.47%	343	14.30%	1.17
2	Japan	116	23.63%	1309	54.59%	11.28
3	USA	20	4.07%	282	11.76%	14.10
4	South Korea	18	3.67%	10	0.42%	0.56
5	Germany	13	2.65%	230	9.59%	17.69
6	Switzerland	5	1.02%	36	1.50%	7.20
7	France	5	1.02%	24	1.00%	4.80
8	Taiwan of China	4	0.81%	1	0.04%	0.25
9	Sweden	3	0.61%	118	4.92%	39.33
10	Brazil	3	0.61%	21	0.88%	7.00

of military refractory metal materials. As shown in Table 2.2.5, China and Japan rank first and second among these countries in terms of core patents, and their published core patents account for 59.47% and 23.63%, respectively. Although China has the most published core patents in the field of military refractory metal materials in the world, the average citation of core patents is relatively low, approximately 1.17. The top three institutions for maximum core patents are Nihon Parkerizing Co., Ltd. of Japan, Chongqing Runze Pharm. Co., Ltd. of China, and JX Nippon Mining & Metals Corp. of Japan. Their corresponding percentages of published core patents are 6.31%, 3.05% and 2.85%, respectively (Table 2.2.6).

Figure 2.2.5 shows the collaboration network among major countries or regions with the most core patents in the field of military refractory metal materials. The collaboration between Japan and Germany is the most frequent, followed by the collaboration between the USA and Germany. Figure 2.2.6 shows the collaboration network among major institutions. According to Figure 2.2.6, Chemetall GmbH of Germany and Nippon Paint Co., Ltd. of Japan have the closest collaboration. In addition, the collaboration between Nippon Stell & Sumitomo Metal Corp. of Japan, Henkel AG & Co. KGaA of Germany, and Nihon Parkerizing Co., Ltd. of Japan is relatively frequent.

Table 2.2.6 Institutions with the greatest output of core patents on “military refractory metal material”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	HOOL	Japan	31	6.31%	512	21.35%	16.52
2	CQRZ	China	15	3.05%	14	0.58%	0.93
3	NIHA	Japan	14	2.85%	41	1.71%	2.93
4	YAWA	Japan	10	2.04%	127	5.30%	12.70
5	CMTL	Germany	9	1.83%	240	10.01%	26.67
6	NIPA	Japan	9	1.83%	206	8.59%	22.89
7	ANSH	China	8	1.63%	18	0.75%	2.25
8	KUNS	China	6	1.22%	20	0.83%	3.33
9	SHAO	China	5	1.02%	2	0.08%	0.40
10	HENK	Germany	4	0.81%	78	3.25%	19.50

HOOL: Nihon Parkerizing Co., Ltd.; CQRZ: Chongqing Runze Pharm. Co., Ltd.; NIHA: JX Nippon Mining & Metals Corp.; YAWA: Nippon Steel & Sumitomo Metal Corp.; CMTL: Chemetall GmbH; NIPA: Nippon Paint Co., Ltd.; ANSH: Pangang Group Panzhihua Iron & Steel Research Institute Co., Ltd.; KUNS: Kunshan Qiaorui Metal Prod. Co., Ltd.; SHAO: Shaoxing Wancheng Metal Sheet Co., Ltd.; HENK: Henkel AG & Co. KGaA

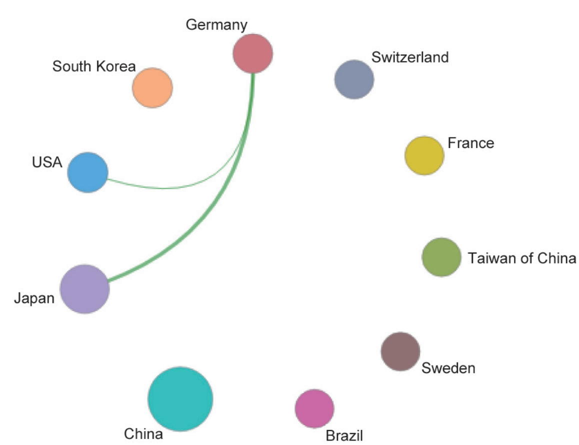

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “military refractory metal material”

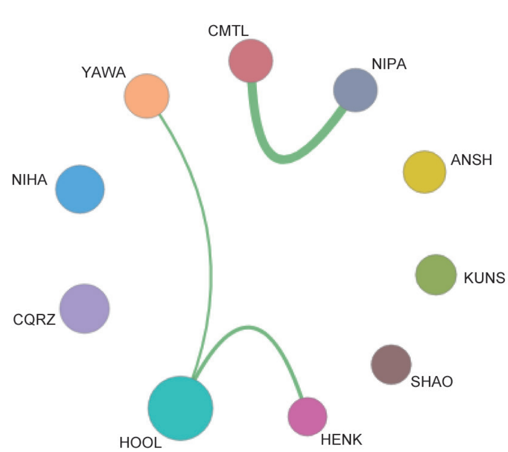

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “military refractory metal material”

Participants of the Field Group

Leaders

WANG Jingkang, LIU Jiongtian

Deputy Leaders

LI Yanrong, LIU Zhongmin, MAO Xinping, NIE Zuoren, TAN Tianwei, ZHOU Yu, QU Lingbo, YUAN Yingjin

Members of the Working Group

CHEN Biqiang, LIU Xingzhao, XI Xiaoli, YANG Zhihua, YAO Changguo, YE Mao, CAI Di, LI Daxin, WANG Man, WANG Jing, WANG Jingtao, CHENG Luli, GAO Yanjing, HUANG Yaodong, SUN Xiuliang, ZHU Xiaowen

Report Writers

CAI Di, CHEN Guangwen, DING Ya, GUO Xiaojia, HUANG Yaodong, KANG Guodong, LI Daxin, LI Jinzhe, LIU Lin, SHAN Meixia, WANG Dan, WANG Man, WANG Meng, WANG Xiuli, WANG Feng, XU Di, YAO Changguo, ZHU Xiaowen

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Wuhan Branch of Baosteel Central Research Institute

WANG Yuan, GU Haifang, SUN Zhu

Beijing University of Technology

LIU Yu, MA Liwen, WEN Shengping, YANG Jianshen

Beijing University of Chemical Technology

LIU Jingjing, ZHANG Huili, ZHANG Weidong

Dalian Institute of Chemical Physics, Chinese Academy of Sciences

LIU Huifang, MA Huaijun, QI Yu, SUN Jian, WANG Sheng, XIE Feng, ZHAO Zongbao, ZHU Hejun, ZHU Xuefeng

University of Electronic Science and Technology of China

JIANG Shuwen, YAN Jing, YAN Yichao, ZHANG Wanli, ZHU Bin

Harbin Institute of Technology

LI Qian, NIU Bo, QIU Baofu

Sichuan University

CHEN Sichong, WANG Yuzhong

East China University of Science and Technology

QIAN Feng, ZHONG Weimin

Tianjin University

LI Yanni, QIAO Jianjun, YANG Zuguo

IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in top 12 engineering research fronts

The top 12 engineering research fronts assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involves the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering.

Among these top 12 research fronts, emerging research fronts include "multivariate and high-density energy storage methods coupled with renewable energy," "research on photoelectrochemical-photocatalytic hydrogen production from water splitting," "research on methods of coupling big data and artificial intelligence (AI) in the smart grid," "all-solid-state lithium ion batteries with high energy density and fast charging," and "application of big data technologies and methods in oil-gas field geology–engineering–surface integration." "Characteristics, prevention, and mitigation of severe accidents in nuclear power stations," "critical metal mineralization and enrichment mechanisms," "ultra-high-temperature and high-pressure drilling fluids," and "multiphysics-coupling disaster-causing mechanisms in deep metal mining processes" are further developments of traditional research fields. "AI applied to reservoir prediction mechanisms," and "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas" are the fronts of interdisciplinary integration. "Research on damage mechanisms and verification of advanced nuclear fuel and related materials" is both an emerging front and a subversive front.

The number of core papers published annually from 2013 to 2018 for the top 12 engineering research fronts is listed in Table 1.1.2.

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Multivariate and high-density energy storage methods coupled with renewable energy	210	8856	42.17	2015.9
2	Research on damage mechanisms and verification of advanced nuclear fuel and related materials	106	1064	10.04	2016.8
3	AI applied to reservoir prediction mechanisms	44	244	5.55	2015.8
4	Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas	17	62	3.65	2016.2
5	Research on photoelectrochemical-photocatalytic hydrogen production from water splitting	25	1023	40.92	2017.6
6	Research on methods of coupling big data and AI in the smart grid	397	3180	8.01	2016.1
7	All-solid-state lithium ion batteries with high energy density and fast charging	73	3806	52.14	2016.3
8	Characteristics, prevention, and mitigation of severe accidents in nuclear power stations	209	7518	35.97	2014.3
9	Application of big data technologies and methods in oil-gas field geology–engineering–surface integration	11	185	16.82	2015.8
10	Critical metal mineralization and enrichment mechanisms	243	6785	27.92	2014.6
11	Ultra-high-temperature and high-pressure drilling fluids	111	1005	9.05	2016.0
12	Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes	142	762	5.37	2015.8

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

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Multivariate and high-density energy storage methods coupled with renewable energy	30	17	31	38	49	45
2	Research on damage mechanisms and verification of advanced nuclear fuel and related materials	0	5	15	15	31	40
3	AI applied to reservoir prediction mechanisms	8	8	2	5	9	12
4	Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas	2	3	0	1	6	5
5	Research on photoelectrochemical-photocatalytic hydrogen production from water splitting	0	0	0	2	7	16
6	Research on methods of coupling big data and AI in the smart grid	23	40	74	85	80	95
7	All-solid-state lithium ion batteries with high energy density and fast charging	6	7	9	11	14	26
8	Characteristics, prevention, and mitigation of severe accidents in nuclear power stations	66	62	41	32	7	1
9	Application of big data technologies and methods in oil-gas field geology–engineering–surface integration	1	0	2	6	1	1
10	Critical metal mineralization and enrichment mechanisms	63	63	54	42	17	4
11	Ultra-high-temperature and high-pressure drilling fluids	14	15	13	17	18	34
12	Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes	26	18	18	20	23	37

(1) Multivariate and high-density energy storage methods coupled with renewable energy

Efficient and large-scale utilization of renewable energies, such as hydro, wind, solar, biomass, and geothermal energies, is the inevitable choice and important guarantee for sustainable development of global energy and environment. As far as resources and technology development are concerned, wind, solar, and hydro energies have the greatest prospects for development, and power generation is the most effective way to use them. However, a notable disadvantage of wind and solar power generation is that the output power is directly affected by environmental and climatic factors, resulting in features of randomness, intermittence, and fluctuation. Ensuring the continuous and stable output of qualified power from the power generation system is the basis and key for large-scale connection of renewable energy to the power grid. Constructing a renewable energy system that combines wind, solar, hydro, and thermal energies with energy storage units is an essential way to solve this problem, and is the trend of global power development.

Energy storage technology is an energy utilization technology that absorbs and stores energy for a period of time and then releases it in a controlled manner. It can be divided into five types: mechanical energy storage, electrical energy storage, electrochemical energy storage, thermal energy storage, and chemical energy storage. High-density energy storage, in terms of both high energy density and high power density, is the key to large-scale and efficient utilization of renewable energy, which is also a research hotspot of energy storage technology.

The emerging frontiers include low-cost, high-performance, single-type, and high-density energy storage methods; multivariate and high-density energy storage methods that are complementary to each other and coupled with renewable energy; multivariate, high-density energy storage methods that meet the different needs of renewable energy generation, transmission, distribution, and use; and renewable energy power supply systems based on the complementary coupling of wind, solar, hydro, and thermal energies.

(2) Research on damage mechanisms and verification of advanced nuclear fuel and related materials

Nuclear fuel contains most of the radioactive materials and its containment is the first line of defense against the release of radioactive materials in nuclear power plants. Therefore, while the international community is developing advanced nuclear fuels, it is also vigorously conducting research on the damage mechanisms of nuclear fuels and related materials. At present, the research on the damage mechanisms of the current pressurized water reactor (PWR) fuel is primarily focused on the interaction between the fuel and the cladding during power transients; the instability caused by oxidation of the cladding, the fuel fragmentation, dispersal and relocation behavior in a large water loss accident; and the performance degradation of spent fuel cladding in dry storage. To explain the fuel and material behavior from a macroscopic viewpoint, numerous research institutions have conducted various microscopic studies in materials science to master the material behavior of different materials under a variety of corrosive environments, neutron irradiation, temperature fields, and stress fields. Combined with molecular dynamics methods, the damage mechanisms of advanced nuclear fuel and related materials are predicted, evaluated, and verified.

(3) AI applied to reservoir prediction mechanisms

AI has begun to enter into the petroleum field. Applying AI to reservoir prediction can solve various bottlenecks and problems in oilfield exploration and development. However, the application of AI in the petroleum industry is still in its infancy. The forecasting mechanism aims to store and analyze the massive data obtained during reservoir prediction, such as geological data, geomechanical data, reservoir data, engineering data, and economic data, among others, and use big data analysis techniques for high-precision geological modeling and high-efficiency numerical simulation to accurately describe the underground reservoir. Ultimately, all data is integrated on a unified platform, and reservoir prediction is performed from both data and model levels to facilitate reasonable scientific decisions. In short, with the innovation and technological advances of the times, only by combining the traditional petroleum engineering technical knowledge with AI, and realizing the strategic integration of creativity and creative thinking, can we actively adapt to and promote the future development of the petroleum industry.

(4) Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas

Intelligent perception, intelligent decision-making, and automatic control (execution) are the three elements of intelligent mining. Intelligent mining differs from general automatic mining in that the equipment has the functions of autonomous learning and decision-making, and has the abilities of self-perception, self-control, and self-correction. Only the intelligent and fully-mechanized mining system of this kind can completely respond to the changes of production environment, realize the real sense of intelligent mining, and realize the goal of unattended remote mining under constrained conditions.

The key technologies of intelligent coal mining include intelligent mining of thin seams and extremely thin seams, intelligent mining of large and extremely-large mining heights of thick seams, and intelligent mining of fully mechanized top coal caving in extra-thick seams. The development trend is to comprehensively promote the intelligent technology of fully mechanized mining in the future, realize the goal of limited unmanned mining, and achieve the goal of unattended robotic fluidized mining.

As the oil and gas exploration and development industry gradually turns its attention to the complex oil and gas resources (including unconventional, low-permeability, ultra-deep, deep-water oil and gas), there appears a series of new problems and challenges in the extraction of oil and gas in terms of safety, economy, and efficiency. Therefore, there is an urgent need to accelerate the cross-border integration of big data, AI, information engineering, underground control engineering, and establishment of a sound theoretical system of safe, efficient, and intelligent development. The eventual aim is to achieve advanced detection, closed-loop regulation, real-time warning, and intelligent decision-making, further promote the safe and economical extraction of oil and gas resources, and provide important support for achieving the major breakthroughs of complex oil and gas extraction in China.

The concepts of safe, highly efficient, and intelligent extraction of oil and gas involve reservoir characterization, downhole condition perception, closed-loop parameter control, and intelligent decision-making for choice of extraction scheme.

The reservoir characterization describes and evaluates the oil and gas flow characteristics in the reservoir during the entire production process and provides a basic reference for oil and gas exploitation regulation. The principal research trends of reservoir characterization include the detailed characterization of reservoir elements, dynamic three-dimensional (3D) geological modeling, and real-time correction of geological models and reconstruction theory.

The downhole condition perception identifies and diagnoses downhole conditions and offers early warning of risks, which then provides important support for safe extraction of oil and gas. The research trends related to downhole condition perception include the response mechanisms of underground monitoring equipment, automatic diagnosis of downhole risks, and early warning concepts.

The closed-loop parameter control is primarily intended to transmit downhole data to the ground, and then issue control instructions to the downhole equipment to adjust the parameters based on the dynamic analysis by a ground-based expert system. In this way, the bidirectional transmission of information is established, and the closed-loop real-time control is achieved, which can establish an important foundation for the economical and efficient production of oil and gas. The foremost research trends of closed-loop parameter control include the bidirectional high-efficiency transmission of massive datasets and closed-loop optimization theory applied to the downhole control parameters.

The intelligent decision-making necessary to devise extraction schemes utilizes the big data from oil and gas fields and then optimizes the extraction scheme for the oil and gas fields by using AI. The key research trends of intelligent decision-making include the dynamic optimization of oil and gas extraction schemes using big data and AI techniques, combined with the concepts of intelligent flow, integration, and self-purification of massive data during long-term extraction.

(5) Research on photoelectrochemical-photocatalytic hydrogen production from water splitting

When a semiconductor photocatalyst is irradiated with light, the electrons located on the valence band undergo a transition due to the external light energy. Photogenerated electrons and holes will be generated simultaneously in the semiconductor. Water could then be split into hydrogen and oxygen by the photogenerated electrons and holes, respectively. This catalytic reaction is the so-called photocatalytic hydrogen production reaction. The efficiency of hydrogen production could also be promoted by applying an external bias, whose reaction is called the photoelectrochemical or photoelectrocatalytic hydrogen production reaction. Photocatalysis and photoelectrocatalysis have a great potential for future sustainable solar hydrogen production.

The fundamental limitations to improving the photocatalytic and photoelectrochemical hydrogen production efficiency include the limitation on the efficiency of light absorption, photo-generated carrier separation efficiency, and catalytic reaction kinetics. At present, the research mainly focuses on development of the strategy for regulating the energy bandgap, construction of heterogeneous structures and crystal planet, and modification of photo cathode/anode semiconductor material. The search for high-efficiency photocatalysts and the development of new low-cost and stable catalytic material and reaction systems have also become a research hotspot. Recently, selection of matched catalysts for photocatalytic hydrogen production and degradation of contaminants in water have also attracted wide attention.

(6) Research on methods of coupling big data and AI in the smart grid

Big data is a dataset consisting of extremely large volumes of numerous data types having complex structures. Big data uses data analysis as the core, covering data preprocessing, fusion, storage, and processing. It has the characteristics of high volume, quick response, wide variety, and low value density. Broadly defined, AI is a smart machine that can react in a way that mimics human intelligence. Deep learning, a form of machine learning, is a method to realize AI. The coupling of big data and AI to the smart grid is a deep integration of data, autonomous knowledge learning, and application scenarios, which is an effective way to cope with the increasing complexity and uncertainty of the grid.

The current research directions include renewable energy generation power forecasting considering time-space correlation; automatic mining and extracting key features of grid stability assessment and emergency control; intelligent analysis and decision making of the power grid; intelligent diagnosis and identification of power grid faults; massive load data classification and prediction; and analysis of the power consumers’ behavior.

The emerging fronts are the development and construction of more advanced and intelligent analysis methods and platforms, and the application of the methods and platforms to deeper and more core fields. In the development of analysis methods and construction of platforms, stress should be placed on the introduction of mature, efficient, and advanced methods of big data analysis and AI, and the integration of existing analytics platforms to gradually build an integrated AI system platform for processing tasks in the power grid field. In field applications, emphasis should be placed on appropriate modification of AI methods in combination with the requirements of the power grid, enhancement of the applicability of the algorithm to increase the coupling depth, and the extension of the application to core areas such as grid security and stability analysis and control, and grid dispatching operations, to increase coupling breadth.

(7) All-solid-state lithium ion batteries with high energy density and fast charging

All-solid-state lithium ion batteries (ASSLIBs) are considered to be one of the most important next generation technologies for energy storage, especially for portable electronic devices and electric vehicle (EV) applications. ASSLIBs have many advantages over commercial lithium ion batteries having liquid organic electrolytes; such advantages include improved safety and reliability, higher volumetric energy densities, wider operating temperatures, higher charging/discharging rates, and simpler battery design. Therefore, ASSLIBs have attracted increasing attention in recent years and are being pursued by many world-leading EV manufacturers such as Toyota, Renault, Nissan, BMW, and Tesla.

Solid electrolyte materials are the key to ASSLIBs. The major problem that hinders the development of ASSLIBs to date has been associated to the relatively low ionic conductivity of the solid electrolyte as well as the poor solid/solid contact at the electrolyte/electrode interface. The properties of a good solid electrolyte material must meet several requirements apart from high Li-ion conductivity. These include low activation energy for Li^+ migration, negligible electronic conductivity (to avoid an internal short circuit), good chemical and electrochemical stability against electrode materials, good thermal stability, excellent mechanical properties, simple fabrication processes, and low cost. To date, there are a variety of material choices for solid electrolyte materials such as oxides, sulfides, hydrides, halides, borates or phosphates, thin films, and polymers. However, none of them can meet all of the essential requirements. Breakthrough discoveries of solid-state electrolyte materials with superior properties are in urgent demand.

ASSLIBs are the ultimate solution to achieving a high energy density and fast charging rate for lithium ion batteries. For its commercialization, great efforts are still to be made in key materials, structure designs, and fabrication techniques.

(8) Characteristics, prevention, and mitigation of severe accidents in nuclear power stations

A serious accident at a nuclear power plant refers to an accident in which the severity of the accident exceeds the design-basis accident (DBA) circumstances and causes the core to deteriorate significantly or even melt, and the failure of corresponding safety facilities may cause a large amount of radioactive material to be released, which is part of the nuclear power plant's beyond-design-basis accident. The accident process is divided into core melt disintegration, pressure vessel failure, and containment failure.

The PWR nuclear power plant depends on the three barriers to prevent nuclear fission products from leaking, namely, the fuel cladding, the primary circuit pressure boundary, and the containment. When serious accidents such as core melting occur, the mitigation and treatment of accidents primarily focus on lessening the core damage and ensuring the function of the third barrier (i.e., the containment) to reduce the release of radioactive materials into the environment.

In the design of comprehensive accident mitigation measures for nuclear power plants, it is necessary to consider the serious core damage that is actually eliminated. Accident conditions typically include direct containment heating, large-scale steam explosion, hydrogen explosion, containment heat loss, and melt–concrete interaction.

Study should first be conducted on the core melting mechanism. Accident prevention and mitigation engineering techniques, including the in-throw melt retention technology, core melt traps, and hydrogen elimination technology, should be optimized and improved by conducting research on the processes and phenomena of core melt migration in the reactor and migration outside the reactor. Research should then be conducted on the integrity of containment, including containment failure probability calculation, source removal and other preventive and mitigation measures, as well as response to containment isolation failure, containment bypass, early failure of containment, and other accident sequences that lead to failure of containment. Finally, the elimination of large-scale releases should be verified by deterministic and probabilistic methods and the development of severe accident analysis methods and software.

(9) Application of big data technologies and methods in oil-gas field geology–engineering–surface integration

In oil and gas exploration and development, the "sweet spots" have been gradually reduced, forcing major oil companies to reduce costs and increase efficiency. However, big data, to some extent, can compensate for the theoretical defects. The big data application technologies and methods in oil-gas field geology–engineering–surface integration are thus proposed in this context. Based on the big data methods combined with pattern recognition technology, multi-scale data mining is performed on a large number of actual operational and historical data such as drilling, logging, oil testing, fracturing acidification, and ground testing to improve economic and social benefits. Through research and integration of geological, engineering, ground, and other full-process data; big data collection, processing, and storage; as well as cloud computing, exchange, and sharing, the big data application technology will ultimately be applied to strategic analysis and decision-making. That is to say, through the establishment of an integrated database, the existing mature data mining methods are used for regular analysis, dimensional analysis, correlation analysis, and empirical correlation statistical regression to guide the actual oilfield production practice. At the same time, the applications require a new management model to have a greater decision-making power, insight, and process optimization capabilities. In short, this is an essential technology for scientific exploration and development of oil and gas fields. It can transform data into information faster and more efficiently, quickly discover oil and gas, and reduce production costs. It will bring new vitality to major oil and gas fields and promote the informationization and intelligent development of oil and gas field development.

(10) Critical metal mineralization and enrichment mechanisms

Critical metals, namely strategic metals, including rare trace elements, rare earth elements, dispersed rare elements, and platinum group elements, are the raw materials essential for development of modern advanced manufacturing, low-carbon clean energy technologies and other growing industries. China is well-endowed with a variety of critical metals. For example, China has supplied 95% of the total rare earth elements, 84% of the total tungsten, and 53% of the total scandium resource to satisfy global demands in the past years. However, other critical metals, such as manganese, niobium, beryllium, nickel, cobalt, chromium, and platinum group elements, are relatively scarce but crucially needed, which may increase the risks of bottlenecks in the establishment of advanced manufacturing and growing industries in China.

Most developed western countries have recently been dedicated to unraveling significant factors that lead to enrichment mechanisms and mineralized characterization of strategically critical metals, and encouraging their domestic mining companies to launch exploration projects targeted at critical metal resources. The mineralization of critical metals is characterized by dispersion, low-grade, small tonnage, and challenge in geometallurgy. Some critical metals can be produced on a relatively large scale, but they commonly occur as by-products in extraordinarily small quantities from base metal refining. The mineralization of critical metals is typically uncontinuous and it is difficult to delimit their orebodies. Furthermore, the ore genesis and accumulation mechanism of critical metals remain unclear. Therefore, new theories and deposit models for mineralization of critical metals are urgently needed. It is recommended that scientific research be strengthened to reveal the enrichment processes and mineralization mechanisms related to low-abundance critical metals, to elucidate the microscale occurrence modes and macroscale distribution patterns of critical metal elements, and to define the vital, coupled geological and physiochemical (-biological) factors controlling the mineralization of critical metals. All of the proposed research works aim to discover new types of critical metal ore deposits and increase the resource reservoirs, to maintain a stable supply of critical raw materials that are needed to achieve the strategic plan of "Made in China 2025."

(11) Ultra-high-temperature and high-pressure drilling fluids

Drilling fluid is the lifeblood of drilling engineering, providing important support for removing bottom cuttings, cooling drilling tools, and controlling formation pressure during drilling. Its performance is the key to successful drilling. At present, as energy demand increases year-by-year, deep exploration and development, especially deep and ultra-deep oil and gas, marine oil and gas, and new energy sources such as dry hot rock geothermal resources, have become inevitable. The ultra-high-temperature and high-pressure environment in the well poses severe challenges to the performance of the drilling fluid. This environment may even lead to complete destruction of the drilling fluid system and rapid deterioration of performance, resulting in various complex downhole accidents. Therefore, it is urgent to study ultra-high-temperature and high-pressure drilling fluids to optimize the high-temperature and high-pressure resistance of drilling fluids. As a result, it is necessary to establish ultra-high-temperature and high-pressure water-based drilling fluids, ultra-high-temperature and high-pressure oil-based drilling fluids, and ultra-high-temperature and high-pressure synthetic-based drilling fluid systems to ensure safe and efficient drilling of deep formations. Among them, the research of ultra-high-temperature and high-pressure water-based drilling fluids includes the development of new monomer synthesis and conversion techniques; development of salt-resistant high-temperature and high-pressure fluid loss reducers, viscosity reducers, inhibitors, lubricants, plugging agents, and well-wall stabilizers; and the development of anti-high-temperature thickeners and high-temperature and high-pressure fluid loss reducers. Research on ultra-high-temperature and high-pressure oil-based drilling fluids includes development of oil-based drilling fluid treatment agents such as ultra-high-temperature and high-efficiency emulsifiers, tackifiers, fluid loss additive, and flocculants; development of high-performance adhesives and surfactants; development of new reversible emulsification drilling fluid systems; and rheology control methods for forming a system. Research on ultra-high-temperature and high-pressure synthetic-based drilling fluid includes research and development of new low-cost synthetic base materials, development of emulsifiers, flow modifiers, tackifiers, and flocculants for synthetic-based drilling fluids.

(12) Multiphysics-coupling disaster-causing mechanisms in deep metal mining processes

Deep metal mining faces the complex environment of the “three highs” and “one disturbance,” i.e., high ground stress, high osmotic pressure, high temperature, and strong mining disturbance. This research front aims to explore the multi-field coupling regulation of stress field, seepage field, temperature field, and chemistry field of deep metal mining, revealing gestation, evolution, and occurrence mechanisms of deep metal explosions such as deep rock burst and soft rock deformation under the multi-field coupling condition to lay the foundation for the advanced prediction and regulation of deep metal mine disasters.

Research and development areas include deep high-efficiency stress, seepage, temperature, chemical, and other multi-field environmental identification sensors and rapid detection methods to accurately identify the multi-field coupling environment of deep mining; multi-field coupling mechanics test systems, and discovery of the multi-field coupling rock mechanics behaviors; multi-field environmental intelligence inversion and dynamic monitoring analysis technology, deduction of the multi-field environment in the mining area by limited test data; investigation of the mechanisms of multi-field coupling disasters in deep mining; and development of numerical simulation software for mining disasters under multi-field coupling to develop the rock mass control concepts and the technology of multi-field coupled environmental conditions.

Based on existing research bases, the development in the future will focus on key research fields, i.e., “accurate intelligent identification technology under deep multi-field coupled environment,” “deep multi-field coupling mechanics test system,” “multi-field environmental intelligent deduction and dynamic monitoring analysis technology,” and “multi-field coupling disaster mechanism and rock mass control technology in deep mining,” to achieve innovative theoretical development and equipment-level breakthrough.

1.2 Interpretations for four key engineering research fronts

1.2.1 Multivariate and high-density energy storage methods coupled with renewable energy

(1) Conceptual explanation and key technologies

The efficient and large-scale utilization of renewable energies include hydro, wind, solar, biomass, and geothermal energies is the inevitable choice and important guarantee for the sustainable development of global energy and environment. As far as resources and technology development are concerned, wind, solar, and hydro energies have the best prospects for development, and power generation is the most realistic and prospective way to use them. However, a notable disadvantage of wind and solar power generation is that the output power is directly affected by environmental and climatic factors and, thus, exhibits great fluctuation, randomness, and intermittent behaviors. Such unqualified power cannot be directly connected to the grid on a large scale.

Energy storage technology is an energy utilization technology that absorbs and stores energy for a period of time and then releases it in a controlled way. According to the different storage media, energy storage technologies can be divided into five categories of mechanical, electrical, electrochemical, thermal, and chemical energy storage. Mechanical energy storage includes pump water, compressed air, and flywheel energy storage. Electrical energy storage generally includes supercapacitor and superconductor energy storage. Electrochemical energy storage refers to the energy storage using all kinds of batteries. Thermal energy storage stores electricity in the form of sensible, phase change, or chemical heat in the medium in a thermal insulation container, and then converts the stored heat into power or uses it as a thermal source. Chemical energy storage refers to the use of electricity to produce hydrogen or synthetic gas, ammonia, and other secondary energy carriers. Energy storage density is used to measure the energy storage capacity of energy storage equipment per unit mass or volume, which is also divided into energy density and power density. The former corresponds to the amount of energy stored, while the latter corresponds to the speed of energy storage and release. High-density energy storage with high energy density and high power density is the key to large-scale and efficient utilization of renewable energy. The associated research directions include the development of a single type of energy storage method with a high-density energy performance, and the development of multivariate energy storage systems using a combination of multiple energy storage methods.

(2) Development status and future development trends

The technologies of renewable energy power generation and energy storage are developing rapidly worldwide. By the end of 2018, the total installed capacity of renewable energy power generation in the world had reached 2351 gigawatts (GW), including 1172 GW of hydropower, 564 GW of wind, 480 GW of solar energy, 121 GW of biomass, and 539 GW of geothermal energy. The cumulative in-service installed capacity of energy storage worldwide was 180.9 GW, an increase of 3% over the previous year, of which the pump water storage was 170.7 GW, accounting for 94%. The electrochemistry energy storage reached 4.89 GW, an increase of 66.3% over 2017. Among the electrochemistry energy storage, lithium ion batteries accounted for 86% of the total installed capacity, followed by sodium-sulfur batteries and lead-acid batteries, both accounting for 6%. In 2018, the installed capacity of renewable energy in the world was amounted to 171 GW, a year-on-year growth of 7.9%, of which 94 GW was solar energy, accounting for the largest proportion, while 49 GW and 21 GW was wind power and hydropower, respectively. Two-thirds of the world's new electricity generation came from renewable energies. The newly-added in-service installed capacity of energy storage in the world was 5.5 GW, of which the largest was electrochemical energy storage, with a growth rate of 288% compared with the previous year.

China is the country with the fastest development of renewable energy power generation and energy storage technologies. By the end of 2018, the cumulative installed capacity of renewable energies had reached 729 GW, accounting for 38.4% of the total installed capacity of the country, of which hydropower reached 352 GW, accounting for 18.5% of the total installed capacity, wind power reached 184 GW, accounting for 9.7%, and photovoltaic power reached 174 GW, accounting for 9%. The cumulative installed capacity of in-service energy storage projects in China was 31.2 GW, an increase of 8% over the previous year, of which pump water energy storage was approximately 30 GW, accounting for 96% of the total installed capacity. The next largest two were electrochemical storage and molten salt storage, with a capacity of 1.01 GW and 0.22 GW and an increase of 159% and 1000%, respectively. In 2018, the newly-installed capacity of photovoltaic power was 44.26 GW, while the newly-added in-service installed capacity of the energy storage was 2.3 GW, of which electrochemical energy storage was the largest, with a number of 0.6 GW, an increase of 414% over 2017.

Constructing a power generation system that couples wind, solar, hydro, and thermal energies with energy storage units is an important way to solve the problem of discontinuity and instability of renewable energy generation. In recent years, China has successfully launched several demonstration applications of centralized renewable energy grid connection technologies. In Qinghai Province, the world's largest water–solar complementary photovoltaic power station was established. An 850 megawatt (MW) photovoltaic power station was connected to a hydropower station as a "virtual hydropower unit." The photovoltaic power is smoothly and steadily transferred to the power grid through the rapid regulation of the hydro-turbine units. In Jilin Province, one wind farm realized the fast tracking of the changes of curtailed wind power by means of an energy storage system equipped with regenerative electric boilers, and another wind farm demonstrated the integrated operation of wind power and energy storage systems.

Generally speaking, up to the present, only pump water energy storage and compressed air energy storage are relatively mature among the large-scale energy storage technologies in China and worldwide, but they are restricted by geographical conditions. In-service compressed air storage also burns fossil fuels to provide the heat source. Other energy storage technologies are still at the stage of demonstration and laboratory research. Breakthroughs are needed in their reliability, service life, cost, and application adaptability. These technologies are still not qualified for wide popularization and application in the power grid, restricting the efficient and large-scale utilization of renewable energy. Coupling the renewable energy generation technology with multivariate high-density energy storage can not only make possible the large-scale access of renewable energy to power grid, but also meet the urgent demand of flexible peak shaving required by the smart grid.

The emerging fronts include low-cost, high-performance, single-type, high-density energy storage methods; multivariate and high-density energy storage methods that are complementary to each other and coupled with renewable energy; multivariate and high-density energy storage methods that meet the different needs of power generation, transmission, distribution, and usage stages of renewable energy; and renewable energy power supply systems based on complementary coupling of wind, solar, hydro, and thermal energies.

(3) Comparison and cooperation analysis based on major countries/regions and institutions

As shown in Table 1.2.1, China, the USA, India, and the UK are the countries with the largest number of core papers published in this research direction, with China and the USA ranking first and second, publishing 39.05% and 20.95% of the core papers, respectively. The proportion of core papers published by India and the UK is 9.05% each.

As shown in Table 1.2.2, the Chinese Academy of Sciences, Shanghai Jiao Tong University, the University of Chinese Academy of Sciences, the Universiti Malaysia Pahang, and Tsinghua University are the organizations with the largest number of core papers published in this research direction, the number of core papers being 11, 7, 6, 5, and 5, respectively.

As shown in Figure 1.2.1, China, the USA, the UK, Australia, and Spain are the countries that pay more attention to this engineering research front. China has the largest number of core papers published, and the major countries that cooperate with China in publishing core papers are the USA, the UK, Australia, and Japan. The USA has the second largest number of core papers published, and it cooperates with China, Spain, Australia, and Canada in publishing core papers.

As depicted in Figure 1.2.2, in this research direction the Chinese Academy of Sciences has close cooperation with the University

Table 1.2.1 Countries or regions with the greatest output of core papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	82	39.05%	1929	21.78%	23.52
2	USA	44	20.95%	4388	49.55%	99.73
3	India	19	9.05%	476	5.37%	25.05
4	UK	19	9.05%	681	7.69%	35.84
5	Australia	16	7.62%	1001	11.30%	62.56
6	Germany	12	5.71%	337	3.81%	28.08
7	Canada	11	5.24%	212	2.39%	19.27
8	Spain	10	4.76%	367	4.14%	36.70
9	South Korea	9	4.29%	125	1.41%	13.89
10	Japan	7	3.33%	113	1.28%	16.14

Table 1.2.2 Institutions with the greatest output of core papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	11	5.24%	219	2.47%	19.91
2	Shanghai Jiao Tong Univ	7	3.33%	63	0.71%	9.00
3	Univ Chinese Acad Sci	6	2.86%	110	1.24%	18.33
4	Univ Malaysia Pahang	5	2.38%	136	1.54%	27.20
5	Tsinghua Univ	5	2.38%	83	0.94%	16.60
6	Indian Inst Technol	4	1.90%	112	1.26%	28.00
7	Univ Wollongong	4	1.90%	85	0.96%	21.25
8	Pacific NW Natl Lab	3	1.43%	692	7.81%	230.67
9	MIT	3	1.43%	572	6.46%	190.67
10	Stanford Univ	3	1.43%	753	8.50%	251.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “multivariate and high-density energy storage methods coupled with renewable energy”

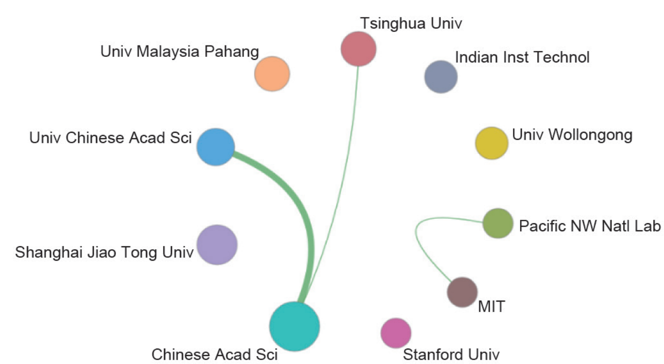

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “multivariate and high-density energy storage methods coupled with renewable energy”

of the Chinese Academy of Sciences, and has cooperation with Tsinghua University. Massachusetts Institute of Technology (MIT) and the Pacific NW National Laboratory also have some cooperation.

Table 1.2.3 shows that the country with the greatest number of citing papers is China, with a percentage of 45.38%, followed by the USA, with a percentage of 17.98%. Germany and South Korea also cite more than 5% of core papers.

In Table 1.2.4, the institution with the greatest number of citing papers is the Chinese Academy of Sciences, with a percentage of 27.65%, followed by the University of the Chinese Academy of Sciences, with a percentage of 10.28%, Tsinghua University and China University of Science and Technology, with a percentage of 9.51% and 8.11%, respectively.

The above data analysis indicates that China and the USA are at the forefront in the number and citation of core papers in the engineering research front of multivariate high-density energy storage methods coupled with renewable energy. The number and citation of the core papers of the Chinese Academy of Sciences and several Chinese universities are of the highest in the world.

1.2.2 Research on damage mechanisms and verification of advanced nuclear fuel and related materials

Nuclear fuel contains most of the radioactive materials and is the first line of defense against the release of radioactive materials. Therefore, while the international community is developing advanced nuclear fuels, it is also vigorously

Table 1.2.3 Countries or regions with the greatest output of citing papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	4173	45.38%	2017.3
2	USA	1653	17.98%	2016.8
3	Germany	631	6.86%	2016.9
4	South Korea	558	6.07%	2017.0
5	Australia	417	4.53%	2017.2
6	UK	342	3.72%	2017.0
7	India	342	3.72%	2017.5
8	Japan	336	3.65%	2016.9
9	Singapore	273	2.97%	2016.9
10	Canada	249	2.71%	2016.9

Table 1.2.4 Institutions with the greatest output of citing papers on “multivariate and high-density energy storage methods coupled with renewable energy”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	573	27.65%	2017.2
2	Univ Chinese Acad Sci	213	10.28%	2017.5
3	Tsinghua Univ	197	9.51%	2017.1
4	Univ Sci & Technol China	168	8.11%	2017.4
5	Univ Munster	159	7.67%	2016.4
6	Huazhong Univ Sci & Technol	137	6.61%	2017.0
7	Nanyang Technol Univ	135	6.52%	2016.9
8	Cent S Univ	133	6.42%	2017.3
9	Forschungszentrum Julich	128	6.18%	2017.5
10	Tianjin Univ	117	5.65%	2017.3

conducting research on the damage mechanisms of nuclear fuels and related materials.

At present, according to the existing engineering experience and material irradiation behavior, it is possible to better predict and evaluate the behavior of cladding corrosion, stress strain, and fission gas release of existing PWR fuel under stable operating conditions. The current research primarily focuses on the material damage and failure mechanism in transient and accident scenarios of nuclear power plants. Among them, the pellet-cladding interaction (PCI) in power transients involves the initial microcrack of cladding under the action of the corrosive fission gas atmosphere, which continuously expands due to the extrusion of fuel and causes the cladding to fail. In addition to the special concern on the instability oxidation of the cladding in a loss of coolant accident, attention should also be paid to the fragmentation, dispersal, and relocation of the fuel itself during the accident, which will have a profound impact on the consequences of the accident. In addition to the above-mentioned damage mechanisms and failure behaviors in the reactor, the material performance degradation mechanisms of spent fuel cladding during dry storage of PWRs, including hydride reorientation and delayed hydrogenation cracking, are closely related to safety of dry storage of spent fuel. Therefore, it is also the focus of research of the international community at present.

The analysis and mechanism of damage and failure behavior of advanced nuclear fuels and related materials are conducted in combination with macro-scale and micro-scale multi-scale research and analysis. Macroscopically, various types of experiments are performed, including various material performance tests, ion irradiation tests, and re-fabricated rod tests to obtain the behavior of materials in specific scenarios. Microscopically, various types of microstructure, morphology, and composition analysis tools, such as metallographic microscopes, scanning electron microscopes, and fluoroscopy electron microscopes, are used to study the internal characterization of defects, dislocations, phase transitions, and segregation, to explain the macroscopic material behavior.

To better carry out the unification of material behavior and mechanism at multi-scales, many countries have conducted research on the damage mechanisms of advanced nuclear fuel and related materials under irradiation conditions in the molecular dynamics field, and have established related models to predict the material irradiation behavior.

According to Table 1.2.5, the countries or regions with the largest number of core papers published in this research direction are the USA, China, and South Korea. Among them, the USA ranked first, having a proportion of core papers reaching 64.15%. The proportion of core papers of China exceeded 10%.

According to Table 1.2.6, the largest number of core papers published in this research direction are from Oak Ridge National Laboratory and Idaho National Laboratory, whose numbers of core papers published are both more than 10.

Table 1.2.5 Countries or regions with the greatest output of core papers on “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	68	64.15%	751	70.58%	11.04
2	China	12	11.32%	55	5.17%	4.58
3	South Korea	10	9.43%	150	14.10%	15.00
4	Sweden	6	5.66%	40	3.76%	6.67
5	UK	6	5.66%	38	3.57%	6.33
6	Japan	3	2.83%	44	4.14%	14.67
7	France	3	2.83%	24	2.26%	8.00
8	Germany	3	2.83%	20	1.88%	6.67
9	Czech Republic	3	2.83%	13	1.22%	4.33
10	Poland	2	1.89%	1	0.09%	0.50

Table 1.2.6 Institutions with the greatest output of core papers on “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Oak Ridge Natl Lab	22	20.75%	328	30.83%	14.91
2	Idaho Natl Lab	10	9.43%	88	8.27%	8.80
3	Penn State Univ	7	6.60%	124	11.65%	17.71
4	Los Alamos Natl Lab	7	6.60%	53	4.98%	7.57
5	MIT	7	6.60%	47	4.42%	6.71
6	Korea Atom Energy Res Inst	6	5.66%	131	12.31%	21.83
7	Westinghouse Elect Co	6	5.66%	108	10.15%	18.00
8	GE Global Res	6	5.66%	7	0.66%	1.17
9	Univ Wisconsin	4	3.77%	21	1.97%	5.25
10	Gen Atom Co	3	2.83%	96	9.02%	32.00

According to Figure 1.2.3, the USA, China, the UK, Germany, the Czech Republic, France, South Korea, and Sweden are more concerned about the cooperation between countries or regions in this field. China has many published papers, mainly in cooperation with the USA and Sweden.

According to Figure 1.2.4, the Oak Ridge National Laboratory, the Idaho National Laboratory, Pennsylvania State University, the Los Alamos National Laboratory, Westinghouse Electric Company, and the University Wisconsin have collaborated.

As given in Table 1.2.7, the country with the largest number of citing papers is the USA, with a proportion of 37.44%. China has a citing proportion of 26.99%, while South Korea has a citing proportion of 10.92%.

As shown in Table 1.2.8, Oak Ridge National Laboratory is the organization that produces the most of core papers, having a proportion of citing papers of 29.03%. The proportion of citing papers of the Korea Atomic Energy Research Institute is 10.26%.

The above data analysis indicates that the USA and China are leading producers of core papers in the field of nuclear fuels and related materials in terms of damage mechanisms and verification techniques. The number of citing papers of US research institutions is comparatively large.

1.2.3 AI applied to reservoir prediction mechanisms

The combination of AI and oilfield technologies may solve various bottlenecks and new problems in oilfield exploration and development. It is imperative to promote the transformation and application of the AI technology in old oilfields and oilfield industries. The greatest revelation of AI on reservoir prediction is that it can still produce significant prediction results by relying on massive data and deep

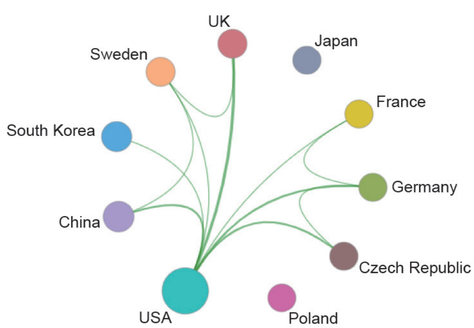

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

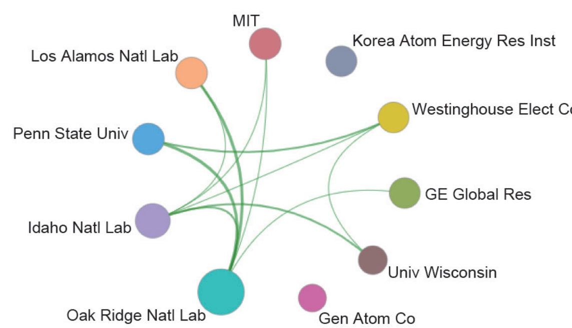

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

Table 1.2.7 Countries or regions with the greatest output of citing papers on “research on damage mechanisms and verification of advanced nuclear fuel and related materials”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	240	37.44%	2017.7
2	China	173	26.99%	2018.2
3	South Korea	70	10.92%	2017.6
4	UK	39	6.08%	2018.2
5	Germany	26	4.06%	2018.1
6	Sweden	22	3.43%	2017.9
7	Japan	21	3.28%	2018.0
8	Russia	18	2.81%	2018.3
9	France	13	2.03%	2018.4
10	Canada	11	1.72%	2018.4

Table 1.2.8 Institutions with the greatest output of citing papers on "research on damage mechanisms and verification of advanced nuclear fuel and related materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Oak Ridge Natl Lab	99	29.03%	2017.5
2	Korea Atom Energy Res Inst	35	10.26%	2017.5
3	Idaho Natl Lab	33	9.68%	2017.8
4	Los Alamos Natl Lab	31	9.09%	2018.2
5	Univ Wisconsin	25	7.33%	2017.8
6	Chinese Acad Sci	25	7.33%	2018.5
7	Univ Tennessee	21	6.16%	2018.1
8	Penn State Univ	19	5.57%	2017.6
9	Nucl Power Inst China	19	5.57%	2018.4
10	MIT	17	4.99%	2018.0

learning algorithms without clear reservoir patterns and laws. The reservoir prediction process involves a large amount of data, including geological data, geomechanical data, reservoir data, engineering data, economic data, and so on. However, the data scale and resolution are not uniform, the spatial density is large, the time and frequency are different, and most of the explanatory data are obtained indirectly with great uncertainty.

Big data techniques should be used for high-precision geological modeling and high-efficiency reservoir numerical simulation, while techniques such as unstructured grids and dynamic simulations should be used to describe the underground reservoirs more accurately. Ultimately, all the data is integrated on a unified platform to facilitate decision-making based on both data and models. Based on the quantitative and visual 3D model, all measurement data and constraints for the specific oil and gas field exploration and development life cycle are presented.

Based on the AI algorithms, the uncertainties of the model are reduced by continuously updating the model, driven by the abundant data, thus automatically facilitating making the most scientific and reasonable predictions and decisions based on full consideration of all data and laws. Based on a series of intelligent tools, equipment, and methods, deep learning and cognitive analysis of various data in the reservoir can help find oil and gas enrichment areas. However, the AI technology is still in its theoretical infancy stage for reservoir prediction applications. It is necessary to clarify the direction in strategic research and implement breakthroughs in key technologies. This is the key to realizing the enhancement of oil and gas exploration and development technology in China. It is hoped that this application will allow the big data and AI technologies to go hand-in-hand with the evolution of oil and gas exploration and development, thereby extracting more oil and gas resources underground to meet the country's growing energy needs.

Relevant papers in this area are published and cited primarily by Iran, Saudi Arabia, the USA, China, and other countries, as given in Tables 1.2.9 and 1.2.11. The foremost institutions include Petroleum University of Technology, King Fahd University of Petroleum and Minerals, Islamic Azad University, and the Technical College of Amirkabir University, as given in Tables 1.2.10 and 1.2.12. Australia has cooperated with the USA and Iran. Saudi Arabia has cooperated with Egypt and Malaysia; the Islamic Azad University, the Petroleum University of Technology, and the Southern Cross University have cooperated, as shown in Figures 1.2.5 and 1.2.6.

1.2.4 Concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas

(1) Concepts of safe, highly efficient, and intelligent extraction of coal

At present, the principals of safe, highly efficient, and intelligent extraction of coal are still in their infancy; they are entering the key stage of technological innovation and development. Therefore, it is necessary to research and develop key technologies such as integration of adaptive control and support systems for intelligent control of mining

Table 1.2.9 Countries or regions with the greatest output of core papers on “AI applied to reservoir prediction mechanisms”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Iran	19	43.18%	140	57.38%	7.37
2	Saudi Arabia	10	22.73%	57	23.36%	5.70
3	USA	5	11.36%	9	3.69%	1.80
4	Canada	4	9.09%	18	7.38%	4.50
5	Australia	4	9.09%	6	2.46%	1.50
6	China	3	6.82%	11	4.51%	3.67
7	Egypt	3	6.82%	18	7.38%	6.00
8	Algeria	2	4.55%	7	2.87%	3.50
9	France	2	4.55%	7	2.87%	3.50
10	Malaysia	1	2.27%	14	5.74%	14.00

Table 1.2.10 Institutions with the greatest output of core papers on “AI applied to reservoir prediction mechanisms”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Petr Univ Technol	9	20.45%	89	36.48%	9.89
2	King Fahd Univ Petr & Minerals	9	20.45%	56	22.95%	6.22
3	Islamic Azad Univ	7	15.91%	83	34.02%	11.86
4	Amirkabir Univ Technol	3	6.82%	35	14.34%	11.67
5	Univ Alberta	3	6.82%	12	4.92%	4.00
6	Southern Cross Univ	3	6.82%	5	2.05%	1.67
7	Univ Tehran	2	4.55%	20	8.20%	10.00
8	Nexen Energy ULC	2	4.55%	11	4.51%	5.50
9	Univ MHamed Bougara	2	4.55%	7	2.87%	3.50
10	Univ Rennes 1	2	4.55%	7	2.87%	3.50

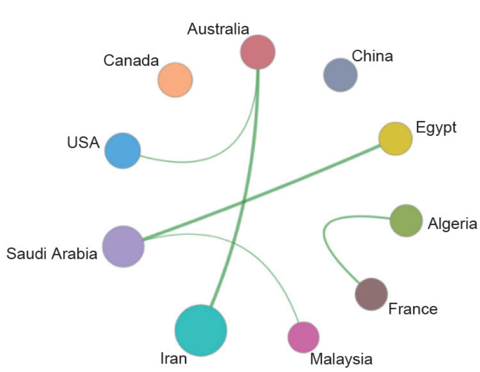

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “AI applied to reservoir prediction mechanisms”

height in surrounding rock, intelligent navigation for working face straightness, multi-information fusion and coordination of systems, intelligent advance support, and auxiliary operation. By realizing self-perception of environmental parameters for comprehensive mechanized equipment and self-regulation of mining behavior, the intelligent mining technology can be upgraded.

With the intelligent development of fully mechanized mining, its strategic position is becoming increasingly prominent. Intelligent mining is one of the core systems of an intelligent coal mine. Precise mining also requires few people or applies unattended remotely-controllable intelligent mining as

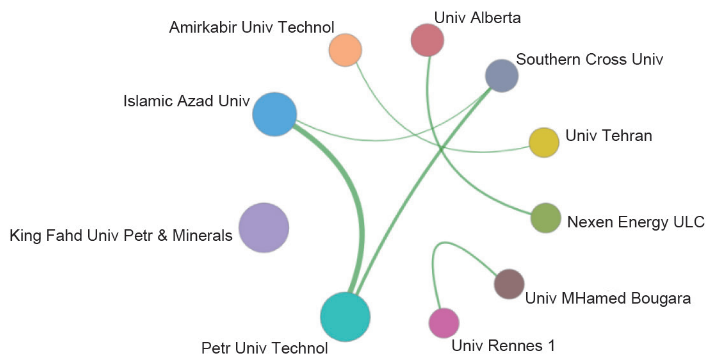

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "AI applied to reservoir prediction mechanisms"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "AI applied to reservoir prediction mechanisms"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Iran	76	31.93%	2016.8
2	China	40	16.81%	2017.6
3	Saudi Arabia	27	11.34%	2017.7
4	USA	20	8.40%	2017.4
5	Canada	19	7.98%	2017.5
6	Australia	16	6.72%	2015.9
7	India	11	4.62%	2017.2
8	France	8	3.36%	2016.6
9	South Korea	7	2.94%	2017.4
10	Malaysia	7	2.94%	2017.1

Table 1.2.12 Institutions with the greatest output of citing papers on "AI applied to reservoir prediction mechanisms"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Petr Univ Technol	31	21.83%	2015.7
2	King Fahd Univ Petr & Minerals	21	14.79%	2017.7
3	Amirkabir Univ Technol	19	13.38%	2017.6
4	Islamic Azad Univ	17	11.79%	2016.1
5	Univ Tehran	13	9.15%	2017.4
6	Shahrood Univ Technol	8	5.63%	2018.5
7	Southwest Petr Univ	8	5.63%	2017.4
8	So Cross Univ	7	4.93%	2015.4
9	Tsinghua Univ	6	4.23%	2017.3
10	China Univ Petr	6	4.23%	2017.7

an important support. At present, many coal enterprises grasp the new trend of technological development and vigorously upgrade mining technologies and equipment, which provides an important opportunity for the intelligent and fully mechanized mining technology. However, there also exist some practical problems such as an insufficient understanding of intelligent mining. The key research directions of safe, highly efficient, and intelligent extraction of coal include the “transparent mining” technology, intelligent coupling and adaptive control of a hydraulic support control group and surrounding rocks, intelligent height control of the shearer, the cooperative control technology based on multi-information fusion systems, and intelligent control of advanced support and auxiliary operation.

(2) Concepts of safe, highly efficient, and intelligent extraction of oil and gas

With the development of oil and gas exploration and development towards unconventional, low-permeability, ultra-deep, deep-water oil and gas, future oil and gas exploitation faces a series of difficulties and challenges in terms of safety, economy, and efficiency. Therefore, it is urgent to accelerate the cross-border integration of big data, AI, information engineering, and underground control engineering, and establish a sound theoretical system of safe, efficient, and intelligent development. The eventual aim is to achieve advanced detection, closed-loop regulation, real-time warning, and intelligent decision-making, further promote the safe and economical extraction of oil and gas resources, and provide an important support for achieving the major breakthroughs in complex oil and gas extraction in China.

The concepts of safe, highly efficient, and intelligent extraction of oil and gas primarily involve reservoir characterization, downhole condition perception, closed-loop parameter control, and intelligent decision-making for selection of extraction schemes. The reservoir characterization describes and evaluates the oil and gas flow characteristics in the reservoirs during the entire production process and provides a basic reference for oil and gas exploitation regulation. Currently, Texas A&M University has conducted research on multi-scale interpretation of oil and gas reservoirs based on geophysical data. Shell Oil Co. has built a 3D transparent reservoir that can be used for real-time interactive analysis. The downhole condition perception identifies and diagnoses downhole conditions, and offers early warning of risks, which can then provides crucial support for safe extraction of oil and gas. At present, British Petroleum (BP) has conducted a study on integrated risk control for safety of underground production. China’s SINOPEC Corp. has established a relatively complete risk identification and hierarchical management mechanism.

The closed-loop parameter control is designed to transmit downhole data to the ground, and then issue control instructions to the downhole equipment to adjust the parameters based on the dynamic analysis by a ground-based expert system. In this way, the bidirectional transmission of information is established, and the closed-loop real-time control is achieved, which can lay an important foundation for the economical and efficient production of oil and gas. At present, Schlumberger, PetroChina, and other companies have proposed a relatively complete automatic regulation mechanism for oil and gas production equipment based on monitoring of real-time data such as downhole temperature, pressure, and flow velocity. The intelligent decision-making of extraction scheme for oil and gas fields utilizes the big data of oil and gas fields, and then optimizes the extraction scheme using AI, which provides key support for China’s progress toward the smart oilfield. Currently, based on analysis of multi-dimensional massive data, Shell has realized the intelligent management of extraction schemes in hundreds of production and injection wells. However, China is still in its early stage of development in this research field.

The predominant research trends of reservoir characterization include the fine-grained characterization of reservoir elements, 3D dynamic geological modeling, real-time correction of the geological models, and the reconstruction theory. The key research trends of downhole condition perception include the response mechanisms of underground monitoring equipment, automatic diagnosis of downhole risks, and the associated early warning concepts. The primary research trends of closed-loop parameter control include the bidirectional high-efficiency transmission of massive data and the closed-loop optimization of downhole control parameters. The foremost research trends of intelligent decision-making include the dynamic optimization of extraction schemes of oil and gas based on big data and AI, and the concepts of intelligent flow, integration, and self-purification of massive data during long-term extraction.

(3) Comparison and cooperation between countries/regions and institutions

As seen in Table 1.2.13, the countries or regions with the largest number of core papers addressing intelligent extraction concepts are China, the USA, and Saudi Arabia. The proportion of core papers published in other countries is less than 10% while the proportion of core papers in China exceeds 50%. It is observed that the largest number of core papers published are from Xi'an Shiyou University with a ratio of more than 10%, while the output ratio of core papers of other institutions is approximately 6% as seen in Table 1.2.14.

Based on Figure 1.2.7, the USA and Saudi Arabia focus more on cooperative research in this field. The USA has cooperated with China and France. Saudi Arabia has cooperated with Pakistan and Malaysia. No collaborative research has yet been conducted between other countries or regions. According to Figure 1.2.8, the Ocean University of China, National Laboratory for Marine Science & Technology (Qingdao), the SINOPEC Research Institute of Petroleum Exploration and Development, Shandong University, Shandong University of Science & Technology, and Shandong Zhengyuan Construction Engineering Co., Ltd. perform cooperative studies. Each institution has cooperated with the other four institutions. However, Xi'an Shiyou University, which has the largest number of core papers published, has not cooperated with any other institution.

According to Table 1.2.15, the countries or regions with the largest number of citing papers published are China, Saudi Arabia, Canada, and the UK. The proportion of citing papers in China is more than 30%, and the proportion of citing papers in

Table 1.2.13 Countries or regions with the greatest output of core papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	10	58.82%	25	40.32%	2.50
2	USA	3	17.65%	11	17.74%	3.67
3	Saudi Arabia	2	11.76%	21	33.87%	10.50
4	Iran	1	5.88%	2	3.23%	2.00
5	France	1	5.88%	7	11.29%	7.00
6	Norway	1	5.88%	0	0.00%	0.00
7	Canada	1	5.88%	7	11.29%	7.00
8	Malaysia	1	5.88%	12	19.35%	12.00
9	Pakistan	1	5.88%	9	14.52%	9.00

Table 1.2.14 Institutions with the greatest output of core papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Xi'an Shiyou Univ	2	11.76%	0	0.00%	0.00
2	Ocean Univ China	1	5.88%	1	1.61%	1.00
3	Qingdao Natl Lab Marine Sci & Technol	1	5.88%	1	1.61%	1.00
4	SINOPEC Res Inst Petr Explorat & Dev	1	5.88%	1	1.61%	1.00
5	Shandong Univ	1	5.88%	1	1.61%	1.00
6	Shandong Univ Sci & Technol	1	5.88%	1	1.61%	1.00
7	Shandong Zhengyuan Construct Eng	1	5.88%	1	1.61%	1.00
8	Univ Southern Calif	1	5.88%	0	0.00%	0.00
9	Birjand Univ Technol	1	5.88%	2	3.23%	2.00
10	Univ Tehran Med Sci	1	5.88%	2	3.23%	2.00

other countries is less than 10% except for Saudi Arabia. It can be seen that the institutions with the largest number of citing papers published are the King Fahd University of Petroleum and Minerals, the China University of Petroleum, the University of Alberta, and the Southwest Petroleum University, with the proportion of citing papers in these institutions being more than 10%, as listed in Table 1.2.16. The average citing dates are in 2017 and 2018.

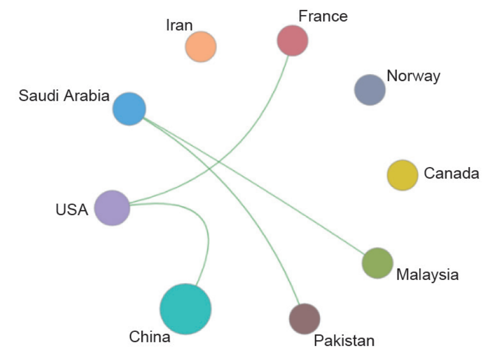

Figure 1.2.7 Collaboration network among major countries or regions in the engineering research front of "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

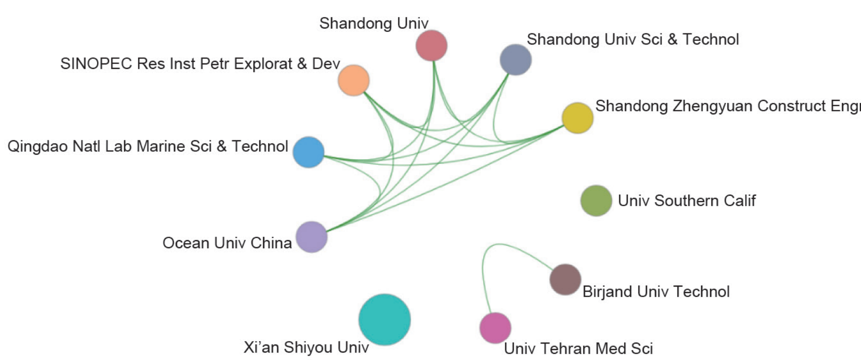

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

Table 1.2.15 Countries or regions with the greatest output of citing papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	23	32.39%	2018.1
2	Saudi Arabia	11	15.49%	2017.5
3	Canada	7	9.86%	2018.4
4	UK	7	9.86%	2018.0
5	USA	5	7.04%	2017.6
6	Malaysia	4	5.63%	2017.3
7	Iran	4	5.63%	2018.0
8	India	3	4.23%	2019.0
9	Tunisia	3	4.23%	2017.0
10	Egypt	2	2.82%	2018.5

Table 1.2.16 Institutions with the greatest output of citing papers on "concepts of safe, highly efficient, and intelligent extraction of coal, oil, and gas"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	King Fahd Univ Petr & Minerals	7	18.92%	2017.3
2	China Univ Petr	7	18.92%	2017.4
3	Univ Alberta	4	10.81%	2018.3
4	Southwest Petr Univ	4	10.81%	2018.5
5	China Univ Petr East China	3	8.11%	2018.7
6	Saudi Arabian Oil Co	2	5.41%	2017.0
7	Univ Malaysia Sarawak	2	5.41%	2017.0
8	Texas A&M Univ	2	5.41%	2018.0
9	Digital Res Ctr Sfax CRNS	2	5.41%	2017.0
10	Higher Inst Comp Sci & Multimedia Sfax	2	5.41%	2017.0

2 Engineering development fronts

2.1 Trends in top 12 engineering development fronts

The top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these top 12 development fronts, "advanced technologies for EV/hybrid electric vehicle (HEV) and power batteries," "highly efficient coal conversion and ultra-low-emission control technologies," "technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation," and "technologies of intelligent, integrated, and small module floating reactors" are emerging fronts. "Fracture shape processing method and system based on microseismic monitoring," "seismic signal acquisition and processing technologies for marine seismic exploration," "research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives," and "development of advanced warning systems for mining disasters in the deep metal mines" are the further developments of traditional existing research fields. "Nuclear high-temperature hydrogen production and helium turbine power generation technology" is the subversive front. "Technologies for safe, intelligent, and precise mining of coal" and "oilfield-integrated digital ecological management system based on wireless sensor networks" are the fronts of interdisciplinary integration. "Digitalized and intelligentized nuclear power plant and reactor technology" is both an emerging front and a subversive front. The numbers of core papers published each year from 2013 to 2018 for the top 12 engineering development fronts are listed in Table 2.1.2.

(1) Advanced technologies for EV/HEV and power batteries

Compared with traditional fuel vehicles, EV refers to a vehicle whose power energy system is composed of motors and power batteries. The HEV is a type of vehicle with a multi-power system combining engine and one or more electrical driving motors.

EVs have the advantages of low greenhouse gas emission, low energy consumption, and low noise. However, compared with traditional fuel vehicles, they generally have the shortcomings of a long charging time, a short effective driving range, and a short battery life. The HEV has the advantages of being both a fuel-operated vehicle and an EV. Compared with a fuel vehicle, the HEV has a lower fuel consumption and less pollution. Meanwhile, it has the advantages of fast charging and longer driving distance compared with the pure EV because of its dual energy storage. However, its structure is more complex and its cost is generally higher than the traditional fuel-operated vehicle.

The commonly used power batteries typically include lithium iron phosphate batteries and ternary lithium ion batteries. In recent years, the key research for the EV/HEV and power battery technology include the advanced powertrain, energy management, advanced auxiliary driving, automatic driving,

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Advanced technologies for EV/HEV and power batteries	290	11 923	41.11	2014.1
2	Nuclear high-temperature hydrogen production and helium turbine power generation technology	196	418	2.13	2015.0
3	Fracture shape processing method and system based on microseismic monitoring	69	861	12.48	2014.5
4	Technologies for safe, intelligent, and precise mining of coal	119	198	1.66	2016.3
5	Highly efficient coal conversion and ultra-low-emission control technologies	316	704	2.23	2015.5
6	Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation	277	1 715	6.19	2014.7
7	Digitalized and intelligentized nuclear power plant and reactor technology	390	1 130	2.9	2014.9
8	Technologies of intelligent, integrated, small module floating reactors	160	556	3.48	2015.2
9	Oilfield-integrated digital ecological management system based on wireless sensor networks	237	2 968	12.52	2014.2
10	Seismic signal acquisition and processing technologies for marine seismic exploration	205	2 253	10.99	2014.3
11	Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives	225	3 872	17.21	2014.1
12	Development of advanced warning systems for mining disasters in the deep metal mines	38	31	0.82	2016.2

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

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Advanced technologies for EV/HEV and power batteries	124	69	53	33	11	0
2	Nuclear high-temperature hydrogen production and helium turbine power generation technology	20	16	12	28	49	32
3	Fracture shape processing method and system based on microseismic monitoring	16	21	17	11	4	0
4	Technologies for safe, intelligent, and precise mining of coal	9	6	11	28	31	31
5	Highly efficient coal conversion and ultra-low-emission control technologies	18	33	79	66	47	55
6	Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation	25	23	35	48	40	48
7	Digitalized and intelligentized nuclear power plant and reactor technology	51	74	44	45	57	73
8	Technologies of intelligent, integrated, small module floating reactors	18	19	20	37	35	19
9	Oilfield-integrated digital ecological management system based on wireless sensor networks	88	71	37	32	9	0
10	Seismic signal acquisition and processing technologies for marine seismic exploration	67	65	31	31	11	0
11	Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives	78	79	44	20	4	0
12	Development of advanced warning systems for mining disasters in the deep metal mines	6	2	5	3	9	13

fast battery charging and life extension, battery material and electrochemical system, and battery model and management. In the future, depending on the advantages brought by the rapid development of AI, big data, intelligent transportation systems, and the fifth-generation (5G) wireless data transmission technology, EVs/HEVs and battery technology will be further developed. The research on new battery materials and electrochemical systems further improved the energy density, power density, safety, cycle life, charging performance, high/low temperature performance of power batteries. The development of a new generation of vehicle power batteries (such as solid-state lithium ion batteries, lithium air batteries, and lithium sulfur batteries) will continue to be the focus of research and development.

(2) Nuclear high-temperature hydrogen production and helium turbine power generation technology

Nuclear energy hydrogen production uses the heat generated by nuclear reactors as a primary energy source to produce hydrogen from hydrous-containing material—water or fossil fuels.

In the technical route for the production of hydrogen using nuclear energy, nuclear-heat-assisted hydrocarbon reforms and uses the process heat of a high temperature gas-cooled reactor (HTGR) to replace the heat source in the conventional technology, which can partially reduce the use of fossil fuels and correspondingly reduce some CO_2 emissions. The use of nuclear power to generate hydrogen by conventional electrolysis is a combination of mature technologies, but the efficiency of converting primary energy to hydrogen energy is low. In some scenarios where the PWR has an excess power generation capacity which should be dissipated or used in special applications, it can be used to realize energy storage or supply of hydrogen. To achieve efficient conversion of nuclear energy to hydrogen energy, the process heat provided by the reactor must be partially or fully utilized to reduce the efficiency loss during the thermo–electric conversion process. The mainstream nuclear hydrogen production technologies currently developed include thermochemical cycles (iodine sulfur cycle and mixed sulfur cycle) and high-temperature steam electrolysis.

The HTGR gas turbine direct-cycle power generation is based on the theory of the closed-type Brayden cycle. The gas turbine is combined with the modular high-temperature gas-cooled reactor (MHTGR), and the high-temperature gas generated by the HTGR is used to directly push the gas turbine to work and generate power. The efficiency of direct-cycle power generation by a helium turbine can be up to 50%.

(3) Fracture shape processing method and system based on microseismic monitoring

With the maturity of the theoretical research of microseismic monitoring technology, the current microseismic monitoring technology is widely used in the fracture exploration of hydraulic fracturing in low permeability oilfields, which can realize the monitoring of reservoir fractures and cracks, and the real-time monitoring of reservoir driving after water injection and gas injection. This technology has an important significance in oilfield exploration and development. The inversion method used in the traditional microseismic positioning consumes significant time and human resources, and the positioning accuracy cannot meet the requirements. Then, the fracture shape processing method and system based on microseismic monitoring emerged.

Through model trial calculation and application of actual data, the system can effectively classify the microseismic events to obtain the shape and distribution of small cracks and micro cracks that form the fracture zone. Combined with time information, the development and extensions of each crack over time can be obtained. After that, the effect of hydraulic fracturing, the formation of the seaming system, and whether natural productivity can be improved can be further determined to achieve maximum development results. In short, this processing method and system can continuously collect and record the microseismic data in the fracturing process and realize real-time processing and visualization, effectively optimize the fracturing scheme, and provide reservoir resource evaluation and drilling position maps, achieving the purpose of increasing production and guiding oil and gas field development.

(4) Technologies for safe, intelligent, and precise mining of coal

By means of different technologies, including intelligent perception, intelligent control, the Internet of Things, cloud computing, and big data, intelligent and precise mining technology and equipment for mining safety are proposed as a new mining mode that integrates the intelligent mining technique requiring few or no workers (remote, unattended operations), providing the functions of risk identification, monitoring, and early warning. This mode is based on transparent spaces and geophysics as well as multi-field coupling to achieve spatiotemporal accuracy and efficiency.

At present, the main research directions are as follows: the innovation of geophysical sciences with transparent functions, a new type of intelligent perception, a multi-internet fusion transmission method and technical equipment, dynamic complex mining analysis of multi-field and multi-parameter information and fusion processing technologies, theoretical models on precise coal mining based on big data and cloud technology, multi-field-coupling composite disaster warning, remote-controlled intelligent coal mining technology and equipment requiring minimal crew, disaster communication, personnel orientation, disaster detection technology and equipment, and intelligent coal mine construction based on cloud technology, all of which provide a technological path for a mode of future mining that requires fewer workers, based on the Internet and scientific mining.

China has concentrated on safety mining that requires a minimal number of workers (ultimately unattended), and it will further accelerate the intensity of innovation for mining technology, with plans to fully implement a safe, intelligent, and precision mining mode by 2050 step by step, thus to upgrade current coal mining industry and eventually build a competitive energy sector.

(5) Highly efficient coal conversion and ultra-low-emission control technologies

There are two ways to realize coal conversion. The first is raw-material based conversion, i.e., to use coal as raw material to convert coal into high-value chemical products, chemical raw materials, or other forms of fuels through a coal chemical process. The second is fuel-based conversion, i.e., the use of coal as fuel to convert chemical energy into heat or electricity through combustion and other processes. Highly efficient conversion and ultra-low-emission control are required for the whole life cycle of coal utilization, including coal processing, coal conversion, and utilization of coal waste.

The emerging fronts in coal conversion include: 1) coal processing technologies, such as highly efficient dust reduction, desulfurization and water-saving coal preparation, and the new process of ultra-clean coal classification, with emphasis on the washing of steam coals for power generation; 2) advanced processes for raw-material-based coal conversion with high efficiency and ultra-low-emission, such as coal gasification, coal liquefaction, coal-to-natural gas, coal-to-chemicals, and low-rank coal pyrolysis; 3) fuel-based coal conversion technologies, including the “three-ultras” (ultra-high parameters, ultra-low-emissions, and ultra-supercritical) coal-fired boiler technology, advanced coal combustion technologies with in-furnace ultra-low-emission, highly flexible coal-fired power generation technology coupled with renewable energy and energy storage, low-cost and efficient flue gas purification technologies with zero secondary pollution, efficient and clean combustion of civic coals, high-reliability integrated coal gasification combined cycle technology, coal-based supercritical CO_2 combined cycle power generation technology, coal-based high-temperature fuel cell technology, oxygen-coal combustion technology, and other advanced CO_2 capture and storage technologies; and 4) coal waste utilization technologies, including harmless utilization of coal ash and desulfurization ash, and efficient regeneration and harmless disposal of SCR catalysts.

(6) Technologies of hydrogen generation from renewable energy sources and integrated system of storage and transportation

Hydrogen energy is widely considered to be the most promising energy in the future owing to its advantages of high energy density, wide sources, and zero emission. The combination of a hydrogen supplying system and the proton exchange membrane fuel cell techniques is the most potential alternative that may replace the conventional internal combustion engine power system for vehicles. However, over 95% of hydrogen currently comes from the production of fossil fuels. Therefore, it belongs to the secondary energy category which cannot be regarded as a complete clean energy source. Besides, the storage and transportation of hydrogen in an efficient and safe manner is also a bottleneck that restricts the application of hydrogen energy. Therefore, hydrogen production from renewable energies (such as wind, solar, and water energy) and integration of hydrogen storage and transportation can effectively solve these problems, which are embodied in the following two aspects:

1) Hydrogen production from renewable energies. In areas where wind energy and hydropower resources are abundant, a large amount of abandoned wind and hydropower resources that cannot be connected to the power grid can be transformed into the chemical energy of hydrogen by electrolysis of water. Similarly, in areas with abundant sunshine, solar energy can be also stored as hydrogen energy

through direct photocatalytic water splitting techniques combined with hydrogen production by photoelectric and photothermal effects.

2) Integration of hydrogen storage and transportation. Due to its natures of low energy density, low boiling point, and difficulty of compression, hydrogen storage and transportation have long been considered as the obstacle for applications of hydrogen energy. Compared with the traditional high-pressure gaseous hydrogen storage and low-temperature liquid hydrogen storage, solid-state hydrogen storage can achieve very high capacity and safety, which is a promising approach in the future. Especially in recent years, the developments of Mg-based hydrogen storage materials make it possible to store and transport hydrogen safely and efficiently with a hydrogen capacity of up to 7.6 wt%. Moreover, the material is inexpensive and easy to obtain. Building Mg-based hydrogen storage trailers has already been attempted in recent years and the hydrogen storage capacity of a single trailer can reach 1.2–1.5 t, which is 3–4 times of the traditional long tube hydrogen storage trailer. By producing hydrogen from renewable energies in energy-rich areas, the underutilized energy will be converted into the chemical energy of hydrogen which will then be delivered to the destinations safely and efficiently through the integrated hydrogen storage and transportation system. In this way, the "green" process of hydrogen production, large-scale storage, transportation, and application can be realized, which will be the only way toward future hydrogen utilization (Figure 2.1.1).

(7) Digitalized and intelligentized nuclear power plant and reactor technology

The rapid development of information technology has "digitalized" and "intellectualized" the design itself, and has made the digital system of nuclear power research and development, design, verification, manufacturing, construction, commissioning, and operation become the current fronts. By making the nuclear power cycle and the data of the entire industry chain be interactively shared on the digital platform, the efficiency and reliability of all aspects of nuclear power will be greatly improved, and the iterative upgrade of nuclear power technology will be further realized based on this platform.

The intelligent development of nuclear power is divided into three stages. The first stage is infrastructure construction. Intelligentization must be based on digitalization. From the adoption of the intelligent instrument and intelligent controller concepts to the nuclear power plant's full digital instrument control system, most of the nuclear power plants in China have been digitalized (with the exception of the few early nuclear power plants). The second stage is the establishment of an AI architecture, the use of "Internet+" to build big data systems, the development of digital nuclear

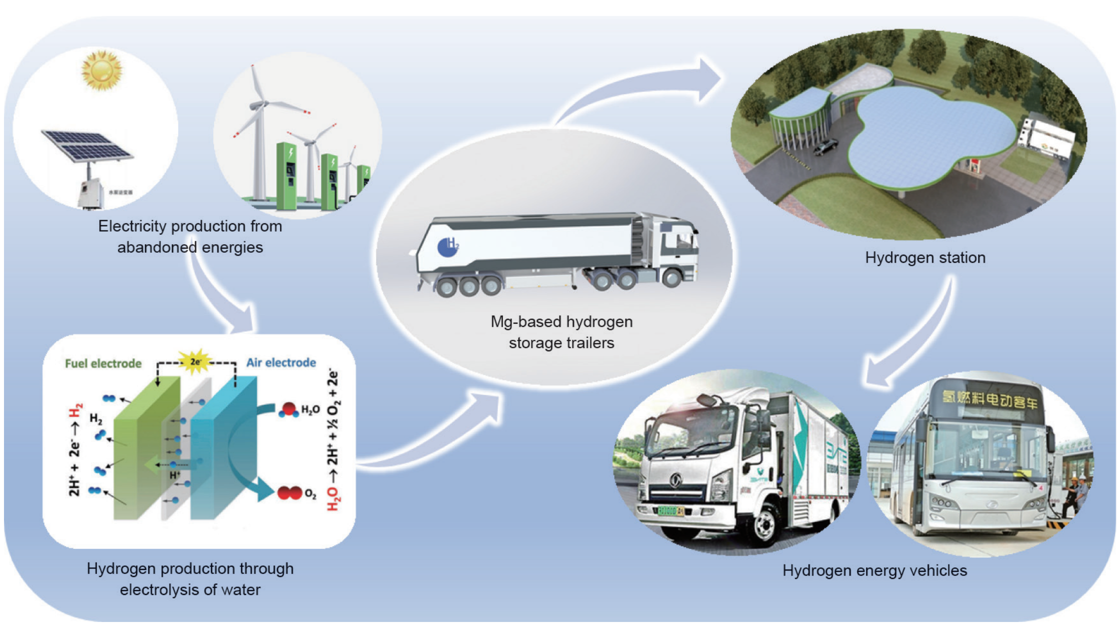

Figure 2.1.1 Hydrogen generation from renewable energy sources and the integrated system of storage and transportation

power plants, and the development of application of virtual reality (VR) technology. The digital nuclear power plants include two types: one is a virtual 3D digital nuclear power plant, for installation and maintenance, while the other is dynamic, displaying various parameters and status of the nuclear power plant in real time. The third stage of intelligent nuclear power is the development of nuclear power AI applications, including operational guidance, accident handling guidance, intelligent maintenance of nuclear power plant equipment systems, and application of robots or robotic system maintenance in high radioactive and unreachable areas. These three stages are not separated from each other, but are cross-developed, which makes the digitalization and informationization maturation occur step by step, gradually realizing intelligence. This is a hot spot in the international arena and a key work to occupy the dominant height of technology and science.

(8) Technologies of intelligent, integrated, small module floating reactors

The intelligent, integrated, modular, floating reactor technology generally refers to a reactor with the thermal power of a single unit being below 1000 MW (electric power 300 MW), with carbon-free emission, small capacity, flexible site selection, small construction investment, and short construction period. The equipment can be assembled and transported at the factory, and can be upgraded and economically improved through modular design. The small reactor belongs to military and civilian dual-use technology, which can be used not only as military power to be applied to ships and border defense construction, but also as residential power supply, icebreaker, urban heating, industrial process heating, and seawater desalination. It has broad application prospects both in military and civilian fields.

Breakthroughs should be made in the key design technologies, major test verification technologies, and key equipment improvement design and manufacturing technologies of small smart reactors, to form a group of advanced small smart reactor technologies with completely independent intellectual property rights. A comprehensive breakthrough should be made in modular design, inherent safety, intelligent control and economics, and the development of small reactor nuclear power technology for heating, power supply, cogeneration, seawater desalination, and special purposes. Specifically, key technologies for the overall design and layout of integrated reactors should be studied, including key technologies of long-life and boron-free core design, key technologies of modular design, key technologies of intelligent design, all-digital intelligent instrument control system, key technologies of multi-reactor control, key technologies for safety review; and key equipment such as the small shielded pump, the small steel containment, the DC steam generator, and the built-in steam regulator should be developed.

(9) Oilfield-integrated digital ecological management system based on wireless sensor networks

The oilfield-integrated digital ecological management system based on wireless sensor network concepts establishes a digital management platform for unified production management and comprehensive research in the whole oilfield by using innovative technology and management concepts, which can significantly improve real-time monitoring of the production process. A wireless sensor network combines the sensor technology, the embedded computing technology, the wireless communication technology, and the distributed information processing technology. It has the characteristics of a high degree of cross-disciplinary and high technology integration. It is the core and foundation of the technology of the Internet of Things. The hardware circuit of the wireless sensor network system is divided into data acquisition, routing node, gateway node, and monitoring center circuits. The software is composed of the wireless communication network software subsystem and the monitoring center management software subsystem. The various types of data collected by the wireless sensor network are transmitted to the control center through the wireless network and stored after corresponding software processing. The functions of automatic input of dynamic information, query, analysis, and mining of complex data are completed, and data report is automatically generated. The flexibility of the sensor acquisition node and the stable application of the network ensure the reliability of the oil well monitoring, contribute to the improvement of the operation efficiency of the oil well and the reduction of the network operation cost, and promote the automation and information development of oil field production.

(10) Seismic signal acquisition and processing technologies for marine seismic exploration

Marine seismic acquisition technology has been innovated and developed to meet the requirements of accurate imaging of seismic data under the new exploration situations as marine oil and gas exploration gradually shifts to deep oil and gas reservoirs, high-speed shielded oil and gas reservoirs, and oil and gas fields with complex structures. It has developed, in terms of mode, from planar source to multi-layer source and stereo source; in terms of receiving mode, from horizontal cable to upper and lower cable and oblique cable (variable depth cable), and from single pressure type detector cable to speed and pressure combination double detector cable; and in terms of marine 3D exploration, from narrow azimuth acquisition of linear routes to annular wide azimuth acquisition. The application of these new seismic acquisition techniques effectively overcomes the shortcomings of marine seismic exploration, increases the low-frequency energy of seismic original signals, broadens the seismic frequency band, improves the signal-to-noise ratio and imaging effect of deep effective reflection signals, and satisfies exploration and development of complex oil and gas fields. Meanwhile, since the noise contained in the seismic data collected during seismic exploration will increase, it needs to be digitally processed to extract useful information to provide reliable information for geological interpretation of seismic exploration, in which signal noise reduction is performed digitally. Signal denoising is, therefore, a particularly important step in processing; it is used to extract useful information from seismic data and improve the signal-to-noise ratio of seismic data.

(11) Research and development of new fracturing technologies, equipment, fracturing fluids, proppants, and additives

Fracturing is the key engineering means to achieve oil and gas production and improve economic efficiency. The fracturing process pumps the fracturing fluid into the oil and gas reservoir through the high-pressure device to produce cracks, and then uses the proppant to support the crack to form permanent cracks, thereby improving the reservoir permeability, providing important support for increasing production, and increasing efficiency. With the increasing complexity of oil and gas exploration and development, the challenges of traditional fracturing, such as low fracturing efficiency and unsatisfactory fracturing effect, seriously restrict the economical and efficient mining of complex oil and gas resources. It is urgent to explore the new fracturing technology, research frontier equipment, and develop high-performance proppants and additives with fracturing fluids to promote efficient mining of complex oil and gas resources. The new fracturing technologies can increase reservoir volume and fracture complex index; these new technologies include infinite fracturing, waterless fracturing, repeated fracturing, high-end fracturing, simultaneous fracturing, zipper fracturing, selective pressure crack, and factory fracturing. Advanced fracturing equipment can meet high pump pressure, low pollution, remote operation, cost reduction, and other purposes; examples of such equipment include the ultra-high pressure high-power fracturing units, high-power fracturing trucks, high-power fracturing pumps, fully soluble multi-stage fracturing systems, infinite-stage fracturing sliding sleeves, fully degradable fracturing bridge plugs, composite fracturing plugs, and so on. High-performance fracturing fluids and proppants can reduce reservoir pollution, reduce leakage, and have good suspension properties; examples of such fluids systems include high-temperature fracturing fluid systems, soft particle fracturing fluids, ultra-high temperature reservoir instant fracturing fluids, high-temperature viscoelastic surfactant based fracturing fluids, composite fracturing fluid systems, low-density proppants, and new functional environmental proppants.

(12) Development of advanced warning systems for mining disasters in the deep metal mines

For mining disasters of deep metal mines under complex multi-field environments, a set of early warning systems, including advanced acquisition of disaster-indicating signals, intelligent analysis of disaster incubation, advance warning of disaster occurrence, and dynamic avoidance of potential disasters, are to be developed to realize intelligent analysis and dynamic control of mining disaster information in deep metal mining, which will greatly improve the safety and efficiency of deep resource development.

The research directions of the advanced warning systems include multi-dynamic monitoring and analysis concepts of mining ground pressure under a multi-field coupling environment of metal ore; time-delay characteristics and prediction methods of rock burst induced by deep strong unloading; dynamic picking and real-time prediction of deep disaster breeding evolution process models; deep mining information intelligence judgment and disaster warning based on big data; intelligent correlation mechanisms of deep mining disaster signals and types; and integrated intelligent systems of deep mining disaster spatial and temporal prediction and dynamic regulation.

Attention should be focused on "accurate and real-time picking of deep mining disaster information," "intelligent analysis of disaster signals and gestation processes," and "predictive and dynamic disposal of mining disasters under multi-field coupling," to realize advanced prediction, early-warning and advanced disposal of deep mining disasters, and further promote the safe, green, and efficient mining of deep mineral resources.

2.2 Interpretations for four key engineering development fronts

2.2.1 Advanced technologies for EV/HEV and power batteries

(1) Conceptual elaboration and key technologies

The EV/HEV is one of the most important components in the field of new energy vehicles. At present, the crisis of energy exhaustion and the pressure of environmental pollution have become a common global problem. The high efficiency and low pollution of EV/HEVs have brought new opportunities for their development. Various countries, including China, have intensified their research, development, and investment to master the core technologies in this field. The power system of the EV adopts a mode that combines battery power (high voltage) and a driving motor. Because of the high efficiency of the motor throughout its working range, EVs generally adopt the direct drive mode. Some EVs are equipped with gearboxes for multi-gear adjustment. The HEV has two sets of energy storage and drive systems, i.e., an internal combustion engine (fuel-based) and an electric motor (power consumption). Its structure is more complex and its modes are more diversified. According to the position of the motor relative to the traditional power system, the hybrid schemes can be divided into six categories: P0–P5.

The performance of power batteries has been greatly improved from the early lead-acid batteries to the nickel-hydrogen batteries and to the lithium batteries currently in use. At present, the commonly used power batteries are lithium ion batteries, consisting of lithium iron phosphate batteries and ternary material batteries.

(2) Current situation and future development trend

From 2013 to 2018, the sales of new energy vehicles in China were 17 600, 74 700, 331 000, 507 000, 777 000, and 1 256 000, respectively. In 2018, the production and sales of new energy vehicles in China were 1.27 million and 1.256 million, respectively, an increase of 59.9% and 61.7%, respectively, over the same period of the previous year. The production and sales of pure EVs were 986 000 and 984 000, respectively, an increase of 47.9% and 50.8% over the same period of the previous year. The production and sales of plug-in HEVs were 283 000 and 271 000, respectively, an increase of 122% and 118% over the same period of the previous year. According to the forecast, the domestic sales of new energy vehicles will exceed two million by 2020, and the annual growth rate of future sales will exceed 40%.

While steadily promoting the progress of traditional energy optimization and management, and power coupling with other research directions, the research focus of EV/HEVs is gradually shifting to advanced research directions such as intelligent networking, intelligent driving, and intelligent travel. Based on the concept of man–vehicle–road collaborative management, the optimization of vehicle power allocation, and enrichment of energy management, EV/HEVs can be integrated into the intelligent city network architecture for comprehensive control, and vehicle performance optimization should consider overall urban travel conditions rather than simply focus on single vehicle. Meanwhile, advanced assisted driving and automatic driving will become the development trend in the future based on networking and deep learning algorithms.

The research of power batteries focuses primarily on energy density, safety, and fast charging. Solid-state batteries are attracting increasing attention due to the advantages of their light weight (high energy density), thin size (less electrolyte/mass), safety, flexibility, wide electrochemical window, and long cycle life. In addition, the research on algorithms based on big data and machine learning also provides powerful support for the state prediction, parameter estimation, and dynamic management of power batteries.

(3) Comparison and cooperation among key countries/regions and institutions

As shown in Table 2.2.1, the countries or regions with the largest number of core patents published in this field are the USA, China, and Japan, with the USA accounting for 50%, and China and Japan accounting for 16.21% and 15.86%, respectively.

From Table 2.2.2, it can be observed that Ford Global Technologies LLC, Toyota Motor Corp., General Motors Corp.,

Table 2.2.1 Countries or regions with the greatest output of core patents on "advanced technologies for EV/HEV and power batteries"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	145	50.00%	6514	54.63%	44.92
2	China	47	16.21%	1290	10.82%	27.45
3	Japan	46	15.86%	1688	14.16%	36.70
4	South Korea	24	8.28%	1032	8.66%	43.00
5	Germany	13	4.48%	605	5.07%	46.54
6	Switzerland	6	2.07%	261	2.19%	43.50
7	Israel	5	1.72%	231	1.94%	46.20
8	UK	3	1.03%	96	0.81%	32.00
9	Canada	2	0.69%	122	1.02%	61.00
10	Sweden	2	0.69%	111	0.93%	55.50

Table 2.2.2 Institutions with the greatest output of core patents on "advanced technologies for EV/HEV and power batteries"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	FORD	23	7.93%	808	6.78%	35.13
2	TOYT	12	4.14%	433	3.63%	36.08
3	GENK	10	3.45%	549	4.60%	54.90
4	HYMR	10	3.45%	403	3.38%	40.30
5	GOOG	9	3.10%	573	4.81%	63.67
6	QCOM	8	2.76%	446	3.74%	55.75
7	TESM	6	2.07%	418	3.51%	69.67
8	GLDS	6	2.07%	199	1.67%	33.17
9	GENE	6	2.07%	197	1.65%	32.83
10	BETT	5	1.72%	231	1.94%	46.20

FORD: Ford Global Technologies LLC; TOYT: Toyota Motor Corp.; GENK: General Motors Corp.; HYMR: Hyundai Motor Co., Ltd.; GOOG: Google Inc.; QCOM: Qualcomm Inc.; TESM: Tesla Motors Inc.; GLDS: LG Chem Ltd.; GENE: General Electric Co.; BETT: Better Place GmbH.

and Hyundai Motor Co., Ltd. are the institutions with the largest number of core patents published.

According to Figure 2.2.1, the USA, South Korea, Japan, Canada, Germany, Israel, and Switzerland pay more attention to the cooperation between countries or regions in this field. Among them, the USA has the largest number of cooperating countries or regions. It cooperates with South Korea, Japan, Canada, and Germany, while Israel and Switzerland cooperate with each other.

According to Figure 2.2.2, there only exists cooperation between Hyundai Motor Co., Ltd. and LG Chem Ltd. in all institutions.

2.2.2 Nuclear high-temperature hydrogen production and helium turbine power generation technology

(1) Nuclear high-temperature hydrogen production

Hydrogen is an important industrial raw material and an ideal secondary energy or energy carrier in the future. Hydrogen is used as a secondary energy source for storage and transportation, and can be used directly as a fuel. In addition to traditional ammonia synthesis, methanol synthesis, and petroleum refining, hydrogen can be used on a large scale in the fields of hydrogen metallurgy, coal liquefaction, and fuel cell vehicles.

Nuclear hydrogen production is an efficient and clean method for large-scale hydrogen production, which can play an

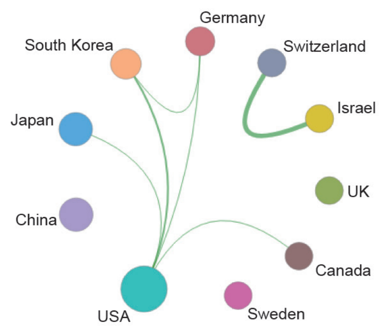

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "advanced technologies for EV/HEV and power batteries"

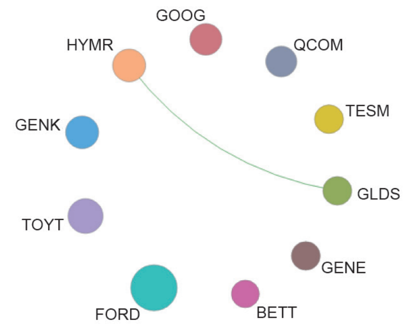

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "advanced technologies for EV/HEV and power batteries"

important role in the large-scale supply of hydrogen in the future. The comprehensive utilization of HTGR technology (combined supply of hydrogen, electricity, and heat) with nuclear energy hydrogen production as the core will provide an important support for the technological revolution in many industrial sectors in China, and play a role in upgrading products, reducing pollution, and reducing carbon emissions.

The idea of nuclear hydrogen production began in the 1970s. After the oil crisis, there have been many studies related to thermochemical cycles. The international cooperation in nuclear energy hydrogen production has been active. At the Generation IV International Forum (GIF), the non-electrical use of nuclear energy such as hydrogen production, desalination, and heat utilization, were discussed, and a research and development plan for the use of nuclear energy to produce hydrogen was developed. A hydrogen project management department was set up for the HTGR system and the International Atomic Energy Agency (IAEA) have set up coordination projects related to the economics of nuclear energy hydrogen production. More than a dozen countries have participated in the evaluation of the nuclear energy hydrogen production technology.

It can be seen from the characteristics and advantages of nuclear energy hydrogen production technology that hydrogen production from HTGRs is suitable for centralized, large-scale, and emission-free applications of hydrogen. Therefore, the hydrogen production technology selected for coupling with the HTGR should also have these characteristics. Nuclear power generation–electrolysis is the most mature technology that can be used to produce hydrogen from small reactors for the consumption of residual nuclear power or in special scenarios. Nuclear-assisted fossil fuel reforming can use nuclear heat as an alternative heat source, saving some fossil fuels and partially reducing emissions. For example, if the HTGR process heat-assisted natural gas reforming technology is adopted to produce hydrogen, approximately 30% of natural gas can be saved to be used as a heat source, reducing CO_2 emissions by 30%. This technology can be used as a recent transition technology for nuclear energy hydrogen production, to further explore and promote the coupling between reactor and hydrogen production plant, nuclear hydrogen safety research and license application, and economic evaluation of the nuclear energy hydrogen production technology.

From a long-term perspective, thermochemical cycles and high-temperature steam electrolysis are promising nuclear energy hydrogen production technologies as they use high-temperature process heat of HTGR as a heat source, and water as a hydrogen-making raw material, and thus can completely eliminate carbon emissions from the hydrogen production process. The development of nuclear energy hydrogen production technology must consider the technical characteristics (including hydrogen production capacity, product hydrogen purity, end users, and waste management), cost (including hydrogen price, applicability of technical and economic evaluation assumptions, and research and development costs), and risks (technology development status and maturity, and research and development risk).

(2) Helium gas turbine direct-cycle power generation

The HTGR gas turbine direct-cycle power generation is based on the theory of the closed-type Brayden cycle. The gas turbine is combined with the MHTGR, and the high-temperature gas generated by the HTGR is used to directly push the gas turbine to work and generate power. The efficiency of direct-cycle power generation by the helium turbine can reach more than 50%.

The electric helium gas turbine compressor unit is the core component of the helium gas turbine direct-cycle power generation system. The turbocharged gas compressor unit under helium conditions has no successful precedent in the world, and the electromagnetic bearing is one of the key technologies in the helium turbine power generation system of the HTGR. Because the core outlet temperature of the HTGR can reach over 900 °C, the structure and materials, capable of withstanding high temperature and high pressure, for pressure shells and turbine blades are also one of the key technologies for gas turbine direct-cycle power generation of HTGRs.

At present, global research on this field is focused on the following projects. The gas turbine modular helium reactor (GT-MHR) program jointly developed by the USA and Russia and the gas turbine high temperature reactor (GTHTR300) project in Japan have a core outlet temperature of 850 °C, both of which adopt direct circulation by a closed helium turbine, whose turbine blades are made of nickel-based alloy without blade cooling. However, it has so far remained at the research design stage. The pebble bed modular reactor (PBMR) program of South Africa initially designed a direct circulation of the helium gas turbine with a core outlet temperature of 900 °C, and the project was terminated due to financial and other problems. The Tsinghua University in China uses the HTGR with gas turbine generator (HTR-10GT) project plan to conduct research on key technologies for commercial HTGRs for helium gas turbine power generation, including the design of the helium gas turbine power plants, the basic characteristics of helium gas turbines, engineering test research on large-scale plate-fin heat exchangers, and engineering test research on large-scale electromagnetic bearings. At present, the first domestic single-stage prototype test device for pneumatic air compressors has been established and many tests have been performed. The large heavy-duty flexible rotor electromagnetic bearing test rig for engineering verification tests has also been completed and engineering experiments are underway.

In the field of HTGRs, MHTGR with inherent safety is an advanced type of reactor, and the direct-cycle power generation of the helium gas turbine is an ideal energy conversion technology. The concept of ultra-high-temperature gas-cooled reactor, developed based on the MHTGR and helium gas turbine cycle, is considered by the international community to be one of the competitive candidates for the fourth-generation nuclear energy system. From a long-term perspective, with the development of ultra-high-temperature gas-cooled reactor technology and breakthroughs in key technologies and components for direct circulation of helium turbines, the direct-cycle power generation technology of the Xenon Turbine will be widely developed and applied, upon which, if the combined power generation method of helium direct turbine and steam turbine is adopted, the power generation efficiency can be further improved.

(3) Comparison and collaboration among major countries/regions and institutions

According to Table 2.2.3, the countries or regions with the largest number of core patents in this research direction are China, Japan, South Korea, the USA, France, Germany, and India. Among them, China holds the first place, at more than 75%.

It can be seen from Table 2.2.4 that the institutions with the largest number of core patents published in this research direction are Tsinghua University, Harbin Electric Co., Ltd., China National Nuclear Corporation, and China Huaneng Group Corp., and the number of core patents is 78.

According to Figure 2.2.3, there is rare cooperation among the major countries or regions, but the cooperation within the GIF organization is not included.

According to Figure 2.2.4, there is cooperation between Tsinghua University, China National Nuclear Corporation, and China Huaneng Group Corp.

According to the above data analysis, China, Japan, and South Korea are at the forefront of the core patent output for nuclear energy high-temperature hydrogen production technology.

2.2.3 Fracture shape processing method and system based on microseismic monitoring

Microseismic monitoring technology is an effective seismic method for monitoring fracture development in hydraulic fracturing. It is widely used in the development and planning of oil and gas fields. The fracture not only determines the water injection effect, but also controls the division of the strata and the injection–production well network. Moreover,

Table 2.2.3 Countries or regions with the greatest output of core patents on “nuclear high-temperature hydrogen production and helium turbine power generation technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	148	75.51%	181	43.30%	1.22
2	Japan	23	11.73%	94	22.49%	4.09
3	South Korea	12	6.12%	91	21.77%	7.58
4	USA	10	5.10%	44	10.53%	4.40
5	France	1	0.51%	8	1.91%	8.00
6	Germany	1	0.51%	0	0.00%	0.00
7	India	1	0.51%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “nuclear high-temperature hydrogen production and helium turbine power generation technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYQI	36	18.37%	105	25.12%	2.92
2	HRBE	15	7.65%	5	1.20%	0.33
3	CNNU	14	7.14%	9	2.15%	0.64
4	CHHN	13	6.63%	9	2.15%	0.69
5	JAAT	7	3.57%	3	0.72%	0.43
6	USHS	7	3.57%	1	0.24%	0.14
7	KAER	5	2.55%	23	5.50%	4.60
8	SUZH	5	2.55%	0	0.00%	0.00
9	KOAD	4	2.04%	2	0.48%	0.50
10	XENE	4	2.04%	0	0.00%	0.00

UYQI: Tsinghua University; HRBE: Harbin Electric Co., Ltd.; CNNU: China National Nuclear Corporation; CHHN: China Huaneng Group Corp.; JAAT: Japan Atomic Energy Agency; USHS: Univ Shanghai Sci & Technology; KAER: Korea Atomic Energy Research Institute; SUZH: Suzhou Hailu Heavy Industry Co., Ltd.; KOAD: Korea Advanced Institute of Science & Technology; XENE: X-Energy LLC.

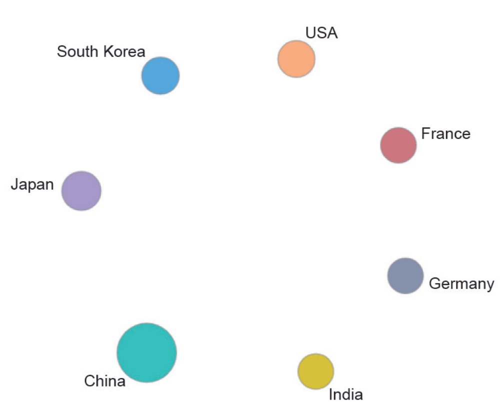

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of “nuclear high-temperature hydrogen production and helium turbine power generation technology”

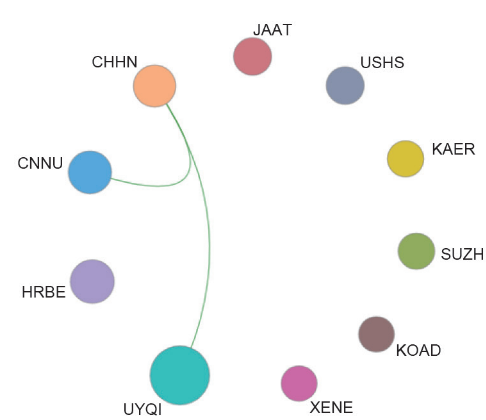

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “nuclear high-temperature hydrogen production and helium turbine power generation technology”

it directly determines the quality of the oilfield development. However, there are still many problems in practical applications. It is very important to employ microseismic focus mechanism inversion, as well as fracture interpretation and imaging technology to provide effective information for reservoir description.

Research directions include using the data information of the target area to simulate the fracture propagation to obtain the shape distribution information of the fracture; using the microseismic monitoring data of the target area to invert the microseismic events caused by the fracturing to obtain the intensity range of the fracture; obtaining a fracturing phase distribution model according to the morphological distribution information and the intensity range; recovering the original signal according to the received signal of the detector by using each volume unit in the target data volume; and calculating the energy of each volume unit to form a four-dimensional imaging result, outputting the result, and obtaining a multi-scale fracture crack model through the fracturing phase distribution model. This technology not only reflects the shape and orientation of the fracture itself, but also considers the distribution range and intensity information of the microseismic inversion, which can more accurately characterize the spatial distribution of hydraulic fracturing cracks and reflect the changes of cracks at different times.

In summary, the fracture shape processing method and system based on microseismic monitoring can continuously collect and record the microseismic data in the fracturing process and realize real-time processing and visual interpretation, effectively optimize the fracturing scheme, and provide reservoir resource evaluation and drilling position to achieve a production increase and guide development of oil and gas field.

The foremost producing countries and regions of the core patents in this front are the USA, Canada, France, the Netherlands, and China (Table 2.2.5), and the main output institutions are Schlumberger Ltd., Halliburton Co., and Prad Research & Development Ltd. (Table 2.2.6). Cooperation and exchanges have taken place between these countries/regions and institutions (Figure 2.2.5 and Figure 2.2.6).

2.2.4 Technologies for safe, intelligent, and precise mining of coal

(1) Concept elaboration and significance

Precise coal mining is based on the coupling of transparent space geophysics and multi-physics fields, and is supported by the unattended mining technology (or requiring fewer people) and safety mining technologies, thereby the zero-death rate of coal mining workers can be realized. The critical approaches are "digitalized" and "informationized," taking full consideration of coal mining disturbance, disaster inducement, mining-induced ecological environment destruction, and the like under different geological conditions, and forming a model of future mining through which precise and efficient intelligent mining and disaster prevention collaborate with each other. Moreover, the continuous mining and resource recovery can be in line with international advanced level. Precise coal mining is of great significance for improving coal mining safety and technology, for resource

Table 2.2.5 Countries or regions with the greatest output of core patents on "fracture shape processing method and system based on microseismic monitoring"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	57	82.61%	707	82.11%	12.40
2	Canada	13	18.84%	220	25.55%	16.92
3	France	10	14.49%	189	21.95%	18.90
4	Netherlands	10	14.49%	189	21.95%	18.90
5	China	5	7.25%	88	10.22%	17.60
6	Russia	2	2.90%	16	1.86%	8.00
7	UK	1	1.45%	28	3.25%	28.00
8	Germany	1	1.45%	9	1.05%	9.00

Table 2.2.6 Institutions with the greatest output of core patents on “fracture shape processing method and system based on microseismic monitoring”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	SLMB	20	28.99%	289	33.57%	14.45
2	HALL	16	23.19%	192	22.30%	12.00
3	PRAD	14	20.29%	255	29.62%	18.21
4	BAKO	5	7.25%	42	4.88%	8.40
5	UYPE	2	2.90%	45	5.23%	22.50
6	CARB	2	2.90%	39	4.53%	19.50
7	TEXA	2	2.90%	22	2.56%	11.00
8	LGNE	2	2.90%	19	2.21%	9.50
9	CONO	2	2.90%	18	2.09%	9.00
10	TATN	2	2.90%	16	1.86%	8.00

SLMB: Schlumberger Ltd.; HALL: Halliburton Co.; PRAD: Prad Research & Development Ltd.; BAKO: Baker Hughes Inc.; UYPE: China University of Petroleum; CARB: Carbo Ceramics Inc.; TEXA: University of Texas System; LGNE: Logined BV; CONO: Conocophillips Co.; TATN: TATNEFT.

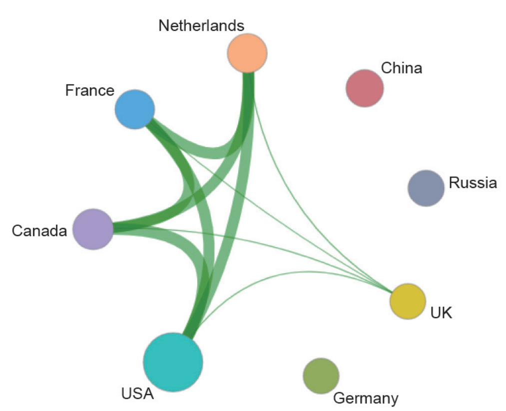

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “fracture shape processing method and system based on microseismic monitoring”

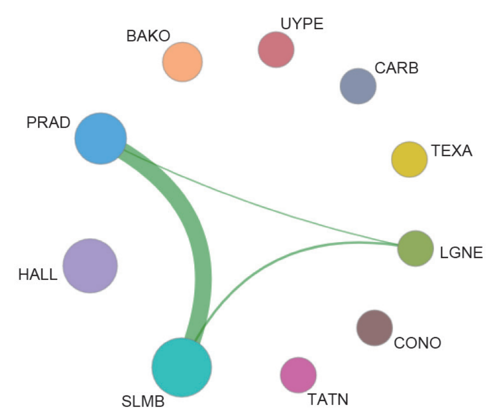

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “fracture shape processing method and system based on microseismic monitoring”

exploitation efficiency, and for transition of the mining industry from a labor-intensive to technology-intensive industry characterized by advanced technology.

The following scientific problems need to be solved for precise and safe coal mining technology: digitized quantification of multi-field dynamic information in coal mining processes such as stress, strain, displacement, cracks, and seepage; collection, sensing, and transmission of multi-source information from working site and mining-induced disturbance zones; multi-source massive dynamic data evaluation and screening mechanisms based on big data cloud technology; multiphase and multi-field coupled disaster inducement theories and research based on big data; in-depth perception on precursor information of disaster and relevant intelligent simulation and control; early warning of mine disasters; and critical emergency rescue technology and equipment for coal mine disasters.

(2) Historical status and trend

Throughout the international mining history, the primary causes of mining disasters include unclear geological situations and disaster-causing mechanisms, unknown disaster threats, and unsolved key technological problems. Therefore, to fundamentally solve the problem of safe and efficient coal production in coal mines, the coal mining industry must evolve from a labor-intensive to a technology-intensive industry characterized by advanced technologies. Additionally, a path specified by intelligent, safe, and unattended mining or mining with fewer people should be followed. The strong momentum of the third industrial revolution and the rapid development of information-dominated technology have provided another opportunity and challenge for the transformation of mining industry from traditional empirical and qualitative decision-making to precise, quantitative, and intelligent decision-making. It is possible to realize scientific, intelligent, and unattended mining of coal, or mining with a reduced crew size.

(3) Comparison and collaboration among major countries/regions and institutions

In Table 2.2.7, it can be noticed that the core patents regarding precise and intelligent mining of coal are generally distributed in China and Australia, among which the percentage of China has surpassed 98% and the average indexing rate is much higher than that of Australia.

In Table 2.2.8, institutions with most patents with regard to precise and intelligent coal mining are China University of Mining and Technology, Beijing; China University of Mining and Technology, Xuzhou; and China Coal Technology and Engineering Group, whose percentage for core patents are all higher than 5%.

In Figure 2.2.7, it can be learned that countries focusing on this area are China and Australia.

In Figure 2.2.8, institutions that have collaborated are China Coal Technology and Engineering Group and Huaibei Mining (Group) Co., Ltd., as well as China University of Mining and Technology, Xuzhou, and China University of Mining and Technology, Beijing.

Table 2.2.7 Countries or regions with the greatest output of core patents on “technologies for safe, intelligent, and precise mining of coal”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	117	98.32%	198	100%	1.69
2	Australia	2	1.68%	0	0%	0.00

Table 2.2.8 Institutions with the greatest output of core patents on “technologies for safe, intelligent, and precise mining of coal”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYMB	24	20.17%	13	6.57%	0.54
2	UYMT	8	6.72%	40	20.20%	5.00
3	CHLY	6	5.04%	23	11.62%	3.83
4	UYCQ	5	4.20%	27	13.64%	5.40
5	ULNT	5	4.20%	2	1.01%	0.40
6	UYXS	5	4.20%	2	1.01%	0.40
7	UYHP	4	3.36%	5	2.53%	1.25
8	UYLG	3	2.52%	16	8.08%	5.33
9	UNBS	3	2.52%	7	3.54%	2.33
10	HUAI	3	2.52%	3	1.52%	1.00

UYMB: China University of Mining and Technology, Beijing; UYMT: China University of Mining and Technology, Xuzhou; CHLY: China Coal Technology and Engineering Group; UYCQ: Chongqing University; ULNT: Liaoning Technical University; UYXS: Xi’an University of Science and Technology; UYHP: Henan Polytechnic University; UYLG: Anhui Science and Technology University; UNBS: University of Science and Technology Beijing; HUAI: Huaibei Mining (Group) Co., Ltd.

Figure 2.2.7 Collaboration network among major countries or regions in the engineering development front of "technologies for safe, intelligent, and precise mining of coal"

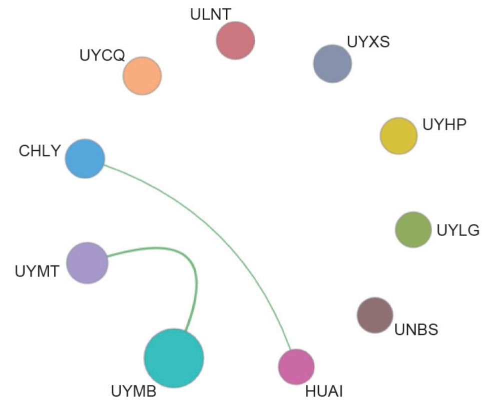

Figure 2.2.8 Collaboration network among major institutions in the engineering development front of "technologies for safe, intelligent, and precise mining of coal"

Participants of the Field Group

Leaders

WENG Shilie, NI Weidou, PENG Suping, GU Dazhao

Deputy Leaders

HUANG Zhen, JU Yonglin, LIU Jing

Members of the Secretary Group

Office of the Ministry of Energy and Mining Engineering: ZONG Yusheng, XIE Guanghui

Frontiers in Energy Editorial Office: LIU Ruiqin, HUANG Dongping

Library and Information Personnel: CHEN Tiantian, YU Xiawei

Members

Energy and Electrical Science, Technology and Engineering Section

Director of Section: WENG Shilie, YUE Guangxi

Secretary-general of Section: JU Yonglin, ZHANG Hai

Participants: CHENG Lin, HU Wei, LIN Jin, LIU Feng, LUO Haiyun, SHANGGUAN Wenfeng, WU Wenchuan, YANG Lin, ZHANG Yang, ZHANG Junliang, ZOU Jianxin

Report Writers: HU Wei, SHANGGUAN Wenfeng, YANG Lin, ZHANG Hai, ZHANG Junliang, ZOU Jianxin

Nuclear Science, Technology and Engineering Section

Director of Section: YE Qizhen, LI Jian'gang

Secretary-general of Section: SU Gang, GAO Xiang

Participants: JIANG Xiaochuan, YUAN Yidan, MA Rubing, GUO Qiang, ZHOU Hongbo, ZHANG Tao, LI Yunyi, GUO Qing, SUN Xiaolong, GUO Yinghua

Report Writers: JIANG Xiaochuan, ZHOU Hongbo, GUO Yinghua, GUO Qing, SU Gang

Geology Resources Science, Technology and Engineering Section

Director of Section: MAO Jingwen, ZHAO Wenzhi

Secretary-general of Section: ZHANG Guosheng, LIU Min

Participants: XIE Guiqing, YUAN Shunda, HONG Wei, WANG Shufang, WANG Kun, LIANG Kun, HUANG Jinliang

Report Writers: HONG Wei, WANG Shufang, WANG Kun, LIANG Kun, HUANG Jinliang

Mining Science, Technology and Engineering Section

Director of Section: YUAN Liang, LI Gensheng

Secretary-general of Section: ZHANG Nong, WU Aixiang, ZHOU Fubao, SONG Xianzhi

Participants: YIN Shenghua, JIANG Bingyou, SUN Jinsheng, HUANG Zhongwei, WANG Haizhu, FENG Xiaowei, LIANG Dongxu, WU Dongmei

Report Writers: YIN Shenghua, JIANG Bingyou, SUN Jinsheng, HUANG Zhongwei, WANG Haizhu, FENG Xiaowei, LIANG Dongxu

V. Civil, Hydraulic, and Architectural Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts related to the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering, architectural design and theory, construction materials, urban planning, bridge engineering, underground space and tunneling, hydraulic structural engineering, photogrammetry and aerospace survey, hydrology and water resource, transportation planning, etc. Among these research fronts, "seismic analysis and safety evaluation of high dams under extreme earthquakes" was recommended by experts, and the other fronts were identified based on the top 10% of highly cited papers using the co-citation clustering method and confirmation by experts. Table 1.1.2 presents the annual statistical data on the core papers published between 2013 and 2018 relevant to the top ten research fronts.

(1) Mechanism and control of long-term performance evolution of structures

This research front refers to revelation of internal physical and chemical degradation mechanisms and realization of effective control of structural performance degradation. Under long-term environmental and mechanical loads, structural properties are degraded, and the degradation rate is controlled by the inherent physical and chemical degradation mechanisms. By grasping the above-mentioned internal mechanisms that cause structural performance degradation, targeted blocking techniques could be adopted to achieve effective control of the long-term performance of structures. Major issues concerning this research front include: 1) revelation of the physical and chemical mechanisms of structural performance evolution under long-term environmental and mechanical loads, and 2) structural performance degradation control technology based on fiber-reinforced materials and other special materials. Clearly revealing and grasping the inherent physical and chemical mechanisms of structural performance evolution contribute to the adoption of economically reasonable performance degradation control technologies. At present, detection

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Mechanism and control of long-term performance evolution of structures	72	1707	23.71	2015.9
2	Green building design method based on the whole life cycle	184	7442	40.45	2015.6
3	Nano-modification and fiber-reinforcement of cement-based materials	75	2137	28.49	2015.6
4	Urban design and planning for reducing urban heat island effect	154	6033	39.18	2015.7
5	Large-span bridge operational smart monitoring and inspection	102	2530	24.80	2014.7
6	Lifecycle deformation prediction and control for urban and undersea tunnels	113	2895	25.62	2016.7
7	Seismic analysis and safety evaluation of high dams under extreme earthquakes	14	274	19.57	2015.6
8	Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning	40	1989	49.73	2015.4
9	Refined prediction and rapid damage assessment of river basin floods	36	1571	43.64	2016.2
10	Traffic flow modeling theory and methods for the ICV and HDV mixed traffic	186	5524	29.70	2015.7

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Mechanism and control of long-term performance evolution of structures	7	11	11	11	16	16
2	Green building design method based on the whole life cycle	19	36	38	27	38	26
3	Nano-modification and fiber-reinforcement of cement-based materials	9	15	11	11	19	10
4	Urban design and planning for reducing urban heat island effect	20	23	20	35	30	26
5	Large-span bridge operational smart monitoring and inspection	32	21	17	14	10	8
6	Lifecycle deformation prediction and control for urban and undersea tunnels	7	8	13	11	16	58
7	Seismic analysis and safety evaluation of high dams under extreme earthquakes	2	3	2	2	2	3
8	Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning	6	8	7	7	6	6
9	Refined prediction and rapid damage assessment of river basin floods	3	2	8	4	9	10
10	Traffic flow modeling theory and methods for the ICV and HDV mixed traffic	19	24	40	37	37	29

and monitoring data based on the physical and chemical properties of engineering materials are used to establish prediction models for the long-term performance of structures. On this basis, structural performance improvements using fiber-reinforced polymer (FRP) and fiber-reinforced cement matrix composite (FRCM) are the research hotspots. Meanwhile, there are also some structural performance control technologies using shape memory alloy (SMA), self-healing concrete, asphalt, and new generation structural steel. Between 2013 and 2018, 72 core papers were published relevant to this research front, and these papers received 1707 citations, averaging 23.71 citations per paper.

(2) Green building design method based on the whole life cycle

The green building design method based on the whole life cycle carries out green design of buildings starting from the production, transportation, and use of the building materials and equipment, through the whole life cycle dimension of building design, construction, operation, and demolition. It aims to realize savings of energy, land, water, and material resources and to provide people with healthful, applicable, and efficient use of space. It is a design theory and method for maximizing the harmonious interaction of human and nature. The main research directions include: 1) the overall method for optimization of building space and performance combined with regional context, 2) the development and utilization of renewable and recyclable regional materials, 3) the development of a basic energy and carbon emission database for building materials and equipment over the life of a building, and 4) the development of related performance design optimization simulation software tools, etc. The trends of future development include: 1) a multi-disciplinary and whole process group collaborative design methods from single buildings to urban scale under the premise of smart, healthy, and people-oriented green building; 2) AI assisted optimization design; 3) performance-oriented digital design; 4) healthful and/or smart building design; 5) active and passive integrated devices and design; and 6) development and application of new materials. Between 2013 and 2018, 184 core papers were published relevant to this research front, and these papers received 7442 citations, averaging 40.45 citations per paper.

(3) Nano-modification and fiber-reinforcement of cement-based materials

Nano-modification and fiber-reinforcement of cement-based materials refers to the regulation of hydration and hardening properties, mechanical properties, and durability of cement-based materials by incorporating nanomaterials and fibers. At present, the research on fiber cement-based composite materials, includes single-fiber cement-based composite and hybrid fiber cement-based composite. Commonly used fibers can be divided into man-made fibers and natural plant fibers. Among them, man-made fibers mainly include such as steel fibers, glass fibers, and polypropylene fibers; whereas, natural plant fibers include such as cotton and hemp. Compared with ordinary cement-based materials, fiber cement-based composites have high tensile strength, extreme toughness, and high crack-resistance. They have good impermeability, frost resistance, and corrosion resistance, and better meet the functions of cement-based materials that the modern construction industry demands. At the same time, the application of natural plant fibers has improved the environmental value of cement-based materials and is more in line with the basic concept of sustainable development. With the rapid development of nanotechnology, nano-modification of cement-based materials has also received extensive attention. Nanomaterials with a particle size of less than 100 nm are usually used in the modification of cement-based materials, and can be classified into nano-mineral powder, nano-metal powder, and nano-oxide according to the material composition. The research on nano-modification of cement-based materials is mainly focused on the preparation of nano-modified cement-based materials, nano-modification mechanisms, and the properties of modified cement-based materials. Between 2013 and 2018, 75 core papers were published relevant to this research front, and these papers received 2137 citations, averaging 28.49 citations per paper.

(4) Urban design and planning for reducing urban heat island effect

Cities occupy 2% of the Earth's surface while their inhabitants consume almost 75% of the global energy. As a result of solar radiation and urban activities, the surface- or canopy-layer temperature in the urban areas of a city is significantly warmer than that of its surrounding areas. This effect is known as urban heat island (UHI). The UHI effect is heavily correlated to underlying surfaces, atmospheric pollution, and anthropogenic activities and it intensifies the impacts of increasing heatwaves and other extreme weather events in cities as a result of climate change. UHI affects human health by causing general discomfort, respiratory difficulties, heat cramps and exhaustion, non-fatal heat stroke, and heat-related mortality. Therefore, it is crucial and urgent to collectively act on mitigating and reducing the UHI effect to make cities sustainable. For this purpose, the design and planning strategies should cover the major factors correlated to the UHI effect, such as buildings, transportation, and greenspaces in the cities. Major research trends relevant to this topic include: 1) advance energy prediction and diagnostic models for buildings and building clusters, 2) measuring and monitoring UHI using advanced remote sensing technologies with high resolution, 3) urban greenspace patterns of spatial urban cool island effect, and 4) comprehensive strategies to mitigate UHI for large- and mega-cities. Between 2013 and 2018, 154 core papers were published relevant to this research front, and these papers received 6033 citations, averaging 39.18 citations per paper.

(5) Large-span bridge operational smart monitoring and inspection

In the process of bridge operation, local plasticity, damage, fatigue, instability, and cracking occur when the bridge interacts with the loads imposed by pedestrians, traffic flow, wind, ground motion, waves, and other operating loads. Smart operation monitoring and inspection of bridges is done to monitor the response and condition of their structures. It is done by means of smart sensing for the purpose of analysis and prediction of further deterioration behavior and operation life of the structure to provide safe and sustainable operation. The main research directions include: 1) the principles and technology of bridge smart sensing, 2) the methods for identification of the physical condition of a structure, 3) disaster early warning analysis of bridge degradation characteristics, and 4) the prediction of bridge residual life. Piezoelectric impedance, Global Position System (GPS), Satellite Aperture Radar (SAR) interferometry, acoustic emission, close-range photography, and other smart sensing methods are mainly used to monitor structural responses to strain, acceleration, displacement, as well as the overall structural physical state in the course of bridge operation. For identification of structural damage, signal processing methods such as Wavelet Transform (WT), Hilbert-Huang Transform (HHT), Kalman Filtering (KF), Least Squares (LS) are mainly used. The methods of smart reasoning such as neural networks, fuzzy reasoning, genetic algorithms, and deep learning are used to identify and evaluate the location and extent of structural damage. Disaster early warning analysis of bridge retrogression characteristics mainly involves study of the main characteristics and disaster early warning methods of non-linear and unsteady retrogression behavior of bridges under different loads. Residual life prediction mainly studies local damage propagation of damaged structures and predicts bridge failure modes and residual life. The main trend in the development of this research is a shift from the monitoring and identification of stationary, steady, and linear damage states to the monitoring and analysis of progressive, unsteady, and non-linear degradation processes. The latter provide more effective monitoring, control, and management of bridge operation. Between 2013 and 2018, 102 core papers were published relevant to this research front, and these papers received 2530 citations, averaging 24.80 citations per paper.

(6) Lifecycle deformation prediction and control for urban and undersea tunnels

Urban and undersea tunnels are key parts of modern infrastructure. With more and more urban and undersea tunnels being constructed and put into operation, the lifecycle deformation prediction and control of these tunnels has drawn growing attention. The interest in the topic of lifecycle deformation prediction and control has risen with concerns about lifecycle serviceability, safety, and durability of urban and undersea tunnels. The main research areas include: 1) long-term ground deformation under cyclic loading, 2) mechanical performance degradation rules of tunnel structure and material, 3) data mining and data analysis of lifecycle monitored structure deformation, 4) structural health evaluation and serviceability assessment, and 5) fast inspection and intelligent control technologies for structural deformation. Compared with traditional tunnel structures, urban and undersea tunnels are characterized by more sensitive surrounding environments and stricter operation restrictions. To ensure the serviceability and long-term safety of such tunnel structures, it is necessary to develop fast inspection technologies to monitor structural deformation and disorders, and to obtain real-time service conditions of tunnel structures. It is also necessary to develop methodologies by combining theoretical analysis, structural tests, and long-term monitoring for analyzing tunnel health conditions and serviceabililty. This must consider interactions between a structure and all related environmental factors and serve to establish an intelligent prediction and control framework for lifecycle deformation. Among these research topics, the fast inspection technologies and intelligent analysis of the big data obtained will be important directions in the near future. Between 2013 and 2018, 113 core papers were published relevant to this research front, and these papers received 2895 citations, averaging 25.62 citations per paper.

(7) Seismic analysis and safety evaluation of high dams under extreme earthquakes

High dams are essential infrastructure for controlling river runoff and realizing the comprehensive utilization of water resources and hydropower. Their failure may cause catastrophic disasters due to uncontrolled release of reservoir water. Therefore, the safety of high dams under extreme earthquakes has attracted wide attention. To evaluate the seismic safety of high dams subject to strong earthquakes reasonably, four factors should be considered: ground motion parameters at dam sites, dynamic behavior of dam materials and foundation, seismic response of the dam-foundation-reservoir system, and safety evaluation criteria. The state-of-the-art trends for seismic analysis and safety evaluation of high dams can be summarized as follows: 1) seismic risk analysis developing from probability methods to parallel with direct numerical simulation methods, 2) seismic response analysis of high dams developing from linear elastic methods to non-linear large deformation procedures, 3) dynamic failure simulation of dam and foundation materials developing from macro-scale to meso-scale mechanical methods, and 4) safety evaluation of high dams developing from traditional safety factors to risk-based decision-making methods. Following the above-mentioned trends in development, there are still many key issues that should be solved in the future, such as 1) numerical simulation of the entire process of faulting, seismic wave propagation, and high dam response, 2) macro-scale and micro-scale dynamic failure mechanisms of dam and foundation materials, 3) ultimate seismic capacity of dam-foundation systems, 4) deformation stability of high embankment dams at risk from strong earthquakes, 5) disaster chains involving cascade high dams, 6) risk assessment considering economic investment, project design, and disaster losses, and 7) real time health monitoring of high dams, along with rapid assessment of earthquake damage and disaster relief. Between 2013 and 2018, 14 core papers were published relevant to this research front, and these papers received 274 citations, averaging 19.57 citations per paper.

(8) Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning

High-resolution spatial-temporal remote sensing images can provide rapid and accurate information on land use change, and it has a variety of applications to land use change detection, disaster mitigation, and decision-making, among others. However, due to limitations of sensor hardware, it is difficult to acquire remote sensing images directly with high temporal and spatial resolution. Spatial-temporal fusion technology can spatially and temporally fuse remote sensing image data from different sensors, scales, and phases without changing the existing observation conditions. Moreover, they produce simultaneous data interpretation with high spatial and temporal resolution, thus alleviating the “spatiotemporal contradiction” of remote sensing data. In recent years, deep network training technology has provided theoretical support for the establishment of high-low resolution image mapping relationships and multi-sensor remote sensing image data has provided a complete data base for the network learning process. The main research directions of this research front include: 1) construction of spatial-temporal integration frameworks for deep learning, including spatiotemporal convolution neural networks, countermeasure generation neural networks, deep residual learning networks, and deep dense connection networks; and 2) construction of space-time loss function of visual perception, including elastic network loss function, space-time joint-structure-similar loss function, and space-time-information residual loss function. The main development trends are as follows: 1) toward a framework of deep learning spatial-temporal fusion coupled with remote sensing physical processes, 2) the technology of deep learning spatial-temporal fusion considering large-scale scene changes, and 3) the theory and methods of spatial-temporal-spectrum integration fusion based on deep learning. Between 2013 and 2018, 40 core papers were published relevant to this research front, and these papers received 1989 citations, averaging 49.73 citations per paper.

(9) Refined prediction and rapid damage assessment of river basin floods

The refined prediction and rapid damage assessment of river basin floods is done to accurately and rapidly simulate the flood propagation process, flood damage, and flood impacts, so as to provide decision-support for flood risk management and emergency response. It is achieved by applying meteorological models, hydrological models, hydrodynamic models, flood damage assessment models, and remote sensing techniques, based on high-resolution data from meteorology, landforms, topography, structure, engineering, and socioeconomics. With the development of advanced computer technology, numerical analyses, information technology, and in-depth study of flood disaster mechanisms in recent years, it has become possible to make refined predictions and to do rapid damage assessment of river basin floods. The current development trends include: 1) high-resolution meteorological numerical prediction based on multi-source data fusion, 2) hydrological forecasting models based on physical mechanisms, 3) hydrodynamic simulation models for whole watersheds, 4) integrated basin flood simulation coupled with meteorological simulation, hydrologic, and hydrodynamic models, 5) flood damage assessment models for all types of assets, 6) artificial intelligence forecasting methods and models, and 7) desktop maneuver systems for river basin flood emergency management. Frontier key scientific and technical issues include: 1) high-resolution rainstorm prediction, 2) GPU high-performance accelerated simulation techniques for unstructured grids, 3) model parameter extraction and rapid flood damage assessment methods based on remote sensing data, 4) real-time correction technology of hydrodynamic models, 5) surface-groundwater exchange mechanisms, 6) dam-break mechanism and development-process simulation, 7) assessment of vulnerability of people and assets, damage relationships between all factors of floods (water depth, flow velocity, duration, and carrying away things and destroying assets), indirect flood damage and impact, and 8) applications of artificial intelligence technology. Between 2013 and 2018, 36 core papers were published relevant to this research front, and these papers received 1571 citations, averaging 43.64 citations per paper.

(10) Traffic flow modeling theory and methods for the ICV and HDV mixed traffic

The development of Intelligent and Connected Vehicles (ICVs) is a trend of future traffic, and the gradual deployment of ICVs in traffic will result in a transition period, in which vehicles with various levels of automation/connection and Human Driven Vehicles (HDVs) co-exist. Due to significant differences between ICVs and HDVs in terms of information acquisition, perception, response time, and interaction, and differences at the automation and connection levels among ICVs, traffic flow will manifest some new characteristics. Current research is focused on developing new traffic flow models for heterogeneous traffic and exploring the implications of mixed traffic on traffic flow and safety. The main research fields include:

1) Modeling heterogeneous driving behavior considering human factors. Proper understanding of how human drivers will respond to ICVs, and how ICVs could interact with HDVs is urgent but lacking. This lack of understanding may result in unsafe and inefficient traffic situations. Therefore,

it is necessary to explore the effects of human factors on heterogeneous driving behavior.

2) Driving behavior modeling incorporating information. "Information" is the core element for ICVs. Different types of information (e.g., descriptive information, advisory information, executive information), information content, information release forms, and information collaboration level of the drivers (e.g., willingness to cooperate, degree of collaboration) will have different effects on driving behavior. Hence, the impact of information must be incorporated into the new traffic flow model.

3) Advanced interactive driving simulator-based experiments to study the interactions between ICVs and HDVs. It is difficult to obtain sufficient empirical data on interactions between ICVs and HDVs in the real world, and limited testing data from testing fields cannot cover all interactive scenarios. Therefore, it is necessary to develop a dedicated traffic flow simulation platform, and design massive scenarios for experiments, in order to obtain sufficient operational data about the interactions between ICVs and HDVs for subsequent traffic flow research. Between 2013 and 2018, 186 core papers were published relevant to this research front, and these papers received 5524 citations, averaging 29.70 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Mechanism and control of long-term performance evolution of structures

Civil engineering structures inevitably suffer from long-term performance degradation due to the environmental and mechanical loads to which they are exposed while in service. In order to project its performance over a structure's life cycle, it is necessary to study the internal damage evolution mechanisms of the structure. Developing long-term performance-evolution principles for concrete, steel, and masonry structures are now the focus of many scholars.

Certain structures tend to degrade prematurely owing to insufficient knowledge concerning the evolution of their structural performance. At present, from the perspective of physics and chemistry, research is being conducted on the inherent degradation mechanisms of engineering materials (e.g., carbon steel bar, concrete, steel) exposed to various loads and environments. This information will be used to provide predictive models for the long-term performance evolution of structures considering key parameters. Moreover, performance repair technologies for seriously damaged structures are being studied, thereby improving the lifetime reliability of structures and achieving the goal of effective control of structural performance.

Currently, major research topics concerning the mechanism and control of long-term performance evolution of structures include:

Establishing evaluation and prediction models for the long-term performance of structures based on long-term performance degradation data about engineering materials. The relevant research includes chloride ion penetration rate models, on-line monitoring of steel corrosion damage, optimization checks based on reliability assessments, and maintenance options.

The improvement and control of structural performance using fiber-reinforced polymer composites (FRP) and fiber-reinforced cement matrix composites (FRCM). For FRP materials, the relevant studies include external bonding technology, near-surface mounting (NSM) technology, and internal reinforcing technology. For FRCM materials, a recent research hotspot involves the strengthening technologies that use FRCMs to provide better bending, shear, and shock resistance of concrete and masonry structures.

Research on control of structural performance based on new technologies such as shape memory alloy (SMA), self-healing concrete, asphalt, and new-generation structural steel. These include, for example, improving concrete performance with nanomaterials, using shape memory alloy for strengthening steel and concrete structures, and the strengthening of structures using super-weathering steel technology.

As shown in Table 1.1.1, 72 core papers were published between 2013 and 2018 concerning "mechanism and control of long-term performance evolution of structures", and each paper was cited an average of 23.71 times. The top five countries or regions in terms of core-paper output in this regard are Italy, the USA, Greece, China, and Switzerland (Table 1.2.1). China is one of the most active players on this topic, publishing 9.72% of core papers. The top five countries or regions receiving the highest average citations were Spain, the USA, Greece, Italy, and China. The papers published by China were each cited 22.00 times on average, which indicates that there is still room for further improvement from Chinese scholars on this front. As illustrated by the international collaborative network depicted in Figure 1.2.1, except for India, close cooperation was observed among the most productive top ten countries/regions, especially the USA and Italy.

As shown in Table 1.2.2, the top five institutions publishing the most core papers were the University of Padua (Italy), University of Patras (Greece), University of Bologna (Italy), Missouri University of Science & Technology (USA), and University of Miami (USA). As illustrated in Figure 1.2.2, collaborative studies were significant among the top ten most productive institutions in this regard.

As shown in Table 1.2.3, the top five most active countries or regions in terms of citing the most papers were Italy, China, the USA, the UK, and Australia. As presented in Table 1.2.4, the top five institutions citing the highest number of core papers were Lehigh University (USA), University of Bologna (Italy), Polytechnic University of Milan (Italy), University of Padua (Italy), and Missouri University of Science & Technology (USA). China ranked fourth in terms of the quantity of core papers produced and second for quantity of core papers being cited. This shows that Chinese researchers pay close attention to this research front.

Table 1.2.1 Countries or regions with the greatest output of core papers on "mechanism and control of long-term performance evolution of structures"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Italy	29	40.28%	813	47.63%	28.03
2	USA	18	25.00%	560	32.81%	31.11
3	Greece	9	12.50%	257	15.06%	28.56
4	China	7	9.72%	154	9.02%	22.00
5	Switzerland	5	6.94%	102	5.98%	20.40
6	Canada	4	5.56%	75	4.39%	18.75
7	India	4	5.56%	23	1.35%	5.75
8	Spain	4	5.56%	146	8.55%	36.50
9	Australia	3	4.17%	45	2.64%	15.00
10	Iran	3	4.17%	52	3.05%	17.33

Table 1.2.2 Institutions with the greatest output of core papers on "mechanism and control of long-term performance evolution of structures"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	University of Padua	9	12.50%	314	18.39%	34.89
2	University of Patras	8	11.11%	250	14.65%	31.25
3	University of Bologna	7	9.72%	175	10.25%	25.00
4	Missouri University of Science & Technology	7	9.72%	194	11.37%	27.71
5	University of Miami	6	8.33%	153	8.96%	25.50
6	Polytechnic University of Milan	5	6.94%	130	7.62%	26.00
7	Qatar University	3	4.17%	28	1.64%	9.33
8	University of Nottingham	3	4.17%	50	2.93%	16.67
9	Roma Tre University	3	4.17%	133	7.79%	44.33
10	University of Naples Federico II	3	4.17%	75	4.39%	25.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "mechanism and control of long-term performance evolution of structures"

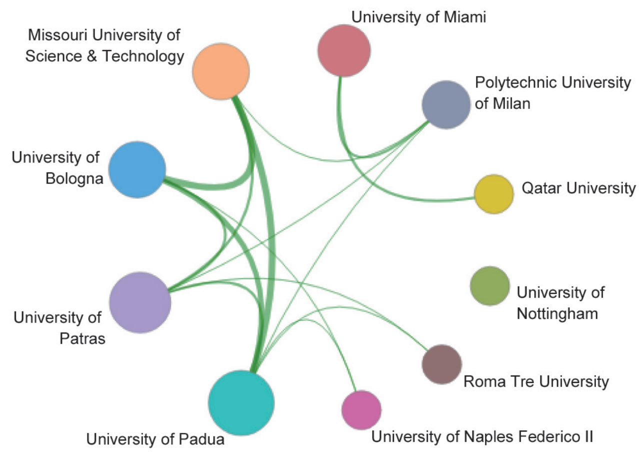

Figure 1.2.2 Collaboration network among institutions in the engineering research front of "mechanism and control of long-term performance evolution of structures"

Table 1.2.3 Countries or regions with the greatest output of citing papers on "mechanism and control of long-term performance evolution of structures"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Italy	256	24.50%	2017.2
2	China	238	22.78%	2017.8
3	USA	181	17.32%	2017.1
4	UK	62	5.93%	2017.3
5	Australia	56	5.36%	2017.9
6	Iran	46	4.40%	2017.6
7	Poland	45	4.31%	2017.2
8	Portugal	42	4.02%	2017.5
9	Spain	41	3.92%	2017.1
10	Greece	39	3.73%	2017.3

Table 1.2.4 Institutions with the greatest output of citing papers on "mechanism and control of long-term performance evolution of structures"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Lehigh University	48	14.50%	2016.9
2	University of Bologna	40	12.08%	2017.2
3	Polytechnic University of Milan	33	9.97%	2016.8
4	University of Padua	31	9.37%	2016.7
5	Missouri University of Science & Technology	29	8.76%	2017.5
6	Roma Tre University	26	7.86%	2016.5
7	Universidade do Minho	26	7.86%	2017.1
8	University of Patras	26	7.86%	2017.1
9	University of Naples Federico II	26	7.86%	2017.5
10	University of Calabria	23	6.95%	2017.0

1.2.2 Green building design method based on the whole life cycle

In recent years, due to social and economic development, advances in science and technology, and people's pursuit of higher quality of life, the demand for green buildings has shifted from "increasing quantity" to "quality-oriented" in the sense of "people-oriented". This directly promotes the connotations of green building from the original "resource conservation" to "safe and durable", "healthy and comfortable", "convenient", and "environment livable". Therefore, in the future, it is necessary to study how to integrate safety, health, comfort, convenience, livability, and perceptibility into all stages of green building and to evaluate overall, the life cycle of structures. The development of information, energy and new technologies for materials has produced the potential for breakthroughs in key technologies in this field. The trend of future development includes: (1) a new multi-disciplinary and whole-process group-collaborative-design method from single building to urban scale under the premise of smart, healthful, and people-oriented green building, (2) AI assisted design optimization, (3) performance-oriented digital design, (4) healthful/smart building design, (5) active and passive integrated devices end design, and (6) development and application of new materials.

The institutions pursuing active research in this field within China are Tsinghua University, Xi'an University of Architecture and Technology, Chongqing University, Zhejiang University, and the China Academy of Building Research. The most active research institutions outside China are the Lawrence Berkeley National Laboratory (USA), University of Melbourne (Australia), National University of Singapore (Singapore), and the University of Perugia (Italy). In addition, there are many international architectural design software companies and architectural design companies active in this research field, such as Revit and Nikken Design. The relevant research output includes international journal articles, databases, software tools, and product patents.

As listed in Table 1.1.1, 184 core papers were published between 2013 and 2018 concerning "green building design method based on the whole life cycle", and each paper was cited 40.45 times on average. The top five countries in terms of core paper output were China, the USA, Australia, Italy, and the UK (Table 1.2.5). China was one of the most active players in this front, producing 22.83% of the core papers. The top five countries receiving the highest average citations were China, Spain, the USA, Australia, and Switzerland. In terms of core-paper citations, papers published by China were each cited 63.36 times on average, exceeding the global average number. This indicates that researchers from China are gradually gaining increasing attention. As illustrated by the international collaborative network depicted in Figure 1.2.3, relatively close cooperation was indicated between China and Australia.

As listed in Table 1.2.6, the top three institutions publishing the highest number of core papers were Hong Kong Polytechnic University (China), National University of Singapore (Singapore), Chongqing University (China), City University of Hong Kong (China), and the University of Melbourne (Australia). As illustrated in Figure 1.2.4, institutions in the same country or region cooperated, but crossover collaborations between different countries or regions were rare.

Table 1.2.5 Countries or regions with the greatest output of core papers on "green building design method based on the whole life cycle"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	42	22.83%	2661	35.76%	63.36
2	USA	27	14.67%	1331	17.89%	49.30
3	Australia	25	13.59%	1130	15.18%	45.20
4	Italy	15	8.15%	394	5.29%	26.27
5	UK	14	7.61%	398	5.35%	28.43
6	Singapore	10	5.43%	224	3.01%	22.40
7	Spain	9	4.89%	556	7.47%	61.78
8	Switzerland	9	4.89%	372	5.00%	41.33
9	Norway	9	4.89%	209	2.81%	23.22
10	Germany	8	4.35%	244	3.28%	30.50

Table 1.2.6 Institutions with the greatest output of core papers on “green building design method based on the whole life cycle”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Hong Kong Polytechnic University	18	9.78%	1021	13.72%	56.72
2	National University of Singapore	8	4.35%	205	2.75%	25.63
3	Chongqing University	7	3.80%	279	3.75%	39.86
4	City University of Hong Kong	5	2.72%	756	10.16%	151.20
5	University of Melbourne	5	2.72%	186	2.50%	37.20
6	Central Queensland University	5	2.72%	163	2.19%	32.60
7	University of Perugia	4	2.17%	255	3.43%	63.75
8	Norwegian University of Science and Technology	4	2.17%	134	1.80%	33.50
9	Yonsei University	4	2.17%	124	1.67%	31.00
10	Swiss Federal Institute of Technology Zurich	4	2.17%	94	1.26%	23.50

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “green building design method based on the whole life cycle”

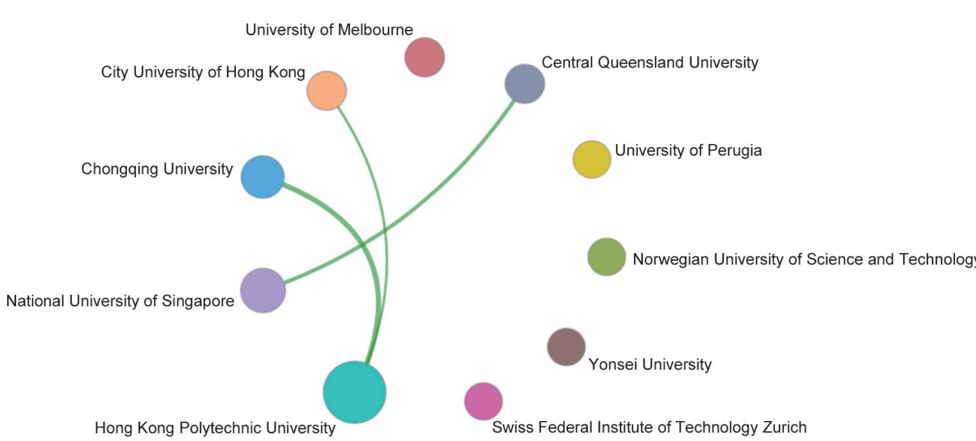

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “green building design method based on the whole life cycle”

As listed in Table 1.2.7, the top five countries/regions citing the most core papers were China, the USA, the UK, Australia, and Italy. As presented in Table 1.2.8, the top five institutions citing the most core papers were Hong Kong Polytechnic University (China), Tsinghua University (China), Chongqing University (China), Chinese Academy of Sciences (China), and National University of Singapore (Singapore). China ranked first in terms of both the number of published core papers and the number of core papers being cited, indicating that Chinese researchers pay close attention to this research front.

1.2.3 Nano-modification and fiber-reinforcement of cement-based materials

With continuous improvement of living standards and the advancement of urbanization, engineering structures have been developing in the directions of high quality, durability, environmental protection, and aesthetics, which require further improvement of the performance of building materials. The fiber-reinforcement of cement-based materials can prevent the development of cracks due to bridging by the fibers and thereby improve the crack resistance of cement-based materials. With the advancement of nanotechnology, nanomaterials have also become a cement modification material with excellent performance. The incorporation of nano-materials accelerates the hydration reaction process of cement-based materials, improves their compactness, and improves the strength and durability of the materials.

The main research directions of nano-modification and fiber-reinforcement of cement-based materials are:

(1) Preparation and performance control of hybrid fiber

Table 1.2.7 Countries or regions with the greatest output of citing papers on "green building design method based on the whole life cycle"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1429	28.43%	2017.4
2	USA	766	15.24%	2017.0
3	UK	518	10.31%	2017.1
4	Australia	502	9.99%	2017.1
5	Italy	471	9.37%	2016.9
6	Spain	333	6.63%	2017.1
7	Germany	235	4.68%	2017.2
8	Canada	205	4.08%	2017.4
9	South Korea	201	4.00%	2017.1
10	France	195	3.88%	2016.8

Table 1.2.8 Institutions with the greatest output of citing papers on "green building design method based on the whole life cycle"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hong Kong Polytechnic University	208	21.73%	2017.3
2	Tsinghua University	104	10.87%	2017.6
3	Chongqing University	94	9.82%	2017.5
4	Chinese Academy of Sciences	81	8.46%	2017.2
5	National University of Singapore	78	8.15%	2017.2
6	City University of Hong Kong	71	7.42%	2016.4
7	Tongji University	67	7.00%	2017.4
8	Yonsei University	66	6.90%	2016.4
9	Shenzhen University	66	6.90%	2017.3
10	University of Perugia	61	6.37%	2016.3

composite cement-based materials. The fiber composites of early cement-based materials were mainly single fiber composites. With deepening research, hybrid fiber composite cement-based materials have received more attention. Hybrid fiber composite refers to the reinforcement of cement-based materials using two or more fibers of different constitutions, different sizes, and different functions. Hybrid fiber composite technology improves the comprehensive performance of cement-based materials, and at the same time, effectively reduces the cost of composite materials, making fiber-composite cement-based materials have more practical value for engineering.

(2) High performance and multi-functionality of plant-fiber-composite cement-based materials. Plant fiber has the advantages of high specific strength, high specific modulus, low density, and attractive heat insulation, along with toughness and wear resistance. It is an ecologically friendly and low-cost renewable resource. At present, research on plant fiber composite cement-based materials mainly focuses on fiber surface-modification treatment and multi-level multi-scale cracking resistance. At the same time, research has gradually been carried out on the properties of flame retardance, sound absorption, heat insulation, and vibration damping of plant-fiber-composite cement composites.

(3) Preparation of nanomaterials and nano-modified cement-based materials. The common nanomaterials for cement-based materials modification include nano-$CaCO_3$, nano carbon-tubes, nano-TiO_2, graphene oxide, nano-kaolin, nano-clay. Dispersion of nanomaterials is one of the key issues in the nano-modification technology. Common dispersion methods include: functional grouping, surfactant encapsulation, polymer encapsulation, ultrasonic dispersion and mechanical agitation dispersion. Nano-modification technology can effectively improve the compressive strength, flexural strength and durability of cement-based materials, but it has an adverse effect on the rheological properties. Therefore, the relationship among nano-materials, water-reducing agents and water used in cement-based materials is also one of the focuses of current research.

(4) Microstructure and nano-modification mechanisms of nano-modified cement-based materials. Nanomaterials can promote the cement hydration reaction and improve the early strength of cement-based materials. In addition, the nucleation effect of nanoparticles improves the orientation of CSH gels, making hydration products more compact; at the same time, nanomaterials have a filling effect on micro pores, which further reduces the porosity of cement-based materials, resulting in an increase in material density. In particular, according to market demand, the modification of some nano materials can make the cement material exhibit other functions. Examples include such as carbon-nanotube modified cement-based materials with electrical conductivity and pressure sensitivity, and nano-TiO_2 modified cement-based materials with self-cleaning performance.

As listed in Table 1.1.1, 75 core papers were published between 2013 and 2018 concerning “nano-modification and fiber-reinforcement of cement-based materials”, and each paper was cited 28.49 times on average. The top five countries/regions for core paper output were Italy, the USA, China, Greece, and Spain (Table 1.2.9). As one of the leading research countries, China published 17.33% of the core papers on this research front. The top five countries receiving the highest average citations were Spain, Brazil, Australia, China, and the USA. The papers published by Chinese authors received 30.62 citations per paper on average, which is slightly above the overall average. From the perspective of cooperation networks between major countries or regions (Figure 1.2.5), close cooperation has been observed among the most productive top ten countries or regions, particularly between the USA and Italy.

Regarding the institutions producing the most core papers (Table 1.2.10), the top five on this front are University of Patras (Greece), University of Padua (Italy), Missouri University of Science & Technology (USA), University of Bologna (Italy), and University of Miami (USA). From the perspective of cooperation networks between the leading institutions on the research front (Figure 1.2.6), the institutions of the USA, Italy, and Greece are more closely cooperating.

The top five countries or regions citing core papers are China, Italy, the USA, Australia, and the UK (Table 1.2.11). The top five institutions citing the core papers are Missouri University of Science & Technology (USA), University of Bologna (Italy), National University of Singapore (Singapore), Polytechnic University of Milan (Italy), and the University of Padua (Italy) as shown in Table 1.2.12. China ranked third in terms of the number of published core papers and first in the citing of core papers, indicating that Chinese researchers pay close attention to research performed on this front.

Table 1.2.9 Countries or regions with the greatest output of core papers on “nano-modification and fiber-reinforcement of cement-based materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Italy	24	32.00%	672	31.45%	28.00
2	USA	22	29.33%	639	29.90%	29.05
3	China	13	17.33%	398	18.62%	30.62
4	Greece	9	12.00%	257	12.03%	28.56
5	Spain	5	6.67%	194	9.08%	38.80
6	Australia	4	5.33%	133	6.22%	33.25
7	Brazil	3	4.00%	102	4.77%	34.00
8	Canada	3	4.00%	51	2.39%	17.00
9	UK	3	4.00%	50	2.34%	16.67
10	Qatar	3	4.00%	28	1.31%	9.33

Table 1.2.10 Institutions with the greatest output of core papers on “nano-modification and fiber-reinforcement of cement-based materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	University of Patras	8	10.67%	250	11.70%	31.25
2	University of Padua	8	10.67%	302	14.13%	37.75
3	Missouri University of Science & Technology	8	10.67%	239	11.18%	29.88
4	University of Bologna	7	9.33%	175	8.19%	25.00
5	University of Miami	5	6.67%	120	5.62%	24.00
6	Polytechnic University of Milan	4	5.33%	95	4.45%	23.75
7	Roma Tre University	3	4.00%	133	6.22%	44.33
8	University of Hartford	3	4.00%	144	6.74%	48.00
9	University of Nottingham	3	4.00%	50	2.34%	16.67
10	Hong Kong University of Science & Technology	3	4.00%	44	2.06%	14.67

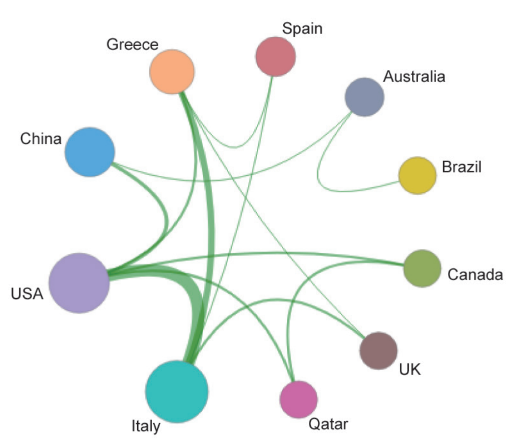

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “nano-modification and fiber-reinforcment of cement-based materials”

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top ten engineering development fronts in the field of civil, hydraulic, and architectural engineering, are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including structural engineering, transportation planning, hydrology and water resources, municipal engineering, architectural design and theory, geotechnical and underground engineering, construction material, and photogrammetry and aerospace survey. Among these

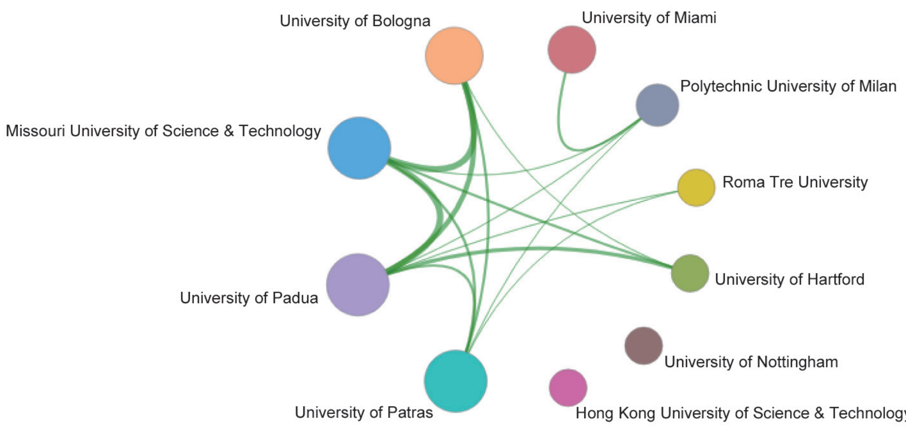

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "nano-modification and fiber-reinforcment of cement-based materials"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "nano-modification and fiber-reinforcment of cement-based materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	459	33.73%	2017.5
2	Italy	227	16.68%	2017.2
3	USA	172	12.64%	2017.4
4	Australia	82	6.03%	2017.5
5	UK	71	5.22%	2017.6
6	Iran	64	4.70%	2017.8
7	India	63	4.63%	2017.8
8	Brazil	63	4.63%	2016.9
9	South Korea	55	4.04%	2017.7
10	Portugal	54	3.97%	2017.4

Table 1.2.12 Institutions with the greatest output of citing papers on "nano-modification and fiber-reinforcment of cement-based materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Missouri University of Science & Technology	43	12.72%	2017.5
2	University of Bologna	40	11.83%	2017.2
3	National University of Singapore	36	10.65%	2016.4
4	Polytechnic University of Milan	30	8.88%	2017.2
5	University of Padua	29	8.58%	2016.6
6	Southeast University	29	8.58%	2017.9
7	University of Minho	28	8.28%	2017.0
8	Beijing University of Technology	27	7.99%	2017.0
9	Roma Tre University	26	7.69%	2016.5
10	University of Patras	25	7.40%	2017.1

development fronts, "comprehensive transportation planning and intelligent safety management of urban agglomeration", "ecologically friendly settlements and ecological restoration technology", and "marine surveying equipment" were recommended by experts, and the others were identified from patent maps and then confirmed by experts. Table 2.1.2 presents annual statistical data on the patents published between 2013 and 2018 related to the top ten development fronts.

(1) Technology for reinforcement, repair, and retrofitting of existing structures

Structures are inevitably subjected to function replacement, load increase, damage accumulation, performance deterioration, and characteristic loss during their service lives. Retrofitting, rehabilitation, and renovation of existing structures are therefore of great importance to ensure structural safety, enhance building functions, and maintain cultural characteristics. Under long-term effects of service

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Technology for reinforcement, repair, and retrofitting of existing structures	2852	1819	0.64	2016.0
2	Comprehensive transportation planning and intelligent safety management of urban agglomeration	1087	1725	1.59	2016.0
3	Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater	506	4463	8.82	2015.5
4	Sustainable technology for resource and energy recovery from wastewater	590	2933	4.97	2015.4
5	Ecologically friendly settlements and ecological restoration technology	3717	3250	0.87	2015.7
6	Standardized construction technology for prefabricated steel structures	1552	4195	2.70	2016.0
7	Techniques and intelligent equipment for efficient and safe excavation of super tunnels	70	167	2.39	2015.6
8	3D printing cement-based materials	104	682	6.56	2016.5
9	Incident response and rapid recovery during underground space construction	1853	2245	1.21	2015.8
10	Marine surveying equipment	606	2054	3.39	2015.6

Table 2.1.2 Annual number of patents published for the top 10 engineering development fonts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Technology for reinforcement, repair, and retrofitting of existing structures	344	367	380	428	591	742
2	Comprehensive transportation planning and intelligent safety management of urban agglomeration	139	95	148	186	239	280
3	Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater	53	82	126	107	105	33
4	Sustainable technology for resource and energy recovery from wastewater	68	120	150	111	71	70
5	Ecologically friendly settlements and ecological restoration technology	413	534	763	702	631	674
6	Standardized construction technology for prefabricated steel structures	85	158	238	329	399	305
7	Techniques and intelligent equipment for efficient and safe excavation of super tunnels	8	9	13	13	12	13
8	3D printing cement-based materials	2	11	13	14	33	31
9	Incident response and rapid recovery during underground space construction	209	237	349	315	351	392
10	Marine surveying equipment	81	121	94	111	93	106

loads and environmental attacks, accumulation of damage, deterioration of performance, and loss of characteristics may occur to existing structures. A transient load may result in a dramatic drop in the structural performance. Renovation of existing structures is sometimes required due to function replacement, and often older structures cannot meet the requirements of modern design standards reflecting more recent developments of the social economy and technology. Therefore, a large number of existing structures need retrofitting, rehabilitation, and renovation. Major issues concerning this development front include: 1) enhancement of durability and repair of damage at the material level, 2) improvement of load bearing capacity at the component level, and 3) seismic strengthening and structural renovation at the structural level. Enhancement of durability and repair of damage at the material level mainly refer to re-alkalization of carbonized concrete, extraction of chloride ions from concrete, protective repair of the envelope materials of historical buildings, and self-healing of cracked concrete. Improvement of load bearing capacity at the component level indicates strengthening of different components and joints subjected to various loads. Seismic reinforcement and structural renovation at the structural level are generally achieved by strengthening the overall performance of the structure, improving the seismic capacity of the structure, changing the structural system, or applying seismic isolation measures to mitigate the seismic action of the superstructure. Currently, upgrading the seismic performance of traditional buildings such as timber structures and masonry structures while maintaining specific characteristics has attracted intense attention. With the development of new materials, fiber-reinforced polymer, graphene, cement-based composites, and shape memory alloys are increasingly being applied. Between 2013 and 2018, 2852 patents related to this topic were published, of which 1819 patents were cited (an average of 0.64 citations per patent).

(2) Comprehensive transportation planning and intelligent safety management of urban agglomeration

The term urban agglomeration indicates urbanized areas of concentrated residency and industry. The emergence of urban agglomeration is an obvious reflection of the growth of urbanization, as well as of engines to boost the economy. Urban agglomerations contribute to a country's balanced development across regions and enable the country to take part in international economic exchange. Different from intra-city transportation that leans heavily on commuting trips, inter-city transportation within urban agglomerations generally crosses spatial jurisdictions and shows multivariate-overlap in terms of trip purposes and demands. The iterative interplay between three components—functional structure, mobility demand, and transportation network and service—is the main concern of comprehensive transportation planning and safety management for urban agglomeration. To underpin an efficient, safe, and cost-effective passenger and cargo transportation system for city clusters, we ought to systematically design comprehensive transportation facility systems, and develop intelligent operation policies, based on informative and quantitative measures. Currently, there are five research directions within transportation planning and safety management for urban agglomeration: 1) the analysis of the correlations between spatial structure and intensity of transportation connections, 2) the planning technology for transportation corridors connecting the cities, 3) the "one-stop" passenger and cargo logistic organization plans, 4) the transportation network resilience in response to disasters and repair technology, and 5) the comprehensive active transportation intelligent safety management systems. Between 2013 and 2018, 1087 patents on this topic were published with 1725 patent citations, an average of 1.59 citations per patent.

(3) Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater

Since the beginning of the 21st century, many countries have paid increasing attention to the protection of aquatic ecosystems while strengthening legislation and have accelerated the pace of research and development of technology for aquatic ecological environment monitoring, evaluation, and restoration. The technologies for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater, in particular, are defined as some of the newest and developing technologies. With the rapid development of information technology and artificial intelligence technology, there has been the rapid emergence of technologies for such as automatic sample collection and automatic water quality monitoring systems that utilize unmanned underwater and aerial vehicles, and robots that can clean water surfaces and navigate automatically. The development of technologies for monitoring and early warning for river, lake, sea, and groundwater environments have driven applications of a variety of emerging technologies.

The integration of high-precision hydrological, water quality, and ecological modeling systems has enabled building of technical systems to provide the future monitoring and early warning technologies needed for aquatic environments. Moreover, these advances are also conducive to the simulation and projection of restoration effects. In terms of the trend in the use of restoration technology, developed countries have gradually shifted from pollution control to prevention-oriented strategies, focusing more on pollution reduction at source, protecting habitat, and restoring ecosystem functions. China is currently focusing on pollution control of surface and groundwater. Between 2013 and 2018, 506 patents on this topic were published with 4463 patent citations, an average of 8.82 citations per patent.

(4) Sustainable technology for resource and energy recovery from wastewater

Sustainable technology for resource and energy recovery from wastewater involves development of efficient technologies for recovering a variety of resources (e.g., nitrogen, phosphorus, metals) and energy (e.g., biohydrogen, methane, bioelectricity) during the process of standard wastewater treatment or deep purification. This also requires the development of novel processes and green technologies with low energy consumption and low discharge, as well as carbon neutral technologies with fully internal recycling of resources and energy. The key frontier technologies include: 1) technology for cascade resource recovery from sewage/sludge, which is being systematically developed for organic carbon recovery, nitrogen/phosphorus recovery, metal recovery, and recycled water production targeting specific characteristics of sewage and various resource elements and 2) resource/energy recycling within sewage treatment systems, for which updating processes or novel technologies are explored for deep reuse of biosynthesized carbon sources in sewage, including such as extracellular polymer substrates and polysaccharides, and resource recovery from excess sludge will be applied for such as thermal hydrolysis, plasma melting, anaerobic digestion, and electricity-heat cogeneration. 3) Other frontier technologies include energy self-sufficient sewage treatment driven by renewable energy, for which technologies based on green material/energy are developed, such as microalgal-photosynthesis systems for nitrogen/phosphorus nutrient recovery, bio-electrochemical systems for energy recovery (e.g., hydrogen, methane, bioelectricity), and advanced technology for treatment of refractory pollutants based on advanced photocatalytic materials. 4) Also involved is unconventional denitrification technology with low consumption of energy and chemicals, which promotes the development of anaerobic ammonia oxidation, whole ammonia oxidation, a partial sub-digestion process combined with anaerobic ammonia oxidation, sulfur autotrophic denitrification, etc., and the development of low-carbon wastewater treatment (carbon neutral technologies), like inverted A2O and multi-stage AO processes. 5) Finally, there is intelligent control, energy saving, and reduced consumption of wastewater treatment plants, for which precise control technology based on big data analysis (such as micro-bubble aeration, energy-saving pump control, etc.), and intelligent pipeline network monitoring systems are being developed to realize the optimal utilization of resources and energy. This also involves the operation management of low-carbon processes during sewage treatment. Between 2013 and 2018, 590 patents on this topic were published with 2933 patent citations, an average of 4.97 citations per patent.

(5) Ecologically friendly settlements and ecological restoration technology

With the continuous acceleration of urbanization, the need to conduct ecological restoration in intensively developed urban settlements is inevitable. A large number of existing communities have suffered declines in quality of life due to ecological damage. Under such circumstances, it is necessary to establish a technological system for complete ecological restoration by means of reusing and recycling the spatial elements, space, energy, and materials of the affected communities. Such a process should employ passive climate control technology and follow the principles of “ecology first, entirety first, and environment first”. Specific ecological restoration strategies include such as landscape integration, water circulation, surface infiltration, and site remodeling. The research on ecological settlements and ecological restoration technology includes: 1) the ecological damage and degradation status of high density neighborhoods and the application status of ecological restoration technology (involving the degree of ecological damage and degradation), the ecological restoration ability of urban settlements, etc., and 2) engineering problems and technical methods for ecological restoration in high-density neighborhoods, involving key technologies of environmental restoration in high-density neighborhoods and methods for ecological restoration based on climate response. This body of research aims to form an ecological settlement system, and to build human habitats that meet the standard of resource-saving and environmental-friendliness. Ecological restoration is an urgent, fundamental imperative in terms of ecological engineering, and a research field of great world-wide concern. The research provides systematic principles, technical methods and design strategies for environmental restoration of urban settlements, establishes design strategies for ecological restoration of high-density settlements based on climate-responsive methods, fills the gap in ecological evaluation and strategy systems in the regeneration of old towns, and improves the mechanism for innovation of ecology-friendly cities. Between 2013 and 2018, 3717 patents on this topic were published with 3250 patent citations, and an average of 0.87 citations per patent.

(6) Standardized construction technology for prefabricated steel structures

Prefabricated steel structures refer to steel buildings integrated with industrialized facades, furniture, facilities, and pipeline systems. Prefabricated steel structures also refer to infrastructure such as steel bridges and facilities that employ ancillary systems of prefabricated members and components. The concept of standardized construction for prefabricated steel structures is closely related to life-cycle sustainability, and it involves standardized design, industrialized production, assembled construction, integrated decoration, information-based management, and intelligent application. In this way, the overall performance and quality of the construction can be improved, and the construction efficiency can be significantly enhanced. In addition, the work required on-site can be greatly reduced, and energy saving and emission reduction can be further promoted. Focusing on the function of the construction object, the standardized construction technology for prefabricated steel structures incorporates the idea of system integration in various stages (i.e., planning, design, manufacturing, transport, construction, and maintenance), so as to realize whole-process synergy. In particular, the following aspects should be ensured. 1) Serialization and diversification of the products should be enhanced by conforming to the design principles of fewer specifications and more combinations according to the requirements of generalization, modularization, and standardization. 2) Construction efficiency should be enhanced by reducing on-site welding and concrete pouring, and also by developing weld-free bolted connections, prefabricated facades and floors, and prefabricated seismic mitigation technology. 3) It is also necessary to establish a well-developed production quality management system, and improve the accuracy of manufacturing. 4) Use various specialties for a construction assembly organization scheme, so as to improve labor efficiency. 5) Carry out integrated design of non-structural systems and other parts. 6) The Building Information Model (BIM) should be used to realize professional and whole-process information management. 7) Artificial intelligence and the Internet of Things technology should be used to realize safe, convenient, comfortable, and environment-friendly systems. With the in-depth development of construction industrialization, the trend in future development is to achieve technological innovation and improvement of construction quality through multidisciplinary research and development in fields that include construction, civil engineering, computers, mechanics, telecommunications, materials, and management. Between 2013 and 2018, 1552 relevant patents were published with 4195 patent citations, averaging 2.7 citations per patent.

(7) Techniques and intelligent equipment for efficient and safe excavation of super tunnels

A super tunnel generally refers to a tunnel project with very large engineering scale (more than 15 kilometers in length or 15 meters in maximum section size). The longest tunnel in the world is more than 50 kilometers in length and the largest tunnel section exceeds 20 meters in diameter. Super-tunnel engineering is mostly used to cross mountainous or water areas with a wide range and complex environments. The construction, operation, and maintenance processes involve great technical problems and challenges. The main technical directions include: 1) high-precision detection and dynamic feedback of deep geological hydrology information in ultra-complex environments, 2) load and structural dynamic design methods in ultra-large-scale tunnels, 3) new intelligent materials and structural forms for super long and ultra-deep buried tunnels, 4) new technology and equipment for tunnel construction under high stress, high ground temperature, and high water-pressure conditions, 5) safety early warning and intelligent construction equipment for ultra-long-distance tunnels in complex environments, 6) new technology and equipment for waterproof and water controlled ultra-deep tunnel construction, operation, and maintenance, 7) intelligent sensing, maintenance technology, and equipment for ultra-long tunnel safety and service performance,

8) operation security, intelligent disaster prevention, and rescue technology for ultra-long and ultra-deeply buried tunnels, and 9) dynamic risk management and monitoring of the entire process for construction of ultra-long and ultra-deep tunnels. Between 2013 and 2018, 70 patents on this topic were published, with 167 patent citations, an average of 2.39 citations per patent.

(8) 3D printing cement-based materials

The technology for 3D Printing has drawn increasing attention in the field of automated construction, and 3D printing cement-based materials have become hot topics of research in recent years. These 3D printing cement-based materials are cement-based materials that allow the 3D printing performance required for 3D printing construction technology. Presently, major research trends relevant to this front include printable performance control, interlayer adhesion performance enhancement, and high-strength high-toughness materials. Printing performance control and mechanism research is crucial to establish design theories and to realize the printing and application of 3D printing cement-based materials. Enhancement of interlayer adhesion performance and knowledge of its mechanism are keys to the safety of 3D printed components and buildings. Development of high-strength and high-toughness cement-based materials for 3D printing is an effective means to achieve 3D printing construction without reinforcement. Developing long-life 3D printing cement-based materials, exploring the environmental sensitivity of cement-based materials for 3D printing, and the evolutionary development and mechanism of 3D-printed cement-based materials in extreme environments are expected to be important research issues in the future. Between 2013 and 2018, 104 patents on this topic were published with 682 patent citations and an average of 6.56 citations per patent.

(9) Incident response and rapid recovery during underground space construction

Disasters often occur during construction and operation of underground spaces due to the difficult ground conditions as well as to internal and external influences on the underground structures. Despite the variety of underground space construction methods and maintenance technologies used, the disasters that still happen in underground spaces mainly include water leakage, instability of underground structures, and excessive ground deformation caused by underground space construction, which also affect environmental safety. Groundwater is the most common factor causing disasters in underground structures. The ground must be strengthened while controlling the stability of the underground structure to repair underground structures after disasters in any emergency. The stability of the surrounding ground is the key to ensuring the long-term stability of the underground structure. The most effective methods commonly used in the stabilization of underground structures during emergency processes are grouting, defect repair, and structural reinforcement. The improvement of the ground can be achieved by means of grouting and anchor reinforcement. To control groundwater leakage, the most effective technical means is to precisely detect the location of the leakage and apply grouting rapidly to stop the inflowing water. Due to the increasingly complex environmental and geological conditions of underground space development and the aging of the underground structures already operating, the safety risks in the development and utilization of underground spaces have increased significantly. Under such conditions, rapid repair technology for imminent emergencies is critical. New materials with high-strength properties that can be realized rapidly, as well as new equipment that can be used in limited underground spaces, are the keys to realizing rapid repair of underground structures in emergencies. Between 2013 and 2018, 1853 patents on this topic were published, with 2245 patent citations and an average of 1.21 citations per patent.

(10) Marine surveying equipment

Marine surveying equipment is one of the development fronts in the field of surveying and mapping engineering, which provides basic support for the surveying of marine geospatial elements. Marine surveying equipment includes marine surveying platforms and professional surveying instruments for tasks that include such as seabed topographic surveying, marine gravity surveying, marine magnetic surveying, and marine seismic surveying. In recent years, ocean survey platforms have evolved from traditional ship-borne platforms to multi-dimensional data-acquisition systems for space, aviation, ground, surface, and underwater applications. Correspondingly, key technical issues relevant to this field include autonomous underwater vehicles, unmanned surface vehicles, unmanned ships, positioning and navigation equipment related to platforms, and towing devices and other ancillary equipment. Regarding professional surveying instruments, the major technical challenges concerning this development front include new sensors and their control. Data processing technologies are the main technical direction at present and include such technologies as ocean array sensors (from single probes to multiple probes) and geometric control methods of towed geophysical sensor arrays. Between 2013 and 2018, 606 patents on this topic were published with 2054 patent citations: an average of 3.39 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Technology for the reinforcement, repair, and retrofitting of existing structures

Owing to rapid industrialization, large-scale infrastructure construction has been undertaken in many countries since the middle of the twentieth century. This infrastructure may be subjected to sudden or transient disasters, such as earthquakes, fires, winds, or explosions, leading to catastrophic loss. Since the twentieth century, earthquake disasters have frequently occurred, causing serious damage to structures and major casualties. Existing structures that were built in previous decades, have a variety of structural configurations and consequently, a variety of seismic performance. In addition to the research on enhancement of the seismic performance of existing structures of different ages regarding structural configurations and materials, it is necessary to conduct symmetric research on retrofitting, rehabilitation, and renovation of structures with seismic damage.

Under the long-term effects of service loads and environmental attacks, the performance of existing structures generally degrades due to deterioration of materials, corrosion of steel, and accumulation of damage. Besides the investigation of rehabilitation techniques of materials themselves (e.g., masonry, timber, concrete, and steel) which exhibit degradation and cracking, deteriorated properties of the materials should also be taken into consideration in repair, reinforcement, and modification of components and structures.

Different from practices with typical existing structures, there are often conflicts or contradictions between reasonable protection of detailed features and spatial forms of historical buildings and retrofitting, rehabilitation, and renovation of such structures. There is still a lack of systematic research on compatible repairs at the material level, recoverable retrofitting at the component level, and system-based controllable strengthening at the structural level for historical buildings.

Major issues concerning this development front include:

(1) Techniques for the repair of materials have rapidly developed in recent years, including repair of carbonized concrete, chloride-ion-eroded concrete, weathered brick masonry, decayed wood, and corroded steel, and rehabilitation of cracked concrete, steel, masonry, and wood (especially the self-healing techniques for cracked concrete).

(2) Retrofitting of structural components generally shifts from static loads to fatigue loads, impacts, or explosions, from intact elements to damaged ones, from short-term to long-term performance, and from deterministic to random analysis.

(3) Seismic retrofitting and renovation at the structural level mainly rely on improvement of the seismic capacity of structures or mitigation of the seismic action of the superstructure by applying seismic isolation measures. The former generally includes strengthening the overall performance of the structure, changing the structural system, providing the desirable bearing capacity of loaded members, and enhancing the stiffness of joints. The latter is normally achieved by providing vibration isolation devices and installing dampers, as well as buckling-restrained brace members.

(4) Rehabilitation and maintenance technologies of historical buildings have been developed continuously, including the compatible repair of typical materials of historical buildings (e.g., lime, white marble, raw earth wall and bricks), enhancement of the ultimate load-bearing capacity and performance of damaged components and joints of traditional timber and masonry structures, as well as theory and methods for system-based structural retrofitting.

(5) With the development of materials science, many new high-performance materials such as fiber-reinforced polymer materials, graphene, cement-based composite materials, and shape memory alloys, have been recognized by researchers and applied to structural retrofitting, rehabilitation, and renovation.

As listed in Table 2.1.1, 2852 patents were published on this topic between 2013 and 2018. The top five countries or regions publishing the most patents were China, Japan, South Korea, Russia, and the USA (Table 2.2.1), and China contributed more than 59.71% of the patents. As depicted in Figure 2.2.1, international cooperation is rare among the top ten patent-output countries or regions in this regard.

As listed in Table 2.2.2, the top five organizations producing the most patents were the China State Construction Engineering Corporation (China), Takenaka Komuten KK (Japan), Shimizu Construction Co., Ltd. (Japan), Taisei Construction Co., Ltd. (Japan), and Luoyang Institute of Science and Technology (China). Cooperation among these organizations is rare (Figure 2.2.2).

2.2.2 Comprehensive transportation planning and intelligent safety management of urban agglomeration

An urban agglomeration is an urbanized area of concentrated residency and industry. The emergence of urban agglomerations is the obvious reflection of the growth of urbanization, as well as of engines to boost the economy. Urban agglomerations contribute to a country's balanced development across

Table 2.2.1 Countries or regions with the greatest output of patents on "technology for the reinforcement, repair, and retrofitting of existing structures"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	1703	59.71%	1248	68.61%	0.73
2	Japan	570	19.99%	248	13.63%	0.44
3	South Korea	323	11.33%	113	6.21%	0.35
4	Russia	59	2.07%	24	1.32%	0.41
5	USA	45	1.58%	100	5.50%	2.22
6	Germany	22	0.77%	11	0.60%	0.50
7	Colombia	11	0.39%	3	0.16%	0.27
8	Italy	9	0.32%	11	0.60%	1.22
9	France	9	0.32%	6	0.33%	0.67
10	Poland	9	0.32%	2	0.11%	0.22

Table 2.2.2 Institutions with the greatest output of patents on "technology for the reinforcement, repair, and retrofitting of existing structures"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CSCE	China	62	2.17%	68	3.74%	1.10
2	TKEN	Japan	53	1.86%	15	0.82%	0.28
3	SHMC	Japan	40	1.40%	13	0.71%	0.33
4	TAKJ	Japan	38	1.33%	15	0.82%	0.39
5	LUOY	China	27	0.95%	21	1.15%	0.78
6	DWHO	Japan	23	0.81%	6	0.33%	0.26
7	UYSE	China	22	0.77%	29	1.59%	1.32
8	SHCG	China	22	0.77%	26	1.43%	1.18
9	CMEG	China	22	0.77%	12	0.66%	0.55
10	RJI	Japan	21	0.74%	7	0.38%	0.33

CSCE: China State Construction Engineering Corporation; TKEN: Takenaka Komuten KK; SHMC: Shimizu Construction Co., Ltd.; TAKJ: Taisei Construction Co., Ltd.; LUOY: Luoyang Institute of Science and Technology; DWHO: Daiwa House Industry Co., Ltd.; UYSE: Southeast University; SHCG: Shanghai Construction Group Co., Ltd.; CMEG: China Metallurgical Group Corporation; RJI: Retrofitting Japan Inst.

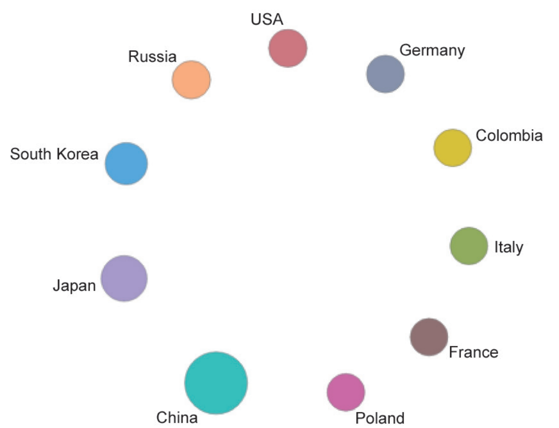

Figure 2.2.1 Collaboration network among countries or regions in the engineering development front of "technology for the reinforcement, repair, and retrofitting of existing structures"

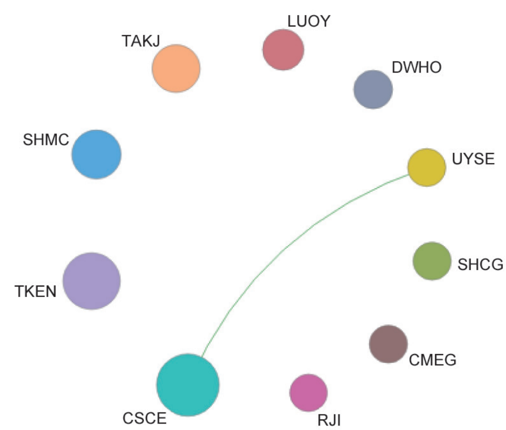

Figure 2.2.2 Collaboration network among institutions in the engineering development front of "technology for the reinforcement, repair, and retrofitting of existing structures"

regions and enable the country to take part in international economic exchange. Different from intra-city transportation that leans heavily on commuting trips, inter-city transportation within urban agglomerations generally crosses spatial jurisdictions and exhibits multivariate overlap in terms of trip purposes and demands. The iterative interplay between three components—functional structure, mobility demand, and transportation network and service—is the main concern of comprehensive transportation planning and safety management for urban agglomeration.

To underpin an efficient, safe, and cost-effective passenger and cargo transportation system for city clusters, we ought to design comprehensive transportation facility systems systematically and develop intelligent operation policies based on informative and quantitative measures.

Currently, there are five research directions for transportation planning and safety management for urban agglomeration:

(1) Analysis of the correlations between spatial structure and intensity of transportation connections. Based on flow space, using multi-source big data such as city-to-city passenger and freight transportation, location-based population migration, nighttime lighting, etc., spatial analysis and social network analysis methods are used to reveal the population mobility of cities between city clusters, and to identify the spatial scale and structure of a city cluster.

(2) Planning technology for transportation corridors connecting the cities. The level of passenger and freight transportation corridors is defined according to the spatial connection intensity of a city cluster. In a transportation corridor, transportation facilities such as roads, tracks, and other backbone facilities, road passenger transportation, and railway passenger transportation, are synergistically integrated to build a multi-channel, multi-mode, and multi-operation mode composite corridor to promote the intensification and synergy of passenger and freight transportation.

(3) One-stop passenger and freight organization method for urban agglomerations. This is about utilizing information technology such as big data, cloud computing, and mobile Internet to integrate efficiently the infrastructure (corridors, hubs) with operational organizations. It promotes the direct communication of supply and demand information, and builds a "one ticket" passenger service system and "one order" freight service system within the urban agglomeration.

(4) Transportation network cascade invulnerability assessment and repair technology for urban agglomerations. This is to construct a cascading failure model of an urban-agglomeration composite transportation network, and to propose criteria for evaluation of network vulnerability. The aim is to identify critical channels and nodes using optimization, simulation, and other technical means, and to format the channel and node capacity repair methods for different damage scenarios to improve resilience in the urban agglomeration transport system.

(5) Comprehensive, proactive, intelligent traffic safety management systems for city clusters. First, it is necessary to

develop holographic detection and proactive identification technologies and equipment to determine the multi-source operation risk within the comprehensive transportation network. Then, cutting-edge research is needed to establish operation risk pre-warning and dynamic-control technical systems. With the traffic risk control domain knowledge graph and information distribution approaches, the remaining frontiers are conducting elaborate and accurate safety management for both city-cluster comprehensive transportation networks and for key traffic operators.

As listed in Table 2.1.1, 1087 patents were published on this topic between 2013 and 2018. The top five countries/regions publishing the most patents were China, South Korea, the USA, Japan, and India (Table 2.2.3); China contributed more than 91.17% of the patents. As depicted in Figure 2.2.3, international cooperation is rare among the top ten core patent-output countries or regions in this regard.

As listed in Table 2.2.4, the top five institutions producing the most patents were Southeast University (China), Jilin University (China), Jiangsu University of Technology (China),

Table 2.2.3 Countries or regions with the greatest output of patents on "comprehensive transportation planning and intelligent safety management of urban agglomeration"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	991	91.17%	1468	85.10%	1.48
2	South Korea	29	2.67%	21	1.22%	0.72
3	USA	19	1.75%	121	7.01%	6.37
4	Japan	11	1.01%	8	0.46%	0.73
5	India	8	0.74%	14	0.81%	1.75
6	Russia	5	0.46%	0	0.00%	0.00
7	Germany	4	0.37%	2	0.12%	0.50
8	Netherlands	3	0.28%	49	2.84%	16.33
9	Australia	2	0.18%	13	0.75%	6.50
10	Canada	2	0.18%	3	0.17%	1.5

Table 2.2.4 Institutions with the greatest output of patents on "comprehensive transportation planning and intelligent safety management of urban agglomeration"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYSE	China	10	0.92%	32	1.86%	3.20
2	UYJI	China	10	0.92%	14	0.81%	1.40
3	JIAA	China	9	0.83%	2	0.12%	0.22
4	HPT	China	8	0.74%	8	0.46%	1.00
5	ADICSS	China	8	0.74%	7	0.41%	0.88
6	ZTEC	China	7	0.64%	27	1.57%	3.86
7	SHCG	China	7	0.64%	10	0.58%	1.43
8	UCHA	China	6	0.55%	10	0.58%	1.67
9	WBDIT	China	5	0.46%	27	1.57%	5.40
10	UYQI	China	5	0.46%	24	1.39%	4.80

UYSE: Southeast University; UYJI: Jilin University; JIAA: Jiangsu University of Technology; HPT: Hangzhou Pule Technology Co., Ltd.; ADICSS: Anhui Dar Intelligent Control System Stock Co., Ltd.; ZTEC: ZTE Corporation; SHCG: Shanghai Urban Traffic Design Institute Co., Ltd.; UCHA: Chang'an University; WBDIT: Wuxi Big Dipper Information Technology; UYQI: Tsinghua University.

Hangzhou Pule Technology Co., Ltd. (China), and Anhui Dar Intelligent Control System Stock Co., Ltd. (China). Cooperation among these organizations is rare (Figure 2.2.4).

2.2.3 Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater

Since the mid-1980s, based on reflection of the consequences of large-scale urbanization and industrialization, many countries have increased research and development of river, lake, ocean, and groundwater remediation engineering technologies to achieve precise governance and remediation. Concurrently, monitoring and evaluation technology were also developed. The Water Framework Directive (WFD) promulgated by the European Union (EU) in 2000 has proven to be a successful model for global management of water resources. The EU's laws on water resource management have changed from protecting public water quality and regulating pollution sources in the last century to focusing on integrated water resource management at the beginning of this century. Since 2010, the EU approach has shifted to focusing on performance and paying more attention to the protection of water ecosystems. In Japan, the River Law was revised again in 1997, which integrates the protection of water ecology, safeguarding of water resources, and disaster prevention into a complete countermeasure system. The 17 sustainable development goals formally adopted at the United Nations Summit on Sustainable Development in September 2015 also focused on ecosystems and protection of underwater biology. It can be seen that after entering the 21st century, developed countries such as the European countries, the United States, and Japan have paid more attention to the research and development of technology for monitoring, evaluation, and restoration of aquatic ecological environments. Developed countries have also played a leading role in the governance and protection of the global water ecological environment.

Monitoring is done to determine the current status and changing trends through continuous investigation and observation. With evaluation, more attention is directed to the development of efficient evaluation-model systems, using a variety of monitoring data to simulate the prediction and impact assessment of possible trends. Through evaluation, we are able to understand the principles of the complex, unseen processes behind appearances. These are the principles upon which we can propose effective environmental management strategies and integrate the hydrology, water quality, and ecological model systems with high precision to achieve the simulation and prediction of the restoration effects. Restoration is the application of various engineering means to repair a damaged water environment. Because artificial restoration often requires a great deal of resources and time, it is particularly important to develop an appropriate and orderly restoration plan based on full consideration of the environmental capacity and natural restoration potential.

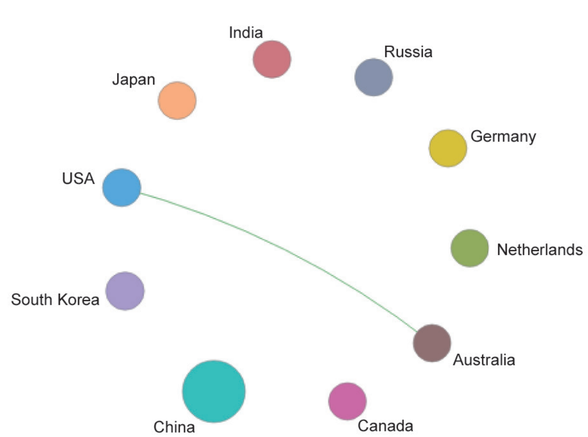

Figure 2.2.3 Collaboration network among countries or regions in the engineering development front of "comprehensive transportation planning and intelligent safety management of urban agglomeration"

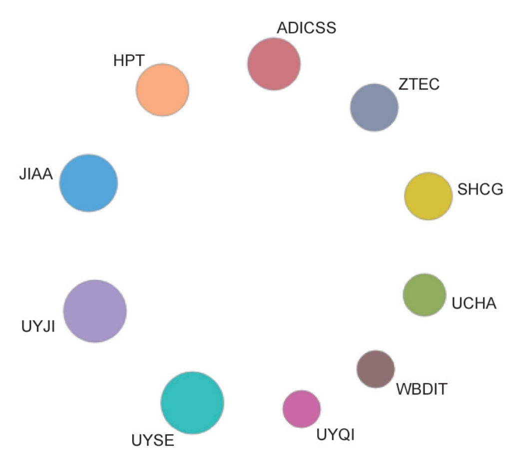

Figure 2.2.4 Collaboration network among institutions in the engineering development front of "comprehensive transportation planning and intelligent safety management of urban agglomeration"

Developed countries have gradually shifted from pollution control to prevention-oriented strategies. For pollution-source control, ecological engineering methods such as natural restoration are used extensively, and the objectives of pollution source reduction, habitat protection, and ecological function restoration are achieved by building green infrastructure. At present, China mainly concentrates on the pollution control of surface and groundwater. However, with the rapid development of information technology and artificial intelligence technology, associated technologies have also developed. These include provisions for automatic measurement, automatic sample collection, automatic water-quality-monitoring systems, automatic algae filtering and cleaning systems, and autonomous navigation for surface garbage cleaning and surface cleaning robots. These develop and utilize unmanned aerial vehicles and unmanned aerial vehicles are emerging endlessly, showing a trend of running parallel to the progress in developed countries.

As listed in Table 2.1.1, 506 patents were published on this topic between 2013 and 2018. The top five countries were China, the USA, South Korea, Japan, and France (Table 2.2.5). Among them, China was one of the key countries at the forefront of development, contributing 91.11% of the patents. The average frequency of Chinese patent citation was 6.62, which indicates that Chinese patents are getting more and more attention. Analysis of the proportion of international patents shows that although the average frequency of patent citation in China was 28.75, which is lower than that of the USA in the period (i.e., 81.79), it was significantly higher than that in developed countries such as South Korea and Japan. This indicates that in China, international competitiveness and awareness of independent intellectual property protection are increasing. In this area, there was no cooperation between countries or regions shown in the cooperation network between countries/regions producing patents (Figure 2.2.5).

As listed in Table 2.2.6, the top five organizations producing the most patents were Hohai University (China), Suzhou Feichi Environmental Technology Co., Ltd. (China), Shenzhen DJI Technology Co., Ltd. (China), Zhejiang Ocean University (China), and Tianjin University (China). Among the top ten institutions regarding patent-output in China, scientific research institutes and enterprises were balanced in number, indicating that Chinese enterprises have a strong sense of independent innovation in the field of technological development against a background of strategies for ecologically sustainable civilization. The top ten cooperation networks of patent producers (Figure 2.2.6), showed no cooperation among these organizations.

Table 2.2.5 Countries or regions with the greatest output of patents on "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	461	91.11%	3051	68.36%	6.62
2	USA	22	4.35%	1196	26.80%	54.36
3	South Korea	6	1.19%	36	0.81%	6.00
4	Japan	3	0.59%	48	1.08%	16.00
5	France	3	0.59%	40	0.90%	13.33
6	Denmark	2	0.40%	28	0.63%	14.00
7	Canada	2	0.40%	22	0.49%	11.00
8	Russia	2	0.40%	6	0.13%	3.00
9	Germany	1	0.20%	18	0.40%	18.00
10	Netherlands	1	0.20%	8	0.18%	8.00

Table 2.2.6 Institutions with the greatest output of patents on "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYHO	China	11	2.17%	61	1.37%	5.55
2	SFET	China	11	2.17%	52	1.17%	4.73
3	DJII	China	9	1.78%	257	5.76%	28.56
4	UYZO	China	7	1.38%	40	0.90%	5.71
5	UTIJ	China	6	1.19%	57	1.28%	9.50
6	CNPW	China	6	1.19%	19	0.43%	3.17
7	WDMM	China	6	1.19%	7	0.16%	1.17
8	CRHK	China	5	0.99%	41	0.92%	8.20
9	UYCR	China	5	0.99%	22	0.49%	4.40
10	UQT	China	4	0.79%	52	1.17%	13.00

UYHO: Hohai University; SFET: Suzhou Feichi Environmental Technology Co., Ltd.; DJII: Shenzhen DJI Technology Co., Ltd.; UYZO: Zhejiang Ocean University; UTIJ: Tianjin University; CNPW: POWERCHINA Water Environment Management Technology Co., Ltd.; WDMM: Wuxi Dagong Machine Manufacturing Co., Ltd.; CRHK: Chinese Research Academy of Environmental Sciences; UYCR: China Three Gorges University; UQT: Qingdao Technological University.

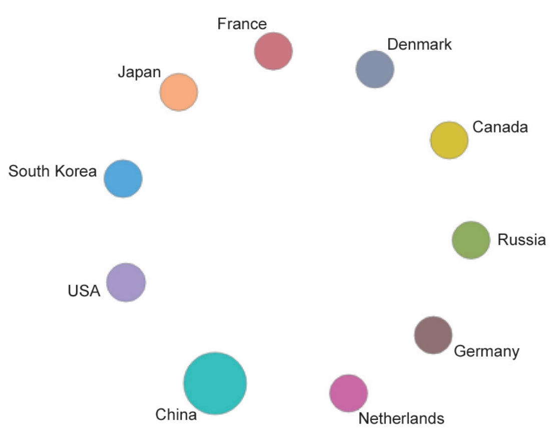

Figure 2.2.5 Collaboration network among countries or regions with the greatest output of patents in the engineering development front of "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

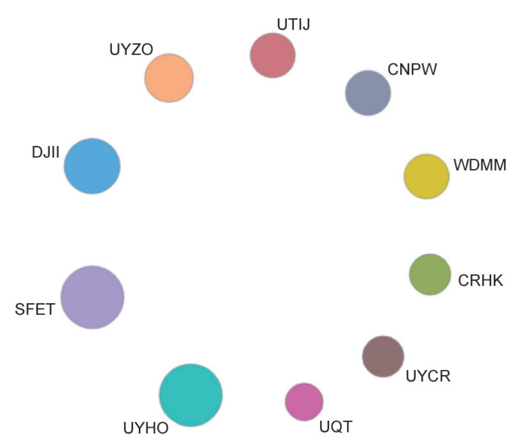

Figure 2.2.6 Collaboration network among institutions in the development front of "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

Participants of the Field Group

Leaders

CUI Junzhi, ZHANG Jianyun, CHEN Yiyi

Members of the Expert Group

JIANG Yi, OU Jinping, YANG Yongbin, MIAO Changwen, DU Yanliang, CHEN Zhengqing, CHEN Xiangsheng, DENG Mingjiang, KONG Xianjing, YUE Qingrui, CHEN Yuli, CHI Mingmin, FAN Feng, FENG Shouzhong, HE Chuan, HUA Xugang, HUANG Dongmei, JIANG Yiqiang, LI Angui, LI Hui, LIANG Heng, LIN Borong, LIU Feixiang, MEI Shilong, NIU Ditao, PAN Haixiao, PAN Peng, QIAO Pizhong, REN Gang, SHEN Di, SHEN Guoyi, SHI Beiling, SONG Dexuan, SUN Lijun, TAN Guangming, WANG Aijie, WANG Xin, WANG Yuanzhan, WANG Shuangjie, XIA

Shengji, YAN Li, YANG Dawen, YANG Zhongxuan, ZENG Bin, ZHANG Peng, ZHANG Song, ZHENG Ji, ZHU Ruolin

Members of the Working Group

CAI Yi, CHEN Peng, CHEN Qing, CHEN Xin, GE Yaojun, GU Xianglin, HE Yuexiang, HUANG Wenrui, JIA Liangjiu, JIANG Zhengwu, LING Jianming, LI Chen, LI Yan, LIU Fang, LIU Shuguang, SUN Jian, SUN Zhi, TAN Zheng, TONG Xiaohua, WANG Huaning, WANG Wei, WANG Yayi, WU Yuqing, XIA Siqing, XIAO Feipeng, XU Xiaoqing, YAO Junlan, YE Wei, YE Yu, ZHANG Shangwu, ZHANG Xu, ZHAO Xianzhong, ZHOU Xiang, ZHOU Xingang, ZHU Hehua, ZHU Xingyi, ZHUANG Xiaoying

Report Writers

LIU Jiaping, CHEN Peng, CHEN Qing, FANG Cheng, DONG Zhiqiang, LI Jianhua, LI Xiaojun, LIN Borong, LIU Fang, SONG Dexuan, SUN Jian, SUN Zhi, TAN Zheng, WANG Aijie, WANG Jinting, WANG Wei, WANG Yanyan, WANG Yi, WU Gang, WU Wei, XIANG Liyun, XIAO Jianzhuang, YAN Li, YAO Junlan, YE Wei, YU Qianqian, YU Qian, ZHANG Dawei, ZHANG Dongmei, ZHANG Weiping

VI. Environmental and Light Textile Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the field of environmental and light textile engineering (hereafter referred to as environmental engineering), which includes the subfields of environmental science engineering, meteorological science engineering, marine science engineering, food science engineering, textile science engineering, and light industry science engineering, are summarized in Table 1.1.1. The annual number of core papers for individual research fronts between 2013 and 2018 are summarized in Table 1.1.2.

(1) Application of nano-composite materials in wastewater treatment

Along with increases in socio-economic development, large amounts of sewage have been discharged into the environment, and this waste has degraded aquatic environments in many areas and is presently posing threats to the ecological environment and human health. Therefore, effective treatment of pollutants in water is an important research topic in the environmental field. Although traditional water treatment methods have achieved certain positive effects in many applications, they also have disadvantages such as high energy consumption, low efficiency, and secondary pollution. With the advancement of science and technology, many new materials have begun to be used in water treatment. Nanomaterials are considered to be good reagents for handling many pollutants because of the superior surface area and active sites of nanomaterials. Nano-photocatalytic technology, nanofiltration membrane technology, nano-reduction technology, and nano-adsorption technology all have shown some success in the field of water treatment. Compared to single-component nanomaterials, nano-composite materials composed of a variety of nanomaterials generally have superior properties. The advantages of each component can be achieved by designing the raw material use, distribution of components, and process conditions accordingly. Therefore, the application of nanocomposites in wastewater treatment potentially will have a huge impact on future environmental protection goals and sustainable development, and it has broad application prospects.

(2) Efficient seawater desalination technology

Desalination of seawater involves the use of seawater desalination technology to produce fresh water. It is a type

Table 1.1.1 Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Application of nano-composite materials in wastewater treatment	69	5 402	78.29	2015.4
2	Efficient seawater desalination technology	43	3 689	85.79	2014.9
3	Effects of soil pollution on crop metabolism	37	2 105	56.89	2014.2
4	Environmental pollution and mitigation of antibiotic resistance genes	32	807	25.22	2016.0
5	Climate change and the ecological environment	1400	303 709	216.94	2014.0
6	Severe smog in winter	192	4 613	24.03	2016.8
7	Monitoring and control of marine microplastic pollution	115	18 840	163.83	2014.6
8	Rapid screening and intelligent identification of harmful chemicals in food	10	514	51.40	2014.8
9	Preparation and application of highly efficient oil–water separation materials	17	1 598	94.00	2015.2
10	Biomass clean energy	130	11 108	85.45	2014.5

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Application of nano-composite materials in wastewater treatment	6	14	17	16	12	4
2	Efficient seawater desalination technology	12	7	8	6	9	1
3	Effects of soil pollution on crop metabolism	14	9	8	4	1	1
4	Environmental pollution and mitigation of antibiotic resistance genes	3	3	4	5	14	3
5	Climate change and the ecological environment	587	391	267	112	34	9
6	Severe smog in winter	4	8	18	32	63	67
7	Monitoring and control of marine microplastic pollution	19	39	32	17	8	0
8	Rapid screening and intelligent identification of harmful chemicals in food	3	2	1	2	2	0
9	Preparation and application of highly efficient oil–water separation materials	0	5	6	4	2	0
10	Biomass clean energy	39	38	22	19	10	2

of open source incremental technology for water resource utilization, which can increase the total amount of fresh water available for use. The development of high-efficiency seawater desalination technology is of great significance for alleviating the shortages of water resources in coastal water-deficient areas and islands, promoting the desalination and utilization of brackish water in inland areas, optimizing the water use structure, and ensuring the sustainable use of water resources. How to improve the efficiency of seawater desalination, reduce energy consumption and costs, and increase the scope of its applications are difficult problems facing researchers working on high-efficiency seawater desalination. Seawater desalination methods currently used include the seawater freezing method, electrodialysis method, distillation method, reverse osmosis method, and ion exchange method. Presently, the reverse osmosis membrane method and distillation method are the most common methods in use. Key technologies such as large-scale thermal membrane desalination and large-scale seawater circulation cooling, as well as key components such as reverse osmosis desalination membrane modules, high-pressure pumps, and energy recovery and thermal seawater desalination core components are hot topics in efficient seawater desalination research. The development of technologies that utilize waste heat from power plants and renewable energy sources such as nuclear, wind, ocean, and solar energy are also the focus of much attention. Actively researching and developing engineering technologies and complete facilities capable of seawater withdrawal, pretreatment, desalination, desalinated water post-treatment, and concentrated brine utilization and disposal represent the future development directions of efficient seawater desalination technology.

(3) Effects of soil pollution on crop metabolism

Soil is the basis of plant growth and development. Soil supplies water, fertilizer, gas, and heat for the normal growth and development of plants. These basic properties affect the growth and development of plants both directly and indirectly. Soil pollution is caused by excessive harmful substances in the soil that exceed the self-purification ability of the soil and change its composition, structure, and function. The effects of soil pollution on crop metabolism mainly occur in the following ways. First, inorganic pollutants such as heavy metals can destroy the normal absorption and metabolic functions of crop roots, which is usually related to the inhibition of enzymes in plants. For example, under Cd stress, the absorption of water and nutrients by crop roots is weakened, the permeability of cell membranes is enhanced, the soluble substances in cells are exuded, and the metabolic activity of intracellular enzymes is hindered. Second, contaminated pollutants can affect the normal physiological functions of crops. For example, trichloroacetaldehyde can destroy the polar structure and components of plant cell protoplasm. Chemically induced functional impairments can lead to alterations in the division of cells and nuclei, the formation of pathological tissues, reductions in normal growth and development, and even plant death. Third, pathogenic microorganisms in soils can enter crops, blocking normal metabolic pathways and causing related diseases such as bacterial and fungal wilt, rot, smut, and root swelling.

(4) Environmental pollution and mitigation of antibiotic resistance genes

Antibiotics enter the environment along with the discharge of municipal wastewater, livestock wastewater, hospital wastewater, pharmaceutical wastewater, etc., and these chemicals can cause environmental pollution problems in aquatic ecosystems and soil. The presence of antibiotics results in selective pressure on environmental bacteria, and this enhances antibiotic resistance and the generation of resistance genes. Antibiotic resistance genes (ARG) have been regarded as an emerging environmental pollutant. The wide spread occurrence and diffusion of ARG may reduce the curative effects of antibiotics and has attracted global attention due to its risk to public health and ecosystems. Wastewater treatment systems that discharge antibiotics and bacteria are the primary source of anthropogenic induced ARG. Conventional wastewater treatment processes have a limited capacity for ARG removal. Current research indicates that activated sludge in the biological treatment units may concentrate more ARG compared with the wastewater, and many bacteria isolated from the wastewater treatment systems show resistance to multiple antibiotics.

The recent hot papers in this field have mainly focused on evaluations of the effects of different wastewater treatment processes (including coagulation/sedimentation, filtration, membrane processes, chlorination, UV irradiation, ozonation, UV/H_2O_2, photocatalysis, photoFenton) on ARG removal. The separation techniques such as precipitation have been shown to reduce the ARG concentration in wastewater via sedimentation of ARG into the sludge but could not eliminate the ARG. However, advanced oxidation processes (AOPs) have significant effects on ARG removal via the destruction of the structure of ARG and thus can reduce the corresponding environmental risks. However, the degree of ARG removal depends strongly on the dose and duration of the AOP. For example, some studies have reported that there is an increase in the resistance level after treatment with low dose chlorination or ultraviolet radiation (UV) processes. Therefore, it is necessary to further investigate the technologies and processes that can remove ARP from source wastewaters such as hospital wastewater, pharmaceutical wastewater, and livestock wastewater. Currently, the ARG relevant studies have mainly focused on soil and water environments, while less attention has been paid to the atmospheric environment. It will be important to enhance such research on the characteristics, spread, transport, and mitigation of ARG in the environment.

(5) Climate change and the ecological environment

Climate change refers to the evolution of climate conditions over long time periods, and the impacts of climate change can be severe. For example, thousands of people die from climate change each year, and the ecological environment is greatly affected. Climate change not only causes the rise of global mean surface temperature and global warming, but also leads to increases in the number and severity of various types of disasters including droughts, sandstorms, floods, heat waves, hurricanes, tropical storms, tornadoes, and wildfires.

In recent years, the impacts of climate change on the ecological environment have attracted the attention of various countries around the world, therefore each country should develop a plan for responding to and adapting to future climate changes, especially in regard to construction activities. For example, research is needed to provide scientific and technological support for the formulation of major national strategic policies, and an assessment framework for new climatic carrying capacities should be established, which considers the characteristics of economic and social development and ecosystem services, with an emphasis on urbanization climate effects, regional air pollution control, watersheds, and protection of vulnerable areas.

China has further considered improving the layout of eco-meteorological observation stations in key eco-functional areas, eco-sensitive areas, and vulnerable areas in different national plans, which could enhance the capacity of meteorological monitoring networks in forests, grasslands, deserts, wetlands, and other eco-regions. Establishment of a comprehensive early warning system for eco-meteorological related disasters and extreme climate events, such as air pollution, soil erosion, droughts, and land desertification would be valuable. Strengthen eco-meteorological assessment and eco-security meteorological support, and promote fine assessment and planning of climate resources.

(6) Severe smog in winter

Smog is a kind of disastrous weather event that occurs in the near-surface layer of the atmosphere. Because of the decreases in atmospheric visibility caused by such haze, these events can have an important impact on socioeconomic activities and people's lives. At the same time, when smog occurs, atmospheric aerosols gather in the near surface layer of the atmosphere, which degrades the air quality and represents an important hazard to human health. Previous studies have shown that the long-term trends of fog and haze are closely related to human activities and climate change. The expansion of cities and the associated heat island effects can actually cause the frequency of fog to decrease in urban areas but increase in suburban areas. The decreasing trend of the frequency of heavy fog in urban areas is related not only to the increasing trend of urban heating, but also to the decreasing trend of suspended particulate matter.

Obvious seasonal and interdecadal variations in the number of fog days in China have been detected, in which most of the events occur in winter and fewer occur in spring, and the overall number was higher in the 1970s to 1990s than the period after the 1990s when the number of events decreased; meanwhile, the number of haze days has increased sharply since 2001. The decreasing trend of foggy days in China is related to the increase of the minimum temperature and decrease of the relative humidity in winter. The increase of haze days is closely related to the increasing trend of atmospheric pollutant emissions caused by human activities and the decreasing trend of average wind speed. In addition, the spatial distribution of the changes of haze in China is closely related to economic activities. In the economically developed eastern and southern parts of China, an increasing trend of haze days has been observed, while in the relatively less developed northeast and northwest regions, a decreasing trend is occurring.

Concerning the relationship between the occurrence of smog and meteorological factors in China, studies have focused on the relationship between the long-term trend of haze and that of meteorological factors, the evolution process of local meteorological conditions and fog generation and disappearance, and the relationship between local meteorological conditions and haze weather. At the same time, in order to prevent the occurrence of smog weather, the state has formulated a variety of control and environmental protection measures, which are intended to reduce the occurrence of haze.

(7) Monitoring and control of marine microplastic pollution

Microplastics pollution is an emerging marine environmental issue that has attracted great concern worldwide. Microplastic particles, which are generally less than 5 mm in diameter, can be detected in almost every marine habitat including those in polar regions. These particles are easily ingested by marine organisms and usually adsorb other chemical pollutants. Hence, microplastics can migrate and be enriched along the food chain and have ecotoxic effects. Standardized monitoring methods for microplastics have been established. Visual detection after density separation and digestion of environmental samples, combined with Fourier transform infrared spectroscopy or Raman spectroscopy, is a widely accepted method for qualitative and quantitative research on microplastics.

Based on standard and reliable detection technology, the source–sink processes and ecological risk mechanisms of microplastics in the ocean are hot scientific issues that are engaging researchers all over the world. In addition, nano-scale microplastics may have more significant physiological and ecological toxicity, and efficient monitoring techniques are still a challenge for such material.

The prevention and control of microplastic pollution is mainly carried out at two levels, namely, legislation in the political realm and technological advances in the scientific and engineering realm. At the regulatory level, measures can be taken such as government regulations mandating the recycling of plastic products and prohibiting the addition of micro-plastic particles to household products such as toothpaste and facial cleansers. Such measures can effectively help to reduce and control plastic emissions. At the technical level, low-cost production of biodegradable plastic products such as polylactic acid can be used to replace a portion of the traditional plastic source stock for products, and plastic products that show little to no degradation can be banned. Moreover, breakthroughs in plastic decomposition technology, such as the use of enzymes and organisms with high plastic degrading activities, to degrade plastic waste is expected to contribute to the environmental remediation of contaminated areas.

(8) Rapid screening and intelligent identification of harmful chemicals in food

There are various kinds of exogenous and endogenous hazards in food. Many food hazards are complex in terms of the chemical structures, and some of these may experience a series of complicated chemical changes during food processing, the products of which are associated with great uncertainties. Therefore, rapid screening and identification of hazardous compounds are of great significance for the effective management of food safety hazards. At present, with the application of novel analytical instruments such as in high-resolution mass spectrometry, and with the developments in information analysis techniques for data detection, there are great technical potentials for continuous innovation in establishing powerful platforms for the rapid-screening of unknown harmful substances.

(9) Preparation and application of highly efficient oil–water separation materials

The continuous discharge of oily industrial wastewater and domestic sewage and the frequent occurrence of marine oil spill accidents have resulted in the formation of a large number of oil–water mixtures, environmental pollution, and economic losses. Thus, the development of oil–water separation technology has important practical significance and application value. The presence of oil contaminants in the water can hinder the exchange of water and air and the normal incidence of sunlight, thus causing fatal damage to aquatic organisms, and the oil contains a large number of mutagenic and carcinogenic hydrocarbon compounds that will pass through the ecosystem. Contaminants ingested in the food chain and eventually enriched in the human body can pose a serious threat to human health. Therefore, this type of water pollution is a global problem that needs to be solved urgently. When oil enters a water body, it will form the following four types of oil–water mixtures: oil slicks, dispersed oil, emulsified oil, and dissolved oil. The oil slicks and dispersed oil can easily coalesce into a continuous oil layer because of the large particle size and be removed by adsorption, sedimentation, and mechanical method. For the separation of relatively stable emulsified oils and dissolved oils, traditional demulsification techniques such as sedimentation, biological methods, ultra/microfiltration membrane separation, etc., are required. While a certain separation effect can be obtained with existing technology, these methods are associated with high rates of energy consumption and low processing efficiencies. At present, oil–water separation technology is a focus of research in all countries around the world. The main research directions in this field focus on the preparation of fiber-based, high-efficiency oil–water separation membranes, the synthesis of new high-efficiency oil–water separation materials, the construction of super-infiltration oil–water separation systems, and the development of ceramic-based/bio-based oil-water separation materials, among other aspects.

(10) Biomass clean energy

The energy demands of human society are continuously growing, but there are limited supplies of fossil energy. At the same time, environmental problems caused by the excessive consumption of fossil energy have become increasingly significant. Therefore, the development of renewable and clean energy has become a primary focus for achieving sustainable development in future human societies. Biomass energy represents the solar energy stored in biomass in the form of chemical energy. As a new type of renewable energy, biomass energy features several desirable properties including rich sources for production, renewability, and low pollution potential and safety compared with traditional fossil energy. The effective utilization of biomass energy cannot only help to meet current energy demands, but also reduce pollutant emissions to the environment. Therefore, biomass energy has great potential for optimizing the structure of the energy supply.

The key to developing biomass energy is figuring out how to take full advantage of biomass energy in a clean and efficient manner. At present, the main components of utilizing biomass energy include 1) biomass power generation, e.g., agricultural and forestry biomass power generation, biogas power generation, and garbage power generation; 2) biomass gas supplies, e.g., biogas, biomass gasification gas; 3) biomass solid fuel, e.g., agricultural and forestry biomass-based molded fuel; 4) biomass liquid fuel, e.g., bioethanol, biodiesel. However, the full utilization of biomass energy faces many challenges. In the future, it will be essential to scale up the utilization of biomass energy in the fields of electricity, heat supply, and transportation, and the further development of new technologies for biomass energy utilization also will be crucial.

1.2 Interpretations for three key engineering research fronts

1.2.1 Application of nano-composite materials in wastewater treatment

Along with increases in socioeconomic development, large amounts of pollutants have been discharged into the environment, which has led to many environmental problems such as air, soil, and water pollution. In particular, large amounts of untreated sewage are directly discharged into the environment in many areas, which has caused severe deterioration in water quality. Presently, there are many kinds of pollutants in water bodies. Common pollutants include heavy metals, bacteria, viruses, radionuclides, and organic dyes. Due to the high toxicity, stability, and refractory characteristics of many pollutants in water, these pollutants pose great threats to the ecological environment and human health. Therefore, how to effectively treat pollutants in water has become an important research topic in the environmental field.

Although conventional water treatment methods such as adsorption techniques, coagulation techniques, and activated sludge techniques have achieved certain positive effects in various applications, they also have disadvantages such as low efficiency, high cost, high energy consumption, and secondary pollution. With the advancement of science and technology, innovations in water treatment technology have not only been limited to the development of traditional treatment technology, and in fact, many new materials also have begun to be applied in water treatment, thus leading to rapid developments in water treatment technology. Nanomaterials are attracting attention because of their superior surface area, active sites, and other advantages, and these are considered to be good reagents for handling many pollutants. Nano-photocatalytic technology, nanofiltration membrane technology, nano-reduction technology, and nano-adsorption technology have achieved certain positive achievements in the field of water treatment.

Compared with single-component nanomaterials, nanocomposites composed of a variety of nanomaterials generally have superior performance in terms of contaminant removal. Nanocomposites may also bring about new properties that are not available with the original components while maintaining the properties of the original components. In addition, the composite material can achieve the complementary advantages of each component and maximize the advantages through the proper design of raw materials, distribution of various components, and process conditions.

With the deepening of nanotechnology research, and people's increasing attention to the environment, nanotechnology and nano-composite materials will likely become more and more widely used for environmental protection, especially in water treatment applications. The application of nanocomposites in wastewater treatment could have a huge impact on future environmental quality and sustainable development, and this technology has broad application prospects.

As shown in Table 1.2.1, China ranks first with 43 core papers, which indicates that many Chinese experts and scholars are committed to this front of research. Although China is still the first in terms of Citations the USA has nearly doubled the number of citations per paper in China, thus indicating that the research results of the USA are among the highest in the world. Among the top 10 countries or regions with the greatest output of core papers, developing countries account for a high proportion, which may reflect the current seriousness of problems related to water pollution in developing countries.

Hunan University ranks first in terms of core papers and citations as shown in Table 1.2.2. In terms of citations per paper, the rankings of the institutions that have been cited more than 100 times are from Central South University, Hunan University, Fuzhou University, and South China University of Technology. These results show that Central South University is at a high level in terms of this research topic.

As shown in Figure 1.2.1, China, the USA, Malaysia, Iran, and Saudi Arabia have shown relatively more cooperation with other countries. China cooperates most closely with the USA, followed by Saudi Arabia.

In general, there has been less cooperation among major institutions as shown in Figure 1.2.2. Hunan University has shown close cooperation with Central South University, Chinese Academy of Sciences, and Yanshan University. South China University of Technology has worked in cooperation with Central South University and Hunan University as well.

According to Table 1.2.3, the citing papers of China is far ahead of other the countries or regions, followed by the USA and India. The mean year of citing papers for the top ten countries is around 2017.

According to Table 1.2.4, Hunan University and Chinese Academy of Sciences have significantly higher citing papers values than the other institutions, and these rank first and second, respectively. The gap between the two institutions is small. The mean year of citing papers for the top ten institutions is around 2017.

Table 1.2.1 Countries or regions with the greatest output of core papers on the “application of nano-composite materials in wastewater treatment”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Citations per paper
1	China	43	62.32%	3329	77.42
2	USA	8	11.59%	1098	137.25
3	Malaysia	6	8.70%	416	69.33
4	India	4	5.80%	263	65.75
5	Iran	3	4.35%	209	69.67
6	Saudi Arabia	3	4.35%	206	68.67
7	South Korea	2	2.90%	135	67.50
8	Italy	2	2.90%	127	63.50
9	Turkey	2	2.90%	116	58.00
10	Singapore	2	2.90%	128	64.00

Table 1.2.2 Institutions with the greatest output of core papers on the “application of nano-composite materials in wastewater treatment”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper
1	Hunan Univ	9	13.04%	1064	118.22
2	South China Univ Technol	5	7.25%	531	106.20
3	Chinese Acad Sci	5	7.25%	391	78.20
4	Yanshan Univ	5	7.25%	450	90.00
5	Cent S Univ	3	4.35%	470	156.67
6	Univ Kebangsaan Malaysia	3	4.35%	253	84.33
7	Univ Teknol Malaysia	3	4.35%	163	54.00
8	Fuzhou Univ	2	2.90%	228	114.00
9	Wuhan Univ Technol	2	2.90%	169	84.50
10	Nanyang Technol Univ	2	2.90%	128	64.00

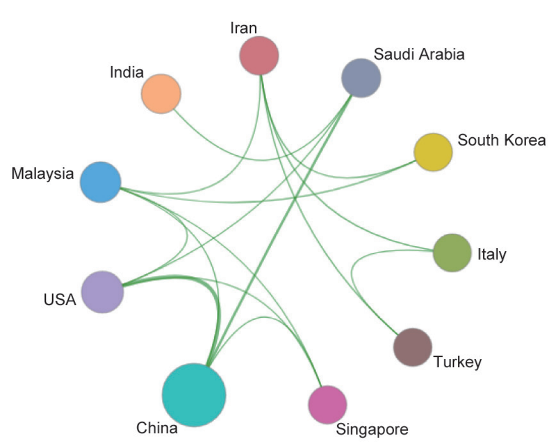

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “application of nano-composite materials in wastewater treatment”

1.2.2 Climate change and the ecological environment

Climate change is not only causing a rise of global mean surface temperatures and global warming, but also leading to increases in the number and severity of disasters. Thousands of people die from climate change related events each year, and the ecological environment is being greatly affected. The impacts of climate change on the ecological environment have attracted the attention of various countries around the world. In China, climate change is being considered in the layout of ecological and civil construction projects.

In order to understand the impacts of climate change on different aspects of the world, the Intergovernmental Panel on Climate Change (IPCC) has released five climate change assessment reports, which discuss the scientific facts, impacts,

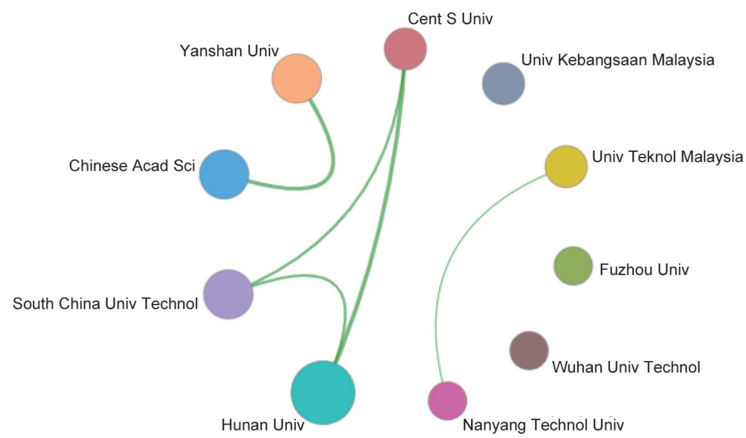

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "application of nano-composite materials in wastewater treatment"

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "application of nano-composite materials in wastewater treatment"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	2726	55.95%	2017.5
2	USA	441	9.05%	2017.3
3	India	423	8.68%	2017.5
4	Iran	370	7.59%	2017.4
5	South Korea	204	4.19%	2017.4
6	Malaysia	153	3.14%	2017.2
7	Australia	141	2.89%	2017.3
8	Saudi Arabia	140	2.87%	2017.1
9	Singapore	100	2.05%	2017.4
10	Canada	88	1.81%	2017.5

Table 1.2.4 Institutions with the greatest output of citing papers on the "application of nano-composite materials in wastewater treatment"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hunan Univ	280	23.53%	2017.8
2	Chinese Acad Sci	273	22.94%	2017.5
3	Cent S Univ	96	8.07%	2017.7
4	Jiangsu Univ	81	6.81%	2017.5
5	Univ Chinese Acad Sci	75	6.30%	2017.8
6	Islamic Azad Univ	71	5.97%	2017.2
7	Harbin Inst Technol	70	5.88%	2017.5
8	South China Univ Technol	69	5.80%	2017.9
9	Univ Teknol Malaysia	59	4.96%	2017.3
10	Tianjin Univ	59	4.96%	2017.3

adaptation measures, and mitigation strategies. Impact assessment reports on climate change in different areas are published from time to time. In 2019, the *Global Assessment of Biodiversity and Ecosystem Services*, the *Special Report on Climate Change and Land*, and the *Special Report on Oceans and the Cryosphere in Climate Change* were published. The *Special Report on Climate Change and Land* shows that better land management can help society adapt to climate change. With the expected increases in population and the negative impacts of climate change on vegetation, land must retain its productivity to maintain food security. The *Special Report on Oceans and the Cryosphere in Climate Change* aims to assess how climate change will affect the oceans and marine life, as well as areas where water exists in solid form, such as polar or alpine regions, and to assess the impacts of climate change on communities around the world and the options for adapting to climate change for a more sustainable future. The knowledge assessed in the report provides an overview of the climate-related risks and challenges that people around the world are currently experiencing and that future generations will face. It proposes adaptation options to deal with unavoidable changes, programs to manage and control related risks, and programs to build resilience for a sustainable future.

At present, in addition to the impacts of climate change on land and the oceanic cryosphere, studies also are being carried out on the establishment of new climate carrying capacities, urbanization climate effects, regional air pollution control strategies, and the protection of watersheds and other vulnerable areas, with considerations given to both the characteristics of economic and social development and the integrity of ecosystem services.

Table 1.2.5 shows the main output countries or regions for core papers in this engineering research front. It can be found that the USA ranks first in both the proportion of papers and the frequency of citations. Other countries have a big gap with the USA, which indicates that the USA has great research advantages in this respect. China has a relatively small number of core papers in this area, ranking sixth. In terms of the major output countries or regional cooperation networks (Figure 1.2.3), each country has shown extensive cooperation with the USA, and many countries also have cooperated extensively. Table 1.2.6 shows the main output organizations for core papers in this engineering research front. The institution that has published the most core papers is in China. According to the main inter-agency cooperation network (Figure 1.2.4), the Chinese Academy of Sciences has worked in cooperation with the other nine major institutions including the National Oceanic and Atmospheric Administration US Department of Commerce, Columbia University, and the National Center for Atmospheric Research, and the cooperation among these 10 institutions also has been very close. In the rankings of countries or regions that cite core papers, China ranks fifth, and there is still a big gap between the top ranked countries (Table 1.2.7); the Chinese Academy of Sciences ranks first among the institutions that cite core papers (Table 1.2.8). It can be seen that the USA is not only ahead of the world in the study of “climate change and the ecological environment,” but also has worked in close cooperation with other countries; however, the Chinese Academy of Sciences is also in a leading position among the research institutions in this field and should continue to maintain a relevant research focus on this front.

Table 1.2.5 Countries or regions with the greatest output of core papers on “climate change and the ecological environment”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	847	60.50%	190 153	62.61%	224.50
2	UK	455	32.50%	108 554	35.74%	238.58
3	Australia	311	22.21%	76 281	25.12%	245.28
4	Germany	299	21.36%	75 125	24.74%	251.25
5	France	252	18.00%	60 795	20.02%	241.25
6	China	224	16.00%	50 343	16.58%	224.75
7	Canada	217	15.50%	54 853	18.06%	252.78
8	Netherlands	207	14.79%	53 571	17.64%	258.80
9	Switzerland	177	12.64%	46 432	15.29%	262.33
10	Sweden	143	10.21%	36 842	12.13%	257.64

Table 1.2.6 Institutions with the greatest output of core papers on “climate change and the ecological environment”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	100	7.14%	22 942	7.55%	229.42
2	NOAA	93	6.64%	19 773	6.51%	212.61
3	Columbia Univ	80	5.71%	20 041	6.60%	250.51
4	Natl Ctr Atmospher Res	71	5.07%	16 546	5.45%	233.04
5	NASA	71	5.07%	15 969	5.26%	224.92
6	Univ Maryland	69	4.93%	18 395	6.06%	266.59
7	Univ Washington	64	4.57%	16 506	5.43%	257.91
8	Univ Exeter	63	4.50%	14 846	4.89%	235.65
9	Univ Calif Berkeley	62	4.43%	14 244	4.69%	229.74
10	Univ Colorado	61	4.36%	15 725	5.18%	257.79

NOAA: National Oceanic and Atmospheric Administration US Department of Commerce; NASA: National Aeronautics and Space Administration.

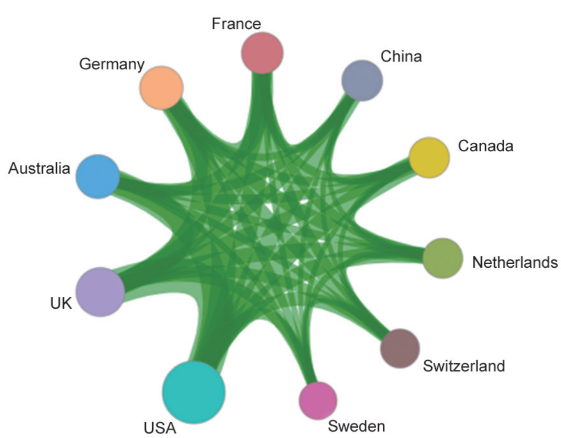

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “climate change and the ecological environment”

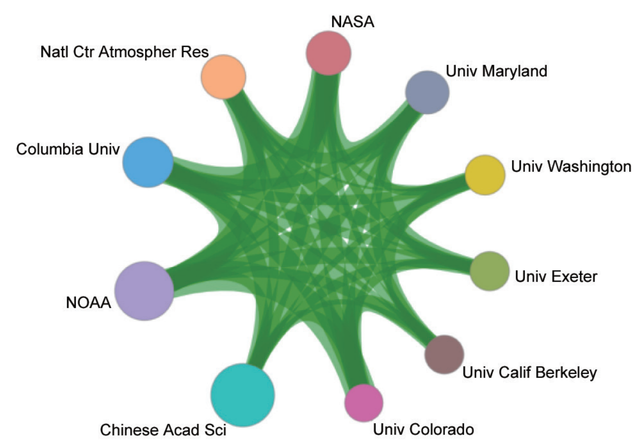

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “climate change and the ecological environment”

Table 1.2.7 Countries or regions with the greatest output of citing papers on “climate change and the ecological environment”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	997	25.02%	2014.8
2	UK	530	13.30%	2014.9
3	Germany	377	9.46%	2014.9
4	Australia	365	9.16%	2015.0
5	China	343	8.61%	2015.3
6	France	287	7.20%	2014.9
7	Canada	261	6.55%	2015.0
8	Netherlands	256	6.42%	2015.1
9	Switzerland	220	5.52%	2015.0
10	Spain	181	4.54%	2015.1

Table 1.2.8 Institutions with the greatest output of citing papers on “climate change and the ecological environment”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	110	11.98%	2015.1
2	Univ Calif Berkeley	91	9.91%	2014.8
3	Stanford Univ	87	9.48%	2015.1
4	Univ Washington	87	9.48%	2015.4
5	Univ Oxford	86	9.37%	2015.5
6	Univ Colorado	82	8.93%	2015.1
7	Columbia Univ	81	8.82%	2015.1
8	NOAA	81	8.82%	2014.5
9	Univ Maryland	72	7.84%	2015.2
10	Harvard Univ	71	7.73%	2015.5

1.2.3 Preparation and application of highly efficient oil–water separation materials

The continuous discharge of oily industrial wastewater and domestic sewage and the frequent occurrence of marine oil spill accidents have resulted in the formation of a large number of oil–water mixtures, which are causing environmental pollution and economic losses. Thus, the development of oil–water separation technology has important practical significance and application value. The presence of oil contaminants in the water will hinder the exchange of water and air and the normal incidence of sunlight, thus causing fatal damage to aquatic organisms, and the oil contains a large number of mutagenic and carcinogenic hydrocarbon compounds that will pass through water bodies. Such contaminants ingested in the food chain and eventually enriched in the human body pose a serious threat to human health. Therefore, water pollution is a global problem that needs to be solved urgently. When the oil enters a water body, it will form four types of oil–water mixtures, namely, oil slicks, dispersed oil, emulsified oil, and dissolved oil. The oil slicks and dispersed oil easily coalesce into a continuous oil layer due to the large particle size. Adsorption, sedimentation, and mechanical simmering oils can be easily removed; for the separation of relatively stable emulsified oils and dissolved oils, traditional demulsification techniques such as sedimentation, biological methods, ultra/microfiltration membrane separation, etc., can be used. While a certain separation effect can be obtained with these methods, there still are limitations related to the high energy consumption and low processing efficiency of such techniques. At present, oil–water separation technology is the focus of research in all countries around the world. The main research directions in this field focus on the preparation of fiber-based, high-efficiency oil–water separation membranes, the synthesis of new high-efficiency oil–water separation materials, the construction of super-infiltration oil–water separation systems, and the development of ceramic-based/bio-based oil–water separation materials, among other aspects.

Through the interpretations of core papers on the preparation and application of highly efficient oil–water separation materials, it was found that the core papers in this front of research were cited 94.00 times (Table 1.1.1). Among them, the main research areas were located in China, Singapore, and the USA. Among these countries, the number of core papers published by China accounted for 64.71% of the total, and citations per paper was 92.45 times, which represents the leading position (Table 1.2.9); Singapore, the USA, and Saudi Arabia showed relatively close cooperation in this field, and China displayed strong independent research and development capabilities in this field (Figure 1.2.5). Among major institutions, National University of Singapore, Donghua University, and Northeast Forestry University occupied the top three, and their core papers were frequently cited (Table 1.2.10). These major institutions showed a preference for independent research and development in this field, and only the National University of Singapore, King Abdullah University of Science and Technology, and Kraton Polymers LLC have conducted collaborative activities (Figure 1.2.6).

According to the rankings of the top ten countries or regions and institutions that cited the core papers, China, the USA, Singapore, and Canada have paid more attention to this research front; moreover, there are nine Chinese institutions among the top ten institutions (Tables 1.2.11 and 1.2.12).

In summary, China is in the leading position in the research and preparation of high-efficiency oil–water separation materials, but there has been little regional cooperation. It is recommended that China continue to increase investments in this front and promote the accelerated development of relevant research levels around the world.

Table 1.2.9 Countries or regions with the greatest output of core papers on “preparation and application of highly efficient oil–water separation materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Citations per paper
1	China	11	64.71%	1017	92.45
2	Singapore	4	23.53%	448	112.00
3	USA	3	17.65%	212	70.67
4	Saudi Arabia	1	5.88%	84	84.00
5	Japan	1	5.88%	58	58.00

Table 1.2.10 Institutions with the greatest output of core papers on “preparation and application of highly efficient oil–water separation materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper
1	Natl Univ Singapore	3	17.65%	206	68.67
2	Donghua Univ	2	11.76%	363	181.50
3	Northeast Forestry Univ	2	11.76%	172	86.00
4	Nanyang Technol Univ	1	5.88%	242	242.00
5	Shanghai Jiao Tong Univ	1	5.88%	100	100.00
6	King Abdullah Univ Sci & Technol	1	5.88%	84	84.00
7	Kraton Polymers LLC	1	5.88%	84	84.00
8	Univ Akron	1	5.88%	75	75.00
9	China Univ Petr	1	5.88%	72	72.00
10	Natl Engn & Technol Res Ctr Wood Based Resources	1	5.88%	70	70.00

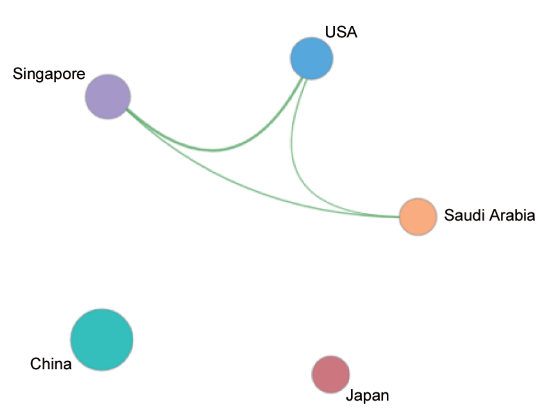

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “preparation and application of highly efficient oil–water separation materials”

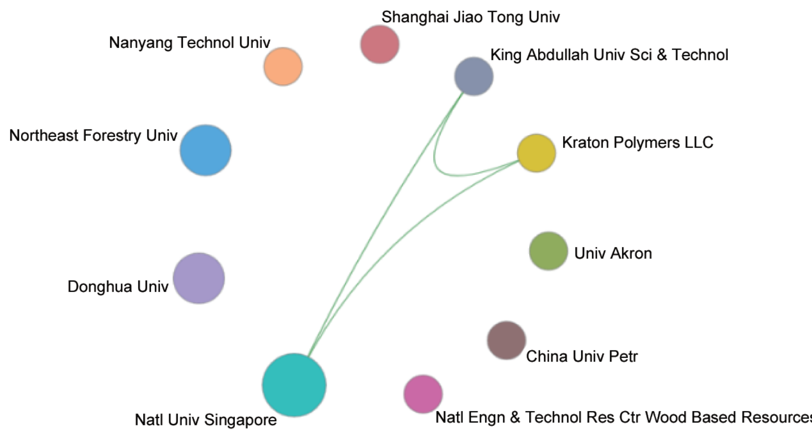

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "preparation and application of highly efficient oil–water separation materials"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "preparation and application of highly efficient oil–water separation materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	918	66.96%	2017.5
2	USA	115	8.39%	2017.5
3	Singapore	57	4.16%	2016.9
4	Canada	48	3.50%	2017.8
5	India	46	3.36%	2017.6
6	Japan	38	2.77%	2017.2
7	South Korea	36	2.63%	2017.1
8	Saudi Arabia	31	2.26%	2016.8
9	Australia	30	2.19%	2016.9
10	UK	26	1.90%	2017.5

Table 1.2.12 Institutions with the greatest output of citing papers on "preparation and application of highly efficient oil–water separation materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	116	24.89%	2017.3
2	Donghua Univ	66	14.16%	2016.9
3	Univ Chinese Acad Sci	46	9.87%	2017.3
4	South China Univ Technol	40	8.58%	2017.7
5	Hubei Univ	31	6.65%	2017.3
6	Harbin Inst Technol	30	6.44%	2017.5
7	Natl Univ Singapore	30	6.44%	2016.3
8	Jiangsu Univ	30	6.44%	2017.9
9	Soochow Univ	27	5.79%	2017.5
10	Zhejiang Univ	26	5.58%	2017.0

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts in the field of environmental engineering are summarized in Table 2.1.1., and these include the subfields of environmental science engineering, meteorological science engineering, marine science engineering, food science engineering, textile science engineering, and light industry science engineering. The number of patents between 2013 and 2018 related to these individual topics are summarized in Table 2.1.2.

(1) Multi-technology coordinated soil pollution remediation

In recent years, soil pollution and its environmental risks have emerged as a prominent issue in China, and the level of soil pollution is serious in some areas. Because of the coexistence of various types of old and new pollutants, inorganic and organic pollution, and multi-media (soil–water) pollution, there is an urgent need to develop multi-technology coordinated soil pollution remediation technology.

Traditional soil remediation techniques including physical, chemical, and biological remediation, have limitations in terms of pollutants, remediation time, and cost. Compared with a single processing technology, multi-technology coordinated soil pollution remediation systems (such

Table 2.1.1 Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Multi-technology coordinated soil pollution remediation	1119	1170	1.05	2016.6
2	Complex microbial communities useful for processing sewage	117	92	0.79	2016.7
3	Environmental nanocatalysts	1000	5022	5.02	2015.5
4	Development of membrane separation materials and processes	47	158	3.36	2014.4
5	Intelligent weather forecasting technology	744	5376	7.23	2015.8
6	Efficient and comprehensive utilization of ocean energy technology	1258	8690	6.91	2015.5
7	Integrated ocean environment observing technology	1301	3103	2.39	2016.1
8	Rapid and accurate detection of food-borne pathogenic microorganisms	1000	17 494	17.49	2012.9
9	3D printing system with fiber	3147	12 351	3.92	2016.4
10	Biomass energy conversion technology	1000	19 943	19.94	2012.8

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Multi-technology coordinated soil pollution remediation	32	72	111	200	235	444
2	Complex microbial communities useful for processing sewage	2	4	16	23	32	40
3	Environmental nanocatalysts	51	61	60	118	252	305
4	Development of membrane separation materials and processes	2	11	2	10	5	7
5	Intelligent weather forecasting technology	53	51	84	152	139	206
6	Efficient and comprehensive utilization of ocean energy technology	190	213	198	270	217	170
7	Integrated ocean environment observing technology	132	138	158	240	293	340
8	Rapid and accurate detection of food-borne pathogenic microorganisms	82	93	98	122	99	140
9	3D printing system with fiber	99	155	379	559	863	1008
10	Biomass energy conversion technology	134	144	100	95	65	27

as chemical oxidation–microbial degradation of organic pollutants, combination technology involving soil vapor extraction and thermal desorption, combination technology involving elution and bioremediation) are more adaptable during the treatment of different types of combined pollutants, as well as multi-media pollution. Multi-technology coordinated soil pollution remediation technology has developed rapidly in recent years. In particular, the number of patents has increased from 32 in 2013 to 444 in 2018, and the number has increased year by year. Remediation technology has gradually changed from single pollutant treatment to multiple pollutant treatment, from ex-situ, fixed equipment to in-situ, automatic and intelligent equipment, and from pollutant removal to combined control of processing regulation and terminal treatments.

China presently lacks original, integrated technology, and equipment. Demonstrations of integrated remediation technology for special high-risk contaminated sites such as electronic waste sites and highly contaminated petroleum soil are limited. Searching for modular, automatic, and intelligent integrated remediation technology and equipment should be a priority focus area in the future.

(2) Complex microbial communities useful for processing sewage

Complex microbial communities are generally composed of many different types of microorganisms capable of degrading pollutants to various degrees. These communities contain mutually beneficial and coexisting mixed organisms. The pollutants are gradually degraded during processes in which the growth and metabolism of microorganisms occur, thus achieving the purpose of purifying sewage. The main ways to obtain strains for complex microbial communities are as follows: 1) to purchase microorganisms from preservation institutions; 2) to screen for wild-type microorganisms from the natural environment; 3) to modify or stimulate the degradation performance of microorganisms by means of genetic engineering; and 4) to induce specific metabolic pathways of microorganisms through domestication and the retention of strains that degrade specific compounds. Compared with conventional sewage treatment technology, the complex microbial communities can be directly added to sewage without any additional equipment or process. The use of complex microbial communities in treatment technology has obvious advantages such as convenient operations, economic efficiency, wide application ranges, and no secondary pollution. Presently, such communities have been used in industrial, agricultural, pharmaceutical, and animal husbandry sewage treatment processes. Although there have been numerous related research projects and patents on complex microbial communities for sewage treatments, there are still some problems facing this field, such as the dispersion of products from the complex microbial communities and the influences of environmental factors on the treatment effects of complex microbial communities, especially in domestic research. Therefore, it will be necessary to further study this technology to achieve specific, efficient, and inexpensive complex microbial communities that are optimal for local applications. Additionally, by standardizing the use of products of complex microbial communities, countries can avoid the economic losses and ecological imbalances caused by misuse.

(3) Environmental nanocatalysts

Nanomaterials refer to materials with a size of 1–100 nm in at least one dimension. Many nanomaterials (including metal oxides, noble metals, carbonaceous materials) have exhibited huge advantages in the catalytic degradation or transformation of pollutants due to their large specific surface area and high reactivity, and thus, these materials have become the focus of environmental catalyst development. This development front mainly is focused on the following technologies: 1) nano-photocatalysts, especially those responsive to visible light, for the degradation of gaseous pollutants such as formaldehyde and aqueous pollutants such as dyes; 2) three-way nanocatalysts, for redox transformation of CO, carbohydrates, and NO_x from the automobile exhaust gas to CO_2, N_2, and H_2O; 3) nanocatalysts for atmospheric pollution control such as flue gas treatment, etc.; 4) nanocatalysts for water treatment, such as for catalytic ozonation and catalytic Fenton oxidation reactions, etc.; and 5) electronanocatalysts for hydrogen production, etc. The developed materials mainly include rare earth nanomaterials, bismuth-based nanomaterials, transition metal oxide nanomaterials, g-C_3N_4 nanocomposites, graphene nanocomposites, quantum dot nanocatalysts, and magnetic nanocatalysts.

In order to overcome the difficulty of manipulating nanomaterials in engineering applications, it is a generally accepted strategy to fabricate nanocomposites via the immobilization of nanoparticles in porous hosts of a large size. According to the different application scenarios, the hosts should also be resistant to high temperatures, oxidation, etc. Honeycomb ceramics, porous ceramic balls, and ceramsites have been extensively developed as hosts for nanocatalysts. However, it is important to develop new immobilization technologies to extend the function of the hosts from simple supports to more advanced features such as pollutant enrichment and activity modulation of embedded nanoparticles.

(4) Development of membrane separation materials and processes

Membrane separation technology is widely used in water treatment applications, mainly for industrial sewage recycling, municipal sewage treatment, municipal drinking water treatment, and seawater desalination. The key to the efficiency of membrane separation technology lies in the membrane materials and processes employed. In the future, the hot topics and frontiers of membrane separation technology will likely be focused on the R&D of high-performance membrane materials and modules, as well as the development and optimization of membrane separation processes and reactors.

In regard to the R&D of membrane materials, China has currently established a certain technological foundation and industrial scale for R&D activities and production of polymer membrane materials involved in ultrafiltration, microfiltration, nanofiltration, ion exchange, and other technologies, but research in China remains relatively weak in terms of gas membranes, liquid membranes, highly selective nanofiltration, reverse osmosis membranes, and other fields. In terms of reverse osmosis membranes used in seawater desalination and strong brine reduction/zero emission technology, there remains gaps between domestic and foreign products in regard to several aspects including special ion removal, temperature sensitivity, energy consumption per ton of water produced, and long-term operation stability. Novel nano-material compositions, two-phase interface fine controls, and low flow resistance are the key technologies to solving the above problems and shortening the gaps. In addition, for membrane separation technology, the diversity of water quality characteristics requires membrane materials to have a broad-spectrum fouling resistance, and thus, research on mixed matrix membrane materials and novel structure-designed membrane materials is getting more attention; such research has become a hot topic in the R&D of membrane materials in recent years.

In regard to the R&D of membrane modules, the development of low/ultra-low pressure anti-fouling membrane modules is the main direction for improving the membrane separation capacity and service life, as well as for solving the problem of membrane blocking and fouling. In particular, the development and optimization of the membrane module preparation process has become a hot topic. Through the optimization of the coating method, as well as through R&D for online detection technologies, automatic film rolling machines, and other hardware facilities, the separation performance, homogeneity, and stability of membrane modules can be improved. In addition, China needs to reduce its dependence on imports of pumps, valves, energy recovery devices, and pressure vessels, which are key parts related to the membrane separation system and its components, and instead, China should develop self-owned technologies and products.

In regard to the optimization of the membrane separation process, in recent years, with the continual improvements in the requirements and standards for industrial water reuse and strong brine emission reductions, membrane system integration coupling, emission reduction, and zero emission technology have raised the low consumption and high efficiency requirements for membrane processes. For example, the continuous microfiltration/continuous ultrafiltration (CMF/CUF) + reverse osmosis coupling process has been demonstrated to have application advantages and potential for seawater desalination and sewage reuse. The CMF/CUF process can improve the subsequent reverse osmosis inlet water quality without the addition of any flocculant, fungicide, or residual chlorine remover, and it has the advantages of extending the service life of reverse osmosis membranes, improving the recovery rate of the system, reducing the equipment occupation area and operating costs, reducing the labor intensity, realizing automatic control, and so on. Anaerobic membrane bioreactors have shown good application prospects in the low-consumption and high-efficiency treatment of highly concentrated organic wastewater and municipal sewage. Future research will focus on how to better control membrane fouling and large-scale engineering applications.

(5) Intelligent weather forecasting technology

Weather forecasting is a science of prediction, and thus, it is impossible to achieve 100% accuracy. The essence of forecasting involves the use of supercomputer calculations based on massive datasets, which are produced according to known meteorological conditions. However, there will be inevitable deviations between the calculated results and the real weather conditions. To make the weather forecasts more accurate, a process to continuously narrow the gap between the calculation results and the real situation is needed, and this has proved to be a difficult problem in the real world. The weather forecasts mainly depend on big data at different temporal and spatial scales, which is a very good situation for the use of artificial intelligence. On the one hand, sufficient meteorological data provides support for the advancement of artificial intelligence technology; on the other hand, the application of artificial intelligence technology will effectively promote the accuracy of the calculation results and calculation speed of weather forecasts, thus making "the weather forecast more accurate." Recently, a research team in Japan has developed a new high-precision identification method using deep learning technology, which can identify the characteristics of tropical depressions in the Northwest Pacific Ocean one week before the occurrence of a typhoon. As these data can be used to predict the occurrence of a typhoon one week in advance, the data can cause great concern and need to be accurate. The artificial intelligence algorithm corrects the results of a supercomputer as much as possible, automatically and without human intervention, to be closer to the actual observation data, thus achieving the ultimate goal of "more and more accurate weather forecasts."

In the field of artificial intelligence, computing power, algorithms, and data are indispensable. The use of high-performance computers in meteorological departments can provide a foundation for the development of intelligent weather forecasts.

(6) Efficient and comprehensive utilization of ocean energy technology

Ocean energy refers to the renewable energy derived from infrastructure installed in seawater. The ocean receives, stores, and emits energy through various physical processes, which exist in the ocean in the form of tidal energy, wave energy, ocean thermal energy, ocean salinity energy, and ocean current energy. The utilization of ocean energy relies on the use of certain methods and equipment to convert various kinds of ocean energy into electrical energy or other available forms of energy. Ocean energy is a kind of new energy with strategic significance that needs to be developed urgently because of its advantages of reproducibility and non-polluting characteristics.

At present, the hot topics and main research directions in the field of efficient and comprehensive utilization of ocean energy technology include international tidal and tidewave energy technology, wave energy technology, ocean thermal energy technology, ocean salinity energy, and ocean current energy.

Marine energy reserves are typically large in size. According to preliminary estimates, the total theoretical installed capacity of China's ocean energy exceeds 2 billion kilowatts, three times the total installed capacity of China's electricity in 2007. Recently, the ocean energy industry has begun to take shape. The installation costs of ocean energy power generation equipment have been decreasing rapidly, which has accelerated the industrialization of ocean energy technology.

(7) Integrated ocean environment observing technology

Integrated ocean environment observing technology refers to the equipment and technology that is used to study the dynamic changes of the marine environment, and it includes satellites and aircraft, surface survey and observation vessels, surface anchor buoys, submerged buoys, drifting buoys, underwater mobile observation platforms, submarine observation platforms, shore-based observation platforms, etc.; this technology is used to obtain various marine environmental information in real time or in near real time, so as to realize stereoscopic observations of the marine environment. The development of integrated ocean environment observing technology is one of the keys to the future development of marine science and technology.

At present, the hot topics and main research directions in the field of integrated ocean environment observing technology include 1) multi-parameter, wide range, real-time, and three-dimensional satellite remote sensing of marine environment observations; 2) miniaturization, intelligence, standardization, and industrialization of sensors and detection equipment;

and 3) globalization, stratification, synthesis, and intelligent applications of ocean network observations.

Nowadays, there is already a relatively mature global planning framework that reaches around the world, and China has launched a plan to build a national integrated ocean observing network. In the long term, given the needs for marine activities centered on marine information services, an adaptive ocean environment stereoscopic observation network composed of multiple platforms remains an important development direction of integrated ocean environment observing technology.

(8) Rapid and accurate detection of food-borne pathogenic microorganisms

With the change of food consumption patterns in China, the risk of food-borne pathogenic microorganisms has gradually increased, and dealing with these risks will be necessary for ensuring food safety in China in the future. Rapid detection of food-borne pathogens has long been a difficult problem in the field of microbiology. The traditional technology for food microorganism detection mainly relies on methods such as culture enrichment, separation and purification, biochemical analyses, and so on. However, the current process suffers from problems such as low efficiency, long detection times, and unsatisfying sensitivity, and it is unable to meet the safety detection requirements of the modern food industry. Therefore, it is imperative to develop novel food-borne pathogen rapid detection technology with a high sensitivity, high throughput, high accuracy, and rapid detection capacity. There are two major directions for the future development of rapid detection techniques, and these include time shortening for single pathogen detection and simultaneous detection of multiple samples. Among the various new rapid detection technologies for food-borne pathogenic microorganisms, constant temperature amplification detection technology and immunoassay technology may become the main development directions in the future. Combinations of different detection technologies are another research focus in the development of rapid detection technology for food-borne pathogenic microorganisms.

(9) 3D printing system with fiber

Three-dimensional printing technology is based on digital model files. By adding printing ink, a printer can customize the required shape through the integration of line to plane and plane to 3D structure rapid prototyping technology. The 3D printing of fiber-based materials uses fiber-based material as raw material to prepare printing ink and customize the sample structure needed as defined through 3D printing technology. The 3D printing technology prints interwoven fibrous structures, generally at the micron level, and with it, one can achieve structural control from micro to macro scales; this technology is suitable for making some special woven structures. At present, the main application fields of fiber-based material 3D printing are smart wearable textiles, flexible electronic components, high-performance composite materials, and so on. The collection and monitoring of human biological signals, the integration of customized electronic devices, and the enhancement of materials through orientation are the main application directions. A likely trend in the future will involve the use of compound inks to print, realize multi-component printing, and support unique sample performances. Due to its extensive and advanced application field, the further development of fiber-based material 3D printing technology can be expected.

(10) Biomass energy conversion technology

The extensive use of non-renewable fossil energy such as coal, oil, and natural gas has caused serious environmental problems. Therefore, developing green energy is critical for human society to fulfill the demands for energy in the future and simultaneously to solve environmental problems. Biomass energy will play an important role in the development of green energy, as it is one of the promising alternatives to replace fossil energy in the future.

Biomass energy conversion mainly refers to the conversion of biomass energy into secondary energy by biochemical methods, physical methods, thermochemical methods, and other technologies. The converted secondary energy includes heat or electricity, solid fuel (charcoal or molding fuel), liquid fuels (biodiesel, methanol, ethanol, vegetable oil, etc.), and gaseous fuels (hydrogen, biomass gas, and biogas). There are a variety of biomass sources, and accordingly, the technologies for biomass energy conversion are numerous. Currently, biomass energy conversion still faces many challenges in terms of practical utilization and cost effectiveness. As a consequence, it will be critically important to develop low-cost and efficient techniques for realizing the industrialization of biomass energy conversion in the future.

2.2 Interpretations for three key engineering development fronts

2.2.1 Multi-technology coordinated soil pollution remediation

Soil pollution is usually regional, complex, and of a multi-media nature. Traditional physical, chemical, and biological remediation technologies typically have limitations such as pollutant type restrictions, long remediation times, or high costs, which makes it difficult to remediate soil pollution efficiently and economically. Multi-technology coordinated soil pollution remediation technologies include integrated equipment of thermal desorption, vapor extraction, elution, and oxidation, and new materials (microbial agents, biochar, nanomaterials, biomass-mineral composite materials, etc.) for the stabilization or degradation of soil pollution, as well as improved devices for energy optimization (electric, microwaves, solar energy, plasma) and chemical/microbial/plant remediation.

In recent years, soil remediation technology has developed rapidly in China, and the R&D investments have remained in the top rank worldwide. As shown in Table 2.2.1, China has issued 998 patents on multi-technology coordinated soil pollution remediation over a recent five year period, which represents 73.16% of all of the 1119 patents issued. Japan and South Korea ranked second and third, with 40 and 33 patents, respectively. The total number of patents for multi-technology coordinated soil pollution remediation in China was much higher than that in developed countries such as Japan and the USA.

In terms of the citation frequency (Table 2.2.1), the citations per paper in China was only 0.86, a value much lower than that in developed countries such as the USA and Japan, which lack of original techniques, innovation, and influence. As for the relevance (Figure 2.2.1), a strong correlation existed between the USA and Japan, while China had no cooperative relationship with other developed countries. Developed countries such as the USA and Japan have focused on source disposal and end-treatment technology such as renewable remediation materials; however, materials used in chemical–biological remediation processes and the invention of integrated remediation equipment were the primary focus areas in China. As the integrated remediation technology and equipment is relatively mature in developed countries, it is imperative to develop integrated remediation technology and equipment systems based on advanced sources and process control-end treatments.

The top 10 patents output institutions were all from China (Table 2.2.2). The multi-technology coordinated soil pollution remediation technology market has gradually become mature. Jiangsu Gaiya Environmental Technology Co., Ltd., had the largest number of disclosed patents, and these were mainly related to in-situ and ex-situ soil remediation equipment and agents. Chengdu Shengling Biotechnology Co., Ltd., and Jiangsu Shibang Bioengineering Technology Co., Ltd., ranked as the second and fifth, respectively, with a focus on the microbial agents and materials for soil remediation. Qingdao University of Technology and Hunan Agricultural University, which focused on the remediation of high-risk oil contaminated sites, heavy metal–organic compound contaminated soils, and combined remediation technology for biochar and plants, ranked as the third and fourth with 10 and 7 patents issued, respectively.

As shown in Figure 2.2.2, there was no cooperation between the universities and companies. Thus, industry–university–research collaboration is still challenging. Patents mainly focused on the development of microbial agents and new materials, and presently, research and development on integrated technology and equipment need to be strengthened. Furthermore, high-tech companies have begun to step into the industry of soil remediation, while mainly focusing on chip development and process operations for soil remediation equipment. Trends indicate that soil remediation is gradually becoming more modularized, automatic, and intelligent in China.

2.2.2 Efficient and comprehensive utilization of ocean energy technology

Ocean energy refers to renewable energy derived from infrastructure installed in seawater, and it includes tidal energy, wave energy, ocean thermal energy, ocean salinity energy, ocean current energy, etc. In a broad sense, ocean energy also includes wind energy over the ocean, solar energy on the ocean surface, and ocean biomass energy. According to the storage forms, it can be divided into mechanical energy, heat energy, and chemical energy. Ocean energy has the characteristics of large reserves, sustainable use, and green and clean processes, and it is one of the most important

Table 2.2.1 Countries or regions with the greatest output of core patents on "multi-technology coordinated soil pollution remediation"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	998	89.19%	856	73.16%	0.86
2	Japan	40	3.57%	186	15.90%	4.65
3	South Korea	33	2.95%	22	1.88%	0.67
4	USA	16	1.43%	41	3.50%	2.56
5	Taiwan of China	9	0.80%	0	0.00%	0.00
6	Canada	6	0.54%	5	0.43%	0.83
7	Russia	6	0.54%	0	0.00%	0.00
8	Belgium	2	0.18%	48	4.10%	24.00
9	Australia	2	0.18%	24	2.05%	12.00

Table 2.2.2 Institutions with the greatest output of core patents on "multi-technology coordinated soil pollution remediation"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	JSGY	21	1.88%	21	1.79%	1.00
2	CDSL	11	0.98%	8	0.68%	0.73
3	UNQT	10	0.89%	4	0.34%	0.40
4	UYAG	7	0.63%	14	1.20%	2.00
5	JSSB	7	0.63%	0	0.00%	0.00
6	SHGI	6	0.54%	6	0.51%	1.00
7	HSFH	6	0.54%	2	0.17%	0.33
8	ZZSQ	6	0.54%	0	0.00%	0.00
9	CAGS	5	0.45%	14	1.20%	2.80
10	UYHD	5	0.45%	14	1.20%	2.80

JSGY: Jiangsu Gaiya Environmental Technology Co., Ltd.; CDSL: Chengdu Shengling Biotechnology Co., Ltd.; UNQT: Qingdao University of Technology; UYAG: Hunan Agricultural University; JSSB: Jiangsu Shibang Bioengineering Technology Co., Ltd.; SHGI: Shanghai Geotechnical Investigation; HSFH: Hanshan Fenghua Supply & Marketing Co., Ltd.; ZZSQ: Zhengzhou Souqu Information Technology; CAGS: Shandong Academy of Agricultural Sciences Agri-food Institute; UYHD: North China Electric Power University.

choices for the global response to the shortages of fossil energy and climate warming, which will entail the widespread development of clean energy and the adjustment of the energy structure.

According to a research report published by the International Renewable Energy Agency (IRENA) in August 2014, international tidal energy technology is the most mature technology for deriving ocean energy, and it has a Technology Readiness Level (TRL) of 9 (commercial operation stage). The international tidewave energy TRL is 7–8 (full scale prototype under real sea conditions test stage). The wave energy TRL is 6–7 (engineering prototype under real sea conditions test stage). The ocean thermal energy TRL is 5–6 (real sea conditions test stage). The ocean salinity energy and ocean current energy TRL is 4–5 (laboratory technology validation stage).

The ocean energy industry has begun to take shape, with more than 2500 international organizations working in the industry. The installation costs of ocean energy power generation equipment have been decreasing rapidly, which has accelerated the industrialization of ocean energy technology. Current international ocean energy technology has not yet entered the stage of large-scale application, and to catch up with internationally advanced levels, we should

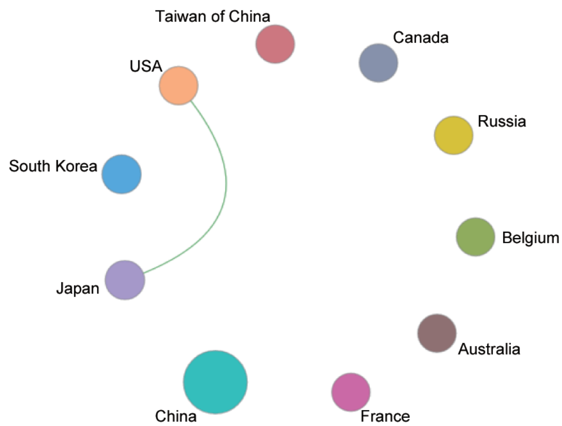

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "multi-technology coordinated soil pollution remediation"

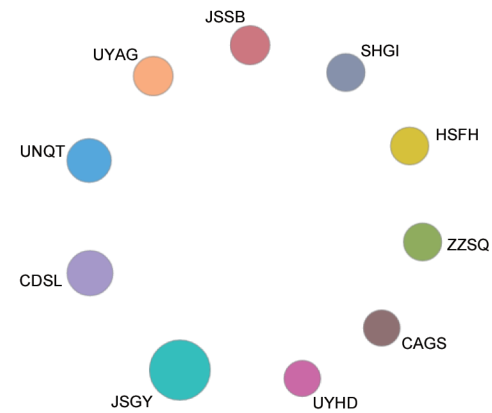

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "multi-technology coordinated soil pollution remediation"

focus on the "construction of marine power" and "construction of the marine silk road" recommendations in the 21st century. Such efforts constitute a strategic opportunity, through demonstration projects of stable operations that drive the development of technology, efforts to accelerate the cultivation of ocean energy industries, projects to initiate the large-scale development of islands, and the development of far-reaching marine resources to provide energy security.

It is estimated that there are over 75 billion kilowatts of ocean energy, among which wave energy represents 70 billion kilowatts, oceanic thermal energy represents 2 billion kilowatts, ocean current energy represents 1 billion kilowatts, and ocean salinity energy represents 1 billion kilowatts. According to preliminary estimates, the total theoretical installed capacity of China's offshore wind, tidal, wave, tidal, and salinity gradient energies, as well as temperature-difference energy in South China Sea exceeds 2 billion kilowatts, three times the total installed capacity of China's electricity in 2007.

Table 2.2.3 shows the countries or regions with the greatest output of core patents on the "efficient and comprehensive utilization of ocean energy technology." China ranked second in the number of core patent disclosures, and it showed only a little gap with Japan, which ranked first. However, the citations per patent for China were the lowest in the top 10 countries, accounting for only 1.21% of the total, which is far from the number for the USA. This shows that although China has many core patents in this field, these patents lack innovation and influence. Thus, China's technological level in this field still needs to be improved. As can be seen from the collaboration network (Figure 2.2.3) among the main countries or regions engaged in this front, the USA, Britain, and Germany each had cooperative relations with two countries, while China only has cooperated with the USA.

Table 2.2.4 shows the institutions with the greatest output of core patents. The top three institutions were General Electric Company (116), Siemens AG (48), and Rolls Royce Holdings PLC (29). China's Wuxi Jintianyang Laser Electronic Co., Ltd. ranks eighth, but the citations value was only 5, which was the lowest in the top 10. Figure 2.2.4 shows the collaboration network among the main institutions working on this front. There were weak associations in terms of research and development cooperation between individual institutes or enterprises in this field. Only General Electric Company and "Converteam Technology, Ltd." have had a cooperative relationship, and the patents of the two institutes were ranked top. This shows that we should further strengthen exchanges and cooperation with other countries and institutions in order to further enhance China's innovation ability in this field.

2.2.3 Rapid and accurate detection of food-borne pathogenic microorganisms

With the development of food supply systems, household consumption of semi-finished and instant foods has been growing rapidly, and so are safety risks from microorganism. Some of the most severe risks stem from semi-finished foods

Table 2.2.3 Countries or regions with the greatest output of core patents on “efficient and comprehensive utilization of ocean energy technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	233	18.52%	1330	15.30%	5.71
2	China	202	16.06%	105	1.21%	0.52
3	South Korea	199	15.82%	116	1.33%	0.58
4	USA	164	13.04%	2517	28.96%	15.35
5	UK	104	8.27%	1761	20.26%	16.93
6	Germany	88	7.00%	1089	12.53%	12.38
7	France	45	3.58%	266	3.06%	5.91
8	Norway	43	3.42%	419	4.82%	9.74
9	Ireland	20	1.59%	272	3.13%	13.60
10	Sweden	20	1.59%	87	1.00%	4.35

Table 2.2.4 Institutions with the greatest output of core patents on “efficient and comprehensive utilization of ocean energy technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GENE	116	9.22%	2442	28.10%	21.05
2	SIEI	48	3.82%	766	8.81%	15.96
3	RORO	29	2.31%	161	1.85%	5.55
4	SMSU	28	2.23%	28	0.32%	1.00
5	DEWO	25	1.99%	6	0.07%	0.24
6	CONV	22	1.75%	806	9.28%	36.64
7	CATE	21	1.67%	57	0.66%	2.71
8	JLEC	20	1.59%	5	0.06%	0.25
9	OPEN	19	1.51%	283	3.26%	14.89
10	NIDE	19	1.51%	118	1.36%	6.21

GENE: General Electric Company; SIEI: Siemens AG; RORO: Rolls Royce Holdings PLC; SMSU: SAMSUNG Heavy Industries Ltd.; DEWO: Daewoo Shipbuilding & Marine Engineering Co., Ltd.; CONV: Converteam Technology Ltd.; CATE: Caterpillar Inc.; JLEC: Wuxi Jintianyang Laser Electronic Co., Ltd.; OPEN: Openhydro Group Ltd.; NIDE: NEC Corporation.

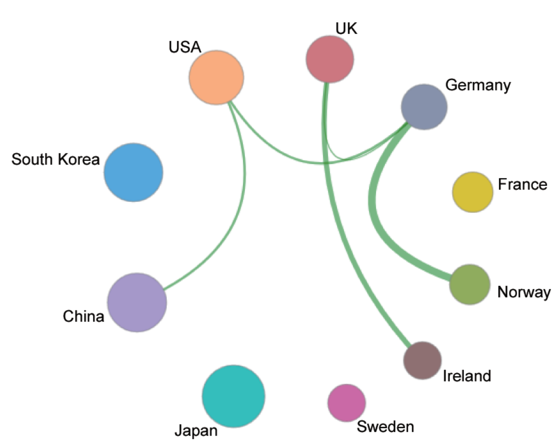

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of “efficient and comprehensive utilization of ocean energy technology”

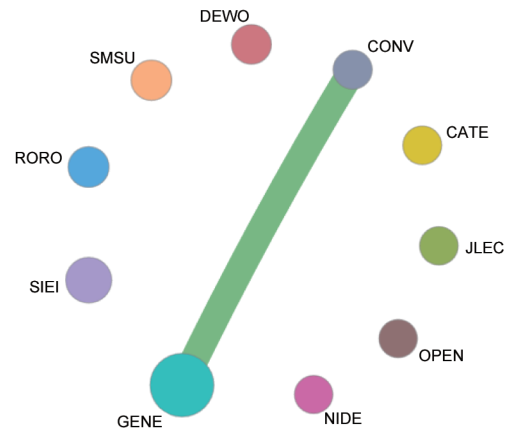

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "efficient and comprehensive utilization of ocean energy technology"

such as preliminary processed meat and vegetables, and instant foods such as cheese and salads, which often contain food-borne pathogenic microorganisms. Therefore, food-borne pathogenic microorganisms are the focus of food safety all over the world, and the proportion of food-borne pathogenic microorganism identification and detection technologies in the field of food safety analysis has been growing.

Rapid and accurate identification and detection of food-borne microorganisms is one of the most effective ways to prevent and control human food-borne diseases. At present, detection of food-borne pathogenic microorganisms is mainly based on the combination of enrichment culture and physiological and biochemical identification methods (Food Microbiology National Standard GB4789). These protocols are highly accurate. Therefore, such methods are indispensable for microbe detection and management domestically. However, culture based and biochemical identification methods have problems including long detection times, low throughput, and low efficiency. In addition, culture based and biochemical identification methods are only suitable for microorganisms that are highly active, and these methods cannot be used for microorganisms that are viable but non-culturable (VBNC) but can restore activity under proper conditions, proliferate rapidly in food, and thereby bring about safety risks. Traditional detection and identification methods for food-borne pathogens are thus more and more unable to meet the safety detection requirements of the modern food industry. Therefore, it is imperative to develop novel detection technologies for pathogenic bacteria that have a high sensitivity, high throughput, and rapid speed.

As a whole, the current rapid detection methodology can only be confined to the preliminary screening of food samples due to the limitations in accuracy and stability. There is still a lack of effective and rapid detection methods that can be used against pathogenic microorganisms at home and abroad. The USA has the most published patents on the rapid and accurate detection of food-borne pathogenic microorganisms. Developing stable, accurate, and sensitive rapid detection technology in advance would promise great advantages in improving food safety levels, promoting the development of the food industry, and stimulating import–export commerce.

There are two major directions for the future development of food-borne pathogen rapid detection technology, and these include time shortening for single pathogen detection and simultaneous detection of multiple samples. Combinations of different detection technologies represent another research focus, with the aim of balancing detection timeliness, sensitivity, and accuracy. Among various new rapid detection technologies for food-borne pathogenic microorganisms, constant temperature amplification detection technologies and immunoassay technologies may become the main development directions in the future.

As is shown in Table 2.2.5, China has published 127 core patents on rapid and accurate detection of food-borne pathogenic microorganisms, ranking second in the number of core patent disclosures, while the USA ranked first with 491 core patents. Japan and South Korea ranked third and fourth, with 95 and 66 patents respectively. The total number of core patents on rapid and accurate detection of food-borne pathogenic microorganisms in China was still not competitive with that in the USA, but was much higher than that in other countries. However, the citations per patent in China was the lowest (1.09) among the top 10 countries, which is much lower than that of the developed countries such as the USA (27.76), the Netherlands (16.54) and Germany(14.27), which expose a deficiency in original innovation and technological influence in patents from China.

The collaboration relationship among most developed countries engaged in this front are close and frequent, as can be seen from Figure 2.2.5. Among the top 10 countries, the USA has established firm cooperative partnership with all the other countries except South Korea. Switzerland has also built strong collaboration network with many countries from Europe and North America. China has only established cooperation relation with the USA, indicating an imperative urge to reinforce and seek more international communication and collaboration.

Table 2.2.6 shows the institutions with the greatest output of core patents on the rapid and accurate detection of food-borne pathogenic microorganisms. University Of California had the largest number of issued patents (25), followed by F. Hoffmann-La Roche AG (22), Massachusetts Institute of Technology (15), and National Council for Scientific Research (15). Figure 2.2.6 shows the collaboration network among the major institutions engaged in this front. There are already some research and development inter-institution collaboration among enterprises in this field. University Of California have had a cooperative relationship with both Massachusetts Institute of Technology and CALY Technologies, among which the patent number of University Of California and Massachusetts Institute of Technology ranked top three. This showed that inter-institution collaboration have a beneficial effect on technique innovation and entrepreneur development.

Table 2.2.5 Countries or regions with the greatest output of core patents on the "rapid and accurate detection of food-borne pathogenic microorganisms"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	491	49.10%	13 628	77.90%	27.76
2	China	127	12.70%	139	0.79%	1.09
3	Japan	95	9.50%	1 180	6.75%	12.42
4	South Korea	66	6.60%	260	1.49%	3.94
5	France	36	3.60%	298	1.70%	8.28
6	Germany	33	3.30%	471	2.69%	14.27
7	Canada	31	3.10%	390	2.23%	12.58
8	UK	24	2.40%	136	0.78%	5.67
9	Switzerland	23	2.30%	254	1.45%	11.04
10	Netherlands	13	1.30%	215	1.23%	16.54

Table 2.2.6 Institutions with the greatest output of core patents on the "rapid and accurate detection of food-borne pathogenic microorganisms"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	REGC	25	2.50%	613	3.50%	24.52
2	HOFF	22	2.20%	242	1.38%	11.00
3	MASI	15	1.50%	61	0.35%	4.07
4	CNRS	15	1.50%	49	0.28%	3.27
5	TEXA	12	1.20%	75	0.43%	6.25
6	CALY	11	1.10%	568	3.25%	51.64
7	STRD	11	1.10%	161	0.92%	14.64
8	UYJO	10	1.00%	234	1.34%	23.40
9	UPEN	9	0.90%	301	1.72%	33.44
10	HARD	9	0.90%	69	0.39%	7.67

REGC: University of California; HOFF: F. Hoffmann-La Roche AG; MASI: Massachusetts Institute of Technology; CNRS: National Council for Scientific Research; TEXA: Texas Tech University System; CALY: CALY Technologies; STRD: Leland Stanford Junior University; UYJO: Johns Hopkins University; UPEN: University of Pennsylvania; HARD: Harvard College.

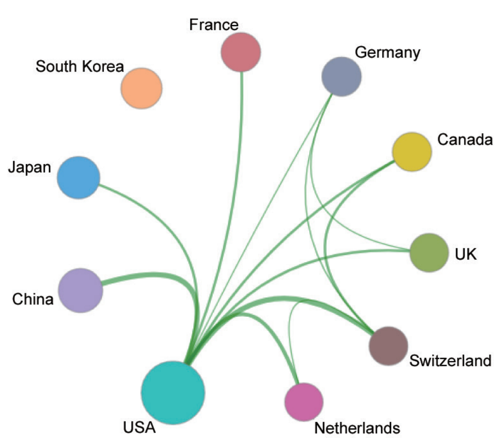

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "rapid and accurate detection of food-borne pathogenic microorganisms"

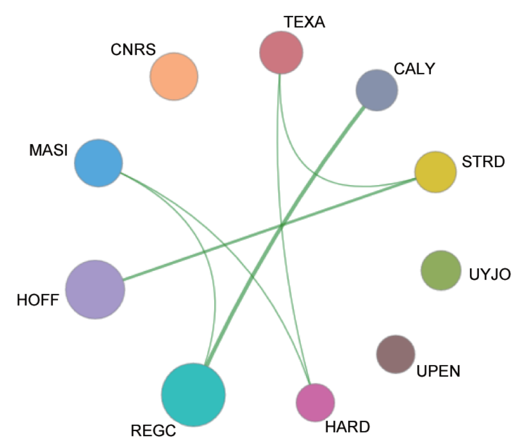

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "rapid and accurate detection of food-borne pathogenic microorganisms"

Participants of the Field Group

Leaders

HAO Jiming, QU Jiuhui

Experts

HE Kebin, WEI Fusheng, ZHANG Quanxing, YANG Zhifeng, ZHANG Yuanhang, WU Fengchang, ZHU Lizhong, PAN Delu, DING Yihui, XU Xiangde, HOU Baorong, ZHANG Si, JIANG Xingwei, SUN Baoguo, PANG Guofang, SUN Jinliang, YU Jianyong, CHEN Kefu, SHI Bi, QU Jinping, YUE Guojun, CHEN Jian

Members of the Secretary Group

HUANG Xia, LU Xi, HU Chengzhi, WANG Xu, XU Renji, HU Min, PEI Yuansheng, CHEN Baoliang, PAN Bingcai, XI Beidou, XU Ying, SONG Yafang, BAI Yan, MA Xiumin, LI Jie, WANG Jing, QIN Xiaohong, HUANG Xin

Office Staff

WANG Xiaowen, ZHU Jianjun, ZHANG Xiangyi, ZHANG Jiao, ZHENG Wenjiang, ZHANG Haichao, MU Zhirui, ZHENG Jing

Report Writers

HUANG Xia, LU Xi, XI Beidou, JIANG Yonghai, JIA Yongfeng, PAN Bingcai, SHAN Chao, HU Chengzhi, WU Yan, WANG Xu, XU Renji, SHENG Yaqi, CHEN Xueqing, HU Shuya, XU Ying, SONG Yafang, SHI Ying, BAI Yan, LI Jie, MA Xiumin, YANG Jian, WANG Zhihong, MA Zheng, SUN Baoguo, WANG Jing, WANG Shuo, WANG Junping, WANG Xueli, QIN Xiaohong, LI Faxue, MAO Zhiping, LI Jun, ZHANG Linping, WANG Bijia, ZHANG Hongnan, QUAN Zhenzhen, HUANG Xin, LI Huifang, KE Le, WANG Yujia

VII. Agriculture

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research frons in the agriculture field can be classified into three categories: (1) In-depth established research fronts. These comprise "mechanisms of plant immunity regulation" of plant protection, "influences of climate change on agroecosystems" of resource ecology, "biodiversity and ecosystem services" of resource ecology, "artificially induced spawning" of fisheries science and "global climate change and crop production" of resource ecology. (2) Emerging research fronts. These comprise "genomic selection breeding of crops" of crop science, "mechanisms, prevention, and control of animal epidemics" of animal science, "intelligent biological factories" of agricultural engineering, and "forest monitoring through hyperspectral remote sensing" of forestry science. (3) Ground breaking research front. This comprises "CRISPR/Cas9 genome editing of agricultural organisms" of agricultural engineering.

The numbers of core articles supporting various fronts were unevenly distributed. There were 30 core articles on average for each front, with an average of 40 citations per article (Table 1.1.1). The articles of all fronts were mainly published in 2015—2017 (Table 1.1.2), with no obvious variation patterns across the years. In particular, the number of published articles on artificially induced spawning exhibited a gradual upward trend with time. Data on relevant publications also showed that the highest proportion of highly cited articles in articles on these fronts was less than 30%, and only an extremely small number of articles had patent citations.

The top 10 engineering research fronts are briefly described below.

(1) CRISPR/Cas9 genome editing of agricultural organisms

This is a ground breaking research front. Genome editing techniques involve the specific cutting of DNA at target sites by endonucleases to generate DNA double-strand breaks (DSBs), which induces DNA repair and enables the achievement of directional genome editing. Among the various genome editing techniques, CRISPR/Cas9 editing is an accurate, effective and convenient technique. CRISPR is a family of

Table 1.1.1 Top 10 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	CRISPR/Cas9 genome editing of agricultural organisms	42	3261	77.64	2015.6
2	Mechanisms, prevention, and control of animal epidemics	11	153	13.91	2017.3
3	Genomic selection breeding of crops	6	174	29.00	2017.3
4	Intelligent biological factories	26	547	21.04	2015.8
5	Mechanisms of plant immunity regulation	43	1265	29.42	2015.8
6	Influences of climate change on agroecosystems	11	795	72.27	2016.1
7	Biodiversity and ecosystem services	35	1356	38.74	2015.9
8	Artificially induced spawning	44	704	16.00	2016.5
9	Global climate change and crop production	85	2298	27.04	2015.5
10	Forest monitoring through hyperspectral remote sensing	15	937	62.47	2015.5

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in agriculture

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	CRISPR/Cas9 genome editing of agricultural organisms	1	5	14	12	8	2
2	Mechanisms, prevention, and control of animal epidemics	0	0	0	2	4	5
3	Genomic selection breeding of crops	0	0	0	0	4	2
4	Intelligent biological factories	3	4	3	5	3	4
5	Mechanisms of plant immunity regulation	7	5	8	1	12	10
6	Influences of climate change on agroecosystems	1	1	2	2	2	3
7	Biodiversity and ecosystem services	6	4	2	3	14	6
8	Artificially induced spawning	1	2	6	10	14	11
9	Global climate change and crop production	10	11	22	18	19	5
10	Forest monitoring through hyperspectral remote sensing	1	4	3	3	1	3

clustered, regularly interspaced, short palindromic repeat sequences found in nearly all archaeal genomes. It mainly depends on the Cas9 core protein for the RNA-mediated identification of target sequences for DNA cutting, which results in DNA DSBs. During DNA repair, CRISPR provides organisms with a specific immunity protection mechanism to resist invasion by genetic material from plasmids or viruses. Therefore, the CRISPR/Cas9 technique effectively solves the issues of multi-generation crossing and the long duration associated with crossbreeding methods, and enables the directional acceleration of breeding processes.

(2) Mechanisms, prevention, and control of animal epidemics

This is an emerging research front. An animal epidemic occurs when infectious disease or parasitic origin in animals endangers the health and lives of humans and animals, thereby necessitating urgent and harsh mandatory measures for epidemic prevention and control. To date, more than 250 types of infectious animal diseases have been discovered globally. Almost 50% of these diseases affect both humans and animals, which not only cause disease-related deaths of animals, but also produces adverse impacts on animal rearers, consumers, and the broader economy. Scientists typically employ information technologies to study biological data and utilize bioinformatics principles to collect, process, and analyze genomic information on pathogens. Through genome comparisons, the protein structures of pathogens can be confirmed, and novel drugs with enhanced therapeutic effects can be developed based on molecular characteristics that result in pathogenesis. With economic globalization, the movement of people, goods, and livestock across borders has increased substantially. This has led to the gradual transformation of certain localized outbreaks into globalized diseases and the emergence of alarming public health issues. For instance, bovine spongiform encephalopathy (BSE), first reported in 1986 in the UK, has now spread to more than 20 countries, including Canada, various European countries, and Japan. Given the negative externalities and publicness of animal diseases, various parties have focused their attention on certain major animal diseases and adopted relevant prevention and control strategies. Animal epidemic prevention and control strategies refer to targeted prevention and control schemes or measures such as technological inputs and institutional arrangements to reduce the impact of infectious animal diseases on human society. The prevention and control of animal epidemics is a key influencing factor of the robust development of animal husbandry. Throughout their life, domestic animals are subject to various measures, such as feed, breeding environment and immunization, to prevent the onset of disease and maintain their health; these measures take livestock health, product safety and environmental protection into account and assures the safety of animal products from source.

(3) Genomic selection breeding of crops

This is an emerging research front. Since the 1980s, the rapid development of molecular biology has created possibilities for molecular genetic marker-assisted breeding, i.e., marker-assisted selection (MAS). The advantages of MAS include its high accuracy, absence of sex limitations, rapid enhancement of favorable allele frequencies or elimination of harmful alleles, and early selection. However, as the mutual validation of quantitative trait loci (QTL) mapping results among various studies is difficult, mapping intervals are excessively large and QTL effects are usually overestimated, the application of MAS in crop breeding is severely limited. To overcome the inadequacies of using a small number of markers for selection, researchers have combined the latest results in functional genomic studies with state-of-the-art single nucleotide polymorphism (SNP) chip technologies. Meuwissen et al. proposed the calculation of the genomic estimated breeding values (GEBVs) of individuals based on high-density markers that cover the whole genome. Compared with estimated breeding values calculated based on genealogical information, GEBVs usually achieve a higher estimation accuracy. Genomic selection breeding (GSB) refers to selection based on the use of GEBVs as the genomic breeding values. The GSB process is as follows. First, a reference population is established, with all individuals of the population having known phenotypes and genotypes. The effect values of each SNP or different chromosome segments are calculated using a suitable statistical model. Then genotyping is performed on each individual of the candidate population, and the GEBVs of the individuals of the candidate population are calculated based on the estimated SNP effect values of the reference population. Finally, individuals are selected based on the ranking of GEBVs. When performance testing of the selected candidates has been completed, these individuals can be included in the reference population for the re-estimation of the SNP effect values, and the entire process is repeated. With the increasing adoption of commercial high-density SNP chips and a decline in sequencing costs, genomic selection has become widely applied in the practice of plant and animal agriculture. The use of high-density SNP chips can accelerate the application of genomic selection in crop breeding.

(4) Intelligent biological factories

This is an emerging research front. At present, the intelligence revolution, which is driven by big data and artificial intelligence, has profoundly changed the connotations and extensions of bioengineering, and achieved transformational results in the fields of crop production, macromolecular design, synthetic biology, and microchemical engineering. Facility agriculture is a modern agriculture method that utilizes engineering technologies and methods for effective plant production under relatively controllable environmental conditions. In particular, intelligent biological factories, which have emerged as part of the prevailing intelligence revolution, represent the cutting edge in the development of facility agriculture. Intelligent facility agriculture includes facility planting, facility culturing, and facilities producing edible fungi. During the transformation of automated facilities from planting and cultivation to high-level intelligent systems, the collection and monitoring of environmental and biological information (including facility environmental factors and the growing and production processes of organisms) as well as the development of control platforms for intelligent systems, management models of organisms (plants, fungi and livestocks), intelligent light sources, intelligent feeding systems, harvesting robots, and Internet of Things (IoT)-based agricultural product quality traceability systems will form the core topics of future research. In addition, synthetic meat products manufactured by intelligent biological factories using animal stem cells will also gradually make their way to the dining tables of consumers in the near future.

(5) Mechanisms of plant immunity regulation

This is an in-depth established research front. Plant disease resistance includes resistance to invasion and infection, resistance to expansion, induced resistance, structural resistance, biochemical resistance, hypersensitive necrotic reaction, and systemic acquired resistance. In natural environments, plants are subject to infection by various types of pathogens. The epidermis serves as the first line of defense against the entry of pathogens, which is a manifestation of non-host resistance. However, when pathogenic organisms successfully invade the internal parts of a plant, the innate immune system of the plant is activated. The immunoregulatory mechanism of the innate immune system consists of four steps: 1) pathogen-associated molecular pattern-triggered immunity (PTI), which involves the detection of molecular patterns on the surfaces of pathogens by pattern recognition receptors; 2) the release of effectors by pathogenic microbes to inhibit PTI and initiate a hypersensitive response (HR) of plant cells toward the pathogens; 3) effector-triggered immunity, which is an immune response triggered by effectors specifically recognized by nucleotide binding leucine-rich repeat proteins; and 4) the disease resistance genes of the plant produces new resistance proteins under natural selection pressure, which induces cell death at the sites of pathogenic microbial infection. This HR effectively prevents the growth of pathogenic microbes, especially parasites that acquire cell nutrients through their mouthparts, in tissues where HR has occurred. Tissues uninfected by pathogenic microbes do not usually produce a HR.

(6) Influences of climate change on agroecosystems

This is an in-depth established research front. The ecological factors of global climate change that exert key influences on agricultural ecosystems are increased CO_2 concentrations, increased temperatures, and changes in precipitation. An increase in CO_2 concentration promotes the translocation of photosynthetic products of crops to the roots, thereby enhancing carbon fixation by the underground parts of agroecosystems and absorption of water by plant roots, which increases the primary productivity of agroecosystems. Higher soil organic carbon levels provide more degradable substrates for soil microbes, consequently enhancing soil respiration. Global warming leads to a greater input of energy from external environments to agroecosystems, which causes changes in the structures and functions of agroecosystems. By influencing the physiological processes of crops and mutual interactions among species or even altering the genetic characteristics of species, climate change may influence the species compositions, structures, and functions of agroecosystems. Changes in precipitation and rises in global sea levels can also have a direct or indirect impacts on the functioning of agroecosystems. It is evident that global climate change will pose unprecedented severe challenges to mankind.

(7) Biodiversity and ecosystem services

This is an in-depth established research front. Biodiversity refers to the variability and diversity of life forms, such as animals, plants and microbes, existing in terrestrial, marine and other aquatic ecosystems, as well as the complex ecological processes among various constituents of ecosystems. It includes species, ecological environmental, nutritional, life-cycle, and genetic diversities, and contributes greatly to the conservation of natural resources. Ecosystem services are defined as the benefits that humans gain from various ecosystems, and are composed of supporting services, provisioning services, cultural services, regulating services, and the interactions between these services. The biological and physical structures and processes of ecosystems are manifested in the structural and functional characteristics of ecosystems, and the stability of these ecosystem structures and functions ensures a continuous supply of ecosystem services. The current global decrease in key ecosystem services poses an enormous threat to human society. As biodiversity serves as the provider and service basis of various ecosystem products, the restoration of lost ecosystem services and biodiversity through ecological restoration projects is of great significance to the alleviation of environmental stresses faced by mankind.

(8) Artificially induced spawning

This is an in-depth established research front. The reproductive activities of most fish and shrimp species are seasonal in nature, with only a small number of year-round spawning species. In addition, precision in the timing of reproductive events of various species ensures that the larvae produced are provided with appropriate conditions for survival. Among the various environmental factors, temperature, photoperiod, rainfall and food are the most crucial for regulation of the reproductive cycles of fish and shrimp. In general, the sense organs of fish and shrimp transmit information regarding the changes in these environmental factors to the brain, causing the hypothalamus to secrete gonadotropin-releasing hormone (GnRH) and other neuroendocrine factors. This triggers the secretion of gonadotropic hormones by the pituitary gland, which stimulates the production of gonadal steroid hormones by the gonads, thereby promoting gonadal development and maturation, as well as sperm and egg production. The external environmental factor-activated cyclic reproductive activities of fish and shrimp are regulated by a series of neuroendocrine hormones, with gonadotropins contributing significantly to regulation. In view of these mechanisms, the following approaches are mainly adopted in artificially induced spawning. 1) Environmental stress methods. When significant changes occur in the living environment (e.g., droughts, floods, and extreme hot or cold weather), species continuation and reproductive needs become the first priority of survival in crayfish. Under such circumstances, the reproductive performance of crayfish undergoes certain changes, which are manifested as early reproduction and increased reproduction under environmental stresses. 2) The use of highly effective, low-cost, and side-effect-free novel uterotonic agents, such as high-activity novel uterotonic agents for fish composed of GnRH analogs (LHRH-A or sGnRHA) and domperidone, a dopamine D2 receptor antagonist.

(9) Global climate change and crop production

This is an in-depth established research front. Since the release of the First Assessment Report of the Intergovernmental Panel on Climate Change in 1990, the investigation of crop production under future climate change scenarios has become extremely important when evaluating the influence of future climate change on agriculture, as it enables the determination of soil production potential and the ability to safeguard food security. The influences of global climate change-induced increases in temperature and atmospheric CO_2 concentrations on crop production must be evaluated on a long timescale. In recent years, researchers have developed a series of models, including ecosystem function, crop growth, net primary productivity, atmospheric, biogeochemical and ecological models, to investigate the relationships between global climate change and crop production. In particular, there has been a considerable amount of crop growth model-based research on the influences of climate change on crop production, growth and development, and the regional climate adaptability of crops. At present, the use of crop growth models for numerical simulation and prediction is the main research method employed in studies on the quantification of the influences of climate change on agricultural production. Such models can also be used to determine the patterns of influence of historical climate change on crops and to analyze the mechanisms by which ecological succession occurs in crop species to achieve adaptation to climate change.

(10) Forest monitoring through hyperspectral remote sensing

This is an emerging research front. Hyperspectral remote sensing is a novel technology involving the acquisition of continuous spectral information on ground objects in extremely narrow and contiguous spectral bands. The combination of imaging and spectroscopy in a single system and an extremely high spectral resolution are unique advantages of hyperspectral remote sensing. Hyperspectral remote sensing utilizes narrow spectral bands to acquire relevant data on ground objects of interest. It enables the acquisition of huge volumes of continuous imaging data in extremely narrow bands in the mid-infrared, visible, near-infrared, and ultraviolet spectral regions, and is mainly used for the following applications. 1) Monitoring of forest fires. Hyperspectral remote sensing can be used to determine whether surface temperatures are abnormal and whether ground objects are combustible at the surveyed locations. By combining these factors with normal remotely sensed data, the locations of forest fires and consequences of burning can be qualitatively and quantitatively analyzed. 2) Forest pest monitoring. When forests are invaded by pests, the chlorophyll content of plants usually decreases and the intensity of chlorophyll absorption bands consequently weakens, which leads to an increase in the overall visible light reflectance. Information on such changes can be extracted from remotely sensed images to provide a reference for the prevention of pest problems. 3) Monitoring of resource changes in forests. Hyperspectral remote sensing can be used for the monitoring of changes in forest land, ecological assessments of forests, and detailed classification of forest types and tree species.

1.2 Interpretations for three key engineering research fronts

1.2.1 CRISPR/Cas9 gene editing in agricultural organisms

Genome editing techniques have sparked research interest in many countries. In 2012, genome editing was named by *Science* magazine as one of the top 10 scientific advances; in 2014, it was named by *Nature Methods* as one of the top 10 research methods that exerted the greatest influence on biological research in the past decade. Genome editing techniques involve the specific cutting of DNA at target sites by endonucleases to generate DSBs, which induces DNA repair and enables the achievement of the directional genome editing. These techniques effectively solve the problem of multi-generation crossing and the long duration associated with crossbreeding methods and enable the directional acceleration of breeding processes. In addition, because of the artificial increase in mutation efficiency and alteration of the natural evolutionary processes of crops, the environmental safety and food safety risks of genome-edited plants have increased. Genome editing has already progressed to the fourth generation, with zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), meganucleases (MGNs), and CRISPR/Cas9 being the major tools employed in various genome editing techniques. In particular, the CRISPR/Cas9 system is an accurate, effective, and convenient genome editing tool. Its working principle is as follows. The conserved protospacer adjacent motif (PAM) sequence NGG (N being any nucleotide and G being guanine) in exogenous genes can be recognized by single-guide RNA (sgRNA), which subsequently directs the Cas9 protein to cleave DNA upstream of the PAM. When the cleaved DNA undergoes non-homologous end joining (NHEJ) for the repair of the DSB, small insertion/deletions are created, causing a frameshift mutation which leads to the achievement of gene knockout. The CRISPR/Cas9 system is advantageous in that the sgRNA of CRISPR can recognize the PAM sequence with a guide sequence of no more than 30 nucleotides, and the monomeric Cas9 protein is sufficient to elicit cleavage. Compared to other gene editing tools, the CRISPR/Cas9 system provides a greater ease of operation, higher knockout efficiency, and higher accuracy in gene editing, which greatly reduces the chances of off-target mutations. Therefore, it is currently widely applied in gene editing in key plant and animal species.

The analysis of data on the relevant literature is as follows. From the distribution of papers by country or region (Table 1.2.1), it can be seen that the main contributors of core papers were China and the USA, followed by Germany and Japan. The number of citations was highest in China, followed by the USA and Germany. From the distribution of papers by research institution (Table 1.2.2), it can be seen that the Chinese Academy of Sciences (China) and University of Minnesota (USA) were ranked at the top with seven core articles each, and the number of citations was highest for papers published by the Chinese Academy of Sciences. The network diagram of inter-country/regional collaborations (Figure 1.2.1) shows that inter-country collaborations were common, with China and the USA sharing the closest collaborative relationship; a significant collaborative relationship also existed between the USA and the UK. From the network diagram of collaborations among the major contributing institutions (Figure 1.2.2), it can be seen that a close collaborative relationship existed between the Chinese Academy of Sciences and the University of Chinese Academy of Sciences; certain collaborative relationships also existed among other institutions. The main contributors of core papers citations were China and the USA, with the proportions of core paper citations being substantially higher than that of other countries or regions (Table 1.2.3). From the list of the major core paper citation-contributing institutions (Table 1.2.4), it can be seen that six out of the top 10 core paper citation-contributing institutions were Chinese institutions. In addition, research institutions located in China (Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, Huazhong Agricultural University, University of Chinese Academy of Sciences, and China Agricultural University) occupied the top five spots on the list. The average core paper citation year of these institutions was 2017, which was generally later than that of other institutions. This is indicative of the strong developmental momentum of research in this field.

An in-depth analysis of the supporting data revealed that more than 40 relevant research articles had a citation frequency of >200, with most of these articles being reviews. In particular, the article entitled *Development and Applications of CRISPR-Cas9 for Genome Engineering* published in *Cell* in 2014 had a citation frequency of >1700, which provides adequate proof of the leading position of the CRISPR/Cas9 system in the field of genome editing. At present, the CRISPR/Cas9 technique has been widely applied in model organisms such as *Arabidopsis*, yeast, mouse, human, and *Drosophila*, and has even enabled the achievement of fixed-location genome editing in economic animals such as cattle, pigs, and sheep, as well as major crops such as wheat, sorghum, rice, and corn. Certain institutions, including the Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, and Huazhong Agricultural University, have made tremendous progress in the genetic improvement of agricultural crops, while other institutions, such as the China Agricultural University, hold leading positions in research related to gene editing in economic animals.

1.2.2 Mechanisms, prevention, and control of animal epidemics

Common animal epidemics include foot-and-mouth disease, African swine fever (ASF), contagious bovine pleuropneumonia (lung plague), BSE (mad cow disease), bluetongue disease, and avian influenza (highly pathogenic avian influenza). To date, more than 250 types of infectious animal diseases have been discovered. Almost 50% of these diseases affect both humans and animals, which not only results in disease-related deaths of animals, but also have adverse impacts on animal rearers, consumers, and the broader economy. Based on the overall epidemic situation, infectious diseases can be classified as contagious or non-contagious according

Table 1.2.1 Countries or regions with the greatest output of core papers on "CRISPR/Cas9 genome editing of agricultural organisms"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	17	40.48%	1437	44.07%	84.53
2	USA	17	40.48%	1399	42.90%	82.29
3	Japan	5	11.90%	156	4.78%	31.20
4	Germany	5	11.90%	455	13.95%	91.00
5	South Korea	3	7.14%	171	5.24%	57.00
6	Italy	2	4.76%	99	3.04%	49.50
7	UK	2	4.76%	219	6.72%	109.50
8	Sweden	1	2.38%	47	1.44%	47.00
9	Mexico	1	2.38%	17	0.52%	17.00
10	Philippines	1	2.38%	17	0.52%	17.00

Table 1.2.2 Institutions with the greatest output of core papers on "CRISPR/Cas9 genome editing of agricultural organisms"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Minnesota	7	16.67%	486	14.90%	69.43
2	Chinese Acad Sci	7	16.67%	688	21.10%	98.29
3	Karlsruhe Inst Technol	4	9.52%	395	12.11%	98.75
4	Yokohama City Univ	4	9.52%	116	3.56%	29.00
5	Chinese Acad Agr Sci	4	9.52%	176	5.40%	44.00
6	Seoul Natl Univ	3	7.14%	171	5.24%	57.00
7	Natl Agr & Food Res Org	3	7.14%	77	2.36%	25.67
8	Univ Chinese Acad Sci	3	7.14%	218	6.69%	72.67
9	Inst for Basic Sci Korea	2	4.76%	111	3.40%	55.50
10	Univ Elect Sci & Technol China	2	4.76%	195	5.98%	97.50

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "CRISPR/Cas9 genome editing of agricultural organisms"

to the route of transmission. When the timelines of a single epidemic are examined, it can be seen that major infectious diseases are typical unexpected events which consist of the life cycle stages of onset, development, evolution, and decline. On this basis, the life cycle of a major infectious disease can be divided into the latent, escalation, outbreak, and termination periods. After a long period of latency, a major infectious disease infects animals, which causes the emergence of symptoms. This is followed by an escalation of the epidemic and a massive outbreak within a short period of time. To control an epidemic, measures such as culling, and disinfection are usually adopted. In the absence of new cases, an infectious disease will enter the subsequent stages of decline and termination. The transmission of an infectious

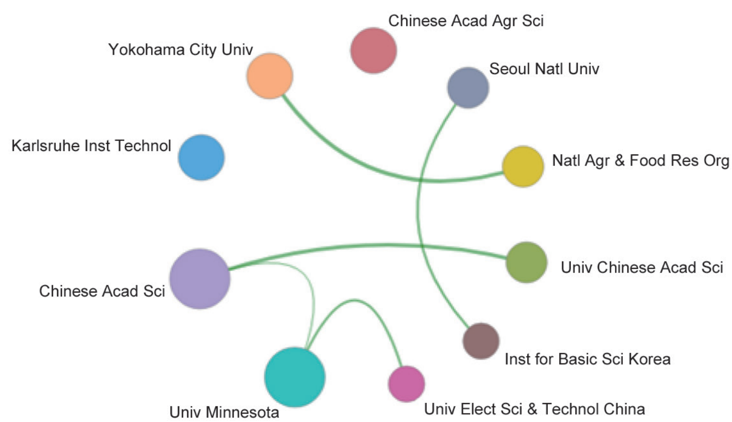

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “CRISPR/Cas9 genome editing of agricultural organisms”

Table 1.2.3 Countries or regions with the greatest output of citing papers on “CRISPR/Cas9 genome editing of agricultural organisms”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	419	30.17%	2017.2
2	USA	388	27.93%	2016.9
3	Germany	104	7.49%	2016.7
4	UK	93	6.70%	2017.1
5	Japan	78	5.62%	2017.0
6	India	70	5.04%	2017.2
7	Australia	68	4.90%	2017.4
8	France	58	4.18%	2017.2
9	Italy	43	3.10%	2017.0
10	Netherlands	34	2.45%	2017.6

Table 1.2.4 Institutions with the greatest output of citing papers on “CRISPR/Cas9 genome editing of agricultural organisms”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	100	23.15%	2017.1
2	Chinese Acad Agr Sci	65	15.05%	2017.3
3	Huazhong Agr Univ	52	12.04%	2017.3
4	Univ Chinese Acad Sci	43	9.95%	2017.3
5	China Agr Univ	34	7.87%	2017.3
6	Univ Minnesota	30	6.94%	2016.4
7	Karlsruhe Inst Technol	24	5.56%	2016.3
8	Iowa State Univ	23	5.32%	2016.8
9	Univ Calif Davis	21	4.86%	2017.0
10	South China Agr Univ	20	4.63%	2016.9

disease requires three elements, namely infection sources, transmission routes and susceptible populations. Infection sources refer to humans, animals or plants infected by the pathogens of the infectious disease. Besides surviving and reproducing within the bodies of infection sources, pathogens can also spread to the external environment through the movement of infection sources. Transmission routes are the processes by which pathogens infect humans or animals after being expelled from the infection sources. Both contagious and non-contagious infectious diseases can only infect animals by transmission through certain types of media. ASF is a highly contagious hemorrhagic viral disease caused by the ASF virus and has a mortality rate of up to 100%. Since the first report of the disease in 1921, it has primarily circulated within sub-Saharan Africa until the occurrence of an outbreak in Georgia in 2007. Subsequently, the epidemic spread to the entire Caucasus region, including Russia. In 2014, ASF spread to most countries in eastern Europe and showed initial signs of escalation. In China, the first ASF outbreak was reported in August 2018 and was followed by a rapid spread of the disease within the country. Consequently, the World Organization for Animal Health (OIE) listed ASF as a reportable animal disease. At present, there are no commercial vaccines available for ASF. BSE is a chronic death-causing neurodegenerative disease of cattle mainly characterized by the occurrence of spongiform lesions in the gray matter. The primary etiological agent of BSE is the prion, which is an infectious protein with the ability to self-replicate. Avian influenza, commonly known as bird flu, is an acute infectious disease. Although this virus mainly affects birds, it can also infect humans and has been listed as a Category A infectious disease by the OIE. The prevention and control of animal epidemics is fundamentally dependent on the research, development, and mass production of vaccines. As the protective effects of subunit, nucleic acid and viral vector vaccines are generally weak, the primary goal of researchers worldwide is the development of gene-deleted vaccines, which can provide complete protection.

From the distribution of papers by country or region, it can be seen that the main contributors of core papers were Brazil, the USA, Germany, and China (Table 1.2.5). The distribution of papers by research institution shows that the number of core papers and number of citations were the highest for Iowa State University (USA) and Boehringer Ingelheim Vetmedica, Inc. (Germany) (Table 1.2.6). The network diagram of collaborations among the major countries or regions indicates a close collaborative relationship between the USA and Brazil, while China had relatively fewer collaborations with other countries. From the network of collaborations among the various research institutions, it can be seen that the collaborations were mostly concentrated in two clusters: collaborations between US and Brazilian institutions, and collaborations between German and Polish institutions (Figures 1.2.3 and 1.2.4). Core paper citations were mainly contributed by China, Germany, and Brazil (Table 1.2.7). The average citation year of core paper was also relatively late, which is indicative of the strong developmental momentum of research in this field (Table 1.2.8).

1.2.3 Genomic selection breeding of crops

The GSB of crops refers to the construction of genomic technical tools for crop breeding through the combination of the latest results in functional genomic studies with state-of-the-art SNP chip technologies developed by international researchers. Through such methods, crop breeders can

Table 1.2.5 Countries or regions with the greatest output of core papers on “mechanisms, prevention, and control of animal epidemics”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Brazil	3	27.27%	18	11.76%	6.00
2	USA	3	27.27%	45	29.41%	15.00
3	Germany	3	27.27%	52	33.99%	17.33
4	China	2	18.18%	16	10.46%	8.00
5	Spain	1	9.09%	9	5.88%	9.00
6	Austria	1	9.09%	24	15.69%	24.00
7	Poland	1	9.09%	3	1.96%	3.00

Table 1.2.6 Institutions with the greatest output of core papers on “mechanisms, prevention, and control of animal epidemics”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Iowa State Univ	3	27.27%	45	29.41%	15.00
2	Boehringer Ingelheim Vetmed Inc	2	18.18%	40	26.14%	20.00
3	Sao Paulo State Univ Unesp	2	18.18%	11	7.19%	5.50
4	Vet Resources Inc	2	18.18%	11	7.19%	5.50
5	Univ Vet Med	2	18.18%	37	24.18%	18.50
6	Generalitat Catalunya	1	9.09%	9	5.88%	9.00
7	Inst Agrifood Res Tech	1	9.09%	9	5.88%	9.00
8	Univ Alabama Birmingham	1	9.09%	9	5.88%	9.00
9	Univ Autonoma Barcelona	1	9.09%	9	5.88%	9.00
10	Traunkreis Vet Clin	1	9.09%	24	15.69%	24.00

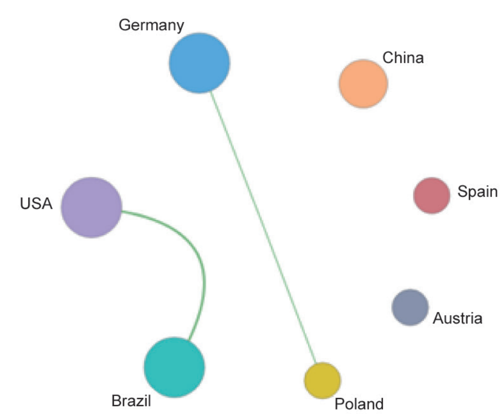

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “mechanisms, prevention, and control of animal epidemics”

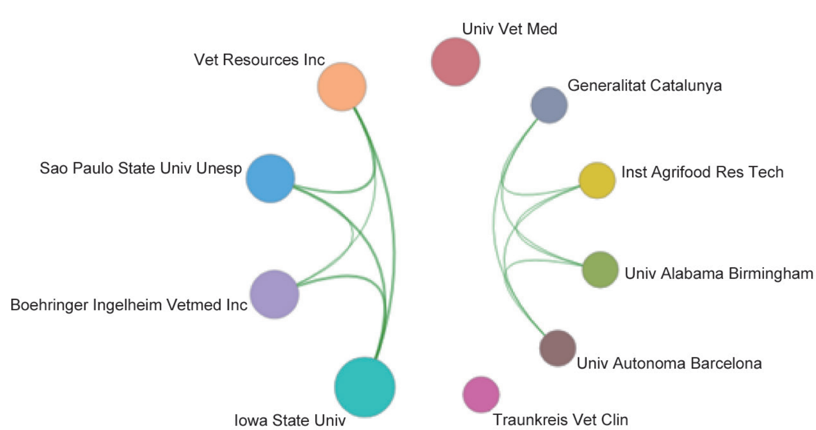

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “mechanisms, prevention, and control of animal epidemics”

Table 1.2.7 Countries or regions with the greatest output of citing papers on "mechanisms, prevention, and control of animal epidemics"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	14	25.93%	2018.0
2	Germany	12	22.22%	2017.3
3	Brazil	10	18.52%	2017.9
4	USA	5	9.26%	2017.6
5	Spain	4	7.41%	2017.8
6	Italy	2	3.70%	2017.5
7	Austria	2	3.70%	2017.0
8	Netherlands	2	3.70%	2017.0
9	Serbia	1	1.85%	2017.0
10	Taiwan of China	1	1.85%	2017.0

Table 1.2.8 Institutions with the greatest output of citing papers on "mechanisms, prevention, and control of animal epidemics"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Univ Vet Med	9	22.50%	2017.2
2	South China Agr Univ	6	15.00%	2017.7
3	Univ Vet Med Hannover	4	10.00%	2018.0
4	Sao Paulo State Univ Unesp	4	10.00%	2018.0
5	Univ Med Ctr Hamburg Eppendorf	3	7.50%	2017.3
6	Univ Autonoma Barcelona	3	7.50%	2017.7
7	Iowa State Univ	3	7.50%	2017.7
8	Heinrich Pette Inst	2	5.00%	2016.5
9	German Ctr Infect Res	2	5.00%	2018.5
10	Generalitat Catalunya	2	5.00%	2017.5

perform laboratory testing of the seeds or seedlings of crops, accurately identify and screen individuals with good genes, and predict trait expression in crops in the field. This enables the enhancement of the purposefulness and targetedness of breeding processes, and the accurate selection and consolidation of multiple suitable gene loci. Strains with the greatest potential in trait expression can then be selected for the breeding of new crop cultivars, thereby achieving the scientific control of the breeding process and providing a means for realizing the ultimate goal of designed breeding. Research has shown that chips for the genomic breeding of crops can be useful in germplasm diversity analysis, gene identification, gene mapping, the selection of genotypes as breeding materials and genetic fingerprinting of cultivars. In actual practice, a specific training group of crops can be designed for the collection of genotype data, phenotype data and related environmental factors (e.g., geographical differences, processing methods during testing and seasons), and specific model construction algorithms can be used to construct the training model, which calculates the breeding values of individuals or the contributions of each marker to the traits of the crop, as well as the predicted phenotype values of the test group. Model accuracy is usually assessed using the Pearson correlation coefficient between the predicted values and actual values. However, models constructed using the training group typically provide poor predictive effects in test groups, which may be caused by overfitting. The enhancement of the predictive ability of a model in the test group requires the screening of optimum model parameters and the use of cross-validation methods to assess the actual predictive ability of the model, followed by the prediction of target traits of all possible combinations by utilizing the genotype data and relevant information, such as environmental factors, provided by the test group, so as to achieve the purposes of prediction and screening.

The analysis of data on the relevant literature is as follows. From the distribution of papers by country or region (Table 1.2.9), it can be seen that the main contributors of core papers were Germany, the USA, and the Netherlands. An identical ranking was observed for the top three countries/regions with the highest number of paper citations. From the distribution of papers by research institution (Table 1.2.10), it can be seen that the Wageningen University and Research (the Netherlands), University of California, Davis (USA), and University of Paris-Saclay (France) shared the top spot. The network diagram of inter-country/regional collaborations (Figure 1.2.5) shows that inter-country collaborations were common, with close collaborative relationships existing among Germany, the USA, the Netherlands, and France. From the network diagram of collaborations among the major contributing institutions (Figure 1.2.6), it can be seen that collaborative relationships existed among all institutions. The main contributors of core paper citations were the USA and China (Table 1.2.11). From the list of the major core paper citation-contributing institutions (Table 1.2.12), it can be seen that the Chinese Academy of Sciences was far ahead of all other institutions. The average core paper citation year of these institutions was 2017.

Table 1.2.9 Countries or regions with the greatest output of core papers on “genomic selection breeding of crops”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Germany	4	66.67%	152	87.36%	38.00
2	USA	4	66.67%	132	75.86%	33.00
3	Netherlands	3	50.00%	115	66.09%	38.33
4	France	3	50.00%	47	27.01%	15.67
5	Australia	1	16.67%	85	48.85%	85.00
6	Saudi Arabia	1	16.67%	85	48.85%	85.00
7	Israel	1	16.67%	19	10.92%	19.00
8	Austria	1	16.67%	11	6.32%	11.00
9	Norway	1	16.67%	11	6.32%	11.00

Table 1.2.10 Institutions with the greatest output of core papers on “genomic selection breeding of crops”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Wageningen Univ & Res	2	33.33%	96	55.17%	48.00
2	Univ Calif Davis	2	33.33%	30	17.24%	15.00
3	Univ Paris Saclay	2	33.33%	36	20.69%	18.00
4	Brigham Young Univ	1	16.67%	85	48.85%	85.00
5	Christian Albrechts Univ Kiel	1	16.67%	85	48.85%	85.00
6	King Abdullah Univ Sci Tech	1	16.67%	85	48.85%	85.00
7	Univ Melbourne	1	16.67%	85	48.85%	85.00
8	Wageningen UR	1	16.67%	85	48.85%	85.00
9	Washington State Univ	1	16.67%	85	48.85%	85.00
10	Commissariat Energie Atom & Energies Alternat	1	16.67%	19	10.92%	19.00

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "genomic selection breeding of crops"

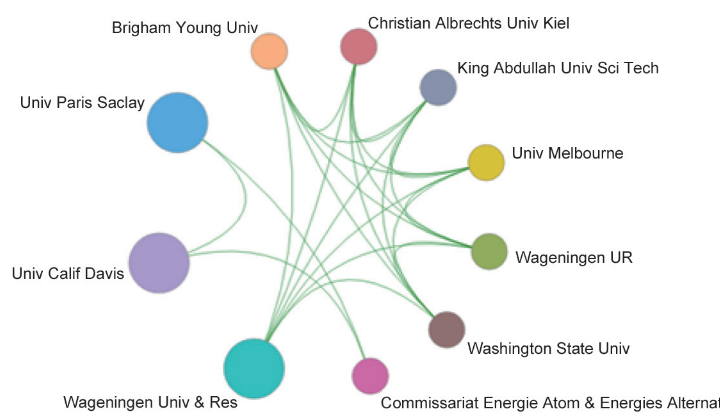

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "genomic selection breeding of crops"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "genomic selection breeding of crops"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	50	29.59%	2017.9
2	China	31	18.34%	2017.9
3	Australia	19	11.24%	2018.0
4	Germany	16	9.47%	2017.9
5	UK	12	7.10%	2018.1
6	France	9	5.33%	2017.9
7	Saudi Arabia	7	4.14%	2018.0
8	Netherlands	7	4.14%	2018.1
9	Denmark	6	3.55%	2017.5
10	South Korea	6	3.55%	2018.0

Table 1.2.12 Institutes with the greatest output of citing papers on “genomic selection breeding of crops”

No.	Institutions	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	12	21.43%	2017.9
2	Univ Copenhagen	5	8.93%	2017.4
3	Univ Illinois	5	8.93%	2017.8
4	Univ Calif Davis	5	8.93%	2017.6
5	Univ Paris Saclay	5	8.93%	2017.8
6	J Craig Venter Inst	4	7.14%	2018.0
7	Univ Tasmania	4	7.14%	2018.0
8	King Abdullah Univ Sci & Technol	4	7.14%	2017.8
9	Donald Danforth Plant Sci Ctr	4	7.14%	2018.0
10	Michigan State Univ	4	7.14%	2017.8

2 Engineering development fronts

2.1 Trends in the top 10 engineering development fronts

The top 10 engineering development fronts in the agriculture field can be classified into three categories: (1) Ground breaking development front. This includes “gene editing techniques for agricultural organisms” of agricultural bioengineering. (2) Emerging development fronts. These include “prevention and remediation of heavy metal pollution in soil” of resource ecology, “intelligent agricultural equipment” of agricultural engineering, “utilization of forest-produced biomass” of forestry science, and “crop DNA sequence and genome analysis” of crop science. (3) In-depth established development fronts. These include “sustainable plant protection technologies” of plant protection, “animal health management systems” of animal science, “selective breeding of new hybrid crop cultivars” of crop science, “precision cultivation technologies” of crop science, and “effective fry cultivation” of fisheries science.

The numbers of patent disclosures for these fields ranged from 100 to 300, the average number of citations of the patents were within the range 10 to 20, and the mean year of patent disclosure was 2014 (Table 2.1.1). In particular, the number of citations of patents related to gene editing techniques for agricultural organisms showed a rapid increase prior to 2017, which is opposite to the trends showed by patents related to other fronts (Table 2.1.2).

The top 10 engineering development fronts are briefly described below.

(1) Sustainable plant protection technologies

This is an in-depth established development front. Pesticide pollution refers to the excessive use of pesticides and the inappropriate selection of types and application timings of pesticides. Besides resulting in pesticide residue limits in agricultural products being exceeded and posing a serious threat to human health, pesticide pollution also eliminates certain predatory and parasitic natural enemies of crop pests, which upsets the natural balance between pests and their natural enemies, causes pest outbreaks and eliminates pollinating insects, ultimately affecting crop production. Moreover, excessive pesticide movement into soil and water bodies through rainfall, agricultural soil leachates and discharges causes damage to ecosystems and may also result in the development of resistance of pest to chemical pesticides. In view of these issues, the adoption of sustainable control techniques are being encouraged. These are environmentally-friendly agricultural techniques that utilize a combination of biological, physical, agricultural prevention and treatment techniques, and scientific fertilizer application methods for disease and pest prevention and control in crops.

(2) Gene editing techniques for agricultural organisms

This is a groud breaking development front. Gene editing techniques refer to techniques that perform site-specific modifications or changes to the genome and transcriptional products of organisms. Since the early 2000s, genome editing techniques have developed rapidly and led to the successive

Table 2.1.1 Top 10 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Sustainable plant protection technologies	225	3129	13.91	2014.8
2	Gene editing techniques for agricultural organisms	198	3301	16.67	2015.9
3	Prevention and remediation of heavy metal pollution in soil	178	1927	10.83	2014.4
4	Intelligent agricultural equipment	106	1382	13.04	2014.7
5	Utilization of forest-produced biomass	122	1343	11.01	2014.4
6	Animal health management systems	121	2517	20.80	2014.5
7	Effective fry cultivation	131	689	5.26	2014.2
8	Selective breeding of new hybrid crop cultivars	269	4330	16.10	2014.5
9	Precision cultivation technologies	102	1659	16.26	2014.3
10	Crop DNA sequence and genome analysis	246	5158	20.97	2014.6

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in agriculture

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Sustainable plant protection technologies	59	50	32	45	35	4
2	Gene editing techniques for agricultural organisms	8	19	37	63	70	1
3	Prevention and remediation of heavy metal pollution in soil	48	46	56	20	7	1
4	Intelligent agricultural equipment	25	22	28	19	11	1
5	Utilization of forest-produced biomass	36	38	27	11	10	0
6	Animal health management systems	41	28	20	20	11	1
7	Effective fry cultivation	42	36	44	9	0	0
8	Selective breeding of new hybrid crop cultivars	75	61	65	50	17	1
9	Precision cultivation technologies	41	24	17	11	7	2
10	Crop DNA sequence and genome analysis	65	67	50	39	21	4

emergence of four novel genome editing tools, namely ZFNs, TALENs, MGNs, and CRISPR/Cas9. Genome editing techniques enable accurate, targeted modifications of specific sites in the genome of organisms, and artificial alterations of genetic information. In particular, the CRISPR/Cas9 system developed in 2013 is a novel technique that enables targeted gene editing. It possesses several advantages over other genome editing tools, including greater ease of operation, lower cost, higher efficiency, and higher targeting accuracy, and has demonstrated great potential in the fields of basic biological research, gene therapy, and genetic modification. Notably, TALENs and CRISPR/Cas9 were listed among the *Science* magazine top 10 scientific breakthroughs of 2012 and 2013, respectively.

(3) Prevention and remediation of heavy metal pollution in soil

This is an emerging development front. Heavy metal pollution of agricultural crops, which directly impacts agricultural production, food security and environments essential for human survival, has become one of the major ecological environmental issues faced by countries worldwide. Heavy metals have a density of at least 4.5 $g \cdot cm^{-3}$ and include arsenic (a metalloid), cadmium, chromium, lead, and mercury. Environmental pollution caused by heavy metals or heavy metal compounds is known as heavy metal pollution, which largely arises from human activities, such as mining, exhaust emissions, sewage irrigation and the use of products with heavy metal content that exceed regulatory limits. In particular, heavy metal pollution in agricultural land is highly elusive. As heavy metals have high toxicities, complex chemical behaviors, adverse ecological effects and extended persistence in soil, they can be absorbed by crops, which leads to their entry into food chains, or migration into water bodies and the atmosphere, thereby posing a severe threat to the survival and sustainable development of human populations. The prevention and remediation of heavy metal pollution in soil produces certain effects on the growth, development, yield, quality, and physiological and biochemical metabolic pathways of crops. There are two main types of heavy metal remediation techniques, with the first being the direct removal of heavy metal-polluted soil and the second being the alteration of the forms in which heavy metals exist in soil to reduce their activity, transferability and bioavailability. At present, remediation methods for heavy metal-polluted soils include physical, chemical, electrochemical and biological remediation. As the heavy metal pollution of agricultural land adversely affects ecological environments, food security and limits agricultural development, it has attracted widespread attention and substantial research efforts in relevant fields, such as environmental science.

(4) Intelligent agricultural equipment

This is an emerging development front. Intelligent agricultural equipment, which were developed based on a combination of advanced manufacturing technologies, information technologies, and artificial intelligence technologies, are important tools in the upgrade and modification of the current agricultural machinery manufacturing industry and the realization of the automation and intelligentization of agricultural production processes. Therefore, they represent a major direction in the development of high-end agricultural equipment manufacturing industries around the world. At present, the focus areas in the intelligentization of control technologies for agricultural equipment are: 1) the in-depth investigation of informatization technologies such as transducers/sensors, communication systems, image processing and computer visuals, as well as the broadening of applications of these technologies, such as the use of transducers/sensors in the control of vehicle steering, the use of level control in the raising and lowering of ground operation parts of vehicles, and the electrohydraulic control of vehicle position and pressure; 2) image sensor monitoring systems based on plant/crop characteristics and the ripeness of agricultural products such as fruits and vegetables, and thinning and weed removal devices with a combination of image processing and visual sensing functions (automated visual monitoring systems); and 3) collaborative control of harvesters and grain carts in multi-machine collaborative operations through the use of visual and image processing technologies (stereo vision systems), including the radio control of harvester loads from granaries, grain conveying controllers that can control conveying speeds, and the improvement of the threshing mechanism of harvesters and performance of grain collectors. Besides satisfying the different levels of current needs for agricultural equipment, future research on intelligent agricultural equipment will mainly be focused on the digital design and simulation systems of intelligent agricultural equipment, testing platforms of intelligent equipment, microelectromechanical systems, agricultural transducers/sensors, agricultural robots, intelligent navigation control technologies and the integration of advanced technologies, such as the IoT, big data, cloud computing, and cloud services, into the design of intelligent agricultural equipment.

(5) Utilization of forest-produced biomass

This is an emerging development front. There are two main sources of utilizable raw materials in forestry biomass: 1) solid biofuels mainly originating from waste materials of the forestry processing industries, such as the wood panel industry and paper industry; and 2) energy forests established based on the development layout of the biomass energy industry, in which trees with fast growing rates, high calorific values and high oil content are grown to ensure a steady production and supply of raw materials. At present, biomass energy development technologies are mainly concentrated in the areas of gasification, compressed fuels, combustion for power generation, the production of ethanol fuel and the production of biodiesel. In particular, the technologies of gasified biomass fuel production and biomass compression are relatively mature and are considered part of established research. High-efficiency direct combustion for power generation, which is regarded as the most feasible biomass utilization method, represents a key direction in future research.

(6) Animal health management systems

This is an in-depth established development front. Healthy breeding practices provide assurance of animal health, enhanced animal productivity and animal product safety. Animal health management is a key link in the promotion of animal health. It includes the monitoring and assessment of animal health for the timely discovery of poor health in animals, and the identification and resolution of factors affecting animal health including breeding, nutrition, disease, environment and production, so as to ensure the health of domestic animals. Animal health management is usually manifested by the establishment of a scientific and reasonable animal health management system by combining the current theories and data of the various links in animal breeding with knowledge discovery and data mining methods. In general, animal health management systems mainly encompass health assessment criteria, health promotion methods, disease diagnosis knowledge, disease prevention and treatment methods, veterinary drug compatibility knowledge, and criteria for the use of veterinary drugs. In recent years, traceability information systems for animal production and animal products have developed rapidly. Through the utilization of technologies, such as network communication, QR codes, radio-frequency identification, embedded equipment, smart cards and databases, the various links of animal breeding, including production sites, production processes, feed formulas, immunity, post-slaughter quarantines and product circulation, can be strengthened. The main business data of animals and animal products are then recorded and tracked throughout the entire animal production process for the achievement of whole-process monitoring and tracking management, starting from ear tag manufacturing to ear tag allocation, animal breeding, circulation, and finally to the slaughtering and sale of animal products. The application of 5G-enabled IoT will further enhance the animal health management and product service systems of large-scale animal breeding.

(7) Effective fry cultivation

This is an in-depth established development front. Developments in the proliferation and breeding of marine fishes are the fundamental measures and strategies for the reasonable development and utilization of marine fish resources and sustainable development of the fisheries industry. Besides adequate pre-cultivation preparations, reasonable fry stocking, suitable rearing methods and appropriate daily management, effective fry cultivation may also involve the adoption of the latest biological technologies and methods to achieve cutting-edge development. Novel technologies are mainly focused on the induction of gonadal development and maturation, improvement of oocyte quality, ovulation and spawning, advancement of the timings of sexual maturity and sex change, regulation of marine cultivated fishes to enable all-year-round gonadal development, gonadal maturation and spawning, improvement of fry cultivation to enhance survival and growth rates, and adoption of genetic engineering technologies to produce various hormones and neuropeptides that promote fish reproduction and growth. Specific techniques include the construction of detailed whole-genome maps of target genotypes, sex control techniques, technologies for the scaled-up production of triploids, and establishment of unisexual sperm banks. In addition, technologies for the production of hyperestrogenic fry, cultivation of high-yield and disease-resistant genotypes, sex control, and crossbreeding have also been utilized for the cultivation of new genotypes of aquatic organisms.

(8) Selective breeding of new hybrid crop cultivars

This is an in-depth established development front. An inbred line of a certain crop refers to a population with identical traits produced from the continuous inbreeding of a single strain. Heterosis achieved from the crossing of inbred lines with high combining ability provides a key route for the substantial enhancement of crop yield, improvement of crop quality, strengthening of stress resistance, and increase in crop adaptability. With the rapid development of cell biology and molecular biology, parent plant selection by plant breeders does not only involve considerations regarding the complementation of agronomic trait advantages, closeness of relationships, combining ability, heritability and resistance, but also involves the screening of parent plants by utilizing genomic in-situ hybridization and molecular marker techniques. By combining genome sequencing techniques with trackable and detectable molecular markers closely linked to the target genes in the genome (e.g., RFLPs, RAPDs, AFLPs, SSRs and SNPs), the efficiency of parental material recombination and screening can be enhanced. The investigation and utilization of target traits at the molecular level by plant breeders also increases the accuracy of breeding value prediction and heterosis effects. Major directions in basic research on the utilization of heterosis are: 1) methods to achieve maximum development and the utilization of heterosis through the use of germplasm resources; 2) in-depth investigation of heterotic populations and the identification of heterotic populations at the molecular level; 3) screening of heterosis related to yield factors for the identification of

QTL; and 4) investigation of populations suitable for heterosis breeding.

(9) Precision cultivation technologies

This is an in-depth established development front. Past agricultural development has mainly been dependent on human labor and has many disadvantages, including long duration, high costs and low efficiency. With advancements in scientific technologies, precision cultivation technologies have emerged and have developed steadily. Such technologies, which have propelled agriculture into the digital and information age, accelerated crop cultivation processes, and reduced the consumption of manpower and material resources, represent a key direction of agriculture development in the twenty-first century. In intelligent precision cultivation technology systems for production regions, greenhouses or plant factories, precision cultivation IoT systems are established to enable the acquisition of big data and characteristic nodule videos of monitored parameters through real-time, whole-process periodic comparisons for the monitoring of cultivation and construction of parameter models for precision cultivation control. Real-time sensor-based monitoring and the processes control parameter iteration are used to construct intelligent expert systems and achieve the purpose of intelligentized precision cultivation. The precision crop cultivation IoT system consists of four major components, namely, on-site infrastructure, equipment monitoring and control, data transfer and storage, and cloud computing platform application and management. It contributes to the achievement of agricultural production under the conditions of intelligent agriculture. The adoption of these novel technologies can effectively reduce labor intensity, enhance production efficiency, and increase crop quality and yields.

(10) Crop DNA sequence and genome analysis

This is an emerging development front. Crop DNA sequence and genome analysis is a basic research area for the realization of transgenic crop breeding, genomic selection breeding of crops, and molecular design breeding. At present, the commonly used technologies are DNA microarrays and massively parallel signature sequencing; other techniques include the serial analysis of gene expression and digital gene expression profiling by expressed sequence tag sequencing. Continuously evolving genome analysis methods facilitates the rapid development of molecular breeding technologies for crops and mainly serve the following roles. 1) The testing of new transgenic cultivars, i.e., the utilization of modern biological technologies for the artificial isolation, recombination, introduction, and integration of desired target genes into the genome of organisms, so as to improve the original traits or confer new superior traits to the organisms. Besides introducing new exogenous genes, transgenic technologies can also be used to alter the genetic characteristics of organisms through methods such as gene processing, gene knockout and genetic screening to obtain the desired traits. 2) In-depth analyses of gene expression profiles, which are beneficial toward the elucidation of molecular mechanisms of heterosis formation.

2.2 Interpretations for three key engineering development fronts

2.2.1 Sustainable plant protection technologies

Research on plant protection is currently directed toward the development of safe, sustainable and environment-protecting technologies. Novel plant protection technologies include ecological comprehensive prevention and control technologies; prevention and control measures for harmful organisms; innovations in immunoregulators for plants; and the development, management, and application of environmentally-friendly pesticides. (1) Ecological regulation measures that are mainly adopted from a macroscopic perspective and include the selective breeding and promotion of disease and pest-resistant cultivars, optimization of crop layouts, breeding of healthy seed and seedlings, and improvement of water and fertilizer management. These measures are combined with biodiversity regulation techniques and methods for the protection and utilization of natural enemies of pests, such as farmland eco-engineering, grass covers in orchards, intercropping, and natural enemy-trapping belts, so as to modify the sources and breeding environments of diseases and pests and artificially strengthen natural pest control properties as well as disease and pest resistance in crops. (2) Biological prevention and control techniques developed that promote the application of crop protection agents, such as *Trichogramma*, predatory mites, *Metarhizium* spp., *Beauveria* spp., microsporidia, *Bacillus thuringiensis*, *Bacillus cereus*, *Bacillus subtilis* and nucleopolyhedrosis virus, as well as mature techniques such as poultry herding and rice–duck/rice–shrimp co-culture systems, key biological prevention and control techniques that involve pest control using pests, mite control using predatory mites, pest control using fungi, and fungi control using fungi. Biological prevention and control techniques also include the active development of application techniques for biological and biochemical formulations, such as botanical pesticides, agricultural antibiotics, and plant immunity inducers. (3) Physicochemical trapping techniques actively developed that use and promote insect pheromones (e.g., sex attractants and acrasin), insect light traps and sticky insect traps (yellow and blue) for the control of pests on crops such as vegetables, fruit trees, and tea plants, other physicochemical trapping techniques, such as plant traps, bait traps, insect-shielding nets, and pest-repelling silver-gray film. (4) Scientific pesticide use techniques that emphasize the following areas: the development and application of effective, low-toxicity, low-residue, environmentally-friendly pesticides; optimization and integration of supporting techniques, such as pesticide rotations, pesticide alternations, and precise and safe pesticide usage methods; strengthening of pesticide resistance monitoring and management; promulgation and standardization of knowledge on pesticide use; and strict adherence to safety intervals for pesticide use. Effective, low-risk pesticides must possess a high activity toward target organisms; low dose per unit area; show non-toxicity toward crops, humans, livestock, and beneficial organisms; and exhibit good biodegradability with nontoxic degradation products.

The major contributing countries/regions of patent disclosures for this focal point were Japan, Germany, the USA, China, and Switzerland (Table 2.2.1). In particular, the number of citations of Japanese patents exceeded the total combined number of citations for Germany, the USA, China and Switzerland with the average number of citations of Japanese patents being 20.54, i.e., around twofold the number of patent citations for other countries or regions. Among the major institutions with the greatest output of core patents (Table 2.2.2), Bayer Cropscience AG of Germany had contributed a significant number of published patents, while the Sumitomo Chemical Co., Ltd. of Japan shows the most citations per patent among the institutions. Other than between Japan and the UK, collaborative relationships for this engineering development front could be found among the major countries and regions (Figure 2.2.1). There were rare collaborations between major institutions (Figure 2.2.2).

2.2.2 Gene editing techniques for agricultural organisms

Gene editing techniques refer to techniques that perform site-specific modifications or changes to the genome and transcriptional products of organisms. Such techniques involve the cutting of genomic DNA at specific sites by restriction endonucleases to generate DSBs. This induces DNA repair via NHEJ or homology-directed repair (HDR), which are major DNA repair mechanisms, thereby achieving the genetic modification of target genes. NHEJ is the main pathway of DNA repair in prokaryotic genomes. It enables the religation of broken DNA ends with or without limited homologous sequences. However, as NHEJ is an error-prone mechanism,

Table 2.2.1 Countries or regions with the greatest output of core patents on “sustainable plant protection technologies”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	74	32.89%	1520	48.58%	20.54
2	Germany	58	25.78%	578	18.47%	9.97
3	USA	40	17.78%	438	14.00%	10.95
4	China	32	14.22%	318	10.16%	9.94
5	Switzerland	15	6.67%	139	4.44%	9.27
6	UK	3	1.33%	123	3.93%	41.00
7	France	2	0.89%	23	0.74%	11.50
8	Netherlands	2	0.89%	12	0.38%	6.00
9	India	1	0.44%	12	0.38%	12.00
10	Belgium	1	0.44%	7	0.22%	7.00

Table 2.2.2 Institutions with the greatest output of core patents on "sustainable plant protection technologies"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	FARB	Germany	52	23.11%	530	16.94%	10.19
2	SUMO	Japan	24	10.67%	748	23.91%	31.17
3	DOWC	USA	24	10.67%	340	10.87%	14.17
4	SYGN	Switzerland	16	7.11%	252	8.05%	15.75
5	NIPY	Japan	16	7.11%	201	6.42%	12.56
6	NISC	Japan	13	5.78%	349	11.15%	26.85
7	BADI	Germany	8	3.56%	68	2.17%	8.50
8	SNCM	China	7	3.11%	52	1.66%	7.43
9	NIPS	Japan	7	3.11%	46	1.47%	6.57
10	SNFI	China	5	2.22%	35	1.12%	7.00

FARB: Bayer Cropscience AG; SUMO: Sumitomo Chemical Co., Ltd.; DOWC: Dow Agrosciences LLC; SYGN: Syngenta Participations AG; NIPY: Nihon Nohyaku Co., Ltd.; NISC: Nissan Chemical Industries Ltd.; BADI: BASF SE; SNCM: Sinochem Agro Co., Ltd.; NIPS: Nippon Soda Co., Ltd.; SNFI: Merial Inc.

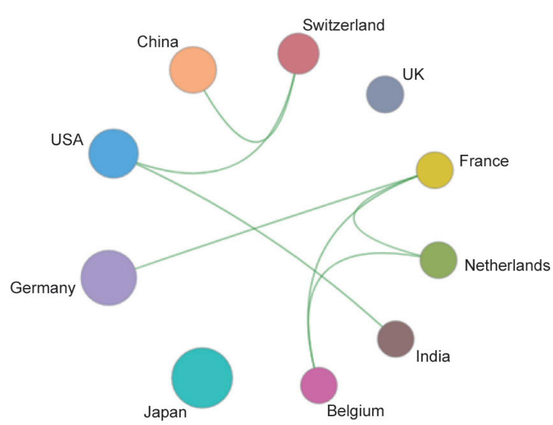

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "sustainable plant protection technologies"

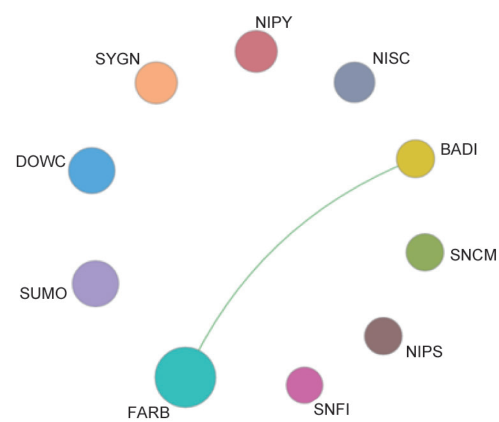

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "sustainable plant protection technologies"

and nucleotide insertions/deletions commonly occur during the repair process, causing frameshift mutations which lead to the achievement of gene knockout. In the presence of homologous sequences, the probability of HDR occurring at DSBs is increased. The HDR pathway enables the achievement of site-specific gene editing or gene knockin through the replacement or recombination of homologous DNA at DSBs for the recovery or alteration of genetic information. Both NHEJ and HDR are dependent on the generation of DSBs; however, naturally occurring DSBs are extremely rare in genomes. Therefore, the key issue in genetic editing in animals is the induction of DSBs at specific sites. Novel genome editing techniques, such as ZFNs, TALENs, MGNs, and the CRISPR/Cas9 system, enable the targeted cutting of genomes for the generation of DSBs, which triggers DNA repair in cells by NHEJ or HDR, and ultimately achieves effective and accurate genome editing in various types of organisms.

The major contributing countries of patent disclosures for this focal point were the USA and China (Table 2.2.3), with the number of patent citations being substantially higher for US patents than other patents. Although relatively few patent disclosures were contributed by Lithuania, Germany, France, Switzerland and the UK, the proportions of patent citations were relatively high for these countries. The average number of citations of US patents was 23, which was threefold the number of citations for Chinese patents. It was also observed that a close collaborative relationship existed between the USA and Switzerland (Figure 2.2.3). From the distribution of core patents among the various organizations (Table 2.2.4), it can be seen that the Harvard University, Massachusetts Institute of Technology, and Broad Institute (USA) occupied the top three spots. Notably, among the patents related to genome editing techniques, the number of applications for CRISPR/Cas9 patents was substantially higher than that of patents related to ZFNs, TALENs, and MGNs, and the patent applications for these techniques mainly pertained to the applied use of the techniques. These three US organizations have collaborated closely to promote the wide application of genome editing techniques in the field of biomedical research (Figure 2.2.4). In the fields of animal improvement and agricultural crop research, the number of Chinese patents has increased at a relatively high rate. China Agricultural University has contributed a great number of patents on animal breeding-related gene editing techniques, which have focused on the development and utilization of pig, goat, and cattle disease models. Other Chinese institutions, including the Institute of Genetic and Developmental Biology, China Academy of Sciences, and Chinese Academy of Agricultural Sciences, have filed a great number of patent applications related to the genetic breeding of agricultural crops.

Table 2.2.3 Countries or regions with the greatest output of core patents on “gene editing techniques for agricultural organisms”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	90	45.45%	2095	63.47%	23.28
2	China	79	39.90%	623	18.87%	7.89
3	Germany	6	3.03%	104	3.15%	17.33
4	Japan	5	2.53%	40	1.21%	8.00
5	France	4	2.02%	94	2.85%	23.50
6	Switzerland	4	2.02%	74	2.24%	18.50
7	Lithuania	3	1.52%	331	10.03%	110.33
8	South Korea	3	1.52%	37	1.12%	12.33
9	UK	2	1.01%	69	2.09%	34.50
10	Netherlands	2	1.01%	24	0.73%	12.00

Table 2.2.4 Institutions with the greatest output of core patents on “gene editing techniques for agricultural organisms”

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	HARD	USA	17	8.59%	475	14.39%	27.94
2	MASI	USA	10	5.05%	501	15.18%	50.10
3	BROD	USA	7	3.54%	451	13.66%	64.43
4	SPHS	China	7	3.54%	55	1.67%	7.86
5	REGC	USA	6	3.03%	94	2.85%	15.67
6	AGIL	USA	5	2.53%	54	1.64%	10.80
7	CARI	USA	4	2.02%	169	5.12%	42.25
8	ALNY	USA	4	2.02%	74	2.24%	18.50
9	UCAG	China	4	2.02%	53	1.61%	13.25
10	WHED	USA	4	2.02%	47	1.42%	11.75

HARD: Harvard College; MASI: Massachusetts Institute of Technology; BROD: Broad Institute, Inc.; SPHS: 2nd People’s Hospital of Shenzhen; REGC: University of California; AGIL: Agilent Technologies, Inc.; CARI: Caribou Biosciences, Inc.; ALNY: Alnylam Pharmaceuticals, Inc.; UCAG: China Agricultural University; WHED: Whitehead Institute for Biomedical Research.

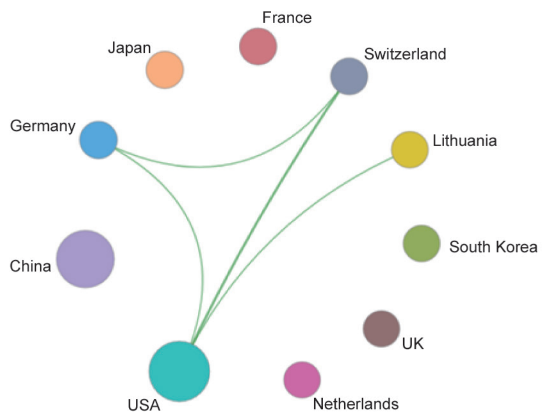

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "gene editing techniques for agricultural organisms"

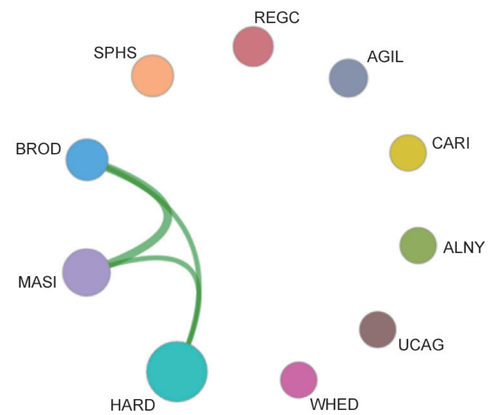

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "gene editing techniques for agricultural organisms"

2.2.3 Prevention and remediation of heavy metal pollution in soil

Heavy metal pollution in soil directly impacts crop growth and development, thereby affecting yield formation in crops and agricultural products. It is characterized by the poor mobility and extended persistence of pollutants in soil, as well as elusiveness and irreversibility. Heavy metal pollutants may also enter the human food chain through crops and could severely impact food safety and human health. In many countries and regions, such as the USA, the EU, Japan, and China, active deployment and research efforts have been devoted toward the development of remediation technologies for soils with heavy metal pollution. At present, the key methods for the remediation of heavy metals in soil include biological, physical, and chemical remediation, and various combinations of these. Japanese-sponsored research projects on soil pollution remediation have mainly focused on measurement methods for heavy metal pollutants in soil, soil remediation technologies (biological and chemical), soil remediation mechanisms, and assessments of the environmental impacts of soil pollution. To tackle the increasingly severe issue of heavy metal pollution, South Korea has devoted greater effort to the development of soil washing and electrokinetic remediation technologies. In Taiwan, China, in-situ combined remediation technologies have mainly been adopted in recent years. The USA holds the leading position in the application of remediation technologies in polluted sites, with projects of the Superfund program mostly employing in-situ soil vapor extraction, ex-situ solidification/stabilization and ex-situ incineration technologies. In the EU, the most common method of soil remediation is the excavation and landfill disposal of polluted soil. With increases in the costs of supervising landfill operations and other related costs, enhancements in ex-situ remediation technologies and the combined use of in-situ and ex-situ remediation technologies and pollution remediation methods have been made. In summary, there are two main types of remediation technologies for heavy metal pollution, with the first being the direct removal of heavy metal-polluted soil and the second being the alteration of the forms in which heavy metals exist in soil to reduce their activity, transferability and bioavailability. The specific remediation technologies can be further classified as (1) in-situ stabilization technologies, including in-situ chemical passivation, microbial adsorption, and plant fixation; (2) engineering remediation technologies, including phytoremediation, soil replacement, dilution by deep soil mixing, and soil washing; (3) agricultural control measures, including water and fertilizer management, the regulation of soil pH, and intercropping; and (4) plant prevention and control technologies, including the physiological prevention and control by plant foliage, application of low-absorption crop genotypes, genetic engineering, and adjustment of crop planting structures.

China accounted for the vast majority of patent disclosures for this focal point, while the USA and Japan have also contributed certain proportions of disclosures. Only seven countries have disclosed relevant patents. Although China has contributed a large number of patents, the average number of citations of Chinese patents was only about half that of US patents (Table 2.2.5). From the distribution of core patents among various organizations, it can be seen that Suntime Environmental Remediation Co., Ltd. in Jiangsu, China had contributed a significant number of patents, while the distribution of patents among organizations of other countries was relatively sparse (Table 2.2.6). The network diagrams of inter-country/regional collaborations and inter-organization collaborations indicate the absence of collaborations in the development of relevant patents (Figures 2.2.5 and 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents on "prevention and remediation of heavy metal pollution in soil"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	154	86.52%	1592	82.62%	10.34
2	USA	12	6.74%	226	11.73%	18.83
3	Japan	7	3.93%	69	3.58%	9.86
4	South Korea	2	1.12%	12	0.62%	6.00
5	Australia	1	0.56%	14	0.73%	14.00
6	Italy	1	0.56%	8	0.42%	8.00
7	Netherlands	1	0.56%	6	0.31%	6.00

Table 2.2.6 Institutions with the greatest output of core patents on "prevention and remediation of heavy metal pollution in soil"

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CAEM	China	4	2.25%	46	2.39%	11.50
2	USCU	China	3	1.69%	56	2.91%	18.67
3	JIAN	China	3	1.69%	52	2.70%	17.33
4	UYJN	China	3	1.69%	42	2.18%	14.00
5	UYHD	China	3	1.69%	40	2.08%	13.33
6	CRSM	China	3	1.69%	35	1.82%	11.67
7	UYGU	China	3	1.69%	34	1.76%	11.33
8	USJT	China	3	1.69%	33	1.71%	11.00
9	UYHU	China	3	1.69%	24	1.25%	8.00
10	CHAN	China	2	1.12%	33	1.71%	16.50

CAEM: Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences; USCU: Sichuan University; JIAN: Jiangsu Suntime Environmental Remediation Co., Ltd.; UYJN: Jiangnan University; UYHD: North China Electric Power University; CRSM: Institute of Rock and Soil Mechanics, Chinese Academy of Sciences; UYGU: Guangxi University; USJT: Shanghai Jiaotong University; UYHU: Hunan University; CHAN: Changsha Hasky Environmental Protection Science and Technology Development Co., Ltd.

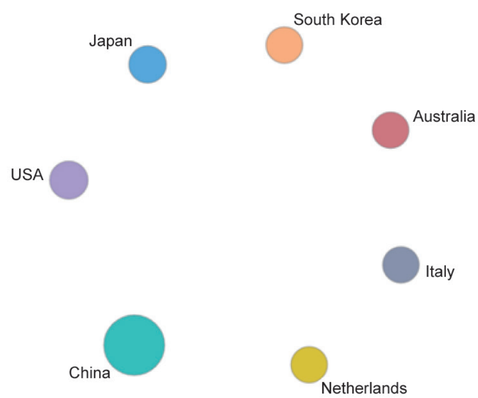

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "prevention and remediation of heavy metal pollution in soil"

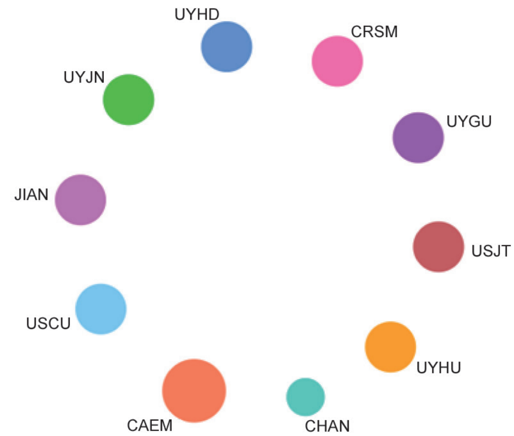

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "prevention and remediation of heavy metal pollution in soil"

Participants of the Field Group

Leaders

KANG Shaozhong, ZHANG Fusuo

Other Members

ZHAO Yaofeng, LI Long, HUANG Haitao, JIAO Xu, LIANG Zhenzhen, WEN Danyan, XU Jianxiang,

YUAN Wenye, LI Chenying, SHI Lijuan, LIU Ziyu, LIU Yingchun, LV Xiaomei, YANG Aidong, WANG Yan, QIN Mei, XING Lu, ZHAO Jie, YAO Yingkun, LI Yunzhou

Report Writers

KANG Shaozhong, ZHANG Fusuo, YUAN Wenye, LI Chenying, SHI Lijuan, XU Jianxiang, ZHAO Jie, LIU Yingchun, LV Xiaomei, YANG Aidong, WANG Yan, QIN Mei, XING Lu

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VIII. Medicine and Health

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

This review describes the top 10 engineering research fronts in the field of medicine and health, which includes the areas of basic medicine, clinical medicine, medical informatics and biomedical engineering, pharmacy, public health, and preventive medicine. These 10 fronts are "artificial intelligence (AI) in biomedicine," "gut microbiota and immune homeostasis," "neural computation and brain-inspired intelligence in the brain sciences," "organoids-on-a-chip and its biomedical applications," "tumor immunotherapy," "personalized tumor therapeutic vaccines," "application of stem cells in regenerative medicine," "metabolic heterogeneity and interactions in tumor microenvironments," "precise diagnosis of diseases based on single-cell sequencing," and "application and research of 3D printing technology in regenerative medicine" (Table 1.1.1). The numbers of core papers on these frontiers published between 2014 and 2018 are listed in Table 1.1.2.

(1) AI in biomedicine

AI is a technical science used to simulate and extend the theory, methods, techniques, and applications of human intelligence. The application of AI in biomedicine can increase accuracy and safety in a range of biomedical fields, such as health screening and warning, disease diagnosis and treatment, rehabilitation training and evaluation, medical services and management, drug screening and evaluation, and gene sequencing and characterization. These fields are all driven by medical data, including images, atlases, medical records, and other medical information sources, which can be processed by AI in various applications. For example, in health screening and warning, these applications include disease screening, chronic disease management, and wearable health monitoring devices. In disease diagnosis and treatment, AI can be applied to automatic lesion recognition, intelligent treatment decision-making, scientific evaluation of curative effects, robotic assisted surgery, and remote surgery. Rehabilitation training and evaluation applications involve cognitive impairment rehabilitation, disability and rehabilitation, robotic care, intelligent prostheses, and orthoses (including assistive exoskeleton devices). Applications in medical services and management include electronic medical record management, intelligent automatic drug delivery, and medical Internet of Things (IoT) services. Drug screening and evaluation can utilize AI in drug target identification, drug screening, drug efficacy tests, drug

Table 1.1.1 Top 10 engineering research fronts in medicine and health

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	AI in biomedicine	670	33 946	50.67	2015.4
2	Gut microbiota and immune homeostasis	63	7 550	119.84	2015.1
3	Neural computation and brain-inspired intelligence in the brain sciences	300	21 173	70.58	2015.3
4	Organoids-on-a-chip and its biomedical applications	20	2 111	105.55	2016.2
5	Tumor immunotherapy	610	159 484	261.45	2015.4
6	Personalized tumor therapeutic vaccines	139	12 063	86.78	2016.1
7	Application of stem cells in regenerative medicine	957	62 555	65.37	2014.9
8	Metabolic heterogeneity and interactions in tumor microenvironments	123	10 501	85.37	2015.4
9	Precise diagnosis of diseases based on single-cell sequencing	32	6 782	211.94	2015.6
10	Application and research of 3D printing technology in regenerative medicine	208	14 259	68.55	2015.4

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in medicine and health

No.	Engineering research front	2014	2015	2016	2017	2018
1	AI in biomedicine	222	165	135	102	46
2	Gut microbiota and immune homeostasis	27	12	17	6	1
3	Neural computation and brain-inspired intelligence in the brain sciences	98	80	60	48	14
4	Organoids-on-a-chip and its biomedical applications	1	3	10	4	2
5	Tumor immunotherapy	189	157	127	99	38
6	Personalized tumor therapeutic vaccines	9	32	49	34	15
7	Application of stem cells in regenerative medicine	414	276	181	81	5
8	Metabolic heterogeneity and interactions in tumor microenvironments	36	29	36	19	3
9	Precise diagnosis of diseases based on single-cell sequencing	9	8	5	7	3
10	Application and research of 3D printing technology in regenerative medicine	35	84	58	30	1

safety evaluation, and adverse reaction data management. Finally, applications in the field of gene sequencing and characterization include gene screening, genome sequencing, gene editing, and individualized medical treatment. The application of AI in biomedicine is changing the approach of modern biomedical development. On the one hand, AI can benefit the whole medical process, including intelligent management of disease pathogenesis, precise diagnosis, safe treatment, and scientific evaluation. This has the result of significantly improving the professional efficiency of doctors, alleviating the shortage of doctors, improving the accuracy of diagnosis and treatment, and optimizing the allocation of high-quality medical resources. On the other hand, AI systems can enable real-time health monitoring and warning, and the rapid development of medical IoT, medical health hardware, and wearable health devices. Overall, the application of AI in biomedicine can aid innovation in medical technology and enable healthcare to progress to a new stage of quantitative analysis.

(2) Gut microbiota and immune homeostasis

The discovery of the important physiological function of human microbiota has subverted our understanding of human health and survival. In recent years, multiple studies have revealed the scale and complexity of microbial communities inhabiting the body surface and coelomic cavities of humans (over 10^{14} cells of bacteria, archaea, fungi, and viruses, dry weight approximately 1%–2% of the total human body weight). These microbes colonize areas such as the gastrointestinal tract, oral cavity, skin, and urogenital tract. As these organisms contain 50–100 times more genes than the human body and encode a myriad of important biological processes, their genome is regarded as the “second genome” of the human body. These microorganisms and their living environment constitute human microbiota, which perform essential physiological functions over the course of human life. By directly or indirectly regulating the functions of the liver, digestive system, immune system, nervous system, and brain, they provide important maintenance of digestion, absorption, immune response, and material and energy metabolism, affecting human development, growth, health, and aging. This subverts the traditional concept of humans functioning as an independent species and opens the new concept of a mutually beneficial coexistence of human beings and microorganisms.

Nearly 80% of human microorganisms are located in the intestinal tract, forming the intestinal microbiota. Intestinal microbiota plays a significant role in disease by significantly affecting the processes of early warning, prevention, diagnosis, treatment, and rehabilitation. In recent years, multiple studies have identified key roles of intestinal microbiota in infections, liver diseases, metabolic diseases, autoimmune diseases, tumors, and brain and neuropsychiatric diseases. This has become a breakthrough for understanding the pathogenesis of major diseases. Research into important pathogenic microorganisms and alterations in intestinal microbiota before the occurrence of disease has opened a new chapter in disease prevention and early warning. New diagnostic methods based on intestinal microbiota alterations will not only become necessary tools for the diagnosis of unexplained and sudden infections, but will also be key for identifying and predicting the complex course of particular diseases, such as cirrhosis and hepatocellular carcinoma. Most chronic diseases are related to inflammation, and the intestine is one of the largest immune organs in the human body. The distribution of immune cells and the production of inflammatory factors can affect the occurrence and development of chronic diseases through direct or indirect contact with intestinal microorganisms and their metabolites. Metabolites of intestinal microorganisms have also been shown to affect the expression and regulation of intestinal inflammatory signals. Therefore, clarifying the interactions between the immune system, intestinal microorganisms, and microbial metabolism is of great significance for the prevention, intervention, and treatment of chronic diseases. The efficacy of most oral and injected drugs is closely related to the composition and function of intestinal microbiota. Relevant assessment of gut microbiota to prescribe accurate treatment could be highly significant for improving disease therapy and saving medical expenses. As well as its importance in directly or indirectly treating infections, liver diseases, metabolic diseases, autoimmune diseases, and tumors, gut microbiota regulation can overcome health problems that result from microbiota damage caused by the occurrence, development, and treatment of most diseases.

(3) Neural computation and brain-inspired intelligence in the brain sciences

Neural computation and brain-inspired intelligence in the brain sciences is a multidisciplinary field incorporating neuroscience and mathematics. It is a new research field that involves theories and analytical methods of mathematics, computer science, neuroscience, biology, physics, cognitive psychology, social and behavioral science, and engineering. It also involves the analysis of big data, including genetics, neurons, neuroimaging, large-scale cognitive functions, and the environment, in multiple dimensions across time and space. In order to investigate mechanisms and dynamics of neural systems, decipher the principles of information processing/neural coding in the brain, and decode the mechanisms of brain function, the field incorporates methods such as quantitative analysis, computational models, and brain-inspired computation. The ultimate aim of the field is to use information technology to simulate higher functions of the brain and develop brain-inspired algorithms in order to establish new fields, such as novel models and algorithms of AI, brain-inspired chips, and brain-inspired engineering technology. In this way, this emerging field embodies the quote that ‘brain-inspired intelligence leads the development of artificial intelligence’.

Research of neural computation and brain-inspired intelligence in the brain sciences has two aspects: First, it involves neurobiological research into the essence of brain computation; second, it uses computational methods to decode the principles of brain intelligence, in order to create new technologies that cover several areas related to AI. Currently, AI, as represented by deep learning is rapidly changing methods of production and consumption. The products and models derived from it have been primarily applied to the Internet, software, digital business, cloud computing, healthcare, and industrial manufacturing. Taking industrial manufacturing as an example, the wave of digitalization is accelerating the development of industry globally. For example, Industry 4.0 in Germany employs algorithms and chips that enable the entire production process to independently perceive, learn, and make improvements, leading to a more flexible and individualized synthetic processes. According to a report published by Deloitte, the global market of AI may increase to 6 trillion USD by 2025. The next generation of AI, led by brain-inspired intelligence, provides very important and far-reaching opportunities. It has the potential to transform traditional industries, including healthcare, consumption, urban management, and industrial manufacturing, revolutionize their development, and potentially exert massive economic and social impact. Moreover, the field will also affect military security, information security, biological security, information analysis, and many other important areas.

(4) Organoids-on-a-chip and its biomedical applications

Organoids-on-a-chip, a recently proposed three-dimensional (3D) culture platform, aims to integrate pluripotent cell culture with microfluidic chips *in vitro*. By simulating and controlling the biological behaviors of cell clusters, the spatial structures of their tissue source can be recapitulated, and their crucial functions can be reproduced on the chip. Due to its high structural comparability and functional consistency, the organoids-on-a-chip approach exhibits enormous potential in drug screening and evaluation, genetic disease modeling, cell therapy, and various other biomedical applications. Although organoids-on-a-chip research is still in the initial stages, it has been highly regarded as a catalyst for the rapid development of translational medicine owing to its possibilities for multi-organ integration and high bio-functional simulation. To realize its potential, several vital scientific issues need to be resolved, including expansion of the cell or tissue sources, exploration of the co-culture system, substitutes for extracellular matrix (ECM), design of integrated chip systems, control of the inner microenvironment, and integration of multiple functions or organs. As for the current status of the field, western research institutes and biotechnology companies are promoting the development of related technologies, and have already dominated some important technological patents. Moreover, the US Food and Drug Administration (FDA) has announced that they are comparing experimental results from organoids-on-a-chip with those from animal models, and the results will be used to verify the feasibility of replacing current *in vivo* methods with organoids-on-a-chip. As an important trend in new drug evaluation systems, the organoids-on-a-chip field has great strategic significance for supporting the national drug research and translational medicine innovation. Despite the remarkable achievements to date, the organoids-on-a-chip field further aims to solve challenges in the areas of physiological-chip-system construction, multi-organ functional association and synergy, sensing integration, and detection standardization. These aims will therefore become the focal development direction of the organoids-on-a-chip field in the future.

(5) Tumor immunotherapy

Tumor immunotherapy is a method used to monitor and eliminate tumor cells by reactivating the specific immune response to the tumor and restoring the normal activity of the anti-tumor immune system. The main methods used in tumor immunotherapy are immune checkpoint inhibitors, adoptive immunotherapy, neoantigen vaccines, and small molecule inhibitors. The prospects for application of tumor immunotherapy, in particular the immunological checkpoint inhibitors PD-1/PD-L1, are highly anticipated. The current key issues for tumor immunotherapy are as follows: 1) The serious adverse reactions of immunotherapy and the mechanism of accelerated progression are unclear; 2) The predictive biomarkers of immunotherapy efficacy are uncertain; 3) The efficacy of combined immunotherapy should be further improved; and 4) Resistance mechanisms and relevant solutions need to be analyzed. Following the development of oncological immunology, tumor immunotherapy has developed as a novel method of cancer treatment, with comparable significance to the traditional methods of surgery, radiotherapy, and chemotherapy. The theme of the 2017 annual progress report of the American Society of Clinical Oncology (ASCO) was “precision and alliance: immunotherapy 2.0,” marking the arrival of the 2.0 era of immunotherapy. Furthermore, the 2018 Nobel Prize in Physiology or Medicine was awarded to two professors of immunotherapy, Professor James Allison and Professor Tasuku Honjo, for their pioneering research on tumor immunotherapy. “Immunotherapy 2.0” has three characteristics: continuously expanding indications, seeking targeted beneficiaries, and obvious trend of combined therapy. At present, tumor immunotherapy has made considerable breakthroughs in the treatment of malignant tumors such as melanoma, ovarian cancer, colorectal cancer, and lung cancer. Immunotherapy, when combined with surgery, radiotherapy, chemotherapy, and other treatments, can significantly improve the survival of patients with malignant tumors, presenting major advantages over conventional radiotherapy and chemotherapy in practice. At present, China has established a relatively complete tumor immune drug research and development (R&D) program, and many domestic original immune checkpoint inhibitors have been marketed. In the field of tumor immunotherapy, in particular the clinical development of original immunotherapy drugs, China is on a par with the developed countries.

(6) Personalized tumor therapeutic vaccines

Personalized tumor therapeutic vaccines are therapeutic vaccines based on specific carcinogenic neoantigens. Neoantigens usually confer strong immunogenicity *in vivo* as they are produced due to specific gene mutations in tumor cells and are distinct from autogenic antigens that are normally tolerated by the central immune system. Therefore, the administration of neoantigens can overcome the immune suppression caused by tumors and activate tumor-specific immune cells, consequently controlling or eliminating the tumor. Since the gene mutations and neoantigens are specific to each tumor, it is necessary to produce neoantigen-based therapeutic vaccine in a personalized manner. The development of a personalized tumor therapeutic vaccine involves screening potent neoantigens, and applying algorithms to predict the binding affinity between neoantigen and human leukocyte antigen (HLA). Tumor therapeutic vaccines have been investigated for almost 20 years. However, early tumor therapeutic vaccines, which used tumor-associated antigens (TAA) as their major constituent, did not sufficiently stimulate the immune system to recognize and eliminate tumor cells, due at least partly to the pre-existence of immune tolerance. However, recent advances in next-generation sequencing (NGS) and bioinformatics have allowed a systematic discovery of carcinogenic neoantigens. In July 2017, the results of two separate clinical trials were simultaneously published by *Nature*, both ushering the dramatic advance of tumor therapeutic vaccine development. The two research teams applied high-throughput second-generation sequencing technology to identify the specific gene mutations in rapidly-dividing tumor cells, used specific algorithms to select targets with strong affinity for HLA, and generated peptide or mRNA vaccines for immunotherapy. The resulting vaccines have demonstrated excellent clinical effects and attracted great public attention. At present, a number of Chinese R&D institutions and enterprises engage in the area of personalized tumor therapeutic vaccines. In the future, the main trends for the development of personalized tumor therapeutic vaccines will be to decipher tumor immune mechanism, optimize the algorithm of screening new antigens, develop preclinical tumor models, shorten the production cycle of vaccines, and develop combinatory therapy strategies.

(7) Application of stem cells in regenerative medicine

Regenerative medicine aims to repair pathological or damaged cells, tissues, or organs, primarily via the use of seed cells, in particular stem cells. Stem cells are a unique cell type that possess the ability for self-renewal and multilineage differentiation. They can currently be divided into two categories according to their functions in the field of regenerative medicine: pluripotent stem cells, which include embryonic stem cells and induced pluripotent stem cells; and somatic stem cells, which include, for example, hematopoietic stem cells, mesenchymal stem cells, and neural stem cells. The key scientific issues of regenerative medicine include effective scaling and quality control of stem cells, efficiently differentiating pluripotent stem cells into targeted functional cells, activating stem cells *in vivo* for tissue regeneration, and constructing 3D tissues by combining stem cells with biomaterials. In addition, there is a lack of standardization in several aspects of the field, including the safety and effectiveness of stem cell treatments combined with gene therapy, particularly for hereditary diseases, the evaluation of the effectiveness of multi-stem cell-based treatment of tissue or organ damage, and the technical standards of stem cell application. The lack of ethics and management policies is also a problem that will need to be solved. Development of stem cell therapy in regenerative medicine may have the potential to revolutionize medicine, offering new ways to tackle many currently incurable and untreatable diseases, such as spinal cord injury, diabetes, Parkinson's disease, cardiovascular disease, and malignant or non-malignant hematological disorders. Although China has made remarkable achievements in basic research in the stem cell field over recent years, clinical and industrial applications of stem cells are not as advanced. Promoting the stem cell industry by introducing new policies and encouraging collaboration between research institutes, medical institutions, and pharmaceutical companies will be key to further developing the application of stem cells in the field of regenerative medicine.

(8) Metabolic heterogeneity and interactions in tumor microenvironments

Tumor cells are known to interact intensively with the surrounding stroma, known as the tumor microenvironment. The tumor microenvironment includes various cells, such as fibroblasts, immune cells, and endothelia cells, as well as many non-cellular components, such as the ECM, cytokines, and the complement system. The tumor microenvironment is characterized by hypoxia, low pH, and localized nutritional deficiency. The complex composition of the tumor microenvironment combined with the non-uniform tumor cell population result in metabolic heterogeneity, which fundamentally affects tumor development. The key scientific issues include reciprocal regulation between metabolic reprogramming and cellular signal transduction in tumors; metabolites functioning as signal molecules; crosstalk between tumor cells and the surrounding stroma cells, particularly immune cells; interplay between the metabolism of different organs and the local tumor microenvironment. During the development of research in this field, it has become clear that cancer metabolism is beyond normoxia glycolysis. Oxidative phosphorylation (OXPHOS) fueled by glucose, glutamine, and other nutrients/metabolites, and redox homeostasis of mitochondrion dramatically contribute to metabolic heterogeneity in tumor microenvironment. Mutations in oncogenes and tumor suppressors can lead to abnormal activation of signaling pathways that rewire the metabolic network in cells, highlighting the critical role of dietary intervention (or precision diet) based on the specific genetic background in cancer prevention and therapy. In addition, there has recently been increased interest in studying on metabolite sensing involved in signal transduction. With the exception of AMPK and mTOR, metabolites sensors remain largely unknown because of the huge number of different metabolites in the human body. Furthermore, there have been developments in targeted therapy of some pivotal enzymes such as IDH1/IDH2, which acquire novel enzymatic activity to produce oncometabolites when being mutated in tumors. Moreover, the metabolism and function of fibroblasts and immune cells in the tumor microenvironment are being widely investigated. Notably, increasing evidence is demonstrating the essential role of gut microbiota in tumor development and treatment. In China, there have been significant achievements in research into the effect of stressful conditions, such as hypoxia, bioenergy, and metabolite deficiency on tumor cell malignancies, while studies on metabolic heterogeneity of the tumor environment is also emerging. More recently, research on metabolites acting as signaling molecules and precision diets are becoming of central interest in this field.

(9) Precise diagnosis of diseases based on single-cell sequencing

Disease diagnosis based on single-cell sequencing involves sequencing the genome, transcriptome, or epigenome of single cell or a small number of cells. It is suitable for precise diagnosis in cases where a limited number of cells are available (such as germ cells, early embryos, and circulating tumor cells) or for tissues with high cell heterogeneity (such as the ovary, uterus, and tumor tissues). The key scientific issue in this field is how to improve the accuracy of disease diagnosis in order to achieve precise prevention and treatment of disease. Over recent years, the development of sequencing technology has greatly expedited research of genetic diseases, metabolic diseases, cancer, and other disorders, leading to major medical advances. At present, single-cell sequencing in global disease diagnosis mainly focuses on pre-implantation genetic testing, cancer typing, and follow-up medication guidance. The ongoing international project “Human Cell Atlas” is of great significance for the diagnosis of genetic and metabolic diseases; single-cell genome, transcriptome, and methylome sequencing can be used in cancer diagnosis to analyze tumor heterogeneity and achieve precision diagnosis to guide precise medical treatment. Moreover, it is possible to continuously track and monitor cancer development via these methods. In China, only ~40% of genetic diseases can currently be diagnosed and treated before embryo implantation, meaning that a high number of people still suffer from genetic diseases and cancers caused by genetic predispositions. However, the “Cancer Genome Atlas of China” has been gradually launched, and is dedicated to depicting the molecular map of cancer in order to provide effective guidance for cancer treatment in the Chinese population. A number of clinical studies based on single-cell sequencing technology are underway.

(10) Application and research of 3D printing technology in regenerative medicine

The application of 3D printing technology in regenerative medicine refers to the use of 3D printing technology to prepare tissues or organs matching the patient’s normal physiological structure and function, thus promoting tissue regeneration and functional reconstruction. 3D printing technology has been widely used to produce various medical models, rehabilitation medical devices, and personalized implants. However, for fabrication of tissues and organs with complete anatomical structure and physiological functions, there remain a number of key issues that need to be resolved. These primarily include successfully constructing 3D models with biological information, developing safe and stable bio-ink, developing 3D printing technology with sufficiently high resolution and efficiency, and providing nutrition to the tissue to maintain survival and functions competency after printing. 3D printing in the field of regenerative medicine has recently developed from single-cell printing to multi-cell printing, and is gradually moving toward tissue and organoid printing. Recent cutting-edge research has involved preparing new bio-printing inks using acellular matrix materials, and combining this with new novel high-speed and high-precision equipment to fabricate the vascular network, heart, lung, and other biological tissues and organs. In addition, 3D printing of some tissues, such as the cornea and skin, has already entered the clinical trial stage, highlighting the rapid progression of 3D printing technology. This trend of rapid development should be maintained in the future by the application of new innovative methods. In particular, we need to accelerate the development of bio-ink, bio-paper, and new types of bio-printing technology, materials, and equipment, as well as accelerate the pace of technical design and application of living bioreactors. With deep research and further development, 3D printing technology is expected to supply personalized regenerative medicine products with appropriate anatomical structures, mechanical properties, and biological functions. This will hopefully not only achieve the precise regeneration of tissues and organs, but also provide materials and theories for the continued development of regenerative medicine.

1.2 Interpretations for three key engineering research fronts

1.2.1 AI in biomedicine

AI is a technical science used to simulate and extend the theory, methods, techniques, and applications of human intelligence. The application of AI in biomedicine can increase accuracy and safety in a range of biomedical fields, such as health screening and warning, disease diagnosis and treatment, rehabilitation training and evaluation, medical services and management, drug screening and evaluation, and gene sequencing and characterization. These fields are all driven by medical data, including images, atlases, medical records, and other medical information sources, which can be processed by AI in various applications. For example, in health screening and warning, these applications include disease screening, chronic disease management, and wearable health monitoring devices. In disease diagnosis and treatment, AI can be applied to automatic lesion recognition, intelligent treatment decision-making, scientific evaluation of curative effects, robotic assisted surgery, and remote surgery. Rehabilitation training and evaluation applications include cognitive impairment rehabilitation, disability rehabilitation, robotic care, intelligent prostheses, and orthoses (including assistive exoskeleton devices). Applications in medical services and management include electronic medical record management, intelligent automatic drug delivery, and medical IoT services. Drug screening and evaluation applications of AI include drug target identification, drug screening, drug efficacy tests, drug safety evaluation, and adverse reaction data management. Finally, applications in the field of gene sequencing and characterization include gene screening, genome sequencing, gene editing, and individualized medical treatment. The application of AI in biomedicine is changing the approach of modern biomedical development. On the one hand, AI can benefit the whole medical process, including intelligent management of disease pathogenesis, precise diagnosis, safe treatment, and scientific evaluation. This has the result of significantly improving the professional efficiency of doctors, alleviating the shortage of doctors, improving the accuracy of diagnosis and treatment, and optimizing the allocation of high-quality medical resources. On the other hand, AI systems can enable real-time health monitoring and warning, and the rapid development of medical IoT, medical health hardware, and wearable health devices. Overall, the application of AI in biomedicine can aid innovation in medical technology and enable healthcare to progress to a new stage of quantitative analysis.

Some key scientific challenges for the application of AI in biomedicine are as follows: how to set up an effective framework to realize the standardized collection and safety-graded management of multi-source and multi-mode medical data; how to design new algorithms to perform unsupervised learning of small or limited datasets; how to integrate AI and traditional methods to perform safe and intelligent diagnosis and treatment; how to enhance the role of doctors in the process of AI interventions, and achieve effective cooperation of clinical human–computer intelligence; and how to formulate ethical management and legal supervision mechanisms for AI-related medical data in order to ensure the security of medical and personal information for patients and doctors. At present, hot topics for international research include: (1) Cancer and cancer diagnosis: Quantitative disease diagnosis and prognosis are organically combined by deep learning methods, leading to reductions in misdiagnosis rates and labor costs. This approach has been used in the pathological diagnosis of lung cancer, cervical cancer, breast cancer, gastrointestinal cancer, nasopharyngeal cancer, skin cancer, and other diseases. (2) Chronic disease management: Deep neural networks and fuzzy control methods can be applied for Alzheimer’s disease classification, hypertension management, and diabetes identification (diabetes classification and screening for diabetic retinopathy and other complications). This allows early warning and effective management of these chronic diseases. (3) Gene engineering: integrating the advantages of patient pathological sampling and genome sequencing. This method is conducted by gene screening, genome sequencing, and gene editing to achieve disease prediction and detection. Clinical guidelines and evidence-based medicine can then be combined to carry out personalized treatment. (4) Intelligent surgery: Intelligent robotics technology has been widely used in endoscopic surgery, orthopedics, neurosurgery, plastic surgery, and other fields. Two examples that have been widely used are the Da Vinci robot in the USA and the TianJi robot in China. The TianJi robot is the first orthopedic surgical robot created entirely in China, and received China Food and Drug Administration approval in 2016. It was produced by a team led by Professor Tian Wei from Beijing Jishuitan Hospital. This kind of AI technology has also been used in the automatic planning of surgical paths, autonomous decision-making of robot motion, and automatic evaluation of surgical effects. Meanwhile, the emergence of 5G technology may further promote the rapid development of telemedicine (particularly telesurgery). At present, China's 5G-assisted robotic surgery is at the forefront of the international field. Professor Tian has achieved the milestone of being able to simultaneously control 2–3 robots remotely. Some researchers are also exploring the possibility of remotely controlling soft tissue robots such as Da Vinci; however, further research is needed to solve the delay between the image data and robot control. (5) Intelligent rehabilitation: virtual reality and intelligent robotics combined with AI technology can be applied to the rehabilitation of disabled people. Intelligent rehabilitation devices, such as artificial limbs, rehabilitation training robots, exoskeleton auxiliary devices and orthoses, escort robots, intelligent bed chairs, virtual reality rehabilitation systems, and electronic artificial larynxes, have been rapidly developed in recent years. (6) Drug R&D: AI technology has been widely used in drug target identification, drug screening, drug safety assessment, drug efficacy tests, and data collection. This has contributed to the pharmacological evaluation of traditional Chinese medicine, with the potential for a broad range of applications.

In recent years, AI has been subject to substantial market demand in the field of biomedicine, with an annual growth rate of 40%. The USA is the main consumer of biomedical AI technologies, followed by China and Europe. The overall development trends are as follows: The application of AI in biomedicine has developed from pathological diagnosis to clinical treatment; the integration of AI, robotics, 5G communication and other frontier technologies are changing the concepts and means of modern treatment; the application of AI in drug research and gene engineering is becoming a hot research topic; and the integration of AI and traditional Chinese medicine is attracting increasing attention.

The top 10 countries in terms of output of core research literature on the application of AI in biomedicine were all located in North America, Europe, and Asia. The USA, China, and the UK ranked as the top three countries, as shown in Table 1.2.1. The USA accounted for 52.24% of core papers, while China and the UK each accounted for over 10% of the core papers. The core literature from each country has been cited less than 70 times, indicating that this research field is in a stage of extremely active innovation, with rapidly changing methods of application. Moreover, the USA appears to be leading the global development of this research field. According to the collaborative network of the top 10 core paper-producing countries, there are close collaborative relationships among these countries, as shown in Figure 1.2.1.

Of the top 10 organizations producing core paper on application of AI in biomedicine, eight were in the USA and two were in Asia. The top three organizations were Harvard University, Stanford University, and Korea University. In terms of the number of published papers, the Chinese Academy of Sciences ranked sixth, as shown in Table 1.2.2. The results regarding collaborative networks between the top 10 core paper-producing organizations revealed collaborative relationships among many of these institutions, as shown in Figure 1.2.2.

Based on the statistical analyses described above, in the research front of "application of AI in biomedicine", China now sits alongside other countries in terms of application, but is still catching up in terms of technological R&D. The current findings give rise to several suggestions for China: (1) Further expand the scope of application of AI technology in disease diagnosis, chronic disease prediction, and health monitoring, to benefit larger populations; (2) Continuously promote the application of AI technology in medical robotics, such as surgery, rehabilitation, and old-age care, to achieve safe, efficient, and efficient AI collaboration; (3) Strengthen the application of AI technology in medicine, especially in the field of traditional Chinese medicine (such as pharmacology and efficacy evaluation), to accelerate the process of innovative drug research, development, and testing; (4) Strengthen

Table 1.2.1 Countries or regions with the greatest output of core papers on "AI in biomedicine"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	350	52.24%	19 780	58.27%	56.51
2	China	100	14.93%	4 496	13.24%	44.96
3	UK	75	11.19%	3 966	11.68%	52.88
4	Germany	58	8.66%	3 181	9.37%	54.84
5	Italy	56	8.36%	2 215	6.53%	39.55
6	Canada	51	7.61%	3 004	8.85%	58.90
7	Netherlands	34	5.07%	2 271	6.69%	66.79
8	South Korea	34	5.07%	1 764	5.20%	51.88
9	Australia	32	4.78%	1 145	3.37%	35.78
10	Spain	31	4.63%	1 325	3.90%	42.74

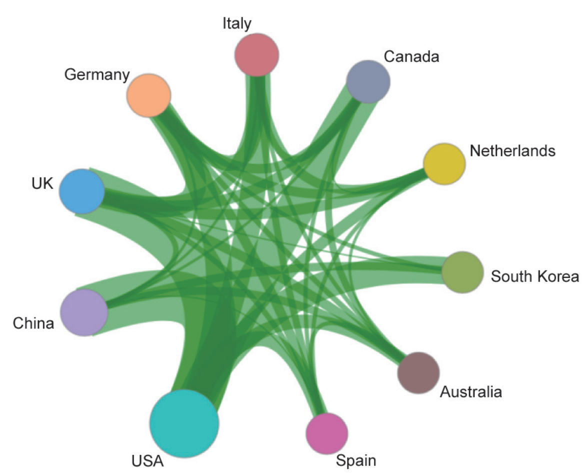

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "AI in biomedicine"

Table 1.2.2 Institutions with the greatest output of core papers on "AI in biomedicine"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	59	8.81%	3714	10.94%	62.95
2	Stanford Univ	27	4.03%	2406	7.09%	89.11
3	Korea Univ	23	3.43%	1390	4.09%	60.43
4	Univ N Carolina	23	3.43%	1493	4.40%	64.91
5	Columbia Univ	17	2.54%	943	2.78%	55.47
6	Chinese Acad Sci	17	2.54%	793	2.34%	46.65
7	Johns Hopkins Univ	16	2.39%	665	1.96%	41.56
8	Univ Calif San Diego	15	2.24%	786	2.32%	52.40
9	Univ Washington	15	2.24%	742	2.19%	49.47
10	Univ Penn	114	2.09%	1117	3.29%	79.79

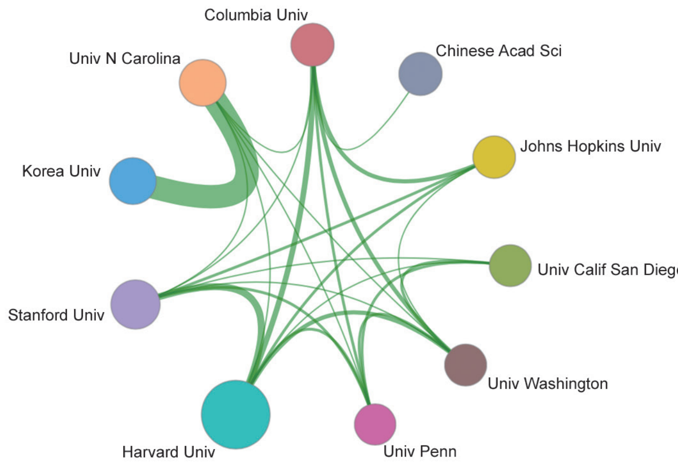

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "AI in biomedicine"

the cultivation of compound talents for medical science and engineering to avoid the separation of engineering development from clinical needs; and (5) Establish an international open innovation platform and collaboration mechanism to maximize the use of educational and scientific research resources.

1.2.2 Gut microbiota and immune homeostasis

The discovery of the important physiological function of human microbiota has subverted our understanding of human health and survival. In recent years, multiple studies have revealed the scale and complexity of microbial communities inhabiting the body surface and coelomic cavities of humans (over 10^{14} cells of bacteria, archaea, fungi, and viruses, dry weight approximately 1%–2% of total human body weight). These microbes colonize areas such as the gastrointestinal tract, oral cavity, skin, and urogenital tract. As these organisms contain 50–100 times more genes than human body, and encode a myriad of important biological processes, their genome is regarded as the "second genome" of the human body. These microorganisms and their living environment constitute human microbiota, which perform essential physiological functions over the course of human life. By directly or indirectly regulating the functions of the liver, digestive system, immune system, nervous system, and brain, they provide important maintenance of digestion, absorption, immune response, and material and energy metabolism, affecting human development, growth, health, and aging. This subverts the traditional concept of humans functioning as an independent species and opens a new concept of a mutually beneficial coexistence of human beings and microorganisms.

Nearly 80% of human microorganisms are located in the intestinal tract, forming the intestinal microbiota. Intestinal microbiota plays a significant role in disease by significantly affecting the processes of early warning, prevention, diagnosis, treatment, and rehabilitation. In recent years, multiple studies have identified key roles of intestinal microbiota in infections, liver diseases, metabolic diseases, autoimmune diseases, tumors, and brain and neuropsychiatric diseases. This has become a breakthrough for understanding the pathogenesis of major diseases. Research into important pathogenic microorganisms and alterations in intestinal microbiota before the occurrence of disease has opened a new chapter in disease prevention and early warning. New diagnostic methods based on intestinal microbiota alterations will not only become necessary tools for the diagnosis of unexplained and sudden infections, but will also be key for identifying and predicting the complex course of particular diseases, such as cirrhosis and hepatocellular carcinoma. Most chronic diseases are related to inflammation, and the intestine is one of the largest immune organs in the human body. The distribution of immune cells and the production of inflammatory factors can affect the occurrence and development of chronic diseases through direct or indirect contact with intestinal microorganisms and their metabolites. Metabolites of intestinal microorganisms have also been shown to affect the expression and regulation of intestinal inflammatory signals. Therefore, clarifying the interaction between the immune system, intestinal microorganisms, and microbial metabolism is of great significance for the prevention, intervention, and treatment of chronic diseases. The efficacy of most oral and injected drugs is closely related to the composition and function of intestinal microbiota. Relevant assessment of gut microbiota to prescribe accurate treatment could be highly significant for improving disease therapy and saving medical expenses. As well as its importance in directly or indirectly treating infections, liver diseases, metabolic diseases, autoimmune diseases, and tumors, gut microbiota regulation can overcome health problems that result from microbiota damage caused by the occurrence, development, and treatment of most diseases.

At present, the key scientific issues in R&D of the gut microbiota and immune homeostasis field are as follows: (1) How to integrate the theoretical and technical basis of modern medicine, biology, and information science to reveal the structure, function, and dynamicity of gut microbiota in humans, and to systematically analyze gut microbiota in immune development, maturity, and pathogenesis. (2) Elucidating the role and mechanism of gut microbiota in important pathological processes such as infections, liver diseases, metabolic diseases, and tumors. (3) Elucidating the role and mechanisms of gut microbiota in drug metabolism and the development of microbial resistance. The overall development trend is shifting from the study of immune regulation mechanisms of single gut microorganisms to the role and mechanism of gut microbiota in the establishment, maintenance, and regulation of host immune homeostasis and disease prevention. The research hotspots include: (1) The co-development and co-evolution of gut microbiota and the immune system; (2) The role and molecular mechanism of gut microbiota in regulating immune homeostasis and promoting host health; (3) The causal relationship and mechanism of gut microbiota imbalance on gut immune homeostasis and disease development; (4) The immune mechanisms and clinical applications of the effect of gut microbiota on disease therapies; (5) Disease early warning, diagnosis, and prognosis analysis based on alterations of gut microbiota and immune homeostasis; and (6) New drugs and therapeutic strategies for health promotion and disease prevention by regulating gut microbiota and immune homeostasis.

Publications relating to the front of “gut microbiota and immune homeostasis” are predominantly published by researchers in the USA, France, and China. China accounted for 14.29% of the published papers, and is one of the leading research countries in this front (Table 1.2.3). Figure 1.2.3 shows the collaborative relationships among these countries.

Of the ten major institutions with the greatest output of core papers in this front, the top four were in the USA and Belgium: Harvard University, The University of Michigan, the Catholic University of Louvain, and Emory University (Table 1.2.4). Figure 1.2.4 shows the collaborative relationships among these institutions.

Based on the above statistical analysis, China is currently in the same research situation as other countries in the “gut microbiota and immune homeostasis” research front, and the

Table 1.2.3 Countries or regions with the greatest output of core papers on “gut microbiota and immune homeostasis”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	34	53.97%	4062	53.80%	119.47
2	France	9	14.29%	1367	18.11%	151.89
3	China	9	14.29%	801	10.61%	89.00
4	Germany	5	7.94%	636	8.42%	127.20
5	Belgium	5	7.94%	807	10.69%	161.40
6	Canada	5	7.94%	407	5.39%	81.40
7	Japan	4	6.35%	556	7.36%	139.00
8	UK	4	6.35%	441	5.84%	110.25
9	Sweden	4	6.35%	549	7.27%	137.25
10	Switzerland	4	6.35%	457	6.05%	114.25

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "gut microbiota and immune homeostasis"

following suggestions apply for the future development of this field: (1) Integrate the existing multidisciplinary advantages: consolidate and develop the foundation of gut microbiota and immune homeostasis knowledge, and lay a good foundation for further development and research by promoting relevant research through industry–university–research linkage and international cooperation. (2) Fully exploit the advantages of China's traditional medicine, investigating novel methods for gut microbiota and immune homeostasis R&D to avoid a lack of progress in this area. (3) Encourage cooperation among different disciplines regarding development strategy, and give full autonomy and initiative to all disciplines and teams. Develop the enthusiasm and initiative of researchers in a flexible and enterprising manner to allow movement into a new chapter of gut microbiota and immune homeostasis

Table 1.2.4 Institutions with the greatest output of core papers on "gut microbiota and immune homeostasis"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	5	7.94%	732	9.70%	146.40
2	Univ Michigan	4	6.35%	587	7.77%	146.75
3	Catholic Univ Louvain	4	6.35%	706	9.35%	176.50
4	Emory Univ	4	6.35%	252	3.34%	63.00
5	RIKEN	3	4.76%	504	6.68%	168.00
6	INSERM	3	4.76%	550	7.28%	183.33
7	INRA	3	4.76%	216	2.86%	72.00
8	Washington Univ	2	3.17%	406	5.38%	203.00
9	Cent Queensland Univ	2	3.17%	322	4.26%	161.00
10	Monash Univ	2	3.17%	322	4.26%	161.00

RIKEN: Institute of Physical and Chemical Research; INSERM: Institut National de la Santé et de la Recherche Médicale; INRA: Institut National de la Recherche Agronomique.

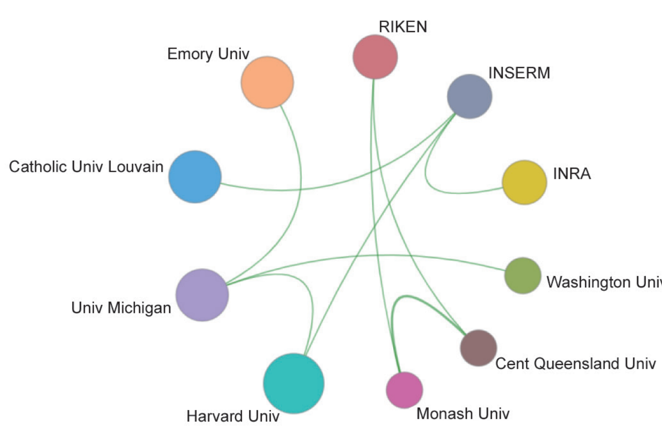

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "gut microbiota and immune homeostasis"

research in China. (4) Establish data standards for the gut microbiota and immune homeostasis field in China, including testing, analysis, and calculation. The government should organize and establish special agencies to coordinate and integrate the research resources of gut microbiota and immune homeostasis research in China, and build platforms for research cooperation and data collection to share at the national level. (5) Formulate relevant policies and designate enterprises to participate in all stages of research in the field of gut microbiota and immune homeostasis, and provide policy support to transform and promote the research results.

1.2.3 Neural computation and brain-inspired intelligence in the brain sciences

Neural computation and brain-inspired intelligence in the brain sciences is a multidisciplinary field incorporating neuroscience and mathematics. It is a new research field that involves theories and analytical methods of mathematics, computer science, neuroscience, biology, physics, cognitive psychology, social and behavioral science, and engineering. It also involves the analysis of big data, including genetics, neurons, neuroimaging, large-scale cognitive functions, and the environment, in multiple dimensions across time and space. In order to investigate mechanisms and dynamics of neural systems, decipher the principles of information processing/neural coding in the brain, and decode the mechanisms of brain function, the field incorporates methods such as quantitative analysis, computational models, and brain-inspired computation. The ultimate aim of the field is to use information technology to simulate higher functions of the brain and develop brain-inspired algorithms in order to establish new fields, such as novel models and algorithms of AI, brain-inspired chips, and brain-inspired engineering technology. In this way, this emerging field embodies the quote that 'brain-inspired intelligence leads the development of artificial intelligence.'

Research of neural computation and brain-inspired intelligence in the brain sciences has two aspects: First, it involves neurobiological research into the essence of brain computation; second, it uses computational methods to decode the principles of brain intelligence, in order to create new technologies that cover several areas related to AI. Currently, AI, as represented by deep learning is rapidly changing methods of production and consumption. The products and models derived from it have been primarily applied to the Internet, software, digital business, cloud computing, healthcare, and industrial manufacturing. Taking industrial manufacturing as an example, the wave of digitalization is accelerating the development of industry globally. For example, Industry 4.0 in Germany employs algorithms and chips that enable the entire production process to independently perceive, learn, and make improvements, leading to a more flexible and individualized synthetic processes. According to a report published by Deloitte, the global market of AI may increase to 6 trillion USD by 2025. The next generation of AI, led by brain-inspired intelligence, provides very important and far-reaching opportunities. It has the potential to transform traditional industries, including healthcare, consumption, urban management, and industrial manufacturing, revolutionize their development, and potentially exert massive economic and social impact. Moreover, the field will also affect military security, information security, biological security, information analysis, and many other important areas.

Research of neural computation and brain-inspired intelligence in the brain sciences originated from research into AI; in particular, from areas fundamentally related to artificial neural networks and computational neuroscience. The pioneers in this field include the following: Von Neumann, the pioneer of the modern framework of computers, whose unfinished great work *The Computer and The Brain* focused on the relationship between the human neural system and the computer; Alan Turing, who used dynamic algorithms in physics to explain pattern formation in biological systems and proposed computing intelligence; Hodgkin and Huxley, who combined electrophysiological experiments and physical dynamics, and used differential equations to construct a precise model of single neural discharge; David Marr, who proposed the computational vision theory in 1940–1960; McCullc and Pitts, who proposed the neural model; Donald Hebb, who proposed the Hebb learning law; Rosenblatt, who proposed the concept of the perceptron algorithm; Shun'ichi Amari, who developed the mathematical basis of neural networks; and John Hopfield, who proposed a key energy function. Recently, researchers in brain sciences and mathematics, aided by the integration of computers and information technology, made two big breakthroughs in artificial neural network technology. On March 27, 2019, the creators of deep learning, Yoshua Bengio, Yann LeCun, and Geoffrey were awarded the Turing award of 2019. These three scientists created the basic concepts of deep learning. They presented impressive experimental results, and made great breakthroughs in the industry. The application of deep learning in various areas has been aided by achievements in computer vision, voice recognition, natural language processing, and robotics. However, the development of AI technology, in particular neural networks, over the past 30 years has been lacking in sufficiently deep integration of brain sciences and mathematics.

Neural computation in the brain sciences and brain-inspired intelligence involves multiple research fields surrounding the three main areas of neuroscience, brain sciences, and AI, including mathematics, computer science, information, (nano) microelectronics, cognitive sciences, psychology, neurosurgery, and basic medicine. One of the key scientific issues is investigating all of the intelligence-related mechanisms of brain information, cognition, consciousness, psychology, and memory, i.e., how to analyze neural circuit structures and neural information-processing mechanisms. It is clearly understood how neurons encode, transduce, and store neural information; however, it is not understood how the properties of these neurons are generated through local and long-range circuits, and that how neural circuit-based information produces various cognitive functions such as perception, emotion, thinking, decision-making, consciousness, and language. The other key scientific issue involves developing new theories, methods, and technologies to achieve human-like intelligence systems, including intelligent models, computing architectures, chip technologies, and related application technologies.

The front of neural computation in the brain sciences and brain-inspired intelligence include four aspects. The first is research based on the abnormal brain (brain disorders) to investigate various characteristics of the nervous system, including its structure and function, the mechanisms underlying its normal or abnormal state, and the computational strategies underlying its function. The second aspect is to develop non-destructive, non-invasive techniques and equipment with sufficient resolution (e.g. micrometers, nanometers, and milliseconds) for brain measurement. The third is to simulate and calculate the neuromorphic nature of trillions of synaptic interactions. The final aspect is to develop new intelligent computing architectures, integrating perception, cognition, psychology, consciousness, value, memory, decision-making, and learning and reasoning mechanisms.

In 2013, the USA launched the initiative Brain Research through Advancing Innovative Neurotechnologies (BRAIN), which is a collaboration of multiple institutes and agencies with a proposed total investment of approximately 3 billion USD. In addition to the National Institutes of Health (NIH) performing traditional brain disorder and medical research and developing new imaging and detection technologies incorporating large scientific devices, the Defense Advanced Research Projects Agency (DARPA) participated in order to investigate brain-inspired intelligence. In addition, the Intelligence Advanced Research Projects Agency (IARPA) currently funds the basic research project "Machine Intelligence from Cortical Networks (MICrONS)." The aim of MICrONS is to reversely engineer the brain's algorithms and completely change machine learning, creating more powerful brain-inspired machine learning algorithms based on a deep understanding of brain representation, transformation, and learning rules. DARPA is committed to funding third-generation AI from 2018–2020 through both new and old projects aiming to break through the basic theory and core technology of AI by investigating machine learning and reasoning, natural language understanding, modeling and simulation, and human–machine fusion. On April 26, 2017, the US military launched Project Maven, a cross-functional team designed to carry out research on algorithm warfare-related concepts, technologies, and application. Project Maven aims to promote the military application of cutting-edge technologies such as AI, big data, and machine learning in order to maintain the US military's technology and combat advantage. The EU also launched the Human Brain Project (HBP) in 2013, which focuses on simulating brain function.

Among the top 10 countries producing advanced core papers in the research front of "neural computation and brain-inspired intelligence in brain sciences," the USA is clearly in the leading position, accounting for 47.33% of total publications. Germany and China rank second and third, respectively. However, China's scientific research in this field is rapidly developing. The citation index of the core papers in this field ranged from 52.55 to 84.53 across the top 10 countries (Table 1.2.5), and the citation index of core papers produced in China was 66.05 This indicates that Chinese scholars in this field have the ability and potential to increase their impact with some improved efforts. According to the cooperation network of the top 10 core paper-producing countries, some close international collaborations have been developed, with the USA demonstrating collaboration with all other nine countries, demonstrating their strength and influence in this research field. The major countries cooperating with China include the USA, Germany, UK, Japan, Italy, and Switzerland (Figure 1.2.5).

Of the top 10 institutions in terms of core papers in this research front, the top three are from the USA and Germany, namely Stanford University, Harvard University, and the University of Tubingen. In terms of the number of published articles, the Chinese Academy of Sciences ranked fourth, as shown in Table 1.2.6. According to the collaboration network diagram of the top 10 core paper-producing institutions, some of the institutions have developed mutual collaborations (Figure 1.2.6).

Based on a statistical analysis of the above data, China is currently among the leading players with regard to research concerning neural computation in the brain sciences and brain-inspired intelligence. However, compared with developed countries, China still has some disadvantages which need addressing, such as relatively smaller research groups and limited international influence. In particular, the lack of cross-border multi-disciplinary research has restricted the progress of major science and technology key programs in this research field. Suggestions for the future development of this field in China are: first, to strengthen training and the introduction of multidisciplinary talents, and

Table1.2.5 Countries or regions with the greatest output of core papers on “neural computation and brain-inspired intelligence in the brain sciences”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	142	47.33%	10 394	49.09%	73.20
2	Germany	53	17.67%	2 936	13.87%	55.40
3	China	42	14.00%	2 774	13.10%	66.05
4	UK	34	11.33%	2 874	13.57%	84.53
5	Switzerland	26	8.67%	2 093	9.89%	80.50
6	Italy	24	8.00%	1 610	7.60%	67.08
7	France	22	7.33%	1 156	5.46%	52.55
8	Canada	20	6.67%	1 469	6.94%	73.45
9	South Korea	13	4.33%	965	4.56%	74.23
10	Japan	13	4.33%	797	3.76%	61.31

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “neural computation and brain-inspired intelligence in the brain sciences”

Table 1.2.6 Institutions with the greatest output of core papers on "neural computation and brain-inspired intelligence in the brain sciences"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Stanford Univ	18	6.00%	1627	7.68%	90.39
2	Harvard Univ	18	6.00%	1632	7.71%	90.67
3	Univ Tubingen	12	4.00%	534	2.52%	44.50
4	Chinese Acad Sci	10	3.33%	589	2.78%	58.90
5	Univ Oxford	9	3.00%	920	4.35%	102.22
6	Univ Zurich	9	3.00%	783	3.70%	87.00
7	Univ Toronto	9	3.00%	583	2.75%	64.78
8	Univ Coll London	8	2.67%	919	4.34%	114.88
9	Univ Calif San Diego	8	2.67%	681	3.22%	85.13
10	Korea Univ	8	2.67%	624	2.95%	78.00

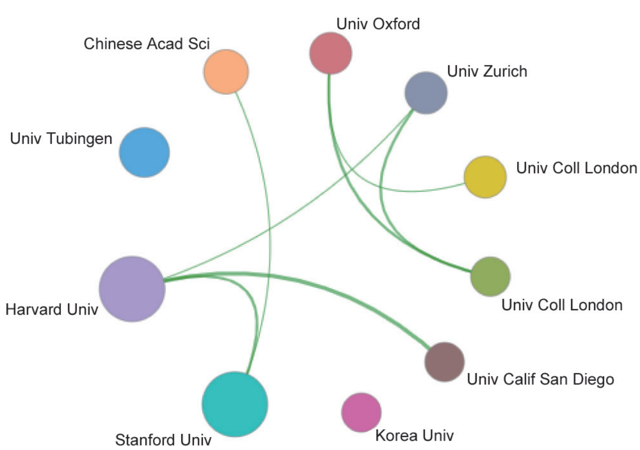

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "neural computation and brain-inspired intelligence in the brain sciences"

make use of the advantages of research funding, scientific facilities, and personnel remuneration. This will allow introduction and training of a number of interdisciplinary talents, including advanced experts in the fields of cognitive neuroscience, brain-inspired intelligence, and AI. The second suggestion is to further promote international scientific and technological collaborations between scientists in the fields of mathematics, physics, brain science, and computer science, as well as promote daily academic communications and in-depth dialogues. Third, China should accelerate the layout of scientific research and focus on the research of computational neuroscience and brain-inspired intelligence research in brain science. We need to integrate the key resources of the whole country, carry out collaborative innovation, focus on key scientific projects, and strive to gain opportunities to win on some key fundamental scientific issues. Fourth, by prediction and analysis of the likely future direction of the brain-inspired intelligence field, we should carry out research and discussions on ethics, data security, data sharing, and regulatory policy, and establish relevant regulations to protect the applications of brain-inspired intelligence technology.

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

This section of the review describes the top 10 engineering development fronts in the field of medicine and health, which includes the fields of basic medicine, clinical medicine, pharmacy, medical informatics and biomedical engineering, public health, and preventive medicine, among other subjects. The three emerging fronts are "intelligence assisted diagnosis technology," "brain–computer interfaces," and "humanized animal models." Traditional research has focused on the engineering development fronts of "tumor immunotherapy technology," "genome editing," "disease prediction and intervention technology based on genomics big data," "intelligent wearable devices for health assistance," "stem cell-based tissue engineering and organ remodeling technology," "single cell analysis techniques," and "biomaterials for tissue regeneration and repair" (Table 2.1.1). All patents involved in these 10 fronts published between the years 2013–2018 are disclosed in Table 2.1.2.

(1) Tumor immunotherapy technology

Tumor immunotherapy (also known as cancer immunotherapy or immuno-oncology) is a method of applying immunological principles and methods to treat cancer by stimulating and enhancing the body's anti-tumor immune response. The main methods of tumor immunotherapy include cancer vaccines, specific monoclonal antibody targeted therapy, cytokine therapy, immune checkpoint blockade, and adoptive cell therapy. Tumor immunotherapy has developed rapidly in the field of translational clinical medicine over the past decade. Its application has improved the quality of life and significantly prolonged survival for a large number of cancer patients, giving new hope for curing various advanced cancers. It has played a significant role in promoting the development of contemporary medical technology, reforming the medical and health system, and developing social welfare and medical systems in various countries. The field of tumor immunotherapy originated from the first tumor vaccine in 1893. However, it was not until the 1990s that cytokine therapy, represented by interleukin-2 (IL-2), and monoclonal antibody targeted therapy brought dawn to the modern era of the field. In 2013, *Science* magazine ranked tumor immunotherapy at the top of the top 10 scientific breakthroughs. In the past 5 years, immune checkpoint inhibitor and chimeric antigen receptor T (CAR-T) cell immunotherapies have made major breakthroughs in various cancers and also promoted the development of other cancer immunotherapies. At present, tumor immunotherapy is the

Table 2.1.1 Top 10 engineering development fronts in medicine and health

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Tumor immunotherapy technology	5 145	16 846	3.27	2016.6
2	Intelligence assisted diagnosis technology	14 975	46 454	3.10	2016.2
3	Genome Editing	2 965	16 363	5.52	2016.7
4	Disease prediction and intervention technology based on genomics big data	11 529	36 476	3.16	2015.9
5	Brain–computer interfaces	5 060	13 702	2.71	2016.0
6	Intelligent wearable devices for health assistance	5 918	25 699	4.34	2016.4
7	Stem cell-based tissue engineering and organ remodeling technology	1 720	3 747	2.18	2015.7
8	Humanized animal models	757	1 900	2.51	2016.0
9	Single cell analysis techniques	2 500	6 669	2.67	2016.0
10	Biomaterials for tissue regeneration and repair	5 591	16 273	2.91	2015.7

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in medicine and health

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Tumor immunotherapy technology	274	384	470	886	1379	1752
2	Intelligence assisted diagnosis technology	1237	1702	1930	2509	3164	4433
3	Genome editing	108	185	301	500	806	1065
4	Disease prediction and intervention technology based on genomics big data	1470	1547	1689	1943	2329	2551
5	Brain-computer interfaces	513	635	745	918	1120	1129
6	Intelligent wearable devices for health assistance	229	507	762	1241	1550	1629
7	Stem cell-based tissue engineering and organ remodeling technology	267	278	236	260	360	319
8	Humanized animal models	89	112	98	123	145	190
9	Single cell analysis techniques	289	321	329	388	525	648
10	Biomaterials for tissue regeneration and repair	852	913	748	925	1062	1091

fourth type of cancer treatment that has been proven to have significant clinical efficacy after the traditional three treatment types: surgery, radiotherapy, and chemotherapy.

(2) Intelligence assisted diagnosis technology

Intelligence assisted diagnosis refers to computers providing assisted disease analysis in clinical diagnosis to help doctors make better use of information and improve the quality and efficiency of diagnosis and treatment. The application of intelligence assisted diagnosis technology can not only alleviate the current shortage of medical resources, but also effectively promote the reform of the medical system, and help to gradually form a new business strategy in the medical field. Intelligence assisted diagnosis technology originated in the late 1950s, and has since developed in three stages. The first stage mainly involved knowledge engineering through the sorting, construction, and accumulation of medical knowledge. The second development stage involves shallow semantic learning and reasoning, which integrates traditional machine learning and feature engineering. The third stage is autonomous learning of medical diagnosis decision reasoning, which is characterized by massive medical data and deep learning methods. At present, intelligence assisted diagnosis technology is in rapid development between the second and third stages.

The key technical problems that need to be solved for the next stage of development of intelligence assisted diagnosis technology are: 1) The representation learning of medical knowledge; 2) The construction of complex reasoning models based on diagnosis and treatment ideas; 3) The generalization of intelligent assisted diagnosis results; and 4) The biological interpretability of intelligent diagnosis models. In recent years, global investment in the field of medical AI has shown a trend of rapid rise. The domestic intelligence assisted diagnosis related industry has also risen rapidly. In 2017, the industry output value in China reached more than 13 billion CNY, with an annual increase of 40.7%. It is predicted that the output value may exceed 20 billion CNY in 2018 according to the current development trend. At present, many technology giants are stepping up their efforts in the field of intelligence assisted diagnosis technology. For example, international companies such as IBM, Google, and Siemens have been engaged in the field of intelligence assisted diagnosis for many years, and have accumulated a large number of invention patents and formed certain technical barriers. Domestic high-tech enterprises such as Tencent, United Imaging Healthcare, and iFLYTEK have also made important breakthroughs over recent years, and are gradually adapting the development path of intelligence assisted diagnostic technology to China's national conditions.

(3) Genome editing

Genome editing refers to the deletion, insertion, replacement, or single base substitution of DNA in the genome by deploying nuclease and cellular DNA repair machinery. This technique is currently in broad use to construct animal models, screen for new therapeutic targets, and improve agronomic traits of livestock and crops. Furthermore, it has made the transition from the bench to clinical trials, for example in the development of anti-virus drugs, CAR-T cell therapy, and blood disease treatments. From the emergence of first generation meganuclease in 1994 to the more recent popularization of zinc finger nucleases (ZFN) and transcriptional activation-like effector nucleases (TALEN), gene editing has continuously been evolving in terms of its precision and efficacy. In 2012, the repurposing of the bacterial anti-phage CRISPR/Cas system for RNA-guided DNA-targeting brought a qualitative leap in the endeavors to re-write genetic information in any organism. It is now possible to achieve simple and efficient editing at single or multiple loci in living cells. In addition, multiple derivative technologies empowered by CRISPR/Cas, such as gene activation, gene silencing, RNA editing, epigenetic engineering, and base editing, provide a powerful tool repertoire for biomedical research to uncover the pathogenesis, mechanism, and treatment of disease. In the coming years, the predicted technical challenges for the development of gene editing technologies include: 1) Improvement of gene editing efficiency and precision; 2) Robust delivery systems for gene editing reagents; 3) Expansion of editable sequence space; 4) More accurate off-target evaluation methods; and 5) Development of RNA editing tools. Since the debut of CRISPR/Cas in 2012, this field has been explored enthusiastically, as evidenced by the explosion in relevant research publications inspired by the enormous potential for the application of CRISPR/Cas, particularly in the clinical sciences.

(4) Disease prediction and intervention technology based on genomics big data

Genomics big data are multi-layer, high dimensional data represented by the human genome, transcriptome, epigenome, and metabolome. In recent years, the rapid development of second- and third-generation DNA sequencing technologies have resulted in rapid growth of genomics data, and have also brought new opportunities and challenges for disease research. On the one hand, genomics data can aid our understanding of the causes underlying complex diseases, thus promoting their prevention and treatment. On the other hand, the complexity of genomics data means that its transformation into practical clinical application can be very slow. In terms of disease prediction, compared with traditional biophysical and biochemical tests, genomics data-based methods have the advantages of being early, accurate, and non-disruptive. For example, the detection of cfDNA in blood can help doctors to screen for early stage cancers. During disease intervention, genomics data can increase the accuracy of drug usage and treatment. Analyses of genomics data for different patients can also facilitate the implementation of personalized medicine. However, three issues need to be resolved before genomics data can be applied to clinics on a larger scale. First, our understanding of genomics big data is not yet deep enough, therefore key genes associated with the onset of specific diseases and their mechanisms of action need to be further tested and confirmed. Second, sequencing technologies need to be further developed, and there are only very few chips that can currently be used for disease detection. Third, the laws and regulations relevant for the clinical application of genomics big data need to be improved. In particular, issues such as the deposition and retrieval of genomics data urgently need to be resolved. For example, although disease-related epigenetics changes have been reported in several thousand research articles, only four FDA-approved drugs are available for their treatment. As a large country with a huge population, China has a big advantage in genomics big data research, and has carried out many such studies on Chinese populations. However, several bottlenecks still exist. For example, China relies heavily on the USA for sequencing technologies, machines, and reagents. In addition, The National Genomics Data Center, which is designed for data management and sharing, was only established very recently. In the future, with the development of sequencing technology and advancement of research, genomics big data will play an increasingly important role in disease prediction and intervention.

(5) Brain–computer interfaces (BCIs)

Brain–computer interfaces (BCIs) measure central nervous system (CNS) activity and convert it into an artificial output that replaces, restores, enhances, supplements, or improves natural CNS outputs, thereby changing the ongoing interactions between the CNS and its external or internal environment. BCI technology collects signals of CNS activity through sensors placed either on the scalp or in the cranium. After signal processing, feature extraction, and pattern recognition, it is possible to obtain the control intentions of the CNS, cognitive or psychological states, and states of nervous diseases. In this way, BCIs can provide new control and communication channels or rehabilitation methods for disabled patients with movement and language disorders. It can also provide more information output channels for healthy people. With the development of electroencephalography (EEG) signal acquisition and processing technology, BCI technology has gradually entered clinical application. It has performed well in clinical rehabilitation of patients with brain injury or other neurological diseases such as stroke and attention deficit disorder. BCI technology can also provide motor function solutions for patients with motor dysfunction disorders such as high paraplegia and amyotrophic lateral sclerosis (ALS). It can also provide objective indicators for the detection and identification of emotion, fatigue, and state of consciousness. Due to its broad prospects in the military and civilian fields, China, the USA, and several countries in Europe attach great importance to the investment in BCI technology research. In recent years, a series of technological start-up companies have emerged, and technological breakthroughs and new products have been launched. Clinical rehabilitation and daily application products based on BCI technology have reached a substantial market level, which is continuing to grow rapidly. The key factors to promote BCI technology breakthroughs in the future will be high spatial resolution of electrical and magnetic brain signal acquisition technology, intelligent signal processing technology, and high-integration software and hardware platforms. The deep integration of BCI technology with materials science, nanotechnology, robotics, and AI will bring new hope for the diagnosis and rehabilitation of many nervous diseases. In time, this may also allow development of BCI technology into a generally available high-performance information interaction channel between brain and computer, bringing great benefits in the military and civilian fields in the future.

(6) Intelligent wearable devices for health assistance

Intelligent wearable devices for health assistance can sense, record, analyze, regulate, and even treat diseases and maintain health. With the development of electronics and information technology, the intelligent wearable health assistance device has gone through three development stages: version 1.0, based on smart phone applications; version 2.0, based on independent communication and intelligent operation; and the new version 3.0, based on edge computing and personal data services. With the improvement of public health awareness and the further development of edge computing, cloud computing, big data, and AI technologies, intelligent wearable health assistance devices have entered a rapid growth period. They are able to provide intelligent operations to monitor, prevent, and treat diseases without temporal or geographical limitations. These characteristics allow both long-term and emergency treatments for the elderly, or those suffering from occupational, chronic, or high-risk diseases. It is predicted that by 2020 the number of wearable devices will increase by 15.3% from the previous year to reach a total of 198.5 million, and the global market size will reach 6 billion USD. With the development of electronic computing hardware and software algorithm performance, together with the improvement of modern medical disease databases and the strong support of national policies, intelligent wearable health assistance devices have a promising future. Specific improvements are that the product features of wearable devices are more focused, the personal database is more abundant, the user experience is better, and remote medical treatment is more popular. These devices will improve the popularity, coverage, and professionalism of medical care while significantly reducing the cost, making significant contributions towards the goals of disease prevention and promotion of public health.

(7) Stem cell-based tissue engineering and organ remodeling technology

Stem cell-based tissue engineering and organ remodeling technology is a biomedical engineering technology that produces bionic tissues and organs by integrating stem cells with biomaterials, tissue microenvironment elements, 3D bio-printing, and other tissue engineering construction technologies. Key technical problems in this field include: producing stem cells with the biological functions of target tissues and organs or stem cell-derived functional cells; producing biodegradable materials with suitable biomechanics and good biocompatibility; providing suitable blood supply, nutrients, cellular matrix, and other tissue microenvironment elements; and developing advanced 3D bio-printing and other construction technologies. The development of this technology will promote in-depth exploration of developmental processes, functional maintenance of normal tissues and organs, disease development, and the regeneration and functional reconstruction of tissues and organs; realize reconstructions of tissues and organs by mimicking their composition, structure, and function, realizing the transformation from basic research to clinical application in humans; provide new technologies, methods, and products for human health; provide a feasible way to improve length and quality of patients' life; and provide strong support for the development of emerging industries of tissue engineering and regenerative medicine.

(8) Humanized animal models

Humanized animal models are experimental animals with stable chimerism, leading to expansion and differentiation of human cells, tissues, or organs. Such animal models are appropriate for modeling development and metabolism of human organs of interest, as well as disease progression, giving the opportunity for fundamental R&D of therapeutic strategies. Generally, key factors to allow further development of the humanized animal model field include the methods for human cell transplantation and chimerism, development of appropriate recipient animals, system standardization, and large-scale application. Indispensably, the humanized animal model can provide a multi-dimensional and multi-model *in vivo* microenvironment for the progression of important human diseases, aiding the development of new drugs and therapeutic strategies. In contrast to other animal models, humanized animal models can be used to overcome the obstacle of species specificity, which has largely limited studies of some important human species-dependent pathogens. Currently, the humanized animal model field and relevant technologies are highly valued and are rapidly being developed both in China and internationally. Humanized animals with chimerism of single primary human tissues or organs have been widely applied in studies of some important pathogens. Important future research directions for this field include humanized animals derived from stem cells and even somatic cells, and humanized animals with chimerism of multiple homologous tissues or organs, in particular for immune system research. This next generation of humanized models will largely promote research on infectious diseases, malignant tumors, and autoimmune diseases. Another important consideration is to establish the standardization and large-scale application of humanized animal models.

China has established a good foundation in this field, having developed a variety of humanized animal models based on target needs and superior resources, highlighting its strong sustainable development capabilities.

(9) Single cell analysis techniques

Single cell analysis is the study of genomics, transcriptomics, proteomics, and metabolomics at the single cell level. It is by far the most powerful approach to investigate the physiological states, developmental trajectories, regulatory circuitry, and interactions of cells in heterogeneous populations. Since the first study of a single cell transcriptome in 2009, there has been tremendous growth in the fields of next-generation sequencing (NGS), mass cytometry (CyTOF), and single molecule imaging technologies. This has made it possible to simultaneously perform multiomic single cell analyses of the transcriptome, genome, metabolome, or proteome of up to one million cells per study. Since 2016, the international project "Human Cell Atlas" consortium have begun to use cutting-edge single cell analyses to create reference profiles of all cell types of the human body. The newly constructed atlases of the immune system, nervous system, and epithelia have already proven instrumental in identifying and annotating specialized or diseased cells in normal and pathological conditions. At the same time, single cell analyses of tumors, embryos, and patients undergoing therapy have provided unprecedented insights into the dynamic process of cellular differentiation and the evolution of intra-patient heterogeneity. With further improvement of single cell technologies, along with the continued decrease in associated experimental costs, the next decade will likely see the application of single cell analysis in constructing the cell atlas of all major human diseases, building the foundation for rapid and accurate diagnosis of abnormal cells at all stages of pathogenesis. This will undoubtedly facilitate our ability to fully realize the potential of precise and personalized medicine.

(10) Biomaterials for tissue regeneration and repair

Biomaterials for tissue regeneration and repair refers to materials that can play an important role in regeneration and functional repair of tissues and organs either through the physical and chemical properties of the materials, or through the loading of cells, growth factors, or drugs, for example. At present, the design and fabrication strategies of the biomaterials for tissue regeneration and repair field include restoring the shape and structure of the defective area, simulating the physiological microenvironment of tissue growth and development, precisely regulating the process of tissue regeneration, and realizing the interaction between host and material. The interdisciplinary nature of biomaterials for tissue regeneration spans the fields of materials science, biology, medicine, and advanced manufacturing technology. So far, biomaterials for tissue regeneration and repair have been successfully applied to repair defects in tissues such as the skin, blood vessels, cornea, bone, cartilage, and soft and hard oral tissues. Moreover, combined with digital medical technology and 3D printing technology, biomaterials for tissue regeneration and repair can also be used for personalized and precise treatment of biological defects. In addition to the applications in tissue regeneration, biomaterial-constructed microtissues, organoids, or organ chips are useful in developmental and pharmacology research, for example drug screening. Due at least partly to the increase in the aging population, the number of patients with injuries of human tissues and organs is increasing. Repairing tissue and organ defects using only traditional treatments is difficult, which has led to an increase in the need for biomaterials for tissue regeneration and repair. It is estimated that the global market for regenerative medicine will grow from 10.07 billion USD in 2018 to 48.97 billion USD in 2025, with a compound annual growth rate of 25.4%. As an important part of the regenerative medicine industry, the biomaterials for tissue regeneration and repair field has great potential for further development. Currently, there are several obstacles in the R&D of biomaterials for tissue regeneration and repair, such as inadequate induction leading to slow tissue regeneration, limitations in the regeneration of large tissues and organs due to the complexity of their structure and function, and differences in body status. Therefore, the development trends of this field include enhancing the inductive activity of biomaterials, constructing functional regenerative materials for large complex tissues and organs, and comprehensively realizing the needs for individualized regeneration.

2.2 Interpretations for three key engineering development fronts

2.2.1 Tumor immunotherapy technology

Tumor immunotherapy (also known as cancer immunotherapy or immuno-oncology) is a method of applying immunological principles and methods to treat cancer by stimulating and enhancing the body's anti-tumor immune response. The main methods of tumor immunotherapy include cancer vaccines, specific monoclonal antibody targeted therapy, cytokine therapy, immune checkpoint blockade, and adoptive cell therapy. Tumor immunotherapy has developed rapidly in the field of translational clinical medicine over the past decade. Its application has improved the quality of life and significantly prolonged survival for a large number of cancer patients, giving new hope for curing various advanced cancers. It has played significant roles in promoting the development of contemporary medical technology, reforming the medical and health system, and developing social welfare and medical systems in various countries. The field of tumor immunotherapy originated from the first tumor vaccine in 1893, but it was not until the 1990s that cytokine therapy, represented by IL-2, and monoclonal antibody targeted therapy brought dawn to the modern era of the field. In 2013, *Science* magazine ranked tumor immunotherapy at the top of the Top 10 scientific breakthroughs. In the past 5 years, immune checkpoint inhibitor and CAR-T cell immunotherapies have made major breakthroughs in various cancers and also promoted the development of other cancer immunotherapies. At present, tumor immunotherapy is the fourth type of cancer treatment that has been proven to have significant clinical efficacy after the three traditional treatment types: surgery, radiotherapy, and chemotherapy.

Presently, the development of tumor immunotherapy technology depends on solving the following key technical problems: (1) Discovery of tumor-specific targets; (2) Investigation of tumor immune escape mechanisms and development of appropriate countermeasures; (3) investigation of methods to overcome solid tumor microenvironments and heterogeneity; (4) Identification and application of tumor biomarkers; (5) Development of more durable and effective immunotherapy; (6) Improvement of the safety of immunotherapy; and (7) Development of new tumor immunotherapy and combination therapy techniques.

The number of cancer patients is currently increasing year by year, and the market demand for cancer therapy is huge. As a new industry that revolutionizes the standards and concepts of cancer treatment, the global market of tumor immunotherapy is growing rapidly. In 2016, the global market for tumor immunotherapy reached 61.9 billion US dollars, and with the increasing market demand it is expected to grow to 120 billion USD by 2021, with a compound annual growth rate above 14%. With the rapid development of the field, the number of tumor immunotherapy drugs and the number of R&D institutions and enterprises involved in tumor immunotherapy projects will continue to increase globally. The level of R&D of Chinese scientific research institutions in the tumor immunotherapy field is gradually integrating with this global expansion. Of the patents for new tumor immunotherapy technologies in 2013–2018, Chinese applications accounted for 18.51%, second only to the USA, indicating that China is one of the most prolific countries in the field of tumor immunotherapy. However, the total number of patents cited and the average number of citations from Chinese research are still considerably lower than those from the USA, and the quality of Chinese patents requires further improvement.

The current fronts in the field of international tumor immunotherapy research include: (1) Cancer vaccines: an active immunotherapy method that induces a patient's own specific immune response by use of an active substance containing a tumor-specific or tumor-associated antigen to overcome the immunosuppressive state and inhibit tumor growth. (2) Specific monoclonal antibody targeted therapy: monoclonal antibodies designed against tumor-specific antigens which lead specifically to tumor cell death either directly, by modifying tumor cell signaling cascades or tumor–matrix interactions, or indirectly, through antibody-dependent cellular cytotoxicity (ADCC) and complement dependent cytotoxicity (CDC). (3) Cytokine therapy: cytokines with multiple biological activities can either exert direct anti-tumor effects or indirectly enhance an anti-tumor immune response. For example, tumor necrosis factor alpha (TNF-α) and interleukin 6 (IL-6) directly affect tumor cell growth and survival, whereas IL-2 and interferon alpha (IFN-α) promote the growth and activation of T cells and natural killer (NK) cells. (4) Immune checkpoint blockade: a method of blocking immunosuppressive signals with specific antibodies of immunological checkpoint molecules (such as PD-1/PD-L1, CTLA-4), which activates immune cell recognition and permanently kills tumor cells. (5) Adoptive cell therapy: a method involves isolation of immunocompetent cells from tumor patients, followed by *in vitro* expansion and functional identification. The cells are then returned to the patient, killing tumor cells directly or stimulating the body's immune system to kill tumor cells. The current representative adoptive cell therapy, CAR-T, involves the use of genetic engineering technology to modify T cells to specifically identify tumor cells in a non-MHC-restricted manner. The modified T cells then directly and efficiently kill the tumor cells in a precise, targeted manner, which has been shown to have long-lasting effects in cancer treatment.

The global incidence of cancer has continued to rise over recent years. China has the largest number of cancer patients of all countries globally, and the incidence and mortality of cancer are still constantly rising. According to *Global Oncology Trend 2019*, the market for cancer treatment in China was 9 billion USD in 2018, and has been growing at an annual rate of 11.1%. The development of tumor immunotherapy improves the length and quality of life for many cancer patients, and even allows many to return to work, greatly reducing social burden and promoting economic development. With the advancement of China's innovative drug policy and the strengthening of R&D in the cancer immunotherapy field in recent years, an increasing number of scientific research institutions and pharmaceutical companies have entered the market, especially in the emerging field of adoptive cell therapy. At present, the overall level of China's tumor immunotherapy development is in a good position to make great strides forward. In the future, based on the promising results achieved in the field, by giving full play to the advantages of clinical sample resources in China, optimizing resource allocation, and encouraging cooperation and exchange among industries, universities, and research institutes, China will closely integrate with the frontier disciplines such as genomics, proteomics, and systems biology, and keep in pace with the cutting-edge of applied immunology research. In this way, it should be possible for China to overcome technical blockades, establish a leading position in the global field of immunotherapy, and ultimately make important contributions to the development of medical treatments and human health.

More than 4000 patents have been applied for in the area of tumor immunotherapy technology within the past five years. The USA, China, and Germany are ranked as the top three countries in terms of the number of active patents. The patents applied by Chinese researchers account for 18.51% of the global total, second only to the USA, indicating that China is one of the most prolific countries in the field of tumor immunotherapy. However, the average citation frequency of Chinese patents is 1.72, compared to 4.28 in the USA (Table 2.2.1), suggesting that China needs to make improvements in patent quality. As shown in the collaboration network of the top 10 patent-producing countries (Figure 2.2.1), the USA, Switzerland, UK, and China have close collaborations in the field of tumor immunotherapy technology.

The top three institutions in terms of patent output in the field of tumor immunotherapy technology are The Board of Regents of the University of Texas System, Dana-Farber Cancer Institute Inc., and Bristol-Myers Squibb Company (Table 2.2.2). In addition, the collaboration network of the top 10 patent-producing institutions shows cooperation between Novartis AG and The Trustees of the University of Pennsylvania, as well

Table 2.2.1 Countries or regions with the greatest output of core patents on "tumor immunotherapy technology"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citation	Citations per patent
1	USA	2786	55.50%	11 927	71.27%	4.28
2	China	929	18.51%	1 596	9.54%	1.72
3	Germany	266	5.30%	1 321	7.89%	4.97
4	UK	198	3.94%	554	3.31%	2.80
5	Switzerland	189	3.76%	1 829	10.93%	9.68
6	Japan	178	3.55%	234	1.40%	1.31
7	France	163	3.25%	765	4.57%	4.69
8	Canada	81	1.61%	230	1.37%	2.84
9	Israel	78	1.55%	159	0.95%	2.04
10	Australia	71	1.41%	50	0.30%	0.70

as between F. Hoffmann-LA Roche AG and Genentech Inc. (Figure 2.2.2) is close.

Between 2013 and 2018, the proportion of patents for “specific monoclonal antibody targeted therapy” and “adoptive cell therapy” was relatively large, and continues to increase year by year. Chinese patents accounted for 15.76% of the global total in the “specific monoclonal antibody targeted therapy” field, whereas USA patents accounted for 60.39%. Chinese patents also accounted for 34.54% of the global total in the field of “adoptive cell therapy”, while USA patents accounted for 44.13%. In 2018, Chinese patents accounted for 36.50% of the global total in the “adoptive cell therapy” field, compared to 43.10% for USA patents (Figure 2.2.3), indicating that China is increasing its focus on emerging areas of adoptive cell therapy. The overall tendency appears to be that China is catching up with the USA in terms of the number of patents.

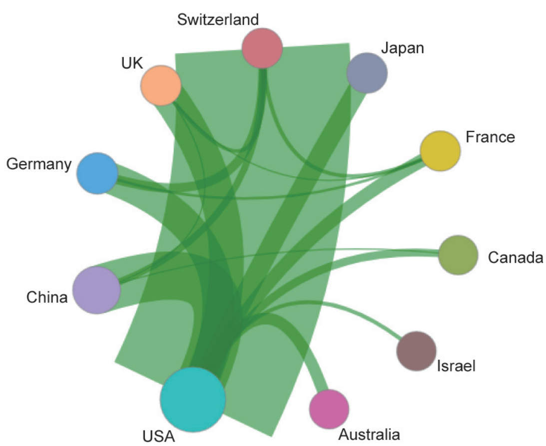

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of “tumor immunotherapy technology”

Based on the above statistical analysis, China is currently at a similar level as other leading countries in terms of the number of patents in the engineering development front of “tumor immunotherapy technology”, indicating that China is one of the leading countries in the field of tumor immunotherapy.

2.2.2 Intelligence assisted diagnosis technology

Intelligence assisted diagnosis refers to computers providing assisted disease analysis in clinical diagnosis to help doctors make better use of information and improve the quality and efficiency of diagnosis and treatment. The application of intelligence assisted diagnosis technology can not only alleviate the current shortage of medical resources, but also effectively promote the reform of the medical system, and help to gradually form a new business strategy in the medical field. Intelligence assisted diagnosis technology originated in the late 1950s, and has developed in three stages. The first stage mainly involved knowledge engineering, through the sorting, construction, and accumulation of medical knowledge. The second development stage involves shallow semantic learning and reasoning, which integrates traditional

Table 2.2.2 Institutions with the greatest output of core patents on “tumor immunotherapy technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citation	Citations per patent
1	TEXA	113	2.25%	405	2.42%	3.58
2	DAND	100	1.99%	725	4.33%	7.25
3	BRIM	89	1.77%	896	5.35%	10.07
4	USSH	88	1.75%	287	1.71%	3.26
5	NOVS	87	1.73%	1280	7.65%	14.71
6	UPEN	83	1.65%	1324	7.91%	15.95
7	HOFF	77	1.53%	689	4.12%	8.95
8	IMMA	67	1.33%	215	1.28%	3.21
9	GETH	65	1.29%	570	3.41%	8.77
10	SLOK	59	1.18%	367	2.19%	6.22

TEXA: The Board of Regents of the University of Texas System; DAND: Dana-Farber Cancer Institute Inc.; BRIM: Bristol-Myers Squibb Company; USSH: The United States of America as represented by the Secretary department of Health & Human Service; NOVS: Novartis AG; UPEN: The Trustees of the University of Pennsylvania; HOFF: F.Hoffmann-LA Roche AG; IMMA: Immatics Biotechnologies GmbH; GETH: Genentech Inc.; SLOK: Memorial Sloan Kettering Cancer Center.

machine learning and feature engineering. The third stage is autonomous learning of medical diagnosis decision reasoning, which is characterized by massive medical data and deep learning methods. At present, intelligence assisted diagnosis technology is in rapid development between the second and third stages.

The key technical problems that need to be solved for the next stage of development of intelligence assisted diagnosis technology are: (1) The representation learning of medical knowledge; (2) The construction of complex reasoning models based on diagnosis and treatment ideas; (3) The generalization of intelligence assisted diagnosis results; and (4) The biological interpretability of intelligent diagnosis models. In recent years, the global investment in the field of medical AI has shown a trend of rapid rise. The domestic intelligence assisted diagnosis related industry has also risen rapidly. In 2017, the industry output value in China reached more than 13 billion CNY, with an annual increase of 40.7%. It is predicted that he output value may exceed 20 billion CNY in 2018 according to the current development trend. At present, many technology giants are stepping up their efforts in the field of intelligence assisted diagnosis technology. For example, international companies such as IBM, Google, and Siemens have been engaged in the field of intelligence assisted diagnosis for many years, and have accumulated a large number of invention patents and formed certain technical barriers. Domestic high-tech enterprises such as Tencent, United Imaging Healthcare, and iFLYTEK have also made important breakthroughs over recent years, and are gradually adapting the development path of intelligence assisted diagnostic technology to China's national conditions.

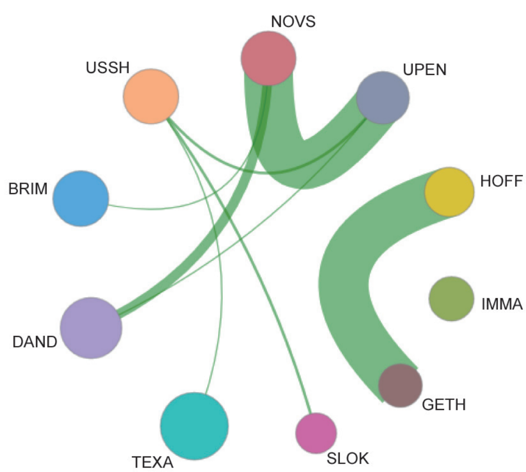

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "tumor immunotherapy technology"

China contributed one of the highest numbers of patent applications in the front of "intelligence assisted diagnosis technology" of all countries during the period 2013 to 2018, with its proportion of the global total reaching 25.1%. However, the quality of China's patents needs to be further

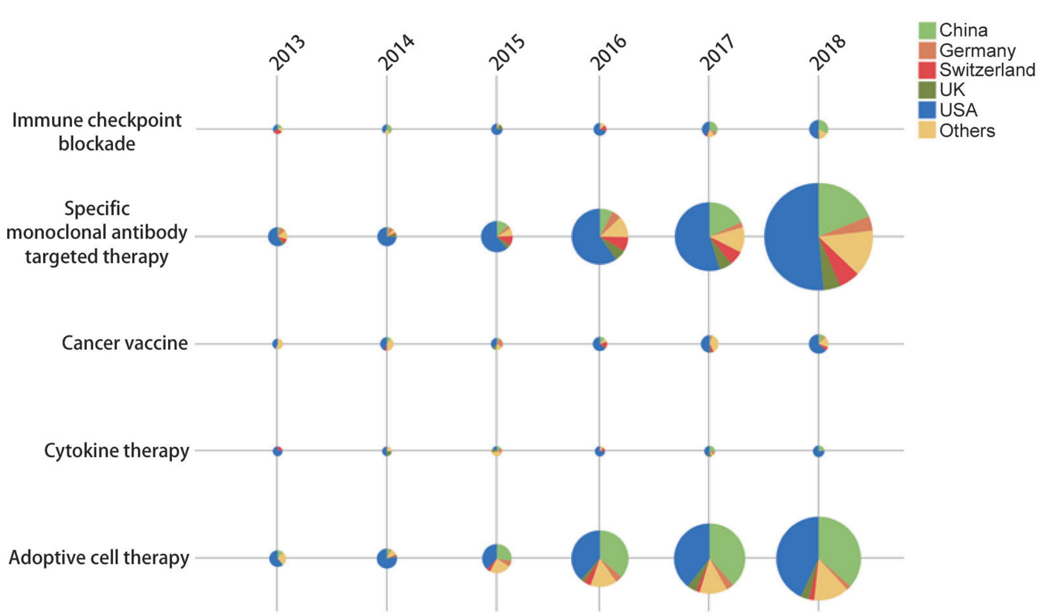

Figure 2.2.3 Major countries or regions producing patents in hot fields of "tumor immunotherapy technology"

improved. Moreover, the total number of patents and average number of patent citations are still far below those of the USA and other developed countries.

The current frontiers in the field of intelligence assisted diagnosis technology research include: (1) The mathematical model of deep learning for medical big data is the basis of intelligence assisted diagnosis technology. Medical data describing molecules, cells, tissues, and organs usually has a multidimensional attribute. The mathematical model of deep learning can be used as an interface that connects the multidimensional data, and illustrates the logical relationships of the data. (2) Radiomics that takes advantage of AI technology to comprehensively process images produced by X-ray, CT scan, magnetic resonance imaging, positron emission tomography, ultrasound, and pathology provides doctors with stacked intelligence assisted decision-making, effectively improving their efficiency and diagnostic accuracy. (3) AI-based gene diagnosis uses intelligent analysis methods to identify cancer cell biomarkers from massive genetic data and develop AI-assisted decision systems to track and predict the activities of cancer cells in the body. (4) Integration of physical sign monitoring and intelligent analysis to integrate intelligent analysis methods into the continuous and real-time monitoring by wearable devices. A deep learning network model can be constructed and applied to electrocardiogram data analysis and continuous blood glucose monitoring, thus to give early warning for potential diseases and provide significant references for subsequent diagnoses. (5) Clinical data intelligence assisted decision-making uses AI to develop a more structured clinical data management platform and allow modeling of clinical data. It can monitor clinical signs, assess diagnostic methods, and visualize the predicted result, thus embedding clinical decision planning in the process of clinical treatment, guiding doctor's medical judgment. (6) Intelligence assisted natural language processing mainly involves researching AI-based processing and application of natural language to provide personalized medical services to patients. It can improve the efficiency of medical treatment and the quality of medical records. (7) Medical AI specialized chips guarantee sufficient computing power for the application of intelligence assisted diagnosis. They not only allow adaption to the real-time requirements of professional medical scenarios, but are also required to fully support the speed and optimization of various deep learning algorithms which are used in medical diagnosis. (8) Medical assistance robots are an interdisciplinary field, incorporating not only intelligence assisted diagnosis technology, but also robotics, biological materials, and other advanced technologies. Through the organic combination of these techniques, it is possible to promote the development of capsule robots, surgical robots, and other high-end medical equipment.

With the rapid development of AI, there has been a steady increase in the accumulation of AI technology in the medical scene. As a typical technology in this field, intelligence assisted diagnosis has attracted extensive attention from the international community. In China in particular, the unique advantage of the high availability of medical big data provides the required foundations for the development of intelligence assisted diagnosis technology. However, due to mismatches in information systems between hospitals, the "isolated information island" phenomenon has become apparent. Meanwhile, a serious lack of standardization and structure has led to a reduction in the amount of useable medical data. These problems seriously restrict the development of intelligence assisted diagnosis technology. Although it is claimed that the currently developed intelligence assisted diagnostic systems have high diagnostic accuracy, they are still far from practical application. The development of intelligent diagnostic models by enterprises, universities, and research institutes has always been based on self-provided limited databases, whereas practical application scenarios are often more complex. Therefore, large-scale clinical testing is required to assess whether new intelligent diagnostic models have any practical value. However, the increasingly close cooperation between industry and hospitals will establish a multi-center open platform for clinical verification of intelligence assisted diagnosis, creating favorable conditions for its clinical application. On the other hand, intelligence assisted diagnosis technology brings many obstacles to the identification of medical liability, particularly in the determination of the scope of responsibility for medical negligence. It is therefore necessary to improve the laws and regulations regarding intelligence assisted diagnosis, and clarify the subjects of medical liability and the scope of rights and responsibilities. China has gathered a large number of high-end talents in the field of medical AI through the establishment of a state-level open platform. This platform accelerates the development of intelligence assisted diagnosis technology to a deeper interdisciplinary direction, and aims to meet future technical challenges.

In the past five years, more than 1400 patents on intelligence assisted diagnosis technology have been applied for. The USA, China, and Japan are ranked as the top three countries in terms of the greatest numbers of active patents. Although Chinese patents account for 25.01% of the global total (Table 2.2.3), the average cited frequency of China (0.93, Table 2.2.3) is much lower than that of the USA and other developed countries. This suggests that China needs to improve the quality of its patents. As shown in the collaboration network of the top 10 patent-producing countries (Figure 2.2.4), the USA and Germany are in close collaboration with each other.

The top three institutions in terms of the number of active patents in this field are Volcano, IBM, and Siemens (Table 2.2.4). In addition, the collaboration network of the top 10 patent-producing institutions shows collaboration exists between Siemens AG and Cerner Innovation Inc. (Figure 2.2.5).

2.2.3 Genome editing

Genome editing refers to the deletion, insertion, replacement, or single base substitution of DNA in the genome by deploying nuclease and cellular DNA repair machinery. This technique is currently in broad use to construct animal models,

Table 2.2.3 Countries or regions with the greatest output of core patents on “intelligence assisted diagnosis technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	6556	43.78%	33 029	71.10%	5.04
2	China	3745	25.01%	3 485	7.50%	0.93
3	Japan	967	6.46%	2 047	4.41%	2.12
4	South Korea	868	5.80%	1 073	2.31%	1.24
5	Germany	541	3.61%	1 500	3.23%	2.77
6	Netherlands	488	3.26%	1 041	2.24%	2.13
7	Canada	297	1.98%	1 244	2.68%	4.19
8	Israel	209	1.40%	920	1.98%	4.40
9	Taiwan of China	193	1.29%	318	0.68%	1.65
10	France	190	1.27%	330	0.71%	1.74

Table 2.2.4 Institutions with the greatest output of core patents on “intelligence assisted diagnosis technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	PHIG	465	3.11%	1101	2.37%	2.37
2	IBMC	352	2.35%	478	1.03%	1.36
3	SIEI	318	2.12%	1257	2.71%	3.95
4	SMSU	204	1.36%	582	1.25%	2.85
5	HEAR	198	1.32%	793	1.71%	4.01
6	GENE	130	0.87%	327	0.70%	2.52
7	BSCI	112	0.75%	319	0.69%	2.85
8	MEDT	95	0.63%	519	1.12%	5.46
9	UBIO	88	0.59%	343	0.74%	3.90
10	CRNR	79	0.53%	213	0.46%	2.70

PHIG: Volcano Corporation; IBMC: International Business Machines Corporation; SIEI: Siemens AG; SMSU: Samsung Electronics Co., Ltd.; HEAR: HeartFlow Inc.; GENE: General Electric Company; BSCI: Boston Scientific Scimed Inc.; MEDT: Medtronic MiniMed Inc.; UBIO: uBiome Inc.; CRNR: Cerner Innovation Inc.

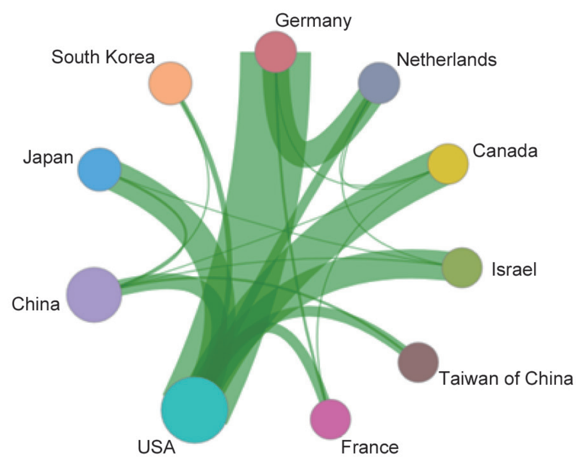

Figure 2.2.4 Collaboration network among major countries or regions in the engineering development front of "intelligence assisted diagnosis technology"

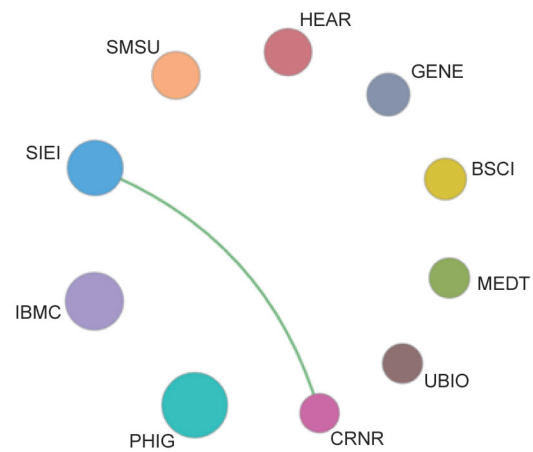

Figure 2.2.5 Collaboration network among major institutions in the engineering development front of "intelligence assisted diagnosis technology"

screen for new therapeutic targets, and improve agronomic traits of livestock and crops. Furthermore, it has made the transition from the bench to clinical trials, for example in the development of anti-virus drugs, CAR-T cell therapy, and blood disease treatments. From the emergence of first generation meganuclease in 1994 to the more recent popularization of ZFN and TALEN, gene editing has continuously been evolving in terms of its precision and efficacy. In 2012, the repurposing of the bacteria anti-phage CRISPR/Cas system for RNA-guided DNA-targeting brought a qualitative leap in the endeavors to re-write genetic information in any organism. It is now possible to achieve simple and efficient editing at single or multiple loci in living cells. In addition, multiple derivative technologies empowered by CRISPR/Cas, such as gene activation, gene silencing, RNA editing, epigenetic engineering, and base editing, provide a powerful tool repertoire for biomedical research to uncover the pathogenesis, mechanisms, and treatment of disease.

In the coming years, the predicted technical challenges for the development of gene editing technologies include: (1) Improvement of gene editing efficiency and precision; (2) Robust delivery systems for gene editing reagents; (3) Expansion of editable sequence space; (4) More accurate off-target evaluation methods; and (5) Development of RNA editing tools. Since the debut of CRISPR/Cas in 2012, this field has been explored enthusiastically, as evidenced by the explosion in relevant research publications inspired by the enormous potential for the application of CRISPR/Cas, particularly in the clinical sciences. Correspondingly, a large number of relevant patent applications have been filed. The top 3 countries or regions in terms of the number of gene editing-related patents are the USA, China, and Spain. Chinese patents make up 28.23% of the global total, second only to the USA, demonstrating China as one of the leading-edge countries in strategic engineering deployment (Table 2.2.5). As shown in the cooperation network of the top 10 patent-producing countries (Figure 2.2.6), the USA has a close relationship with Switzerland. It is worth noting that the core technical gene editing patents, especially those at relatively early stages, are held by European countries and the USA. This results in China having a relatively low average citation frequency of 2.14, ranking 7 in the top 10 countries. The top three institutions in terms of the number of active patents are Harvard College, Massachusetts Institute of Technology, and The Broad Institute Inc. (Table 2.2.6). In addition, the collaboration network among the top 10 institutions shows a close relationship among these top 3 institutions (Figure 2.2.7).

The current hot topics of gene editing include: (1) Treatment of disease caused by point-mutations by base editing: Gene editing enables us to modify target DNA defects on a molecular level, thereby curing diseases that are caused by DNA mutation. Encapsulating the gene editing system in virus allows specific targeting to the pathogenic site, allowing local *in vivo* gene therapy to cure diseases such as inherited blindness or hearing loss. For diseases bearing,

Table 2.2.5 Countries or regions with the greatest output of core patents on "genome editing"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citation per patent
1	USA	1433	48.33%	12 651	77.31%	8.83
2	China	837	28.23%	1789	10.93%	2.14
3	Spain	142	4.79%	28	0.17%	0.20
4	Switzerland	90	3.04%	651	3.98%	7.23
5	France	80	2.70%	669	4.09%	8.36
6	South Korea	79	2.66%	145	0.89%	1.84
7	Japan	68	2.29%	139	0.85%	2.04
8	Germany	55	1.85%	203	1.24%	3.69
9	UK	49	1.65%	203	1.24%	4.14
10	Canada	38	1.28%	120	0.73%	3.16

Table 2.2.6 Institutions with the greatest output of core patents on "genome editing"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citation per patent
1	HARD	144	4.86%	2696	16.48%	18.72
2	MASI	133	4.49%	4066	24.85%	30.57
3	BROD	97	3.27%	3619	22.12%	37.31
4	REGC	79	2.66%	510	3.12%	6.46
5	SAGM	47	1.59%	672	4.11%	14.30
6	EDIT	44	1.48%	521	3.18%	11.84
7	GEHO	42	1.42%	531	3.25%	12.64
8	CECT	33	1.11%	542	3.31%	16.42
9	CRIS	33	1.11%	131	0.80%	3.97
10	STRD	31	1.05%	121	0.74%	3.90

HARD: Harvard College; MASI: Massachusetts Institute of Technology; BROD: The Broad Institute Inc.; REGC: The Regents of the University of California; SAGM: Sangamo Therapeutics Inc.; EDIT: Editas Medicine Inc.; GEHO: The General Hospital Corporation; CECT: Cellectis; CRIS: CRISPR Therapeutics AG; STRD: The Board of Trustees of the Leland Stanford Junior University.

non-local phenotype, such as thalassemia, *ex vivo* editing of an individual patient's cells, followed by transfusion of the successfully edited cells back to the patient, would achieve a similar effect. (2) Genetically engineered immune cell therapy for cancer treatment: In CAR-T cell therapy, personalized cancer therapy is achieved by gene editing of an individual patient's killer T cells to prepare them against the patient's specific cancer cells, followed by transfusion of these customized killer T cells back to the patient. (3) Epigenetic or transcriptomic editing treatment for epigenetically inherited and degenerative diseases: These therapies utilize CRISPR/Cas9 to turn epigenetic markers on or off *in vivo*. For example, activating the gene that stimulate glia cells to neurons could be the key to curing neurodegenerative diseases. (4) Development of more sensitive clinical diagnostic kits: To detect trace amounts of pathogenic nucleic acid sequences in samples, it is crucial to amplify the correct signal. The correct signal can be identified by Cas, which locks onto the target nucleic acid sequence, and the signal can then be amplified with the help of a signal cascade amplification system. (5) High-throughput screening technologies for new therapeutic target identification: The CRISPR/Cas9 system can be applied to high-throughput screening, allowing the identification of new drugs. (6) Construction of animal models: Efficient construction of animal models using miniature model organisms such as drosophila, eelworm, rat, and mouse, and

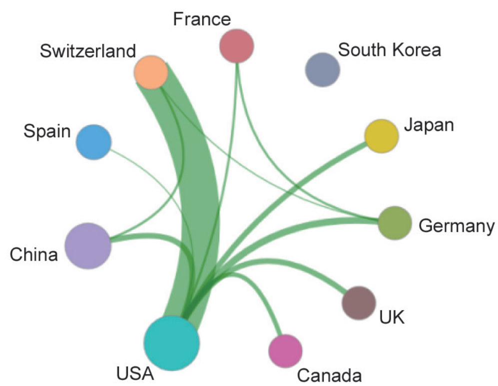

Figure 2.2.6 Collaboration network among major countries or regions in the engineering development front of "genome editing"

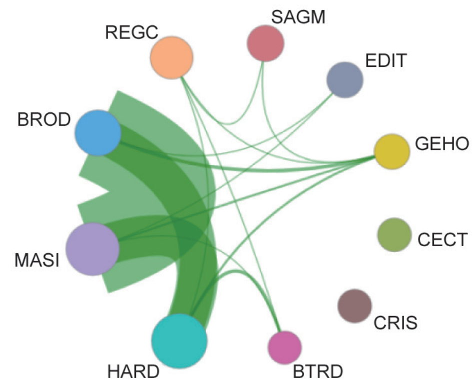

Figure 2.2.7 Collaboration network among major institutions in the engineering development front of "genome editing"

large organisms such as non-human primates, has reached an unprecedented precision, providing robust tools for both science research and clinical trials. (7) Breeding of animals and plants for agronomic trait improvement: This involves gene editing of animals and plants to obtain high quality breeds with the desired traits for agriculture and animal husbandry.

The huge potential of this technique will undoubtedly boost social evolution, particularly within the healthcare sector. As aging of the global population accelerates and patient ratios continue to rise, there will be a huge demand for gene therapy. Gene-based drugs are likely to represent the blue ocean market highly desired by countries all over the world. However, China is not necessarily an easy winner in this competing market; although it is tightly following the trend in patent applications, there is strong core competitiveness in European countries and the USA. China's aim is to discover new drugs, which requires practicing fundamental technology, and this comes with extremely high patent fees. Moreover, while the gene therapy industry has decades of history in western countries, in China the field is still immature. Despite its research quality approaching that of European countries, Chinese inchoate industrial structure displays a lack of referential experience or supporting social policies. Furthermore, the off-target effects of the gene editing technique hinder its progress, even in industry. Accurate off-target detection and further development of high precision editing tools are common goals of scientists in this field globally.

Participants of the Field Group

Leaders

CHEN Saijuan, ZHANG Boli

Academicians

GU Xiaosong, HUANG Luqi, LI Song, LI Zhaoshen, SUN Yinghao, TIAN Zhigang, XU Jianguo, ZHANG Zhiyuan, DONG Jiahong

Other Experts

ZHOU Rongbin, GUO Deyin, YI Fan, LIU Bing, YANG Hui, ZHOU Dawang, CHENG Gong, LIAO Zhuan, ZOU Wenbin, WANG Yueying, SHI Jian, XIAO Jianru, JIANG Jianxin, WANG Linhui, XIAO Liang, JIN Gang, SHENG Yuan, LI Hanzhong, ZHENG Jiasheng, WANG Haifeng, XU Qin, BAI Guo, LU Jinxing, QIN Chengfeng, QIN Chuan, ZHANG Jianzhong, ZHOU Dongsheng, CHENG Xunjia, SONG Hongbing, XIA Ningshao, LI Zhenjun, ZHAO Dongmei, CHENG Tong, ZHONG Wu, ZHOU Xinbo, FENG Jiannan, OUYANG Shaolian, HAN Qianqian, JIANG Qin, GU Zhongze, YAO Dezhong, ZHENG Hairong, LI Luming, XU Lai, XIAO Xiaohe, GUO Lanping, GAO Yue, YANG Hongjun, ZHANG Weidong, DUAN Jin'ao, XIAO Wei, LI Haiyan, LI Jiansheng, WANG Yongjun, MAO Jingyuan, WANG Baohe, WANG Hongwu, HUANG Yuhong, FAN Guanwei, ZHANG Han, YANG Jing

Secretary Group

ZHANG Wentao, ZHAO Xilu, XI Xiaodong, YAN Xiaoyu, CHEN Yinyin, DAI Yuting, QIAO Niu

Data Support Group

QIU Xiaochun, DENG Peiwen, WU Hui, FAN Rong, KOU Jiande, LIU Jie, TAO Lei, JIANG Hongbo, CHEN Daming, LU Jiao, MAO Kaiyun, FAN Yuelei, YUAN Yinchi

Report Writers

Engineering Research Front

TIAN Wei, HAN Xiaoguang, LI Lanjuan, FENG Jianfeng, XIE Xiaohua, XU Li, ZHAO Yuanjin, ZHOU Caicun, XIA Ningshao, CHENG Lin, LEI Qunying, QIAO Jie, DAI Kerong

Engineering Development Front

FAN Xiaohu, ZHENG Hairong, YANG Hui, BAO Yiming, MING Dong, TIAN Xiaohua, GU Xiaosong, XIA Ningshao, LIU Feng, JIANG Xinquan

IX. Engineering Management

1 Engineering Research Fronts

1.1 Trends in top 10 engineering research fronts

In the field of engineering management, the fronts of global engineering research mainly include the following ten parts: (1) research on sustainable development in the Industry 4.0 era, (2) construction management driven by machine vision, (3) resilience of the infrastructure systems, (4) application of big data in remote health monitoring systems, (5) effect of high-speed railway networks on urban development, (6) description of shared socioeconomic pathways and their expansion, (7) building information modeling (BIM) and safety management, (8) analysis and research on the Internet of Energy (IoE), (9) logistic trading and shipping management under the Belt and Road, and (10) research on blockchain alliance of energy exchange. Their core papers are shown in Table 1.1.1 and Table 1.1.2. Of these, research on sustainable development in the Industry 4.0 era, construction management driven by machine vision, and resilience of the infrastructure systems are the key fronts. Their development situations and future trends are detailed below.

(1) Research on sustainable development in the Industry 4.0 era

Industry 4.0 was first proposed by Germany as the development strategy for future manufacturing, which is essentially the digitalization of industrial production. It is the intellectualized transformation of the traditional manufacturing industry by closely combining it with information and communication technology (ICT) and Cyber-Physical Systems (CPS). Industry 4.0 is regarded as the fourth industrial revolution marked by high digitalization, networking, and self-organization of machines following the previous three industrial revolutions, namely, the application of steam engines, large-scale electrified production, and automatic production based on information technology. The core goal of Industry 4.0 is intelligent manufacturing and its core feature is interconnection, representing a new intelligent production model towards "Internet + manufacturing." Furthermore, Industry 4.0 is an interactive embeddedness of the new generation of ICT and

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on sustainable development in the Industry 4.0 era	22	486	22.09	2017.2
2	Construction management driven by machine vision	17	424	24.94	2016.6
3	Resilience of the infrastructure systems	28	691	24.68	2017.3
4	Application of big data in remote health monitoring systems	33	703	21.30	2016.1
5	Effect of high-speed railway networks on urban development	34	771	22.68	2015.4
6	Description of shared socioeconomic pathways and their expansion	20	789	39.45	2016.6
7	BIM and safety management	8	100	12.50	2017.1
8	Analysis and research on the IoE	6	143	23.83	2017.0
9	Logistic trading and shipping management under "the Belt and Road"	9	107	11.89	2017.6
10	Research on blockchain alliance of energy exchange	5	108	21.60	2017.6

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in engineering management

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Research on sustainable development in the Industry 4.0 era	0	0	1	4	7	10
2	Construction management driven by machine vision	0	0	0	9	6	2
3	Resilience of the infrastructure systems	0	0	0	0	21	7
4	Application of big data in remote health monitoring systems	4	2	5	4	11	7
5	Effect of high-speed railway networks on urban development	2	8	9	7	6	2
6	Description of shared socioeconomic pathways and their expansion	2	8	9	7	6	2
7	BIM and safety management	0	0	0	1	5	2
8	Analysis and research on the IoE	0	0	1	1	1	3
9	Logistic trading and shipping management under “the Belt and Road”	0	0	0	2	0	7
10	Research on blockchain alliance of energy exchange	0	0	0	0	2	3

industrial manufacturing technology as well as an intelligent combination of the virtual and real worlds. It reflects the profound evolution of human–machine relationships and socially-networked organizational patterns. The advancement of Industry 4.0 has brought about the rapid increase of output and efficiency, the dramatic reduction of production and human costs, and has put forward new requirements for the production mode, value chain, industrial form, business model, and management promotion of traditional engineering management. Providing the corresponding ecological capabilities of the platform and establishing a complete application ecology and business ecology are especially key to the next stage because the interoperability between different applications has become a bottleneck as the platform technology matures and the application in different industrial scenarios become increasingly abundant. The global Industry 4.0 tide indicates that the manufacturing industry will return to the strategic focus of all countries in the future and will become an important engine for global economic growth, exerting profound effects on the distribution of international industrial labor and value division, and the restructuring of globalization.

(2) Construction management driven by machine vision

Machine vision is the realization of human visual functions in computers—perceiving, recognizing, and understanding the three-dimensional scene of the objective world, and realizing the acquisition, processing, and analysis of digital images. Compared with sensing technology such as radio frequency identification (RFID), global position system (GPS), and ultra wideband (UWB), machine vision can provide more abundant image and video information without wearing sensors. With the development of camera sets and the maturity of deep learning algorithms, machine vision has been widely used in the field of construction, particularly in safety surveillance, productivity analysis, and defect detection of large infrastructure facilities (roads, bridges, tunnels, etc.). In the construction process, the risk identification and surveillance based on machine vision during construction are a hotspot of research. Traditional construction relies on periodic manual inspection which is time- and labor-consuming and cannot achieve full-time monitoring, while automated monitoring based on machine vision can improve safety management. Currently, the research on machine vision often relies on extracting feature information by using algorithms, but it fails to achieve a high degree of semantic understanding of scenes. In addition, because deep learning algorithms often require a large number of data training models, the lack of an open graphics database greatly restricts the further development of machine vision technology.

(3) Resilience of the infrastructure systems

The infrastructure system refers to the network of engineering facilities providing basic services for social production and residents’ lives, including electric power, natural gas, transportation, water feed and drainage, communication, and other related systems. In recent years, the risk of failure of these systems caused by natural disasters, climate change, and rapid urbanization has increased year by year; in addition, these systems are interrelated, causing the internal failure of a single system to spread among the different systems, causing simultaneous damage to multiple systems. This seriously affects the economy of cities and even the whole countries and people's lives. In the 2010s, many countries or regions, such as the USA, Europe, Canada, and Australia, have proposed protection plans for their infrastructure systems. Resilient infrastructure systems, which are systems that can maintain certain basic functions during and restore normal functions soon after disasters, have become the objective of active construction in many countries. Evaluating and improving the resilience of infrastructure systems have been research hotspots for the interdisciplinary international fronts such as urban planning, civil engineering, and industrial engineering.

(4) Application of big data in remote health monitoring systems

With the iterative development of information technology, remote health monitoring systems are becoming the highlight of information analysis in the field of health. For residents, especially for patients in remote or mountainons areas, remote health monitoring systems have improved the health service geography and economic reachability, enabling in-charge doctors to analyze medical and health data of service targets and put out high-quality services while saving health funds. In the field of medical health, the application of big data technology is becoming the consensus of health development. Health and medical big data are a "mine of inexhaustible gold" and will provide a new impetus for high-quality development of health services. Generally speaking, remote health monitoring systems mainly include a health information acquisition module, a monitoring terminal module for processing the health information, and a remote medical service platform module, wherein, data acquisition and transmission are the keys of the whole system. Along with the application of 5G technology, remote health monitoring systems will face larger development opportunity. Building cloud-based regional health big data platforms and using remote health monitoring systems can facilitate the interaction among hospitals, doctors, patients (and their families), and medical devices; they can provide patients with more accurate diagnostic suggestions and better personalized treatment solutions; they can help realize the closed-loop of user health management and directly drive basic health bodies to conduct intelligent medical health management services. Currently, as the application of health big data is still under exploration and the remote health monitoring systems are not yet mature, the difficulties and hotspots of research mainly include intelligent integration of health data, construction of health big data platforms, construction of health management closed loops, interaction of the data from multiple medical institutes, and health data exploitation technology.

(5) Effect of high-speed railway networks on urban development

In recent years, the high-speed railway construction represented by China has been developed greatly, having a significant effect on urban social economies and spatial structures, bringing new opportunities as well as new challenges to urban sustainable development. As a research topic, the fast and convenient high-speed railway network can promote inter-city exchange of economic elements, optimize geographic space layout, reconstruct urban space connections and drive the growth of city clusters. Globally, the current research has construed the internal link between high-speed railway and urban as well as inter-city spatial structures from the perspective of traffic accessibility, connectivity, and station location; revealed the action mechanism of high-speed railways on urban development and urbanization quality based on economic structures, population flow, environmental protection, and residents' behaviors; evaluated the alternative effect of high-speed railways, aviation and other traffic tools; analyzed the interactive interface among different traffic modes; and built convenient and efficient transportation systems inside and outside cities. In addition, the current research has provided the key concerns: to optimize high-speed railway networks, and to promote urban transformation and development; to optimize the layout of the high-speed railways and promote their balanced construction in urban areas; to consummate the construction of high-speed railways and guide the healthy competition of cities; to avoid high-speed railway development mode oriented by quantitative growth of cities and short-term benefit; to co-develop comprehensive operation systems by different departments under the background of big data and artificial intelligence (AI) and realize a seamless connection of high-speed railways, aviation, and common railways; to incorporate the design and site location of high-speed railways into urban development strategies strengthen the selection and design of high-speed railway stations, and construct an organic link with the local ecological, economic, and social cultural environments.

(6) Description of shared socioeconomic pathways and their expansion

The concept of shared socioeconomic pathways (SSPs) is the new scenario framework for the research of land utilization–ecological environment–climate change system and it can describe the development trend of future societies and reveal the co-relation and internal logistics between climate change and socioeconomic elements. The SSP framework takes into account six key elements for building the future socioeconomic scenario, namely, population, human development, economy and lifestyle, policies and mechanism, technology, and environment and natural resources. The SSP framework includes five pathways, i.e., the sustainable development pathway (SSP1), intermediate pathway (SSP2), regional rivalry pathway (SSP3), disequilibrium pathway (SSP4), and development pathway dominated by fossil fuels (SSP5). According to the framework scenarios of SSP, current scholars, in China and abroad, have conducted predictions, research and driving factor analysis on population, economy, energy, greenhouse gas emission, and urbanization levels by comprehensively using models in different scales and scopes all over the world. Such models include the population–development–environment analysis (PDE) model, Cobb–Douglas economic prediction model, integrated appraisal model (IAM), computable general equilibrium (CGE) model, GLOBIOM and IMPACT model, global change appraisal model (GCAM), and future land utilization simulation (FLUS) model. The hotspots of the research in recent years have been researching SSP multi-element coupling mechanisms based on land resource utilization and analyzing the dynamic changes of lands in the different pathways. The SSP is part of the new scenario framework being used in the field of climate change research, and it aims to provide basic data for the research on climate change effects, risks, adaption, and alleviation. Additionally, it illustrates different pathways for possible future socioeconomic development and provides references for the selection of relevant climate change countermeasures and realization of sustainable development.

(7) Building information modeling (BIM) and safety management

The prevention of major accidents and injuries have become the focus of all industries. Due to severe situations of occupational health and safety, the management of the engineering construction sector has always been a concern in the world. Along with the development of AI and ICT, exploring and analyzing the applications of ICTs and intelligence methods in building design, engineering design, and the construction service sector, safety management, in particular, is the current research front. Building information modeling (BIM) is deemed as one of the most valuable methods for improving safety management. Based on information of a project process from design, construction, and operation coordination, the BIM technical method can construct the integral digital integration process flow related to safety management (process visualization, simulation optimization, interactive coordination, etc.). Along with the constant promotion of the application of BIM technical methods in the engineering sector, technical methods of BIM+others have emerged, such as RFID/GIS positioning technology, virtual reality (VR), augmented reality (AR), eye tracker technology, cloud computing, and machine vision method; and the issues related to safety management have further deepened. The key issues for the hotspots of research on BIM and safety management include the following: the BIM automatic safety review method, 3D–*n*D engineering safety simulation and analog analysis methods, safety management information control method integrated with other technologies, BIM and image/data-based engineering safety risk scenario analysis method, etc. BIM has pushed forward the change of data-driven management models and technical methods. Researching BIM and other technical methods is rather significant to information consolidation, visualization, sharing, delivery, integration, and computing in the process of engineering construction, and to scientific issues of engineering whole-process safety management such as effect characteristics, change rules, and control requirements, and the whole-life safety and management of current construction engineering projects.

(8) Analysis and research on the IoE

With the stress of energy marketization and a development mode for a green economy, sustaining social development demands higher requirements of energy systems in view of energy safety, environmental pollution, and climate change. As a new industrial form, the IoE is an important approach for pushing forward the energy revolution and improving energy utilization efficiency. The IoE, a new energy system deeply integrated by the energy system with a core of electric power and the Internet based on electronic information technology, has realized the two interconnections, i.e., the multi-energy physical interconnection and the data interconnection with transparent energy and resources. Although the IoE is still being defined, with the close coupling with renewable energy, natural gas, and traffic networks and other systems, it has become the new focus of current international scientific research and industrial development. Currently, the research hotspots of technical innovation of the IoE include construction of the general structure and standard system, construction of the networking and inter-operational model, modeling simulation and analysis technology development, operation and control equipment research and manufacturing, and construction of security systems. Due to high systematicness and complexity, the IoE requires consolidated planning and top designs. In the future, the IoE needs to be more open in energy types, users, standards, and interfaces, and to have richer applications, realizing multi-energy interconnection and multi-user interconnection. Along with the maturing of scientific technologies and consummation of relevant policies, the IoE will play an important role in energy production, transmission, consumption, storage, conversion, and other links of energy exchange and supply chains.

(9) Logistic trading and shipping management under the Belt and Road

As China is entering the center of the world stage gradually, the Belt and Road Initiative has been initiated. Along with the deepening and promotion of this initiative, the basic significances of logistical channels have been expressed. As an economic bond for surrounding countries or regions, it has realized the coordinated development of the regional economy. This initiative has grown rapidly due to its adaptation to world economy development rules, but it has also challenged logistical risk management. The logistics channel of "the Belt and Road" is important in realizing strong traffic. The research on the improvement of influence and competitive power of the logistics industry of China, the elevation of the sector's standards to regional and even international standards, and the promotion of the internationalization of logistical standards are the development directions in the future; moreover, the logistics sector shall consummate the construction of the talent supply chain, establish the cultivation system of organization and technology professionals to cultivate talents who can connect with international organizations and surrounding countries, incorporate the construction of talent output channels to the key points of research, meet international demand dynamically, and realize the innovative development of the talent supply chain, which is the research direction in the future. The logistics channel is not only for material circulation, but also bears the opportunities to develop China's trade. The construction of a "traffic–trade" corridor mode is an important direction. For realizing the closed-loop development of corridor economies targeted at coordinated and innovative development of "logistics, trade, and industries", promoting the deep application of big data and Internet of Things (IoT) to forge a "supply chain of data" and realize comprehensive optimization is the future feasible direction. In addition, as geopolitics, exchange rates, ecology, and other factors challenge the the Belt and Road Initiative, how to warn the risk through changes of surface features and realize the logistics, trade, and shipping risk management under the Belt and Road as per the decision-making system with fast response is another direction to take.

(10) Research on blockchain alliance of energy exchange

With the evolution of the commercial society, the organizational structure of centralized exchanges with third parties at the core has exposed three problems, i.e., privacy disclosure, high cost, and unclear ownership. With the development of computer technology, the distributed database has become the key to decentralization. Blockchain, a distributed data management technology, can change the way of managing exchange participants from centralized control to distributed collaboration. The multi-party sharing mechanism enables the participants to form blockchain alliances that can access, maintain, and share databases. Auditing and tracking the credits of the database updaters has improved the security of exchange and information sharing. With the development of green and shared economies, the traditional business model of energy enterprises no longer adapt to the demand of the contemporary low-carbon economy, incurring a transformation in the energy sector led by energy enterprises and users. Energy departments apply blockchain technology to provide a distributed energy system so that energy supply contracts can be transmitted directly between producers and consumers. The combination of blockchain technology and energy departments has resulted in abundant energy exchange applications, such as the application of blockchain technology in management of energy enterprise capital, energy user, energy network supply chain, renewable energy power generation, and energy sharing. Improving the computing, storage, and processing capacities of blockchain and determining cross-sector open standards when the blockchain technology provides more channels for capital operation and exchange management of energy departments is of great significance to the deep commercial application of blockchain technology in the field of energy, and it is an important research direction of the future.

1.2 Interpretations for three key engineering research fronts

1.2.1 Research on sustainable development in the Industry 4.0 era

The sustainable development of engineering in the Industry 4.0 era mainly focuses on four typical areas: global industrial development strategy, system framework and key technologies, coupling with circular economies, and construction industrialization.

(1) Global industrial development strategy

The concept of Industry 4.0 was first proposed by the German Federal Ministry of Education and Research and the Federal Ministry of Economy and Technology in 2013, aiming to improve the competitiveness of the German industry. The proposal of Industry 4.0 has triggered a new round of industrial transformation competition all over the world. Many countries have put forward their own re-industrialization strategies. In the era of big data, cloud computing, and mobile interconnection, it is necessary to upgrade enterprises by combining intellectualization and industrialization to break through the existing growth bottleneck in productive forces.

The USA announced its National Strategic Plan for Advanced Manufacturing and proposed the Industrial Internet to improve production efficiency and create the future of the digital industry through machine interconnection, software, and large data analysis. The UK launched The Future of Manufacturing strategy to promote the sustainable development of society and the economy by focusing on a high-value manufacturing industry and adopting individualized low-cost products, production redistribution, and digitization of the manufacturing value chain. The European Union (EU) issued the "Factories of the Future" program to support the research, development, and innovation of advanced production technologies, and it further launched the "Digital Single Market" strategy to improve the usability of digital goods and services, foster a prosperous environment for digital networks and services, and create the European digital economy and society with potential long-term growth. Japan has formulated The Fifth Science and Technology Basic Plan. It plans to build a new super-intelligent society through the integration of cyberspace and real space and the creations of new industries and services. China has promulgated "Made in China 2025," which includes accelerating the deep combination of the new generation of information technology and manufacturing industries, promoting intelligent manufacturing, strengthening the basic industrial capacity, improving the level of comprehensive integration, and promoting industrial transformation and upgrading. The research strand on the development strategies of global industries is mainly based on a policy research perspective, and covers relevant topics such as the core concepts, comparison analysis, strategic choice and path optimization, implementation methods, support system, open cooperation, management change, influence on the sustainable development of national and global societies and economies, and so on.

(2) Industry 4.0 framework, key technologies, and development evolution

Industry 4.0 is a complex engineering system with different objects and subjects. Its objects include the techniques, process, and automation under different standards in the industrial field, as well as information, communication, and Internet technology in information field. The Reference Architecture Model Industrie 4.0 (RAMI 4.0) illustrates Industry 4.0 in three dimensions: product life cycle and value chain, full-level industrial system, and capability level of CPS. RAMI 4.0 defines new standards and a technical framework and points out the direction for enterprises to deploy new infrastructure, apply new technologies, and exploit new standards. The framework of Industry 4.0 exhibits the basic model of transformation from a centralized to a decentralized enhanced control, and the goal is to establish a highly flexible production model with individualized and digitalized products and services.

Currently, the development of Industry 4.0 focuses on four main aspects: 1) Intelligent factories based on intelligent, networked production systems and networked distributed production facilities; 2) Intelligent production based on emerging technologies such as production logistics management, human–computer interaction, and 3D printing technology; 3) Intelligent logistics which integrates demand and matches services with demand based on the IoT, logistics network, and the Internet; 4) Intelligent services based on multi-faceted information technology applications and diversified cross-platform satisfaction of customer demands. The key technologies of Industry 4.0 include the IoT, cloud computing, industrial big data, industrial robots, 3D printing, knowledge task automation, network security, VR, and AI.

Successful implementation of Industry 4.0 involves three affinitive areas of action: digital sovereignty, interoperability, and sustainability. Digital sovereignty is the freedom of market participants to make decisions and participate in fair competition. It mainly touches upon digital infrastructure, security, and technological progress. Interoperability is the key element of the digital business process in Industry 4.0. It mainly involves standards and integration, regulatory framework, distributed systems, and AI. Sustainability covers economic, environmental, and social sustainability, and mainly includes employment and education, social participation, and climate change.

(3) Coupling between Industry 4.0 and circular economies

The development of Industry 4.0 is reconstructing the traditional economic system. The widespread application of intelligent technology could make economic systems more conveniently and harmoniously embedded into the material cycle process of natural ecosystems and realize the ecologization of economic activities. Typical Industry 4.0 and circular economy coupling models are based on the regenerate, share, optimize, loop, virtualize and exchange (ReSOLVE) framework. The five main steps are as follows: 1) Select an approach to ReSOLVE; 2) Identify suitable Industry 4.0 technologies; 3) Adopt sustainable operation management (SOM) decisions; 4) Develop cooperation in the supply chain; 5) Create performance indicators and small and achievable targets. Its core idea is to integrate and optimize the design-based and process-based methods to achieve the cyclic utilization of materials throughout a product life cycle, which would make Industry 4.0 the key enabling factor of a circular economy. The coupling between Industry 4.0 and circular economies involves technological, social, and business paradigm changes. Relevant research topics include an evaluation system of circular economies in the context of Industry 4.0, extended producer responsibility (EPR), green supply chain, zero-waste cities, source control schemes, pollutant process control, benign interference methods, key ecological link technology, etc.

(4) Construction Industry 4.0

As an important subdivision sector in Industry 4.0 era, construction industrialization has attracted much attention in the field of engineering management. Construction Industry 4.0 refers to the informationization and industrialization of the construction industry. It embodies the revolutionary transformation from the traditional manual operation to the building automation mode, from centralized to decentralized enhanced control and governance mode, and to a highly flexible production mode of individualized and digitalized construction products and services. The essence of construction industrialization in the Industry 4.0 era is to reconstruct a heterogeneous and customized construction industry through data flow automation technology with homogeneous and large-scale costs. It also reflects the change from economies of scale to economies of scope. Its goal is to achieve sustainable development of construction products in energy saving, environmental protection, and value maximization in whole-life cycles by technology chain integrating, industrial chain reengineering, and value chain upgrading. There are two important strands in the research of sustainability of construction industrialization in Industry 4.0: BIM and prefabricated construction. Being the core technology platform in construction industry, the integration of BIM and Industry 4.0 will promote the subversive revolution of the construction industry. BIM provides accurate building information, continuous digital records, and a collaborative work platform, which ensures the refined, intelligent, and green management in the whole-life cycle of construction products. Prefabricated construction is a breakthrough innovation of the construction mode. With standardized design, factory production, prefabricated constructing, all-in-one decoration, information management, and intelligent application, prefabricated construction could greatly help the construction industry to realize sustainable development. Highlighted research topics include policy support mechanism, management models, diversified governance, design technology systems, important green and integration technology, collaborative innovation network, cultivation of human resources, and so on.

The research on the sustainable development of engineering in the Industry 4.0 era is still in its infancy.

The number of core papers published has increased rapidly over the past three years. Germany, the USA, and France are the top three countries that have published the largest number of core papers related to sustainable development of engineering in the Industry 4.0 era (Table 1.2.1), while Sweden, Germany, and Brazil are the top three countries with the largest number of citations per paper (Table 1.2.1).

According to the collaboration network among major countries or regions producing core papers (Figure 1.2.1), a close cooperation network does not exist yet, but the network shows some preliminary regional characteristics. Sporadic collaborations exist between the USA and Asia, and similar ones exist between Germany and France, as well as France and Brazil.

Berlin University of Technology, Friedrich-Alexander University Erlangen-Nurnberg, and Montpellier Business School are the top three institutions that have published the largest number of core papers (Table 1.2.2). Based on the cooperation network chart of the institutions producing core papers (Figure 1.2.2), a close cooperation network does not exist, but the network also shows some preliminary regional characteristics which are consistent with the distribution of the country or region. China is still in a leading position.

Table 1.2.1 Countries or regions with the greatest output of core papers on "research on sustainable development in the Industry 4.0 era"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Germany	6	27.27%	195	40.12%	32.50
2	USA	4	18.18%	50	10.29%	12.50
3	France	4	18.18%	85	17.49%	21.25
4	Brazil	3	13.64%	75	15.43%	25.00
5	China	2	9.09%	17	3.50%	8.50
6	South Korea	2	9.09%	22	4.53%	11.00
7	Japan	1	4.55%	7	1.44%	7.00
8	Italy	1	4.55%	4	0.82%	4.00
9	Spain	1	4.55%	3	0.62%	3.00
10	Sweden	1	4.55%	33	6.79%	33.00

Table 1.2.2 Institutions with the greatest output of core papers on "research on sustainable development in the Industry 4.0 era"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Tech Univ Berlin	2	9.09%	97	19.96%	48.50
2	Friedrich Alexander Univ Erlangen Nurnberg	2	9.09%	30	6.17%	15.00
3	Montpellier Business Sch	2	9.09%	22	4.53%	11.00
4	Beijing Inst Technol	1	4.55%	7	1.44%	7.00
5	Doshisha Univ	1	4.55%	7	1.44%	7.00
6	Univ Texas Dallas	1	4.55%	7	1.44%	7.00
7	UFSCar Fed Univ Sao Carlos	1	4.55%	14	2.88%	14.00
8	Sapienza Univ Rome	1	4.55%	4	0.82%	4.00
9	Univ Tuscia Viterbo	1	4.55%	4	0.82%	4.00
10	Fraunhofer Inst Reliabil & Microintegrat	1	4.55%	10	2.06%	10.00

The USA, Germany, and China are the top three countries that have published the largest number of citing papers related to the sustainable development of engineering in the Industry 4.0 era (Table 1.2.3), while University Johannesburg, University Nova Lisboa, and Berlin School of Economic & Law are the top three institutions that have published the largest number of citing papers (Table 1.2.4).

1.2.2 Construction management driven by machine vision

With the development of signal processing theory and computer technology, people began to try to use cameras to obtain environmental images and convert them into digital signals, so that computers could extract environmental information through one or more images. The computers' main tasks are image processing, pattern classification, and

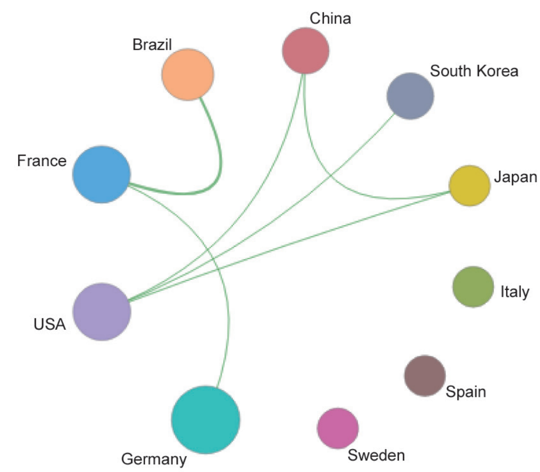

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "research on sustainable development in the Industry 4.0 era"

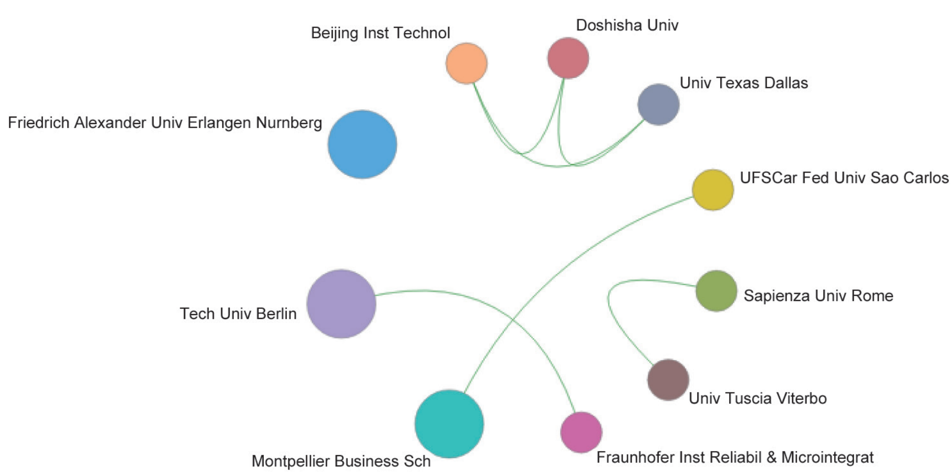

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "research on sustainable development in the Industry 4.0 era"

Table 1.2.3 Countries or regions with the greatest output of citing papers on "research on sustainable development in the Industry 4.0 era"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	42	15.27%	2018.0
2	Germany	39	14.18%	2017.7
3	China	37	13.45%	2017.8
4	Italy	32	11.64%	2017.9
5	UK	27	9.82%	2017.9
6	France	22	8.00%	2017.7
7	Brazil	21	7.64%	2017.8
8	Spain	17	6.18%	2017.5
9	Portugal	14	5.09%	2017.5
10	Russia	12	4.36%	2017.6

Table 1.2.4 Institutions with the greatest output of citing papers on “research on sustainable development in the Industry 4.0 era”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Univ Johannesburg	6	10.34%	2017.8
2	Univ Nova Lisboa	6	10.34%	2017.7
3	Berlin Sch Econ & Law	6	10.34%	2017.3
4	Univ Fed Santa Catarina	6	10.34%	2017.8
5	Norwegian Univ Sci & Technol	6	10.34%	2017.2
6	Worcester Polytech Inst	5	8.62%	2018.0
7	Seoul Natl Univ	5	8.62%	2017.6
8	Friedrich Alexander Univ Erlangen Nurnberg	5	8.62%	2018.2
9	Old Dominion Univ	5	8.62%	2018.0
10	Kyonggi Univ	4	6.90%	2017.5

scene analysis. Machine vision systems are widely used in industries, for applications including detection of the products from automatic production lines, face recognition, and automatic understanding of medical images. The application of machine vision in the construction industry has become a new topic of concern. It can improve the level of automation in the construction field. The mainstream algorithms, hot research issues, and research status of machine vision in the field of architecture are discussed further below.

(1) The main algorithms of machine vision

An important step in machine vision is the detection of a target object, that is, to recognize a specific object from an image. There are many algorithms for target object detection, which can be divided into two kinds: shallow machine learning and deep learning. The main algorithms of the former are histogram of gradient (HOG), histogram of flow (HOF), support vector machine (SVM) and *k*-nearest neighbor. However, these methods need to create features manually, which is time-consuming and cannot satisfy both detection accuracy and computational efficiency. In addition, uncertainties and changing construction scenarios prevailing in a construction site will affect feature extraction in the image, such as viewpoint variance, scale variance, intra-class variance, or background clutter, resulting in reduced accuracy of object detection. As an end-to-end learning method, with a strong ability to represent features and high learning accuracy, deep learning has become the main algorithm in machine learning research of the current construction industry. Examples of deep learning algorithms are Single Shot Multibox Detector (SSD), You Only Look Once (YOLO), and convolutional neural networks (CNN). Of these, CNN is the basic element of deep learning algorithms, including multiple convolution layers, rectification linear unit, pooling layer, and full connection layer. The emergence of CNN greatly improved machine vision in target object detection. Based on CNN, other algorithms have gradually been developed, such as recurrent neural network (RNN), fast region-based convolutional neural network (Fast R-CNN), and mask regions with convolutional neural network (Mask R-CNN).

(2) Construction safety management based on machine vision

The construction sector is one of the high-risk sectors and is prone to safety mishaps and casualties. A major research hotspot is the use of machine vision to realize automated safety supervision in construction processes, and to find out the unsafe behaviors or unsafe states in construction processes in time and feed them back to executives in time.

The research contents include object detection, object tracking, and motion recognition. Of these, object detection is the premise of object tracking and motion recognition and needs to segment an image, extract features, and classify its features using deep learning algorithms. Research in object tracking aims to improve the accuracy of estimation of physical position of an object. Compared with sensing technology, machine vision has a wider coverage, and it can achieve multi-target object tracking without the need to install interventional sensors. Motion recognition aims to extract the movement information of laborers or machines from images, which depends on the extraction and classification of image features.

(3) Productivity analysis based on machine vision

Productivity analysis aims at avoiding inefficiencies arising from waiting, idleness, and excessive transportation during construction. The research mainly focuses on the two aspects: 1) tracking the construction progress of a project and analyzing the deviation of the progress; 2) measuring the efficiency of laborers or equipment during the operation of a project, so as to carry out effective management and maximize operational efficiency. Productivity analysis needs to collect real-time data of construction sites and convert these data into productivity information, such as work sequence and duration. With the popularization and application of camera technology in construction sites, the automatic productivity analysis of recorded images and videos using machine vision technology has attracted wide attention.

(4) Defect detection based on machine vision

Defect detection aims at checking the defects and damages (cracking, peeling, defective joints, corrosion, pits, etc.) and the size of defects (quantity, width, length, etc.) in infrastructure components. This is conducive to assisting investment planning and allocating limited repair and maintenance resources, becoming the main means of ensuring that infrastructure meets its service performance. Defect detection based on machine vision mainly involves image processing technologies such as template matching, histogram transformation, background subtraction, filtering, and feature classification. Most of the research targets are concrete bridges, tunnels, pipelines, asphalt pavements, and other infrastructure. However, data acquisition of bridge images and videos is not fully automated, and the image quality varies with the camera attitude, distance, and environmental conditions. Detecting defects of complex geometric parts is still a challenge; for tunnels and pipelines, the poor illumination condition in the picture, irregular background pattern and contrast, and low-quality data are the main problems at present. For asphalt pavements, detecting and classifying pavement defects in real-time environment is still a challenge.

(5) Current situation and future trend

Currently, machine vision, as a means to realize the automation of construction management, is widely used in all links of construction, such as safety surveillance, productivity analysis, and defect detection. However, in the course of development, it still has some pending problems.

First, deep learning algorithms require a large number of data training models. Moreover, datasets that can be used publicly are still lacking, which greatly hinders the development of machine vision. Second, the current research on machine vision is limited to a specific behavior or scene, such as whether laborers wear safety helmets or not, but practical applications often require the surveillance of a variety of tasks and risks. Third, safety surveillance driven by machine vision is often based on feature extraction but fails to achieve a high level of semantic understanding of a scene. With the increasing complexity of the definition of construction risks, machine vision needs to integrate standard knowledge to improve the ability of scene understanding and risk reasoning. The ontology, as a standardized representation of domain knowledge, can process text standard knowledge and expert experience into a computer-readable mode. Therefore, a research trend in the future is the effective integration of ontology and machine vision to enable ontology to effectively improve background and prior knowledge for image understanding in computer vision.

According to the number of core papers published, the top three countries or regions with the highest number of core papers are China, the USA, and Australia (Table 1.2.5). The top three countries or regions in citations per paper are the USA, Poland, and China (Table 1.2.5). According to the cooperation network chart of major countries or regions outputting core papers (Figure 1.2.3), no closer cooperation network exists yet and cooperation relationships exist between the USA and Germany, and China and Australia. The top three institutions with the highest number of core papers are Huazhong University of Science and Technology, Columbia University, and Hong Kong Polytech University (Table 1.2.6). According to the cooperation network chart of major institutions producing core papers (Figure 1.2.4), no close cooperation network exists yet, but there are preliminary regional characteristics.

China, the USA, and South Korea are the top three countries that have published the largest number of citing papers related to construction management driven by machine vision (Table 1.2.7), while Huazhong University of Science

Table 1.2.5 Countries or regions with the greatest output of core papers on "construction management driven by machine vision"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	7	41.18%	172	40.57%	24.57
2	USA	6	35.29%	169	39.86%	28.17
3	Australia	2	11.76%	49	11.56%	24.50
4	Canada	2	11.76%	38	8.96%	19.00
5	Poland	1	5.88%	26	6.13%	26.00
6	Germany	1	5.88%	19	4.48%	19.00
7	South Korea	1	5.88%	19	4.48%	19.00

Table 1.2.6 Institutions with the greatest output of core papers on "construction management driven by machine vision"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Huazhong Univ Sci & Technol	3	17.65%	75	17.69%	25.00
2	Columbia Univ	2	11.76%	87	20.52%	43.50
3	Hong Kong Polytech Univ	2	11.76%	48	11.32%	24.00
4	Univ Nottingham Ningbo	1	5.88%	30	7.08%	30.00
5	Univ Michigan	1	5.88%	28	6.60%	28.00
6	Curtin Univ	1	5.88%	27	6.37%	27.00
7	Hubei Engn Res Ctr Virtual Safe & Automated Const	1	5.88%	27	6.37%	27.00
8	Tongji Univ	1	5.88%	26	6.13%	26.00
9	AGH Univ Sci & Technol	1	5.88%	26	6.13%	26.00
10	Queensland Univ Technol	1	5.88%	22	5.19%	22.00

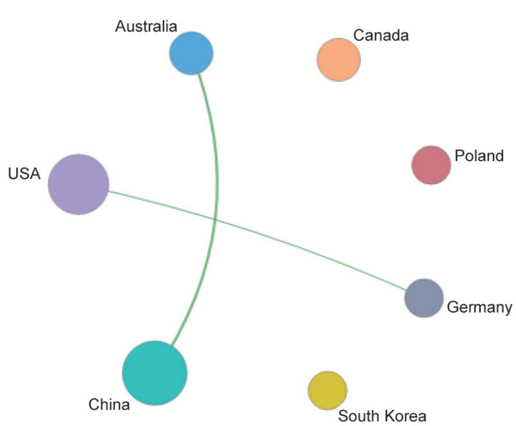

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "construction management driven by machine vision"

& Technology, Hong Kong Polytech University, and Tongji University are the top three institutions that have published the largest number of citing papers (Table 1.2.8).

1.2.3 Resilience of the infrastructure systems

The word "resilience" originated from the Latin word "resilio," meaning "return to its original state." Prof. Holling, a Canadian ecologist, first applied the idea of resilience to system ecology to define the steady-state characteristics of ecosystems. Subsequently, the idea of resilience was applied to different disciplines, including engineering resilience, economic resilience, and infrastructure system resilience. Infrastructure system resilience can be understood as the comprehensive ability of a system to maintain certain basic functions during disasters and restore normal functions soon after disasters. As the infrastructure system sustains the social and economic functions of a city and is the main artery of the city, a resilient infrastructure system is the core and key to realize the resilient city.

The assessment and improvement of the infrastructure system resilience are deeply analyzed and the future development trend of the research on infrastructure system resilience are subsequently summed up below.

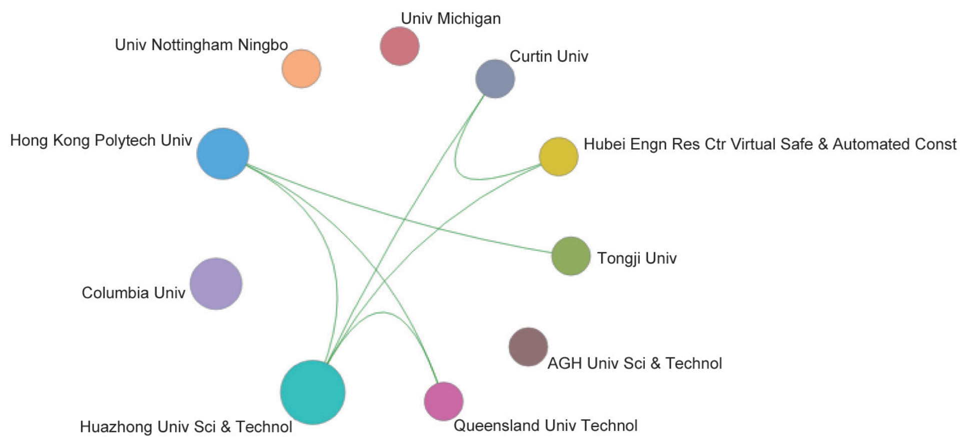

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "construction management driven by machine vision"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "construction management driven by machine vision"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	128	36.26%	2018.1
2	USA	80	22.66%	2017.9
3	South Korea	32	9.07%	2017.9
4	UK	29	8.22%	2018.0
5	Australia	26	7.37%	2018.1
6	Canada	16	4.53%	2017.8
7	Spain	15	4.25%	2018.1
8	Germany	10	2.83%	2017.6
9	Italy	7	1.98%	2017.9
10	Turkey	5	1.42%	2017.8

Table 1.2.8 Institutions with the greatest output of citing papers on "construction management driven by machine vision"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Huazhong Univ Sci & Technol	21	16.28%	2018.2
2	Hong Kong Polytech Univ	19	14.73%	2018.2
3	Tongji Univ	17	13.18%	2018.1
4	Curtin Univ	15	11.63%	2018.1
5	Harbin Inst Technol	11	8.53%	2018.4
6	Columbia Univ	9	6.98%	2017.0
7	Dalian Univ Technol	8	6.20%	2017.9
8	Zhejiang Univ	8	6.20%	2017.4
9	Cent S Univ	8	6.20%	2018.3
10	Yonsei Univ	7	5.43%	2017.7

(1) Research on assessment of infrastructure system resilience

Although different definitions of resilience exist, when evaluating infrastructure system resilience, almost all the resilience indicators in available literature are put forward based on the actual function curve of the system in disaster events and the expected function curve in disaster-free situations. Before an event, the system runs normally with a 100% function index; when the event occurs, there may be a process of fault generation and spread until the function indicator reaches the lowest value; after the event, the system damage condition is evaluated and gradually repaired, and the post-recovery system function indicator may be less than, equal to, or greater than the 100% before the event. Based on the actual function change curve and expected function curve, scholars have put forward various resilience indicators and related resilience assessment methods. The research hotspots of assessment of infrastructure system resilience mainly include: assessment of infrastructure system resilience oriented to multiple disasters, assessment of infrastructure system resilience with system relevance taken into account, setting of resilience objectives of the infrastructure system, verification of the resilience assessment model of the infrastructure system, and construction of a testing system.

(2) Research on improvement of resilience of the infrastructure systems

One of the main purposes of defining and assessing the resilience of infrastructure systems is to research how to improve system resilience. With the purpose to improve the resilience of infrastructure systems, many countries have stipulated infrastructure protection plan documents with a series of management or policy tactics such as optimizing the allocation of resources for disaster prevention and recovery, formulating disaster insurance policy incentives and planning programs for post-disaster land use, promoting cooperation and information sharing among different systems, strengthening the awareness and culture of resilience, enhancing leadership, enriching executives' experience in dealing with large-scale disasters, and attaching importance to the relevance of different systems. For improvement tactics for engineering technology resilience, such as strengthening system components, adjusting system structures, and configuring redundant systems, the resilience improvement can be modeled as a multi-stage dynamic optimization with a limited budget. The research hotspots of infrastructure system resilience improvement include: resilience improvement for infrastructure system organizations, resilience improvement for infrastructure systems based on the whole-life cycle, an efficient solution algorithm of multi-stage resilience improvement and optimization model, resilience-driven decision optimization for post-disaster recovery for infrastructure systems, and resilience improvement for infrastructure systems considering the functional relevance of building communities.

(3) Current situation and future development trend

The National Science Foundation of the USA funded a series of research projects on resilience of infrastructure systems, such as resilient and sustainable infrastructure, and resilient associated infrastructure systems and processes. The National Institute of Standards Testing (NIST) issued guidelines for urban resilience planning in 2016 and funded Colorado State University to establish the research center of "risk-based urban resilience planning" (involving ten universities of the USA) which took the resilience of infrastructure systems as the key point of research and planning. The Federal Emergency Management Administration (FEMA) has developed the software HAZUS and FEMA P58 to analyze the risk, economic loss, and recovery time of the infrastructure systems of different cities of the USA in flood, hurricane, and earthquake disasters. The Infrastructure Transitions Research Consortium, which is charged by the University of Oxford, has researched measures to improve the resilience of associated infrastructure systems to flood disasters. The SYNER-G project funded by the EU's FP7 has researched the vulnerability and resilience of infrastructure systems to earthquake disasters; the European Union Joint Research Centre has developed the software for decision making for post-disaster recovery and resilience improvement of infrastructure systems. In 2015, the National Natural Science Foundation of China issued a joint British–Chinese fund to improve the resilience of earthquake-prone areas in China to natural disasters; in 2017, it issued emergency response projects, i.e., research on theoretical methods and tactics for the construction of the safe and resilient Xiong'an New Area; and in 2018, it held the 204th Shuangqing Forum in Harbin to discuss the basic scientific issues of the construction of anti-seismic and resilient cities, wherein, the infrastructure system resilience was the key point of discussion. Based on the current research situation, the future development trends mainly include: resilience assessment and improvement under the coupling of multi-hazards (especially those related to climate change), modeling and validation of the relevance among systems and between a system and its environment, and efficient solution algorithms for large-scale improvement of system resilience.

The top three countries or regions with the highest number of core papers in the engineering research front of “infrastructure system resilience” are, the USA, China, and the UK, respectively (Table 1.2.9) and the top three countries or regions in the citations per paper are Denmark, Israel, and the UK, respectively (Table 1.2.9). According to the cooperation network chart of major countries or regions producing core papers (Figure 1.2.5), the USA, China, the UK, Australia, and Greece have frequent cooperation.

The top three institutions with the highest number of core papers are, the University of Manchester, the University of Melbourne, and City University of Hong Kong (Table 1.2.10). According to the cooperation network chart of major institutions producing core papers (Figure 1.2.6), University of Manchester, University of Melbourne, National Technical University of Athens, and Newcastle University have frequent cooperation.

From Table 1.2.11, we can see that China ranks first in the number of citing papers. From Table 1.2.12, we can see that Shanghai Jiao Tong University and Tsinghua University are the leaders of the front.

Table 1.2.9 Countries or regions with the greatest output of core papers on “infrastructure system resilience”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	11	39.29%	282	40.81%	25.64
2	China	9	32.14%	230	33.29%	25.56
3	UK	8	28.57%	229	33.14%	28.63
4	Australia	6	21.43%	167	24.17%	27.83
5	Greece	3	10.71%	68	9.84%	22.67
6	Switzerland	2	7.14%	52	7.53%	26.00
7	Germany	2	7.14%	42	6.08%	21.00
8	Denmark	1	3.57%	38	5.50%	38.00
9	Israel	1	3.57%	38	5.50%	38.00
10	Norway	1	3.57%	28	4.05%	28.00

Table 1.2.10 Institutions with the greatest output of core papers on “infrastructure system resilience”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Manchester	4	14.29%	121	17.51%	30.25
2	Univ Melbourne	3	10.71%	86	12.45%	28.67
3	City Univ Hong Kong	3	10.71%	59	8.54%	19.67
4	Lehigh Univ	2	7.14%	64	9.26%	32.00
5	Newcastle Univ	2	7.14%	57	8.25%	28.50
6	Natl Tech Univ Athens	2	7.14%	53	7.67%	26.50
7	Huazhong Univ Sci & Technol	2	7.14%	27	3.91%	13.50
8	Univ Michigan	1	3.57%	69	9.99%	69.00
9	Univ Bath	1	3.57%	44	6.37%	44.00
10	Xi An Jiao Tong Univ	1	3.57%	44	6.37%	44.00

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "infrastructure system resilience"

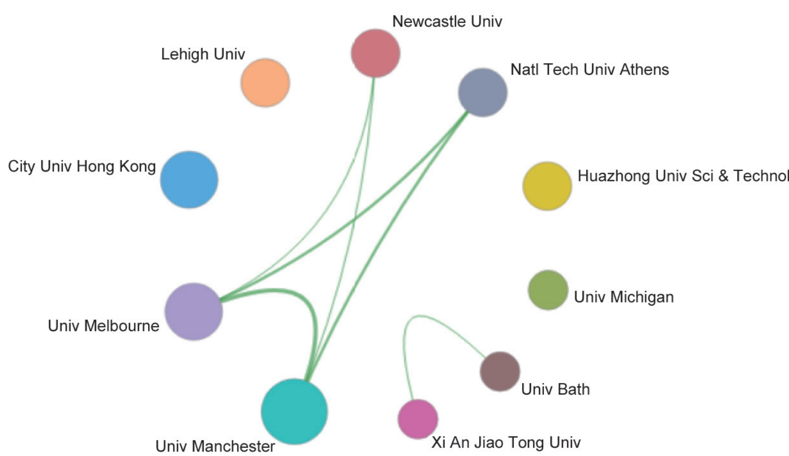

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "infrastructure system resilience"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "infrastructure system resilience"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	191	31.41%	2018.4
2	USA	166	27.30%	2018.3
3	UK	49	8.06%	2018.5
4	Australia	43	7.07%	2018.3
5	Italy	41	6.74%	2018.3
6	Germany	26	4.28%	2018.2
7	Iran	23	3.78%	2018.3
8	France	20	3.29%	2018.2
9	Spain	18	2.96%	2018.5
10	South Korea	16	2.63%	2018.3

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

In the field of engineering management, the fronts of global engineering development mainly include the following ten parts, i.e., (1) visualization technology oriented to engineering management, (2) warning technologies and methods oriented to engineering safety, (3) IoT technology development oriented to engineering management, (4) smart logistics, (5) risk evaluation and management systems, (6) vehicle information and resource sharing systems, (7) intelligent medical health management, (8) cloud-computing-based integration management methods and technology, (9) wearable-device-based management and techniques, and (10) quality engineering technology oriented to intelligent manufacturing. Their core patents are shown in Table 2.1.1 and Table 2.1.2. These engineering development fronts contain mechanisms, transport, medicine, architecture, electronics, and other disciplines. Of these, the visualization technology oriented to engineering management, warning technology and methods oriented to engineering safety, and IoT technology development oriented to engineering management, are the key fronts and their development situation and future trends are detailed below.

(1) Visualization technology oriented to engineering management

Visualization technology refers to a technical method that is based on computer image technology and generates human visual stimulus graphics through computers so that people

Table 1.2.12 Institutions with the greatest output of citing papers on “infrastructure system resilience”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Shanghai Jiao Tong Univ	22	17.60%	2018.2
2	Tsinghua Univ	14	11.20%	2018.4
3	RMIT Univ	12	9.60%	2018.3
4	Swinburne Univ Technol	12	9.60%	2018.0
5	Hong Kong Polytech Univ	10	8.00%	2018.2
6	Univ Hong Kong	10	8.00%	2018.6
7	Huazhong Univ Sci & Technol	10	8.00%	2018.0
8	City Univ Hong Kong	9	7.20%	2018.1
9	Univ Calif Berkeley	9	7.20%	2018.6
10	Lehigh Univ	9	7.20%	2018.0

Table 2.1.1 Top10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Visualization technology oriented to engineering management	14	80	5.71	2014.9
2	Warning technologies and methods oriented to engineering safety	16	59	3.69	2015.3
3	IoT technology development oriented to engineering management	17	55	3.24	2015.5
4	Smart logistics	26	118	4.54	2014.9
5	Risk evaluation and management systems	22	164	7.45	2014.2
6	Vehicle information and resource sharing systems	11	36	3.27	2015.6
7	Intelligent medical health management	23	174	7.57	2014.7
8	Cloud-computing-based integration management methods and technology	31	189	6.10	2014.8
9	Wearable-device-based management and techniques	6	46	7.67	2015.2
10	Quality engineering technology oriented to intelligent manufacturing	26	98	3.77	2014.9

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in engineering management field

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Visualization technologies oriented to engineering management	0	6	4	4	0	0
2	Warning technology and methods oriented to engineering safety	5	0	0	8	3	0
3	IoT technology development oriented to engineering management	0	3	5	6	3	0
4	Smart logistics	2	8	8	8	0	0
5	Risk evaluation and management systems	6	10	1	5	0	0
6	Vehicle information and resource sharing systems	1	1	3	3	2	1
7	Intelligent medical health management	2	7	11	1	2	0
8	Cloud-computing-based integration management methods and technology	5	8	9	7	2	0
9	Wearable-device-based management and techniques	0	1	3	2	0	0
10	Quality engineering technology oriented to intelligent manufacturing	2	8	8	8	0	0

can accept and understand the original data and information. Currently, visualization technology shows a promising application, which can be used in engineering safety, progress management, and human–computer interaction. With the rise of AI technologies such as deep learning, the research and application of visualization technology have become new academic research hotspots, and it is considered to be another revolutionary information technology. However, in the practical application of engineering management, the engineering data types are multi-source and heterogeneous, the amount of data is large, and the information is fragmented; therefore, the advantages of visualization technology in engineering management cannot be fully exploited. A key bottleneck restricting the application of visualization technology in engineering management is its expandability. Parallel computing and deep learning, 5G, IoT and other AI technologies can more accurately, efficiently, and intelligently perceive, calculate, and analyze massive engineering data to support real-time visualization and interactive operation. Therefore, two major trends of future research will be combining large-scale parallel computing, supercomputers, and AI technologies to make the visualization system more intelligent, and upgrading and extending the current valuable visualization methods and human–computer interaction technology to the field of engineering management.

(2) Warning technologies and methods oriented to engineering safety

Engineering includes construction engineering, industrial engineering, mining engineering, traffic engineering, and environmental engineering, and engineering safety is the basic premise and guarantee of various engineering activities. Engineering safety, which is still a serious issue, is a high concern by professionals and executives of all engineering sectors. In terms of how to improve engineering safety levels, the traditional safety management is conducted by safety training, standardized process operation, and site patrol and monitoring, which has prevented the incidence of safety accidents and improved safety management levels to some extent but is not striking in its safety effect. The rapid development of emerging information and data analysis technologies has provided new thinking directions for the solution of engineering safety concerns. Engineering control methods, technologies, and devices integrated with IoT, sensors, cloud computing, visualization, machine vision, and big data are constantly being produced. However, with the purpose of effectively controlling engineering safety concerns, on one hand, the instantaneity of site safety surveillance and warning shall be taken into account and, on the other hand, the acquisition of the data supporting safety management decision making shall be taken into account. Therefore, the future engineering safety control must develop and absorb diverse information technologies, improve the instantaneity and effectiveness of safety warning, as well as develop applicable technologies for engineering data acquisition to support the everlasting decision making of executives for safety management so as to form effective engineering safety control programs for the system.

(3) Development of IoT technology oriented to engineering management

The IoT technology is an Internet technology that connects all items related to the Internet through a series of information sensing devices and in accordance with the provided relevant digital agreements for information exchange and communication so as to realize intelligent recognition, positioning, tracking, monitoring, and management. IoT technology has been widely used in medical logistics, intelligent agriculture, vehicle integrated management, and steel warehousing. The IoT technology oriented to engineering management must adapt to the complex and diverse environment of construction sites and the dynamic changes of engineering elements and should handle a large number of sensors and enormous amounts of communication data. From the perspective of the technical architecture of the IoT, three mainstream architectures based on electronic product code (EPC) global standard, ubiquitous sensor network (USN), and machine to machine (M2M) IoT have been matured. The key technologies include intelligent sensing, high-reliability and secure transmission, integrated application, and public technologies. The core modules of system development include radio frequency communication, network transmission, storage, and data analysis modules.

The development of IoT technology oriented to engineering management mainly solves the collection and transmission of engineering information. Through RFID tags, sensing devices, QR codes, video surveillance, and other sensing technologies, the materials and equipment from a construction site as well as personnel information can be collected and transmitted to the backend of the information system to realize the trace of the basic, location, and transformation status information of the targets monitored. Success cases of the application of engineering IoT have been recorded in bridges, super high-rise structure health surveillance, positioning of metro construction personnel, engineering environment monitoring, material planning and tracking, and dynamic monitoring of construction machinery, in China and abroad. The fronts of the development of IoT technology involve massive sensing data compression, three-dimensional video intelligent analysis, IoT and BIM integration, IoT-based large data analysis, and IoT and 5G mobile communication technologies, etc.

(4) Smart logistics

In the field of smart logistics, the managers always face enormous logistics transportation network and complex business processes. All logistical activities are closely connected by the Internet or IoT and certain logistical operations have realized high automation levels. The managers must require mass data and intelligent optimization algorithms for decision making. The logistical enterprises are increasingly more concentrated, the size of top logistical enterprises are increasingly larger, and the business types, as well as transport modes, are increasingly more diverse, thus making the logistical transport networks of enterprises increasingly larger and the business process as well as the information system increasingly more complex. Logistical activities cannot exist without the Internet and tend to use IoT. The upcoming 5G will become integral to the operational activities of logistical enterprises. Along with the popularization of smartphones and the wide application of image and video collectors as well as various sensors, the logistics-related data have boomed in recent years. A current research front is the exploitation of the potential values of these data. Many logistical enterprises have begun to use industrial robots (including UAVs and unmanned vehicles) instead of laborers for sorting, packaging, handling, and distribution. Another current research front is the designing, deploying, and scientific use of such automation equipment. Making decisions based on labor experience has been inapplicable to modern logistical enterprises and the traditional logistical optimization technologies are unsuitable to the new environment of smart logistics, too; therefore, research must be conducted on the data-driven intelligent optimization technologies to armor the decision-making brains of enterprises and work out a series of new theories and new methods in demand prediction, network design, transport planning, stock management, warehouse operation, and staff duty shift.

(5) Risk evaluation and management systems

The risk evaluation and management system is a management information system that stores and analyzes the acquired basic data and identifies and evaluates risks by various risk evaluation methods, thus to realize risk control. Its main functional modules include data acquisition, storage, risk analysis and processing, and risk warning-control modules. From the perspective of system design level structure, it includes an infrastructure service level, data service level, supporting service level, application program service level, and user level. The system operation process generally includes: to acquire data through traditional data input or hardware sensor sampling, conduct structure or semi-structured storage, analyze and process data through risk evaluation algorithms, evaluate risk incidence and determine risk level, and finally put forward countermeasures and push the relevant information to the managers. It has been widely applied in industrial production, water supply, electric power generation, mechanical equipment management, medical resource distribution, and business exchanges.

In the field of engineering management, the risk evaluation and management oriented to the whole life cycle of projects have always been the keys to research. Especially for safety risk evaluation and management of construction sites, the research hotspot has been the real-time automatic acquisition of site surveillance data, intelligent dissection of monitor videos and images, real-time sensing as well as evaluation on safety risks with the help of the backend risk evaluation rules (including incidence threshold value and risk classification rules), and timely risk warning and control. The current main quantitative analysis methods include FMEA, HAZOP, FTA, Improved Interval AHP, and Multivariate Weight Matrix Analysis. Future risk evaluation and management systems will be combined with engineering IoT, cloud service platform, engineering big data, data combination, data exploitation methods, and swarm intelligence algorithms and trends to be more integrated, digitalized, and intelligent.

(6) Vehicle information and resource sharing systems

The vehicle information and resource sharing system is a resource utilization mode for the entities that use vehicle sharing to realize the effective flow of information and resources through various coordination mechanisms, satisfy the scarcity of vehicles for demanding clients, and achieve vehicle sharing. The vehicle information and resource sharing system provides a new trip mode, and it shows a promising application for the present stage where traffic congestion has severe impact on people's living quality, which can alleviate the trouble in urban trips incurred by traffic congestion and reduce the cost of trips. As a new concept of resource sharing, the research and development of vehicle information and resource sharing systems has entered a stage of fast development and all countries are conducting R&D of relevant devices and technical updates. This technology includes at least one sharing unit and one delivery unit which are connected with available communication. The sharing unit includes one sharing tactic generation module and one selection module, and the delivery unit includes one delivery module. They can communicate with each other according to certain rules. The key technology restraining the development and extensive application of vehicle information and resource sharing systems is the vehicle distribution optimization algorithm during receiving the reservation request. This optimization algorithm is always implemented based on a pre-set processor with the purpose of showing users reservation results in a rapid manner and reducing the operation cost of vehicle sharing services. The efficient vehicle information and resource distribution optimization algorithm is the foundation of future vehicle sharing and it can reduce the operation cost of systems, as well as improve user satisfaction; therefore, it is the most convenient and feasible approach to promote the development in this direction.

(7) Intelligent medical health management

As the third health revolution is upcoming, medical health management service has become the leading tactic of the health system—a system oriented by health. The so-called medical health management is a whole-life, whole-process, and all-around intervention management process for the factors influencing the health of individuals and communities, their action process, and the health results, with the purpose of improving the health level and life quality of individuals and communities. Along with the development of Internet technology, the medical health management service has not been limited by face-to-face communication between doctors and patients nor by time, space, and method. The service targets can learn their health status and obtain related health guides as well as interventions through information and intelligence technologies in time. Currently, big data platforms for regional health are being built gradually. Guided by evidence-based medicine, through deep learning and machine learning, AI has achieved initial success in medical imaging, clinical decision support, speech recognition, pathology, and other fields, making the O2O (online-to-offline) intelligent medical health management a new trend of medical health service development. However, the development of intelligent medical health management is currently at a primary stage. It lacks organic combination of online and offline management as well as the ability to regulate health management programs in a timely manner in light of the actual conditions of the service targets, making the health management effect unideal. Supported by 5G technology, with the intelligent medical elements such as wearable health devices, remote diagnosis, and remote imaging, the intelligent medical health will become more mature.

(8) Cloud-computing-based integration management methods and technology

Cloud computing is an information processing mode to realize mass computation through consolidated organization and flexible utilization of various ICT information resources, and the software and hardware resources and information through this mode can be provided to users' computers and other devices as required. So far, storage, medical, financial, and education clouds have been formed, showing extremely promising applications in finance, governmental affairs, industries, and medical treatment. Cloud computing has characteristics such as expandability, high flexibility, high reliability, and high-cost performance. In the future, it will be combined with AI to form ABC (AI + Big Data + Cloud Computing) and enter multi-application scenes of multi sectors.

Carrying out effective combinations of various data and resources is the basic function of the dynamic resource management of cloud computing while cloud data management technology is the key to realizing cloud computing. The data management technologies based on cloud computing mainly include GFS technology (document/data management), MapReduce technology (cluster parallel operation), BigTable technology (data management system), and Dynamo technology (data storage platform). They can provide services of different resources and different levels through data resources sharing at cloud end which involve infrestrncture as a service (IaaS), software as a service (SaaS), and platform as a service (PaaS). Of these, PaaS is the ultimate aim of cloud computing. In terms of cloud data integration management, with strong distributed storage and computing power, the cloud computing can conduct specific retrieval and analysis for mass data, realize effective combination of various isomerous data and service resources through mass data integration management, and can provide services for virtualized computing resources, Internet construction applications, business hosting, and management software applications.

(9) Wearable-device-based management and techniques

Wearable devices are portable devices with local computing and wearable properties, which are capable of sensing the physiological state, motion mode of human bodies, and the environment. Through communicating with diverse smart terminals (smartphones, clouds, etc.), they can provide continuous personal health monitoring and management, and regional residential health and life information management. Currently, wearable devices have taken notable evolutionary leaps in terms of product forms (watches, glasses, clothes, accessories, etc.) and interactive modes (touch, gesture, voice, etc.), which have been accepted by the market. However, new problems and challenges are gradually emerging as wearable devices are bringing great changes to our daily lives. Because wearable devices collect and record a huge body of data on personal physiology, daily activities, and the surrounding environment, it is important to process, integrate, and manage these data. On the one hand, the devices should provide accurate health status information to the wearer in a timely and dynamic manner, containing effective exercise methods, pre-emergency alarms, etc.; on the other hand, they should avoid the disclosure of personal information or infringement of personal privacy such as one's life preferences and behavioral habits. With the emergence of various wearable devices, enhancing the secure communication among the wearable devices, smart terminals, and the central servers; improving the natural interaction between the wearable devices and human beings; developing the intelligent management and techniques based on wearable devices; and providing multi-scenario and multi-level service experience are of great significance for the improvement of people's health status and living standards.

(10) Quality engineering technology oriented to intelligent manufacturing

Along with the extensive application of various robots, intelligent sensors, built-in chips, and edge computing devices, and the fast development of the Internet, IoT, big data, AI, cloud computing, and 3D printing, the manufacturing system is gradually evolving toward intelligence. Intelligent manufacturing, the deep combination based on the new generation of ICT and advanced manufacturing technology, can realize the full sensing of the real-time status of humans, machines, and materials, conduct intelligent analysis and processing for mass isomerous data from industrial sites, and push forward the transformation of manufacturing businesses to product demand, design, manufacturing, sale, and service based on industrial big data analysis and application intelligence. A lot of quality control methods based on traditional mathematical statistics are inapplicable to the intelligent manufacturing system which features real-time data acquisition (high-dimension and high-frequency) and highly-customized requirement (small quantity and even single piece). The quality engineering research oriented to intelligent manufacturing aims to resolve the quality control problems arising from product design, process monitoring, and manufacturing service in the environment of intelligent manufacturing. Its major technical directions include intelligence-sensing-based acquisition of big data of product utilization and consumer preference and user portraits; quality assurance modes and methods for integration design of products and arts oriented to personalized demands; parametric optimization technologies of the processes based on the combination of real-time, high-dimension, and isomerous big data; process quality monitoring technologies oriented to high frequency, high dimension, and small quantity; quality diagnosis technologies based on the big data of production process parameters, product quality, and device status; quality tracing technologies of supply chains based on the new generation of information technology (in particular blockchain); and operation status monitoring, remote fault diagnosis, and device prevention management technologies based on big data during equipment and product services. In the future, the quality engineering technology oriented to intelligent manufacturing shall be combined with modern information technology and big data technology and the statistic learning method will be the main tool for quality engineering technology of intelligent manufacturing.

2.2 Interpretations for three key engineering development fronts

2.2.1 Visualization technology oriented to engineering management

"Visualization" means "turning something invisible, inexpressible, or abstract into a visible image or an image that can be imagined by the brain." In 1986, the concept of Visualization in Scientific Computing was proposed, and visualization technology was considered an independent major computer technology. Visualization technology is an interdisciplinary subject, which covers many research fields, such as computer graphics, computer vision, human–computer interaction, and other technologies. Visualization technology makes the invisible phenomena hidden in data be visible to better analyze, understand, and exploit the rules of data. The rise of AI technologies such as deep learning has promoted the development of visualization technology, making the research and application of visualization technology in engineering management become a new academic research hotspot and be considered as another revolutionary information technology for engineering management.

In practical engineering management applications, engineering data types are multi-source and heterogeneous, and the amount of data is large and the information is fragmented, so the advantages of visualization technology cannot be fully utilized to serve engineering management. A key bottleneck restricting the application of visualization technology in engineering management is its expandability. From the point of view of patent analysis, visualization technology for engineering management mainly includes computer vision, AR and VR, BIM, geographic information systems (GIS), and graph visualization technology.

(1) Computer vision: Computer vision is an interdisciplinary scientific field, which mainly solves the use of computational models to obtain high-level information from images or multi-dimensional data in order to build AI systems. From the point of view of engineering, computer vision mainly aims at automatically completing tasks that human visual systems can accomplish. Machine vision can automatically detect and understand the information in pictures for engineering management, for example, identification of unsafe behaviors of the laborers at a construction site. However, due to low real-time performance and low accuracy, the engineering requirements for complex and large scenarios cannot be satisfied. Parallel computing, deep learning, and other AI technologies can analyze and process data in graphics more accurately, efficiently, and intelligently, making machine vision serve engineering management better.

(2) AR and VR: AR refers to the application of virtual information to the real world through computer technology, superimposing the real environments and visual objects in one frame or space. VR is a computer-generated artificial simulation process or the reproduction of some real-life situations or environments with the aim to immerse users by giving them the feeling of simulating reality. Currently, the application of AR and VR in practical engineering management is still primary, which is mainly due to many challenges in practical applications, such as the inconvenience of using VR and AR, the inability to process large amounts of data in

real time, and the vulnerability to external environmental interference. The combination of deep learning, 5G, and other AI technologies with VR and AR is expected to achieve real-time data acquisition and analysis.

(3) BIM: BIM is a kind of digital three-dimensional modeling which contains the building information in design, construction, operation, and maintenance. BIM functions through calculation, collaboration, sharing, and visualization, which can realize the integration of building information through digital technology. Although BIM can promote the transformation of the construction industry from the extensive management to refined management mode, the current BIM software are weak in application, insufficient in computing power, and unavailable in seamless management of whole-life cycles, which is a concern to be solved in future.

(4) GIS: GIS is an interdisciplinary technology of computer science, geography, surveying, and cartography and has not been uniformly defined yet. However, the information involved in the actual project management has the characteristics of massive heterogeneous data, bringing new challenges to the current GISs.

(5) Graph visualization technology: Graph visualization technology refers to the application of graph theory to store the information of relationships among entities, represented by the visualization of nodes and edges. For massive engineering data, visualizing nodes and edges in limited space will be the key challenge to be solved. In addition to visualizing the static network topology, large engineering data often evolve dynamically as time goes. Therefore, visualizing the features of dynamic networks is also an important research concern.

According to the number of published patents, the top two countries or regions by number are China and the USA (Table 2.2.1). The top three countries or regions in the citation frequency per paper are the USA, South Korea, and China (Table 2.2.1). According to the cooperation network chart of major patent output countries (Figure 2.2.1), no close cooperation network exists yet. The top two institutions in the number of patents are the State Grid Corporation of China and the International Business Machines Corporation (Table 2.2.2). According to the cooperation network chart of patent output institutions (Figure 2.2.2), we can see that no close cooperation network exists yet. Jiangxi Jiujiang Power Supply Co. has cooperation with the State Grid Corporation of China, and China Design Group Co., Ltd. has cooperation with Jiangsu Transportation Planning & Design.

2.2.2 Warning technologies and methods oriented to engineering safety

Engineering, as a basic activity for human beings to learn and transform the world, has been evolving and deepening from ancient times to the present. In this process, safety concerns have been accompanied by engineering. Safety surveillance and warning is an effective means to prevent engineering accidents, that is, it can provide safety warning information to engineering executives in time by identifying safety hazards or accident causes, analyzing status, and distinguishing safety extents so as to effectively reduce the likelihood of the occurrence of an accident or even avoid it. However, along with the growth of engineering size and the improvement of complexity in recent years, the engineering safety concern has been rather striking. For example, in construction engineering, the number of housing accidents in municipal engineering production has been up to 3000 and that of the deceased up to 3600 in the last five years and has trended to grow, which has brought enormous economic loss, as well as enormous social loss. Under the general background of a national safety

Table 2.2.1 Countries or regions with the greatest output of core patents on “visualization technologies oriented to engineering management”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	6	42.86%	34	42.50%	5.67
2	USA	5	35.71%	34	42.50%	6.80
3	South Korea	1	7.14%	6	7.50%	6.00
4	Denmark	1	7.14%	4	5.00%	4.00
5	Japan	1	7.14%	2	2.50%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on "visualization technologies oriented to engineering management"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	State Grid Corporation of China	3	21.43%	18	22.50%	6
2	International Business Machines Corporation	2	14.29%	11	13.75%	5.5
3	Boeing Co. (THE)	1	7.14%	13	16.25%	13
4	Jiangxi Jiujiang Power Supply Co.	1	7.14%	9	11.25%	9
5	China Design Group Co., Ltd.	1	7.14%	8	10%	8
6	Jiangsu Transportation Planning & Design	1	7.14%	8	10%	8
7	PurePredictive Inc.	1	7.14%	8	10%	8
8	Korea Institute of Civil Engineering and Building Technology	1	7.14%	6	7.50%	6
9	Changzhou Agriculture and Aquatic Products Quality Supervision and Inspection Testing Center	1	7.14%	4	5%	4
10	Changzhou Rongrui Information Automation Co., Ltd.	1	7.14%	4	5%	4

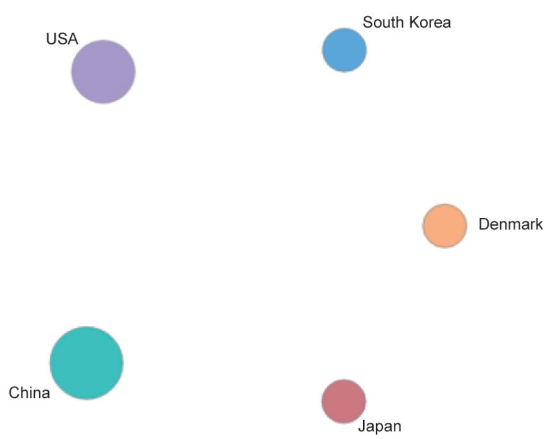

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "visualization technologies oriented to engineering management"

development strategy, further research and development is required in applicable engineering safety warning methods and technologies combined with characteristics of various types of engineering, as well as improving the overall level of engineering safety.

Currently, the warning methods and technologies oriented to engineering safety, supported by emerging information technologies and related safety warning methods, technologies, or devices, are formed in combination with the uniqueness of concrete engineering activities, mainly including: safety warning technology based on IoT or sensors, safety warning technology based on machine vision, and safety warning technology based on mobile terminals.

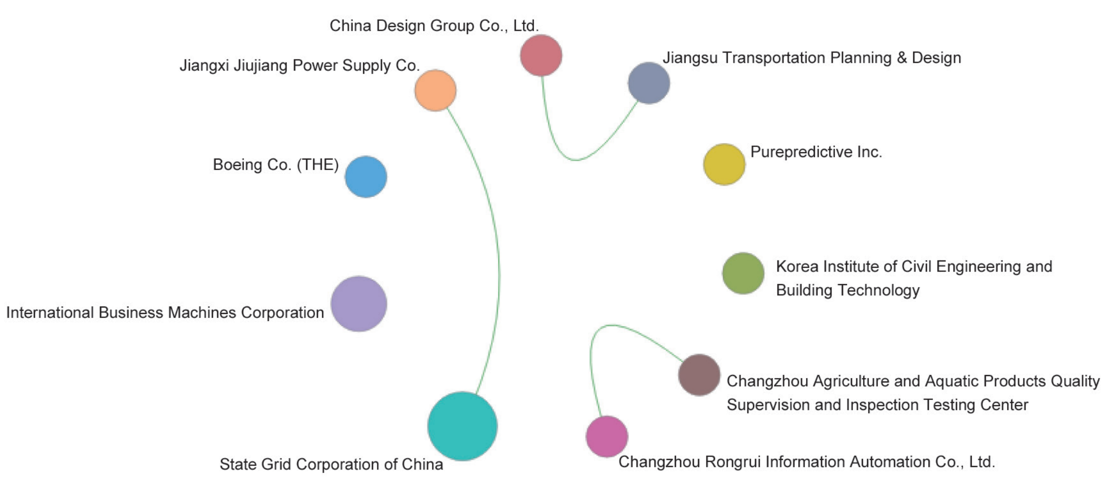

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "visualization technologies oriented to engineering management"

The safety warning technology based on IoT or sensors is a technology that automatically acquires and transmits engineering safety data in real time through integration and application of various sensors as well as network facilities (wired or wireless) and conducts real-time analysis, distinguishing, and warning of safety risks combined with data analysis methods and warning mechanisms. The safety warning technology based on machine vision is a technology that conducts rapid automatic processing of engineering safety images or videos and extracting of safety elements by the method or technology of image and video analysis, and further distinguishes and warns of safety risks. The safety warning technology based on mobile terminals is a technology that acquires engineering safety data, identifies and reports engineering safety hazards through artificial methods, and further conducts comprehensive distinguishing as well as warning of safety risks. In view of the differences in engineering environments and the advantages and disadvantages of all technologies, these safety warning technologies are always integrated and applied in engineering practices.

(1) Safety warning technology based on IoT or sensors: This technology involves various sensors such as the sensors for temperature, humidity, pressure, gas, light, sound, stress, strain, displacement, location, and ID. Of these, the frequently-used location sensors include UWB, RFID, Beacon, and GPS; and ID sensors include RFID, UWB, Beacon, and NFC QR Code. This technology is mainly used in safety surveillance and warning in environmental engineering (e.g. air quality and geographic environment), construction engineering (e.g. deep pits, major structures, and openings), traffic engineering (e.g. dangerous item transportation vehicle management), and mine engineering (e.g. dangerous geology and dangerous gas). However, due to the complexity of engineering environments, the signal transmission of sensors can be easily influenced by site environment, making its precision fluctuate greatly.

(2) Safety warning technology based on machine vision: This technology relies on video and image acquisition of engineering sites, such as cameras, 3D scanners, radar, UAVs, aircrafts, and aerial photography equipment; and image processing technologies such as background subtraction, sliding detection window, HOG, SVM, *k*-nearest neighbor method, CNN, and long short term memory (LSTM). This technology is mainly used in safety surveillance and warning in construction engineering (e.g. labor practices and dangerous areas), environmental engineering (e.g. landslide and flood), and traffic engineering (e.g. cargo safety detection). However, it is influenced much by site light, sightline, and dynamics, and also limited by algorithms and performance of computing devices.

(3) Safety warning technology based on mobile terminals: This technology has benefited from the rapid development of mobile terminal devices (e.g. smartphones, smart tablet PCs, and smart bracelets) and the development technology of WeChat, WhatsApp and other small programs. It is mainly used for safety surveillance and warning in construction engineering (e.g. site safety hazards or risk factors), environmental engineering (e.g. natural disasters and artificial disasters), and mine engineering safety (e.g. site safety hazards or risk factors). Although it is widely applied, limited by artificial detection and reporting of relevant data, it has narrow or incomplete data coverage.

The R&D of engineering safety warning methods and technologies in China and worldwide has trended as follows: (1) Support technology diversification. Along with the constant consummation and performance improvement of sensor technologies, image processing technologies, and communication technologies, the safety warning support technologies have trended toward diversification and due to the difference of the environments applicable to various technologies, the warning technologies have trended toward integration. (2) Warning method automation. Along with the automatic acquisition of data and improvement of transmission and processing technical capabilities, safety distinguishing and warning have trended toward automation. (3) Application field popularization. Along with the improvement of safety warning technical capabilities, the engineering application field is being constantly deepened. In addition, along with the constant accumulation of safety data and continuous development of big data analysis technologies, the decision making of engineering safety management has trended toward data-supported decision making from subjective decision making.

The top three countries or regions with the highest output of core patents in this engineering development front are, respectively, China, the USA, and South Korea. Of these, the number of core patents output by China is 10, ranking the highest (Table 2.2.3). The institution outputting the largest number of core patents in this field in China is China Yangtze

Table 2.2.3 Countries or regions with the greatest output of core patents on "warning technologies and methods oriented to engineering safety"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	10	16.95%	33	55.93%	3.30
2	USA	2	3.39%	13	22.03%	6.50
3	South Korea	2	3.39%	10	16.95%	5.00
4	France	1	1.69%	1	1.69%	1.00
5	Japan	1	1.69%	2	3.39%	2.00

Table 2.2.4 Institutions with the greatest output of core patents on "warning technologies and methods oriented to engineering safety"

No.	Institution	Published patents	Percentage published patents	Citations	Percentage of citations	Citations per patent
1	China Yangtze Power Co., Ltd.	2	12.50%	16	27.12%	8
2	Jubix	1	6.25%	9	15.25%	9
3	Fluor Corp.	1	6.25%	9	15.25%	9
4	Tsinghua University	1	6.25%	6	10.17%	6
5	Wuhan Shuzhen Information Integration	1	6.25%	5	8.47%	5
6	Verizon Communications Inc.	1	6.25%	4	6.78%	4
7	Chongqing Hehang Internet Things Technol	1	6.25%	3	5.08%	3
8	Nanjing Xuean Network Technology Co., Ltd.	1	6.25%	3	5.08%	3
9	NTT Docomo Inc.	1	6.25%	2	3.39%	2
10	Hangzhou Hikvision Digital Technology Co., Ltd.	1	6.25%	2	3.39%	2

Power Co., Ltd. which has two published patents and eight citations per paper (Table 2.2.4).

According to the cooperation network charts of major patent output countries (Figure 2.2.3) and institutions (Figure 2.2.4), no close cooperation network exists yet, and Tsinghua University has cooperation with China Yangtze Power Co., Ltd.

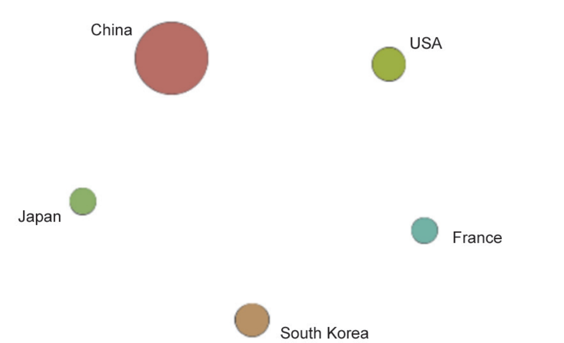

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "warning technologies and methods oriented to engineering safety"

2.2.3 IoT technology development oriented to engineering management

The IoT technology is an Internet technology that connects all related items to the Internet through a series of information sensing devices and in accordance with the provided relevant digital agreements for information exchange and communication so as to realize intelligent recognition, positioning, tracking, monitoring, and management. The IoT oriented to engineering management is defined as engineering IoT to distinguish it from the industrial IoT of manufacturing. The engineering IoT technology must adapt to the complex and diverse environment of the construction site and the dynamic changes of engineering elements and can handle a large number of sensors and enormous communication data. The technology architecture of IoT is relatively mature with the key pending issues—data perception, transmission, and management application.

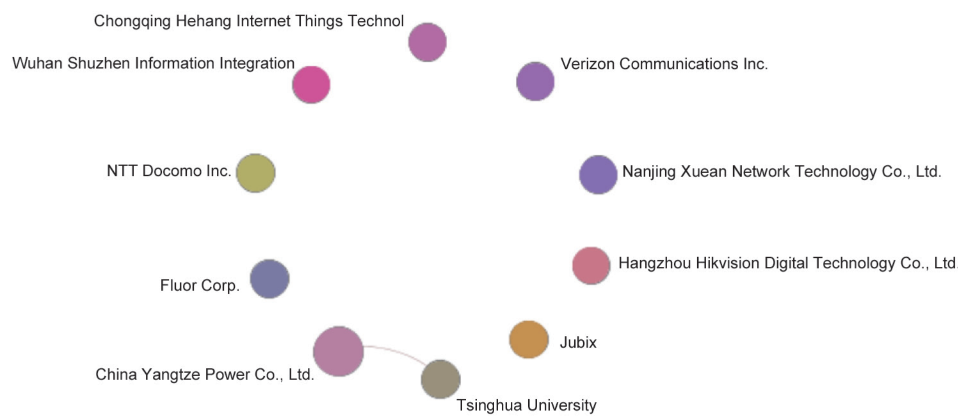

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "warning technologies and methods oriented to engineering safety"

Success cases in the development of IoT technology oriented to engineering management have been observed in China and abroad, and the future technology is developing towards integration, standardization, and intellectualization.

The development of engineering IoT technology involves many fields such as modern sensor technology, embedded computer technology, distributed information processing technology, modern network, and wireless communication technology. The key technology system can be divided into four levels: perception technology, network technology, application technology, and public technology levels.

(1) Intelligent sensing technology: The engineering IoT mainly uses RFID tag, QR codes, various sensors, video surveillance, and other sensing, acquisition, and measurement technologies to collect and acquire real-time information of targets being monitored. Communication between an RFID tag and RFID reader is usually encapsulated as middleware for system development. There are many kinds of sensors in complex engineering environment (including stress, strain, temperature, water level, etc.). As there are a large number of RFID tags for personnel, materials, and equipment identification, the intelligent sensing technology must solve sensor power supply, electromagnetic shielding, enormous communication data, etc.

(2) Highly reliable and secure transmission technology: This technology can achieve short-distance transmission, and self-organized local area network (LAN) and wide area network (WAN) transmission of perceived information without obstacles and with high reliability and security. The engineering IoT integrates sensor networks with mobile communication technology and Internet technology. With the purpose to improve data transmission efficiency in complex engineering environments, different sampling frequencies and transmission time intervals shall be set according to the type and management requirements of sensors. For the trajectory monitoring of personnel and equipment, it is also necessary to meet the technical requirements of data acquisition, data transmission, and monitoring instructions feedback.

(3) Integrated application technology: The engineering IoT applications can be divided into monitoring (bridge health monitoring), inquiry (personnel identification), and control (equipment movement trajectory control). Integrated application technology includes general technology for supporting information collaboration, sharing, and interoperability across industries, applications, and systems. An application support platform sub-level is established by deploying ONS servers, PML servers, and EPS/IS servers to isolate the technology level; and then an application service sub-level is constructed for intelligent transportation, construction, and logistics to provide industry applications.

(4) Public technology: Public technology includes data analysis, data security, network management, and quality of service (QoS), which are of universal significance. These technologies are applied to all technical levels of the engineering IoT.

The concept of IoT originated from the proposal by Auto-ID Research Center of Massachusetts Institute of Technology (MIT) in 1999 that an RFID technology of the Internet shall be applied in daily articles so as to realize intelligent recognition and management. In 2005, the International Telecommunication Union (ITU) formally put forward the concept of “Internet of Things,” describing IoT features and future opportunities as well as challenges in the report *ITU Internet reports 2005——the Internet of Things* and expressed that the future IoT can connect to any item at any time and place and the sensor technology and intelligent terminal technology would have deep space of research and development. In 2008, IBM put forward the concept of “smart earth” and proposed to mount sensors in items to form a network through universal connection. In 2009, the EU Commission issued its IoT strategy, describing the development trend of IoT in the coming two decades, and Chinese Premier Wen Jiabao visited the Research and Development Center of Micro/Nano Sensor Engineering Technology and delivered an important speech, opening the prelude of the IoT technology in China. IoT technology has been widely used in medical logistics, intelligent agriculture, vehicle integrated management, steel warehousing, and other fields.

The engineering IoT is a key technology of data perception, transmission, analysis, and decision control. The engineering IoT can realize ubiquitous perception, interconnection, and monitoring of various engineering elements (including human, machine, material, method, loop, and product) in the process of engineering construction. Foreign countries have more mature experience in the application of engineering IoT in the field of construction. For example, the Akashi Kaikyō Bridge in Japan, the Miyo Bridge in France, and the Asker Bridge in Norway have been provided with IoT systems for surveillance of bridge structure health; the Gotthard-Basistunnel in Switzerland has been provided with an automatic monitoring IoT platform composed of 2600 km cables, 200 000 sensors, and 70 000 data nodes.

The engineering IoT has been successfully applied in bridges, super high-rise structure, health surveillance, and personnel positioning as well as engineering environment monitoring in Metro Construction in China. It is especially widely used in the field of construction engineering. For example, it can measure and transmit the changes of stress, vibrating frequency, temperature, deformation, and other parameters inside the machines and equipment such as crane towers, elevators, and scaffolds to realize the dynamic monitoring of the operation of construction machinery and equipment; acquire the values of displacement, deformation, and cracks of components through the reading of their RFID tag information and seek the components in danger by RFID positioning technology promptly for timely reinforcement and restoration; make statistics using BIM technology and engineering IoT technology; and according to time, position, and work procedure, prepare detailed material procedure plan and provide RFID tags to material lot to control the entrance or exit time as well as quality status of materials.

From the perspective of the technical architecture of the IoT, three main architectures based on EPC global standard, USN, and M2M IoT have been matured. In the future, the IoT will develop toward several key areas: massive-sensing data compression technology, three-dimensional video intelligent analysis technology, IoT and BIM integration technology, IoT-based large data analysis technology, and IoT and 5G mobile communication technology. From the perspective of the development of engineering IoT technology in China, life-cycle engineering IoT integration technology, engineering IoT architecture design theory supporting edge computing and cloud computing collaboration, and the networking technology with wide coverage, hyperlink, low power consumption, and low cost, will become the research directions in future.

From Tables 2.2.5 and 2.2.6, China is still in a leading position. According to the cooperation networks of major patent output countries or regions (Figure 2.2.5) and institutions (Figure 2.2.6), no close cooperation network exists yet.

Table 2.2.5 Countries or regions with the greatest output of core patents on “IoT technology oriented to engineering management”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	17	100%	55	100%	3.24

Table 2.2.6 Institutions with the greatest output of core patents on "IoT technology oriented to engineering management"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Qingda Tianyan View Control	1	5.88%	9	16.36%	9
2	Chongqing Shengxin Technology Co., Ltd.	1	5.88%	6	10.91%	6
3	Hefei Caixiang Information Technology Co.	1	5.88%	6	10.91%	6
4	Shanghai Renywell Technology Co., Ltd.	1	5.88%	5	9.09%	5
5	Guangzhou Baosteel Southern Trade Co., Ltd.	1	5.88%	4	7.27%	4
6	Qingdao Lianggu Wireless Technology Co.	1	5.88%	4	7.27%	4
7	Guizhou Normal University	1	5.88%	4	7.27%	4
8	Chengdu Gips Energy Technology Co., Ltd.	1	5.88%	3	5.45%	3
9	Chengdu Chuangshi Technology Co., Ltd.	1	5.88%	2	3.64%	2
10	Zhejiang China Tobacco Industrial Co., Ltd.	1	5.88%	2	3.64%	2

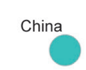

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "IoT technology oriented to engineering management"

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "IoT technology oriented to engineering management"

Participants of the Field Group

Leaders

DING Lieyun, HE Jishan, HU Wenrui, XIANG Qiao

Experts

DING Lieyun, HE Jishan, HU Wenrui, XIANG Qiao, CHEN Xiaohong, CAO Yaofeng, CHAI Hongfeng, CHEN Qingquan, FU Zhihuan, LIU Renhuai, LU Youmei, LUAN Enjie, LING Wen, SUN Yongfu, SHAO Anlin, WANG An, WANG Jiming, WANG Liheng, WANG Longde, WANG Yingluo, WANG Yupu, WANG Zongtuo, XUE Lan, XU Qingrui, XU Shoubo, YANG Shanlin, YIN Ruiyu, YUAN Qingtang, ZHU Gaofeng, ZHENG Jingchen, ZHAO Xiaozhe, Mirosław SKIBNIEWSKI, Peter E. D. LOVE, BI Jun, CAI Li, CHEN Jin, DING Jinliang, DU Wenli, FANG Dongping, GAO Ziyou, HU Xiangpei, HUA Zhongsheng, HUANG Jikun, HUANG Wei, JIANG Zhibin, LI Heng, LI Yongkui, LI Zheng, LIU Xiaojun, LUO Hanbin, REN Hong, TANG Jiafu, TANG Lixin, WANG Hongwei, WANG Huimin, WANG Mengjun, WANG Xianjia, WANG Yaowu, WEI Yiming, WU Desheng, WU Jianjun, WU Qidi, YANG Hai, YE Qiang, ZENG Saixing, ZHOU Jianping

Members of the Working Group

WANG Hongwei, LUO Hanbin, ZHONG Botao, LI Yong, HE Ling, QIU Luting, WANG Xiaobo

Office Members

NIE Shuqin, CHANG Junqian, ZHENG Wenjiang, MU Zhirui, QIAO Xiaoyan

Report Writers

DING Lieyun, WANG Hongwei, LUO Hanbin, ZHONG Botao, LI Heng, HE Zhen, GUO Hongling, WANG Ke, ZHEN Lu, OUYANG Min, YE Kunhui, LIU Jun'an, LIN Han, LI Hongbo, YU Hongliang, QIN Hu, GUO Jian, ZHANG Yongcheng, DONG Chao, FANG Weili, WU Haitao, HE Ling, QIU Luting, WANG Xiaobo

Participants of General Plan Group

Leader

CHEN Jianfeng

Members

DUAN Zhengcheng, GUO Dongming, PAN Yunhe, LU Xicheng, WANG Jingkang, LIU Jiongtian, WENG Shilie, NI Weidou, PENG Suping, GU Dazhao, CUI Junzhi, ZHANG Jianyun, CHEN Yiyi, HAO Jiming, QU Jiuhui, KANG Shaozhong, ZHANG Fusuo, CHEN Saijuan, ZHANG Boli, DING Lieyun, HE Jishan, HU Wenrui, XIANG Qiao, HAN Jun, WU Xiang, ZHOU Weixing, JI Jiuming, CAI Fang, JIANG Zhiqiang, ZHANG Weidong, GAO Yanjing, WANG Dan, ZHENG Wenjiang, MU Zhirui, LIU Jingjing

Writers of General Plan Report

ZHENG Wenjiang, MU Zhirui, ZHOU Weixing, JI Jiuming, CAI Fang, JIANG Zhiqiang, GAO Yanjing

Data Support Group

Clarivate Analytics

Secretary Group

Leaders

AN Yaohui, JIAO Dong, HAN Jun

Assistant leaders

WU Xiang, YAN Jianlin, DING Ning, ZHOU Yuan, ZHENG Wenjiang

Members

JI Xue, WANG Chengjun, WANG Aihong, ZONG Yusheng, ZHANG Song, WANG Xiaowen, HUANG Haitao, ZHANG Wentao, NIE Shuqin, ZHAO Xilu, WEN Danyan, YANG Bo, MU Zhirui, CHEN Bingyu

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