Book Description

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. Since 2017, the Chinese Academy of Engineering (CAE) has been organizing the research "Global Engineering Fronts", which aims to bring together talents in engineering science and technology and put forward the global engineering research and development fronts by reviewing global papers, patents and other data each year. The results are also expected to provide a reference for people to respond to global challenges and achieve sustainable development. This book is the result of the 2020 research and it consists of two parts—methodology and reports in different fields, describing and analyzing the engineering research and development fronts in the fields of Mechanical and Vehicle Engineering, Information and Electronic Engineering, Chemical/Metallurgy and Materials Engineering, Energy and Mining Engineering, Civil/Hydraulic and Architecture Engineering, Environmental and Light Textile Engineering, Agriculture, Medicine and Health, and Engineering Management, and explaining the key fronts in detail.

As one of the "Global Engineering Fronts" series, this book is suitable for scientific researchers, engineers, teachers and students in universities, and civil servants in relevant government departments.

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Contents

Foreword

Engineering science and technology are important driving forces in the development of society, and engineering fronts set important guidelines for the future development of engineering science and technology. Today, a new round of technological revolution and industrial transformation is triggering profound changes, accelerating the evolution of engineering science and technology. Understanding trends and aiming to be at the forefront of global engineering science and technology has become a strategic choice for countries worldwide.

The Chinese Academy of Engineering (CAE), the most honorable consulting academic institution in China, shoulders the historical mission of playing an academic leadership role and promoting the development of engineering science and technology. Since 2017, the CAE has been organizing a project known as “Global Engineering Fronts” every year, which aims to assemble talents in the field of engineering science and technology to present global engineering research and development fronts by reviewing global papers, patents, and other data. The results are also expected to provide a reference for people on responding to global challenges and achieving sustainable development.

The 2020 Global Engineering Fronts project continues to rely on nine academic divisions and academic journals of the CAE to identify 93 global engineering research fronts and 91 global engineering development fronts. This is done by paying equal attention to the engineering research and development fronts, integrating quantitative analysis and qualitative research, and combining data mining and expert argumentation. Among these, 28 key engineering research fronts and 28 key engineering development fronts are selected for detailed interpretations.

In 2020, more experts from the field of engineering science and technology and informatics science were invited, and there were deep interactions between experts and diversified data sources. In the process of data analysis, experts are involved in reviewing and adjusting the results to effectively maximize the utility of papers, patents, and data indicators, thereby ensuring the reliability and objectivity of the results.

This report presents the results of the 2020 project and comprises two parts. Part A explains the data and methodology. Part B presents the technology reports focusing on nine fields: (i) Mechanical and Vehicle Engineering; (ii) Information and Electronic Engineering; (iii) Chemical, Metallurgical, and Materials Engineering; (iv) Energy and Mining Engineering; (v) Civil, Hydraulic, and Architectural Engineering; (vi) Environmental and Light Textile Engineering; (vii) Agriculture; (viii) Medicine and Health; and (ix) Engineering Management. Each report describes and analyzes the engineering research and development fronts in these fields and explains the key fronts in detail.

Identifying engineering fronts is a complex and challenging task. In this process, the research team gradually explored a unique research path, that is, the research, forums, and journals were closely integrated to promote each other. The project was supported by thousands of academicians and experts from various fields and institutions. We are grateful to all of them!

Part A Methodology

An engineering front is defined as the key direction that is forward-looking, leading, and exploratory. It has a major influence and a leading role in the future development of engineering science and technology and serves as an important guide for cultivating the capabilities for innovation in the field of engineering science and technology. The front is focused on the theoretical research or application development of engineering science and technology. Engineering fronts are divided into engineering research fronts and engineering development fronts. In this research, engineering front identification is based on public data and expert research; hence, it does not involve nonpublic domains.

Underpinned by evaluation of experts and data, the 2020 Global Engineering Fronts project has adopted multiround interactions between experts and data for iterative research and analysis, realizing the deep integration of judgments of experts and data analyses. In 2020, 93 global engineering research fronts and 91 global engineering development fronts were selected, with 28 engineering research fronts and 28 engineering development fronts listed as the key focus for interpretation. The distribution of engineering research and engineering development fronts among the nine fields is presented in Table 1.1.

Research on fronts consists of three stages: data preparation, data analysis, and expert review. In the data preparation stage, domain, library, and information experts revise the initial literature and patent data to clarify the scope of data mining. In the data analysis stage, co-citation clustering method is used to obtain clustered literature topics and ThemeScape patent maps. In the expert review stage, the fronts are gradually selected and determined through patent map interpretation, expert panel discussions, questionnaire surveys, and other methods. Then, the list of the top 10 fronts is modified, and the front-naming is improved based on the performance of the front in literature or patent data. To address the problem of the lacking of novelty due to algorithm limitations or lags in data mining, experts from different fields were encouraged to check the results of the data analysis to fill in the gaps and nominate engineering fronts. A flowchart of the operating procedure of the Global Engineering Fronts project is illustrated in Figure 1.1, in which the green, purple, and red boxes indicate the data analysis, expert research, and multiround iterative interactions between experts and data, respectively.

1 Identification of engineering research fronts

The identification of engineering research fronts is performed in two steps. The first step involves determining the clustered literature topics through clustering method of co-

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

Field	Number of engineering research fronts	Number of engineering development fronts
Mechanical and Vehicle Engineering	10	10
Information and Electronic Engineering	10	10
Chemical, Metallurgical, and Materials Engineering	10	10
Energy and Mining Engineering	12	12
Civil, Hydraulic, and Architectural Engineering	10	10
Environmental and Light Textile Engineering	10	10
Agriculture	11	9
Medicine and Health	10	10
Engineering Management	10	10
Total	93	91

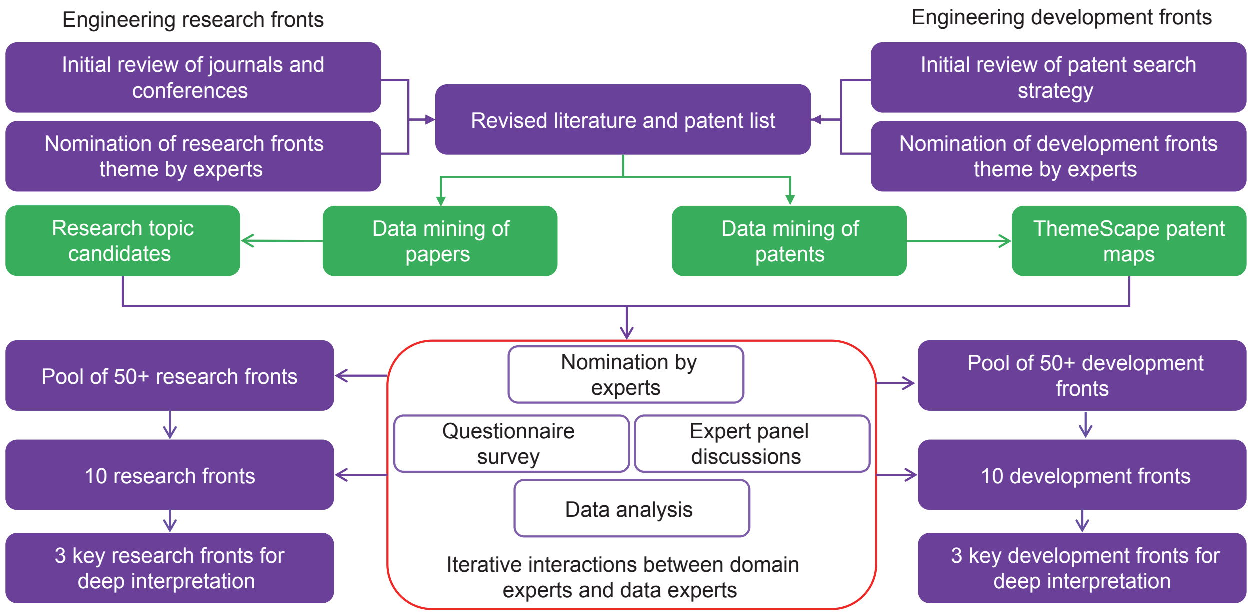

Figure 1.1 Operation procedure of the Global Engineering Fronts project

citation according to the SCI journal papers and data of conference proceedings collected from the *Web of Science Core Collection* of *Clarivate*. The second step is defining the engineering research fronts through expert nomination. Alternative engineering research fronts that were identified through expert argumentation and refinement went through questionnaire surveys and multiple rounds of expert discussions, yielding 93 engineering research fronts in the nine fields.

1.1 Acquisition and preprocessing of paper data

Clarivate mapped the fields of the *Web of Science* and nine academic division fields of the CAE and obtained a list of journals and conferences in each field. After correction and supplementation by domain experts, the sources for data analysis in the nine fields were determined to be 11 730 journals and 41 734 conferences. For the articles from 70 multidisciplinary sciences journals, such as *Nature* and *Science*, the field of each article was reassigned to the most relevant subject area according to the subjects cited in its references. Accordingly, the articles and conference papers published between 2014 and 2019 were retrieved (the cut-off date of the citations was February 2020).

For each field, *Clarivate* comprehensively considered the differences between journals and conferences, publication year, and so on. Next, the list of aforementioned papers was retrieved and extracted. By processing journals and conference proceedings separately, the papers with high impact that are ranked among the top 10% of highly cited papers were selected as the original dataset for the analysis of research hotspots, as presented in Table 1.1.1.

1.2 Mining of clustered literature topics

Through the co-citation clustering analysis of the top 10% highly cited papers in the aforementioned nine datasets, all the clustered literature topics in the nine fields were obtained. The topics of papers published during 2018–2019 were selected according to the number of core papers, total number of citations, and proportion of consistently cited papers. Thereafter, 25 different literature topics were obtained. The topics of the papers published before 2018 were selected according to the mean publication year of core publications and the proportion of consistent citations. Consequently, 35 diverse 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 by keywords. Finally, 800 clustered literature topics in the nine fields were obtained (Table 1.2.1).

1.3 Determination and interpretation of research fronts

While processing and mining the paper data, domain experts present research front issues by a comprehensive analysis of data pertaining to science and technology news and national strategic layouts of different countries, and integrated them into each stage of front determination.

In the data preparation stage, the library and information experts transform the front research questions raised by the domain experts into search formulas, which are an important part of the initial data source. In the data analysis stage, for subjects that are not covered by clustered literature topics, the domain experts provide keywords, representative papers, or representative journals to support *Clarivate* for customized search and mining. In the expert review stage, the domain experts check for omissions based on the clustered literature results provided by *Clarivate* and conduct a second round of nominations for fronts that do not exist in the data mining results, but are considered important. Library and information experts provide data support. Finally, the domain experts merge, revise, and refine the engineering research front topics obtained through data mining and expert nomination. Subsequent to questionnaire surveys and multiple rounds of conference discussions, approximately 10 engineering research fronts were selected for each field.

In each field, three key research fronts were selected

Table 1.1.1 Number of journals and conferences in each field and the 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	512	2 641	70 748
2	Information and Electronic Engineering	958	17 418	199 347
3	Chemical, Metallurgical, and Materials Engineering	1 144	3 939	253 221
4	Energy and Mining Engineering	594	2 181	105 674
5	Civil, Hydraulic, and Architectural Engineering	560	1 075	56 402
6	Environmental and Light Textile Engineering	1 326	1 174	186 022
7	Agriculture	1 167	951	70 293
8	Medicine and Health	4 675	11 163	445 940
9	Engineering Management	794	1 192	45 716

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	7 596	31 816	144
2	Information and Electronic Engineering	19 294	85 292	64
3	Chemical, Metallurgical, and Materials Engineering	26 703	111 032	65
4	Energy and Mining Engineering	11 621	49 722	95
5	Civil, Hydraulic, and Architectural Engineering	6 133	27 449	135
6	Environmental and Light Textile Engineering	20 849	86 909	85
7	Agriculture	7 784	32 821	72
8	Medicine and Health	47 145	202 238	65
9	Engineering Management	4 675	19 012	75

according to the development prospects and the significance. Authoritative experts on front direction were invited to interpret the fronts in detail from the perspectives of national and institutional layouts, cooperation networks, development trends, and R&D priorities.

2 Identification of engineering development fronts

The identification of engineering development fronts is primarily performed using two methods. First, based on the *Derwent Innovation* patent database of *Clarivate*, the top 10 000 patent families on 53 subjects in the nine fields with high citations were clustered, and 53 ThemeScape maps were obtained. The domain experts interpreted alternative engineering development fronts from these maps. The second approach involves nominations by an expert or patent analysis by a small peer group. The alternative development fronts obtained through these two methods went through questionnaire surveys and several special seminars. Consequently, approximately 10 engineering development fronts were identified in each field.

2.1 Acquisition and preparation of the ThemeScape maps

In the data preparation stage, based on the *Derwent Innovation* patent database, *Clarivate* developed initial patent data retrieval scope and search strategies for the 53 disciplines in the nine fields using the Derwent World Patents Index (DWPI) Manual Codes, International Patent Classification numbers, United States Patent Classification numbers, and other patent classification numbers and specific technical keywords. Domain experts deleted, supplemented, and improved the DWPI Manual Codes to determine the patent retrieval criteria; further, the nominated alternative front topics were selected, which were then transformed into patent search formulas by the library and information experts. *Clarivate* integrated the above two parts of the search formulas, determined the patent search formulas of the 53 disciplines, searched the DWPI and Derwent Patent Citation Index databases, and obtained the patent literature of the corresponding disciplines. The retrieved patents were published between 2014 and 2019; the cut-off date of the citations was February 2020.

To further concentrate patent literature, the millions of patent documents were screened according to the annual average number of citations and technical coverage width indicators, thereby obtaining the top 10 000 patent families in each discipline.

2.2 Mining of patent topics

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

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

2.3 Determination and interpretation of development fronts

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

In the data preparation stage, the library and information experts transformed the key front issues raised by the domain experts into patent search formulas as an important part of the basic dataset. In the data analysis stage, the domain experts conducted the second round of front nomination to supplement the emerging technology points that are significant, but have been submerged in data mining with few patents, and yet to show their influence. In the expert review stage, the domain experts studied highly cited patents, and the library and information experts assisted them in interpreting patent maps from multiple perspectives, such as "peaks" and "blue oceans." Finally, the domain experts merged, revised, and refined the interpreted results of the patent maps and fronts nominated by experts to obtain candidate engineering development fronts, and then selected approximately 10 engineering development fronts in each field through questionnaire surveys or multiple rounds of seminars.

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

3 Terminologies

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

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

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

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

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

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

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

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

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

Consistently cited papers: Papers included in the top 10% based on citation velocity.

Highly cited patents: The top 10 000 patent families cited in each discipline.

Core patents: According to the different ways of obtaining the development front, core patents have two meanings. If it comes from the front of the patent map, then the core patent refers to the highly cited patent; if it arises from the front nominated by domain experts, then the core patent refers to all patents obtained by topic search.

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

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

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

Part B Reports in Different Fields

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering reseach fronts in the field of mechanical and vehicle engineering include mechanical, transportation, ship and marine engineering; weapon science and technology; aeronautical and astronautical science and technology; and power and electrical equipment engineering and technology (as listed in Table 1.1.1). Among these, “hybrid additive–subtractive manufacturing method,” “fault monitoring and diagnosis based on machine learning,” “supersonic combustor technology,” “aerial manipulator,” and “high power wireless power transmission” are extensively studied traditional topics. “Intelligent manufacturing driven by digital twin,” “air-breathing hypersonic vehicles,” “3D printing of continuous-fiber-reinforced composite,” “large space deployable antenna,” and “vehicle-to-everything (V2X) and real-time traffic management based on 5G” are considered as emerging topics.

The annual publication of papers during the years 2014–2019 is listed in Table 1.1.2. “Fault monitoring and diagnosis based on machine learning” and “supersonic combustor technology” are the most rapidly growing topics in terms of paper publications in recent years.

(1) Intelligent manufacturing driven by digital twin

Digital twin is an emerging technology for enhancing the performance and operational efficiency of physical products/factories by building digital twin models of products/factories and visualizing, commissioning, experiencing, and analyzing the models based on the integration of key enabling technologies, such as 3D modeling and designing, simulation, and industrial Internet of Things (IIoT). Digital twin has attracted considerable attention from academic and industrial communities, with Gartner ranking it among the top 10 emerging technologies for three consecutive years from 2017 to 2019. The basic feature of digital twin is the two-way mapping of physical entities and digital twin models. Digital twin-driven intelligent manufacturing is mainly embodied in two aspects. First, digital twin is applied throughout a complete life cycle of smart products, including virtual testing and semi-physical simulation in the product design and production phase; collecting product operation data via IIoT during the product operation phase; comparing the simulation results of its digital twin models, performing

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 driven by digital twin	9	847	94.11	2017.6
2	Hybrid additive–subtractive manufacturing method	11	625	56.82	2015.3
3	Air-breathing hypersonic vehicles	25	984	39.36	2016.6
4	Fault monitoring and diagnosis based on machine learning	41	2 986	72.83	2017.7
5	3D printing of continuous-fiber-reinforced composite	10	750	75.00	2017.2
6	Supersonic combustor technology	28	640	22.86	2016.8
7	Large space deployable antenna	11	215	19.55	2016.7
8	Vehicle-to-everything and real-time traffic management based on 5G	17	1 225	72.06	2017.1
9	Aerial manipulator	46	1 221	26.54	2015.2
10	High-power wireless power transmission	20	1 600	80.00	2016.8

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	2014	2015	2016	2017	2018	2019
1	Intelligent manufacturing driven by digital twin	0	0	1	3	4	1
2	Hybrid additive–subtractive manufacturing method	2	4	5	0	0	0
3	Air-breathing hypersonic vehicles	1	6	4	7	4	3
4	Fault monitoring and diagnosis based on machine learning	0	1	5	10	14	11
5	3D printing of continuous-fiber-reinforced composite	0	0	2	5	2	1
6	Supersonic combustor technology	2	4	4	8	9	1
7	Large space deployable antenna	1	0	3	5	1	1
8	Vehicle-to-everything and real-time traffic management based on 5G	2	2	2	3	3	5
9	Aerial manipulator	18	14	6	5	3	0
10	High-power wireless power transmission	0	5	2	6	5	2

fault prediction, performance analysis and optimization, etc.; and combining digital twin models in product scrap recycling phase to determine which parts can be reused and remanufactured. Second, digital twin is applied throughout a complete life cycle of smart factories, including virtual commissioning of smart production lines through digital twin models prior to the construction of physical production lines; visualization, optimization, and fault warning of operating status through digital twin models during smart factory operation; and optimization of improvement schemes using digital twin models during smart factory transformation and upgrading. Important research directions for digital twin include establishing and maintaining high-fidelity digital twin models, 3D interactive real-time rendering, digital thread throughout the product life cycle, multidisciplinary simulation and optimization of digital twin models, and introduction of artificial intelligence (AI) and industrial big data technology to carry out real-time analysis of IIoT data and mapping with digital twin models.

(2) Hybrid additive–subtractive manufacturing method

Hybrid additive–subtractive manufacturing technology uses layer-by-layer additive manufacturing and timely subtractive processing to realize continuous or simultaneous manufacturing process of “additive accumulation–subtractive finishing” of parts on the same machine tool; integrate the subtractive manufacturing into the entire forming process of additive manufacturing; improve the accuracy and quality of additive manufacturing parts; obtain parts with complex structure, dense organization, high shape precision, and high surface quality directly; and meet performance requirements of precision parts in the field of industrial high-grade field. The three main aspects of hybrid additive–subtractive manufacturing are 1) method and equipment; 2) software; and 3) manufacturing technique. The first aspect aims to investigate the hybrid additive–subtractive manufacturing method of different energy sources and materials; develop multi-axis computer numerical control (CNC) machine tools, additive manufacturing mechanism, feed mechanism, and other systems; and develop hybrid additive–subtractive manufacturing equipment. The second aspect aims to develop three major types of software, namely, layered data processing of part feature recognition, path generation and planning, and processing technique simulation. The third aspect aims to optimize the additive–subtractive manufacturing technique and realize shape and performance control according to forming material and performance requirements. To improve the performance and accuracy of hybrid additive–subtractive manufacturing parts, online detection technology has been introduced to realize real-time detection. Defects during the forming process can be timely detected and composite process parameters can be dynamically adjusted or the defect parts can be removed in real time utilizing the subtractive technology. This hybrid additive–subtractive manufacturing process with the online detection system has turned out to be an effective method and become the research frontier and development trend of hybrid additive–subtractive manufacturing.

(3) Air-breathing hypersonic vehicles

Air-breathing hypersonic vehicles generally refer to vehicles that have a flying Mach number of not less than 5 and is powered by an air-breathing scramjet engine or a combined engine. The speed range and airspace of air-breathing hypersonic vehicles span from taking off from the ground at zero speed to reaching the orbit, covering the flying range of all current aerospace vehicles. It usually includes near-space vehicles and aerospace vehicles. Near-space vehicles include hypersonic cruise missiles, hypersonic cross-domain mobile missiles, and hypersonic aircraft, whereas aerospace vehicles refer to reusable space vehicles that can freely enter and exit space. Given the unique advantages of fast speed, long range, and excellent performance, air-breathing hypersonic vehicles will considerably influence the development of human society. Hypersonic flight technology has become a criterion of measuring the advanced level of a country's aerospace technology. Research on hypersonic vehicles mainly focuses on scramjet engine and its combined-cycle power technology, hypersonic thermal protection structure and material technology, vehicle/propulsion-integrated aerodynamic exterior design technology, hypersonic vehicle navigation and control technology, and hypersonic ground test and flight demonstration verification technology. At present, the United States, Russia, and China regard air-breathing hypersonic vehicle technology as an important direction for future aerospace technology development and thus have invested resources to win the high ground.

(4) Fault monitoring and diagnosis based on machine learning

In recent years, many process data are generated with the development of big data mining and AI technology and the large complex scale of computer networks. Therefore, the demand for the data analysis of a large amount of data increases at the historic moment. This condition makes intelligent fault diagnosis methods based on machine learning increasingly favored by industries. Currently, traditional machine learning and deep learning are used as the mainstream intelligent diagnosis methods. The former mainly includes Bayesian network, artificial neural network, support vector machine, and hidden Markov model. The latter mainly includes the automatic extraction of powerful data features, such as convolutional neural networks, recurrent neural networks, automatic encoders, adversarial learning networks, and impulse neural networks, for end-to-end fault diagnosis. Traditional machine learning is limited in terms of generalization ability and accuracy. The performance bottlenecks can be found for complex multi-working conditions and multi-classification problems. Deep learning with strong big data adaptability, wide coverage, good adaptability, and portability has been widely investigated to solve the above problems. The first-generation neural network represented by artificial neural network is weak under long learning time and large network scale. The second-generation neural network represented by convolutional neural network achieves good results in fault monitoring and diagnosis. However, calculation and storage requirements are of a great amount. The third-generation neural network represented by impulse neural network can effectively perform pulse encoding through the characteristic information transmitted by time-varying pulse sequences. This network is used to meet the needs of intelligent diagnosis and coincides with the current development direction of intelligent fault diagnosis.

(5) 3D printing of continuous-fiber-reinforced composites

Continuous-fiber-reinforced composites are advanced high-performance and lightweight materials. Issues in regard to long manufacturing cycle, high cost, and manufacturing complexities in the preparation process severely hinder the wide application of continuous-fiber-reinforced composites. As a newly developed manufacturing technology, 3D printing possesses merits such as simplified processing, low cost, high raw material utilization rate, mold-free, and environmental friendliness. This technology is expected to enable the manufacturing of structures with arbitrarily complex geometry. Currently, the mostly applied 3D printing technologies for continuous-fiber-reinforced composite include selective laser sintering, fused-deposition manufacturing, layered solid manufacturing, and stereolithography. Among them, fused-deposition manufacturing is the most extensively used for low cost, simplified equipment, and easy operation. Although much effort has been conducted in both academic and industrial communities on printing equipment, manufacturing processing, and printing materials, printed structures are less qualified in terms of engineering application standards on stiffness, strength, surface quality, and density. Therefore, to achieve large-scale industrial application of the 3D printing of continuous-fiber-reinforced composite, the following research directions should be considered in priority: development of continuous fibers with specialized behavior properties, the mechanism on the fusion of 3D-printing and traditional molding, construction of a standard evaluation system for the 3D printing of continuous-fiber-reinforced composites, and developing more wide-applied 3D-printing processes.

(6) Supersonic combustor technology

With the development of hypersonic technology, research on scramjet has gained great attention. Under the condition of hypersonic incoming flow, the so-called supersonic combustion problem occurs when it is supersonic upon entering the combustion chamber after the airflow is compressed by the inlet. A series of performance indicators, such as total pressure loss, is considered. The combustor must complete a series of processes, including fuel injection, atomization, evaporation, blending, ignition, and stable combustion within a few milliseconds, and achieve efficient energy conversion and small pressure loss. Such process is tantamount to igniting in a tornado for achieving stable combustion and is of large difficulty. Supersonic combustor technology is mainly studied in the following directions: the overall optimization design technology of the flow channel, fuel injection and atomization, reliable ignition and flame stabilization, high-efficiency and low-resistance combustion organization, controllable combustion, and high-precision measurement of combustion. Currently, breakthroughs have been successively made in supersonic combustion technology by all major aerospace countries in the world at the engineering level. They can develop scramjets and dual-mode ramjets that can meet the thrust requirements of certain engineering applications. However, many problems, such as wide area combustion, low-pressure combustion, multimodal combustion, high Mach number combustion, large-scale combustion, and high-precision numerical simulation, need to be solved urgently. The solution of these problems is related to the improvement of engine performance and the expansion of engine application directions. These factors will become the emphasis of future supersonic combustion technology. In particular, vigorously developing the basic science research related to supersonic combustion, such as flame generation and transmission mechanism, vaporization and atomization mechanism of liquid fuel, unstable combustion, combustion mode, and conversion, is necessary.

(7) Large space deployable antenna

Spaceborne antennas apply in space and ground wireless communications, electronic reconnaissance, navigation, remote sensing, deep space exploration, and radio astronomy. Communication satellites must be equipped with large-caliber spaceborne antennas to meet multiband, large-capacity, and high-power requirements and achieve communication connections and network services. However, spaceborne antennas are required to be light and compact due to limitations of existing rocket fairing size and launch cost. Therefore, large-caliber spaceborne antennas must be deployable. Deployable antennas are divided into three types, namely, reflector, array, and microelectronic mechanical antennas. Reflector antennas are commonly used in various application satellites, such as communication satellite antennas in ultra high-frequency, micro-wave, and even millimeter-wave bands. Reflector antennas can be divided into four categories according to the structure of the reflecting surface, namely, rigid, inflatable, mesh, and film reflector antennas. Array antennas with flexible designs, such as in linear, planar, and conformal arrays as well as phased arrays, can achieve high gain, narrow beam, multitarget, space-division multiple-access, autonomous control, etc. New-type microelectronic mechanical antennas combined with micro-electromechanical systems technology, including microelectronic mechanical phased array, microelectronic mechanical reconfigurable, microstrip grid, and microelectronic mechanical multiband antennas, are characterized by their low cost and satisfactory performance. Research on large space deployable antenna technology is mainly focused on the design of flexible structure and deployment mechanism, analysis and adjustment of the reflector surface, electromagnetic performance analysis, and reliability analysis. Basic theories and methods include electromechanical and thermal comprehensive optimization design theories and methods, beam-forming reflector antenna design, performance testing, mesh antenna passive intermodulation, and new material applications. Large-aperture and high-precision antennas that realize high-frequency communication are the development trend of next-generation deployable antennas. At present, it is mainly focused on deployable structured reflector, inflatable deployable reflector, large-space assembled, and smart array antennas.

(8) Vehicle-to-everything and real-time traffic management based on 5G

The 5G mobile communication network is characterized by large bandwidth, high speed, low latency, high reliability, and massive connections, which promote the continuous evolution of cellular vehicle-to-everything (C-V2X). The 5G C-V2X business is mainly focused on smart road monitoring, autonomous driving, remote driving, and cooperative driving. It integrates with direct communication and organically connects traffic participation elements, such as “pedestrian–vehicle–road–cloud.” Through the integration of the transportation, information, and energy networks, an intelligent network that can communicate at any time, monitor in real time, and make timely decisions is formed. “Smart + network” is the basic route for the development of V2X in the future. Through the information interaction and sharing of vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian and vehicle-to-cloud intelligent collaboration and cooperation between vehicles and infrastructure are achieved. In addition, functions, such as the intelligent comprehensive perception of road conditions and dynamic collaborative traffic control, are enabled. Therefore, the optimization and application of system resources, the improvement of road traffic safety, and the alleviation of traffic congestion are achieved. Moreover, transportation systems become safer, more coordinated, more intelligent, and green. C-V2X will be combined with technologies, such as ultralarge-scale multiple input multiple output, millimeter wave communications, mobile edge computing (MEC), radar, and high-precision positioning based on 5G enhancement. The 5G V2X information security technology must be studied to ensure traffic safety, privacy, and data security. The digital twin mapping of ground transportation in the cloud is achieved through global perception and hierarchical cloud control, whereas fast and efficient real-time intelligent management of traffic can be realized through AI technology.

(9) Aerial manipulator

Aerial manipulators are a new type of robots composed of aircraft and operating devices (manipulator arm, etc.) with active operation capability. The propeller provides lift for aircraft, which is flexible and highly controllable. Aerial manipulator systems have many advantages: 1) During the flight process, it can quickly capture air or ground targets; 2) it can also quickly reach complex environments, such as earthquakes, volcanoes, and other disaster sites, where ground robots cannot enter to perform delicate tasks; 3) multiple aerial manipulators can perform collaborative transportation and assembly of large loads; and 4) the combination of flight capability and operating mechanism flexibility can achieve a new concept of multi-habitable mobile platform. Affected by the strong coupling between the operating device and the aircraft, and the impact of contact between the operating device and the external target on the aircraft’s own motion, the application of aerial manipulators still faces many problems, such as the influence of underactuated, multivariable, strong coupling complex nonlinear systems on its control. The system design, visual guidance, and motion control research of aerial manipulators has received great attention in recent years. However, related research remains at an early stage. Many problems, such as coupling effect modeling and analysis, high-performance flight and operation control, motion/state planning, and experimental system construction, must be studied.

(10) High-power wireless power transmission

Wireless power transfer (WPT) is a non-contact power transfer technology that comprehensively utilizes power electronic technology and control technology to obtain electrical energy from the power supply to the load. Of these, the most important is the magnetic coupling wireless power transfer (MC-WPT), which uses the high-frequency alternating coupling magnetic field between the transmitting/receiving coils to realize power transmission, has the advantages of safety, reliability, flexibility, and ability to operate with zero contact. WPT technology was rated by the World Economic Forum in 2013 as one of the “top ten emerging technologies with the greatest impact on the world and the most likely to provide answers to global challenges.” The MC-WPT technology provides new power supply solutions in many fields, such as electric vehicle charging, implantable medical equipment power supply, underwater energy transmission, high-voltage electrical equipment power supply, etc. The main research directions include WPT system maximum power point tracking, analysis of transmission distance and transmission efficiency, optimization and control of multi-coil coupling mode, multi-pick dynamic wireless power transmission system control method, and foreign body detection technology of MC-WPT system. The main development trends include: improving the power of wireless energy transmission, increasing the power density of the energy supply system, enhancing the energy supply efficiency, increasing the transmission distance, and optimizing the system structure and control method to increase the reliability, stability, and robustness of the energy supply.

1.2 Interpretations for three key engineering research fronts

1.2.1 Intelligent manufacturing driven by digital twin

The application of digital twin technology stems from NASA's application in the design, manufacture, testing, and operation of aviation products, such as the simulation and remote operation of the "Curiosity" rover. Digital mockup, virtual prototyping, and functional virtual prototyping as well as other technologies have been proposed in the process of developing 3D modeling and designing, virtual simulation technology, and integrated application to realize motion, assembly, and performance simulations of complex products. IIoT has been widely used in the operation monitoring and maintenance of high-value industrial equipment due to the development of sensor and wireless communication technologies. Driven by academic research and demonstration effects of industrial giants, such as GE and Siemens, digital twin technology has been gaining widespread attention, and the virtual mapping between digital twin and physical models based on the IIoT has been realized.

Digital twin is the application research hotspot and frontier technology in the field of intelligent manufacturing. Digital twin applications of smart products aim to improve the performance of products continuously via virtual mapping, enhance experiences for customers, and improve safety, reliability, and stability of product operation to upgrade the competitiveness of products in the market. The value of digital twin applications in smart factory is mainly reflected in the construction of transparent factories, enhancement of the level of operation and management of factories, improvement of overall equipment efficiency, reduction of energy consumption, and promotion of safe production. Typical scenarios for digital twin technology include the research and development of mechatronic complex products, operation monitoring and intelligent operation and maintenance of smart products, real-time simulation and remote monitoring of smart factory operation, production line virtual commissioning, and digital marketing.

At present, the application of digital twin technology is still in the early stage and its main research directions include creation of integrated platform for digital twin technology applications; development of backbone platform that can carry out interactive and real-time 3D rendering of lightweight 3D models and support virtual reality/augmented reality applications; opening of digital thread throughout the product's life cycle; integration of digital twin models in all the stages to ensure consistency of each digital twin model in the event of change; establishment of 3D visualization technology for real-time monitoring of the operation of smart products and factories; executing system and multidisciplinary simulations of smart products, such as structure, fluid, electromagnetic, and other technologies, as well as down-order processing to ensure synchronization of multidisciplinary simulation computations; real-time analysis of sensor and IIoT data based on AI and industrial big data technology; and analysis and comparison of IIoT data from edge and digital twin model simulation result data from the cloud based IIoT platforms.

Countries with the highest number of core papers published on "intelligent manufacturing driven by digital twin" engineering are China and Singapore, and countries dominant in citations are the United States, Australia, France, and Germany, as seen in Table 1.2.1. Among the top seven countries with the most published papers, China has more cooperation with Singapore, as shown in Figure 1.2.1. Institutions with the highest number of core papers published are Beihang University and National University of Singapore. Top institutions on citation frequency are University of Iowa, University of New South Wales, Friedrich-Alexander Universität Erlangen-Nürnberg, and University of Paris-Saclay, as shown in Table 1.2.2. Beihang University and National University of Singapore have a lot of cooperation, as shown in Figure 1.2.2. The top three countries for citing core papers are China, the United States, and Germany, as shown in Table 1.2.3. The main output institutions for citing core papers are Beihang University, Chalmers University of Technology, and Wuhan University of Technology, as shown in Table 1.2.4.

1.2.2 Hybrid additive-subtractive manufacturing method

The layer-by-layer manufacturing and overlaying principle are used in additive manufacturing to form any complex structure theoretically without constraints of complex conditions, such as tools, molds, and fixtures in traditional machining. Thus, typical problems of traditional processing methods when forming complex parts are avoided. Therefore, German Industry 4.0, American Advanced Manufacturing, Made in China 2025, British Industry 2050, Japan's Revitalization

Strategy, and other national development strategies consider additive manufacturing as an important direction for future development. However, compared with traditional machining, additive manufacturing parts have serious problems, such as poor geometric accuracy and surface quality as well as many internal defects. The hybrid additive–subtractive manufacturing technology uses layer-by-layer additive manufacturing and timely subtractive processing to realize the continuous or simultaneous manufacturing process of "additive accumulation–subtractive finishing" of parts on the same machine tool, so as to obtain the parts with complex structure, dense organization, high shape precision, and high surface quality directly, and to meet the performance requirements of precision parts in the field of industrial high grade field. This technology has become the emphasis and focus of the global manufacturing industry because of its advantages of complex forming parts and high material utilization rate in additive manufacturing and high-quality and high-precision subtractive processing.

At present, the relevant research mainly includes three aspects: method and equipment, software, and technology. In terms of hybrid additive–subtractive manufacturing method and equipment: study the hybrid additive–subtractive manufacturing method of different energy sources and materials, develop multi-axis CNC machine tools, additive manufacturing mechanism, feed mechanism and other systems, and develop hybrid additive–subtractive manufacturing equipment; in terms of hybrid additive–subtractive manufacturing software, to develop three major types of software: parts feature recognition layered data processing, hybrid additive–subtractive manufacturing path generation and planning, additive–subtractive processing technic simulation; in terms of hybrid additive–subtractive manufacturing technic: according to the forming material and performance requirements, to optimize the additive–subtractive manufacturing technic, and finally to achieve the purpose of shape control and performance control. Internal defects, such as cracks and pores, easily produced in

Table 1.2.1 Countries with the greatest output of core papers on "intelligent manufacturing driven by digital twin"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	7	77.78%	630	90.00	2017.7
2	Singapore	3	33.33%	88	29.33	2017.0
3	Australia	1	11.11%	148	148.00	2018.0
4	USA	1	11.11%	148	148.00	2018.0
5	France	1	11.11%	134	134.00	2017.0
6	Germany	1	11.11%	134	134.00	2017.0
7	Sweden	1	11.11%	83	83.00	2017.0

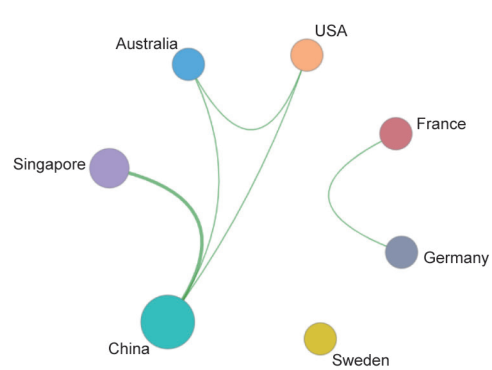

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "intelligent manufacturing driven by digital twin"

Table 1.2.2 Institutions with the greatest output of core papers on "intelligent manufacturing driven by digital twin"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Beihang University	6	66.67%	575	95.83	2017.7
2	National University of Singapore	3	33.33%	88	29.33	2017.0
3	University of Iowa	1	11.11%	148	148.00	2018.0
4	University of New South Wales	1	11.11%	148	148.00	2018.0
5	Friedrich-Alexander Universität Erlangen-Nürnberg	1	11.11%	134	134.00	2017.0
6	University of Paris-Saclay	1	11.11%	134	134.00	2017.0
7	Chalmers University of Technology	1	11.11%	83	83.00	2017.0
8	Beijing Institute of Technology	1	11.11%	55	55.00	2018.0

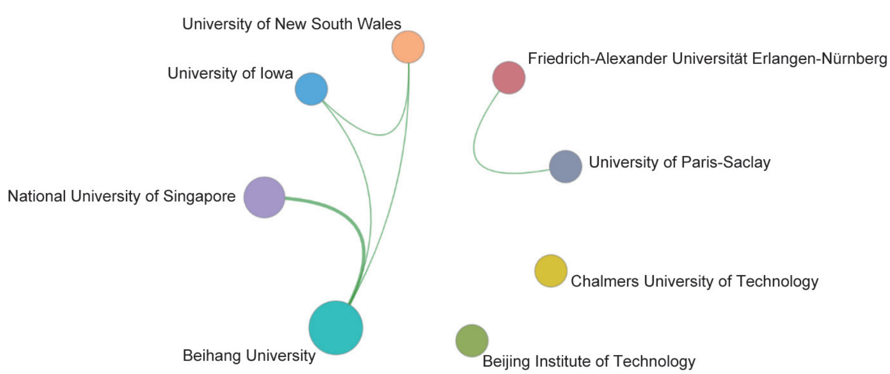

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "intelligent manufacturing driven by digital twin"

Table 1.2.3 Countries with the greatest output of citing papers on "intelligent manufacturing driven by digital twin"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	238	40.07%	2018.9
2	USA	78	13.13%	2019.1
3	Germany	47	7.91%	2019.0
4	UK	46	7.74%	2018.9
5	Sweden	39	6.57%	2018.8
6	Italy	33	5.56%	2019.1
7	France	33	5.56%	2018.6
8	Singapore	24	4.04%	2019.0
9	South Korea	23	3.87%	2018.9
10	India	19	3.20%	2018.7

the additive process seriously affect mechanical properties of parts, such as tensile and fatigue strength, especially in the manufacture of demanding large-scale aviation metal components. To this end, the introduction of on-line detection and control technology in the hybrid additive–subtractive manufacturing process, the realization of real-time detection

Table 1.2.4 Institutions with the greatest output of citing papers on "intelligent manufacturing driven by digital twin"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Beihang University	45	23.32%	2018.6
2	Chalmers University of Technology	24	12.44%	2018.8
3	Wuhan University of Technology	18	9.33%	2018.2
4	Guangdong University of Technology	16	8.29%	2018.6
5	Nanyang Technological University	15	7.77%	2019.3
6	Shanghai Jiao Tong University	14	7.25%	2019.0
7	Northwestern Polytechnical University	14	7.25%	2018.9
8	University of Hong Kong	14	7.25%	2019.4
9	The Hong Kong Polytechnic University	13	6.74%	2019.4
10	Zhejiang University	10	5.18%	2018.9

feedback in the manufacturing process, timely detection of defects and size deviation in the forming process, dynamic adjustment of the composite process parameters in the forming process, and the formation of closed loop control, are effective methods to improve the performance and accuracy of hybrid additive–subtractive manufacturing parts, which has become the research frontier and development trend of hybrid additive–subtractive manufacturing.

The top two countries with the maximum number of core papers published in the forefront of engineering research on "hybrid additive–subtractive manufacturing method" are the United States and the United Kingdom. The top countries cited by frequency are South Korea, the United Kingdom, Finland, and France, as shown in Table 1.2.5. The United States has published cooperative studies with both South Korea and China, as shown in Figure 1.2.3. Institutions with the maximum number of core papers are University of Bath and Youngstown State University. Institutions with the maximum frequency of citations are Lawrence Berkeley National Laboratory, Seoul National University, and University of Washington, as shown in Table 1.2.6. Seoul National University, Lawrence Berkeley National Laboratory, University of Washington, Tampere University of Technology, Grenoble Alpes University, and Aalto University are organizations with published cooperative studies, as shown in Figure 1.2.4. The top three countries for citing core papers are the United States, China, and Germany, as shown in Table 1.2.7. The main output institutions for citing core papers are Polytechnic University of Turin, Seoul National University, and Dalian University of Technology, as shown in Table 1.2.8.

1.2.3 Air-breathing hypersonic vehicles

The air-breathing hypersonic vehicles' concept predates the space shuttle. To achieve the goal of attacking any place in the world fastly, the United States developed multi-type air-breathing hypersonic vehicles, such as X-30, X-43A/B/C, SR-72, X-51A. In 2004, NASA led the completion of the second flight test of X-43A, which was the first to achieve the key technology verification of an air-breathing hypersonic vehicle flying at Mach 10. After 2010, the United States launched the Hypersonic Air-breathing Weapon Concept project as a continuation of X-51A, aiming to develop air-breathing tactical-grade hypersonic cruise missiles that have a speed of Mach 5–6, a range of approximately 1000 km, and can be built into the bomber and mounted on the fighter. Beside, Russia tested the new hypersonic antiship cruise missile "Zircon", which has an actual flight speed of Mach 6–8; Russia revealed the hypersonic stealth strategic bomber plan. The bomber adopts the combined power mode, and the speed exceeds Mach 5.

The development of aerospace planes is difficult and unlikely to be developed in the short term; thus, current international breakthroughs in air-breathing hypersonic vehicles are mainly focused on the weapon application of near-space missiles. With the increasing antagonism of competition among major powers, advanced weapons, such as hypersonic weapons that combine high tactical practicality and strategic deterrence, are attracting worldwide attention and contributing to a full-scale game on offensive and defensive capabilities and potential arm control. From the perspective of technology development, the single-use air-breathing hypersonic missile technology has broken through and is expected to see a blowout deployment in 2023–2025. From the perspective of technological development, the recent air-breathing hypersonic vehicle still needs to focus on tackling key technical problems, including the overall design of the vehicle, scramjet and combined propulsion, integrated aerodynamic design of the vehicle/propulsion system, thermal protection of structural materials, and advanced high dynamic fast response control.

The top three countries with the largest number of core papers published on the forefront of “air-breathing hypersonic vehicles” engineering research are China, Canada, and the United Kingdom; the top three countries with the highest average citations per paper are China, Canada, and the United Kingdom, as shown in Table 1.2.9. Among the top three countries with the largest number of publications, China and Canada have more cooperation, as shown in Figure 1.2.5. The top three organizations with the largest number of core papers are Air Force Engineering University, Harbin Institute of Technology, and Northwestern Polytechnical University. The institutions with the highest citations per paper are Northwestern Polytechnical University, Tianjin University, Tsinghua University, and University of Science & Technology Beijing, as shown in Table 1.2.10. Among the top 10 institutions with the largest number of publications, more cooperation is observed between Air Force Engineering University and Northwestern Polytechnical University, and also between Harbin Institute of Technology and University of Waterloo, as shown in Figure 1.2.6. The top three countries for publishing papers that cite core papers are China, Canada, and the United States, as shown in Table 1.2.11; for institutions, the top three are Northwestern Polytechnical University, Harbin Institute of Technology, Air Force Engineering University, as shown in Table 1.2.12.

Table 1.2.5 Countries with the greatest output of core papers on “hybrid additive-subtractive manufacturing method”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	6	54.55%	318	53.00	2015.2
2	UK	2	18.18%	189	94.50	2015.5
3	South Korea	1	9.09%	133	133.00	2014.0
4	Finland	1	9.09%	56	56.00	2016.0
5	France	1	9.09%	56	56.00	2016.0
6	Belgium	1	9.09%	37	37.00	2014.0
7	China	1	9.09%	25	25.00	2016.0
8	Germany	1	9.09%	25	25.00	2016.0

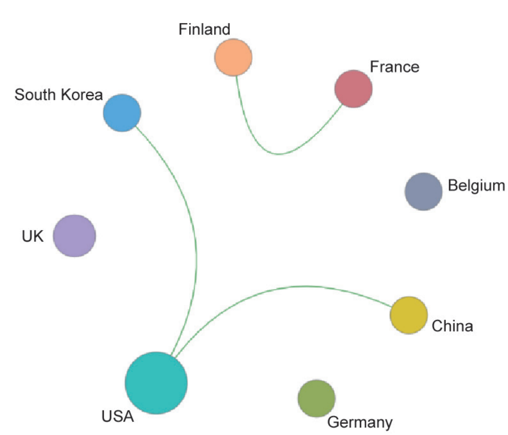

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “hybrid additive-subtractive manufacturing method”

Table 1.2.6 Institutions with the greatest output of core papers on “hybrid additive-subtractive manufacturing method”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	University of Bath	2	18.18%	189	94.50	2015.5
2	Youngstown State University	2	18.18%	52	26.00	2015.5
3	Lawrence Berkeley National Laboratory	1	9.09%	133	133.00	2014.0
4	Seoul National University	1	9.09%	133	133.00	2014.0
5	University of Washington	1	9.09%	133	133.00	2014.0
6	University of California, Berkeley	1	9.09%	97	97.00	2015.0
7	Aalto University	1	9.09%	56	56.00	2016.0
8	Tampere University of Technology	1	9.09%	56	56.00	2016.0
9	Grenoble Alpes University	1	9.09%	56	56.00	2016.0
10	Catholic University of Leuven	1	9.09%	37	37.00	2014.0

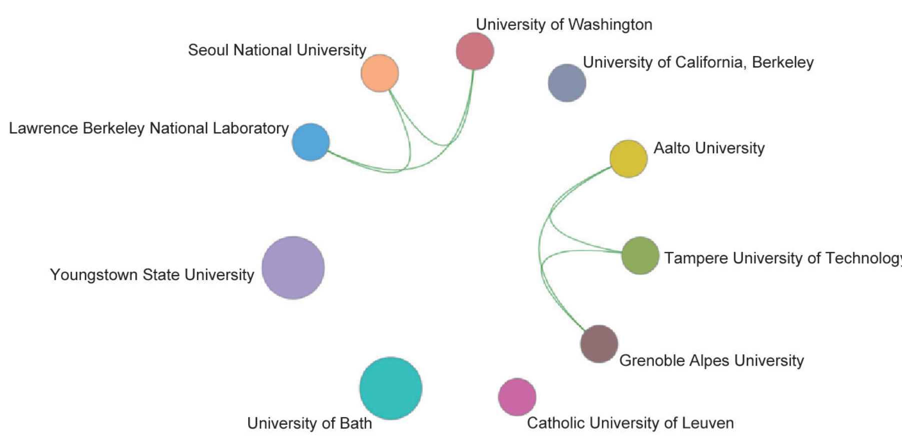

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “hybrid additive-subtractive manufacturing method”

Table 1.2.7 Countries with the greatest output of citing papers on “hybrid additive-subtractive manufacturing method”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	99	22.45%	2018.2
2	China	75	17.01%	2018.6
3	Germany	53	12.02%	2018.2
4	Italy	46	10.43%	2018.2
5	UK	43	9.75%	2017.9
6	South Korea	39	8.84%	2016.8
7	France	28	6.35%	2018.1
8	Spain	18	4.08%	2018.6
9	Canada	18	4.08%	2018.7
10	Netherlands	11	2.49%	2018.9

Table 1.2.8 Institutions with the greatest output of citing papers on “hybrid additive-subtractive manufacturing method”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Polytechnic University of Turin	16	14.29%	2018.1
2	Seoul National University	15	13.39%	2016.4
3	Dalian University of Technology	12	10.71%	2018.3
4	University of Illinois	9	8.04%	2017.3
5	Zhejiang University	9	8.04%	2018.6
6	University of Nottingham	9	8.04%	2017.3
7	Harbin Institute of Technology	9	8.04%	2018.8
8	University of Palermo	9	8.04%	2017.7
9	Grenoble Alpes University	8	7.14%	2017.6
10	Mississippi State University	8	7.14%	2018.6

Table 1.2.9 Countries with the greatest output of core papers on “air-breathing hypersonic vehicles”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	25	100.00%	984	39.36	2016.6
2	Canada	2	8.00%	42	21.00	2018.0
3	UK	1	4.00%	19	19.00	2017.0

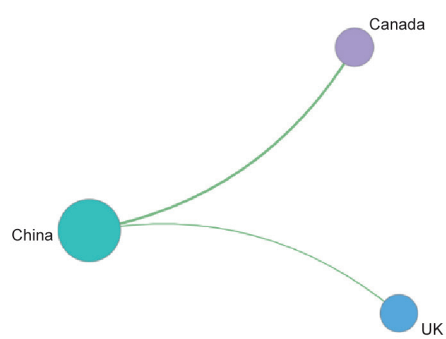

Figure 1.2.5 Collaboration network among major countries in the engineering research front of “air-breathing hypersonic vehicles”

Table 1.2.10 Institutions with the greatest output of core papers on “air-breathing hypersonic vehicles”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Air Force Engineering University	8	32.00%	186	23.25	2017.1
2	Harbin Institute of Technology	7	28.00%	221	31.57	2017.3
3	Northwestern Polytechnical University	5	20.00%	310	62.00	2017.2
4	Tianjin University	3	12.00%	159	53.00	2015.3
5	Beihang University	3	12.00%	112	37.33	2015.7
6	University of Waterloo	2	8.00%	42	21.00	2018.0
7	Tsinghua University	1	4.00%	43	43.00	2019.0
8	University of Science & Technology Beijing	1	4.00%	43	43.00	2019.0
9	China Academy of Space Technology	1	4.00%	41	41.00	2015.0
10	Beijing Research Institute of Mechanical & Electrical Engineering	1	4.00%	37	37.00	2015.0

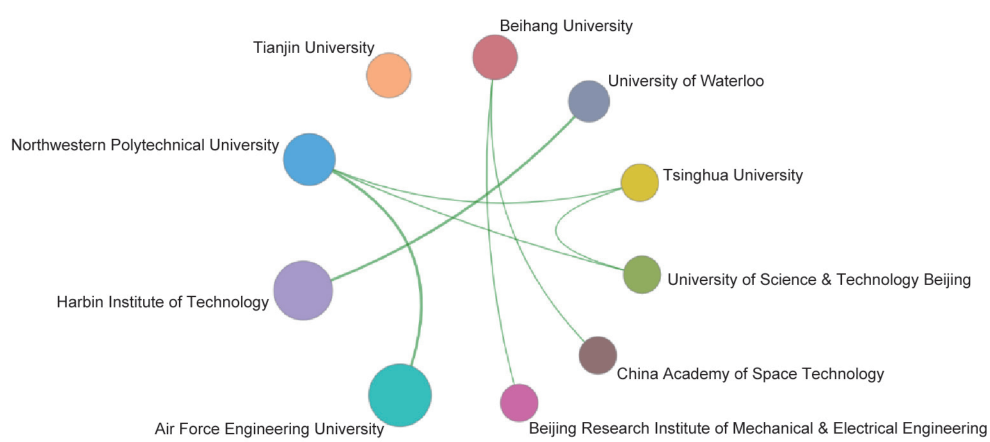

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “air-breathing hypersonic vehicles”

Table 1.2.11 Countries with the greatest output of citing papers on “air-breathing hypersonic vehicles”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	502	83.25%	2018.1
2	Canada	26	4.31%	2017.9
3	USA	22	3.65%	2018.1
4	UK	16	2.65%	2017.7
5	Singapore	10	1.66%	2017.2
6	Iran	7	1.16%	2018.1
7	India	5	0.83%	2018.4
8	Italy	4	0.66%	2018.0
9	France	4	0.66%	2018.5
10	Australia	4	0.66%	2018.2

Table 1.2.12 Institutions with the greatest output of citing papers on "air-breathing hypersonic vehicles"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Northwestern Polytechnical University	87	20.81%	2018.0
2	Harbin Institute of Technology	60	14.35%	2018.3
3	Air Force Engineering University	49	11.72%	2017.7
4	Nanjing University of Aeronautics and Astronautics	48	11.48%	2018.2
5	Beihang University	46	11.00%	2018.3
6	Tianjin University	32	7.66%	2017.6
7	Chinese Academy of Sciences	29	6.94%	2017.7
8	University of Chinese Academy of Sciences	19	4.55%	2018.1
9	Concordia University	18	4.31%	2017.9
10	National University of Defense Technology	15	3.59%	2018.0

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

Top 10 development (as opposed to research) fronts in mechanical and vehicle engineering are listed in Table 2.1.1. Seven of these fronts are characterized by in-depth traditional research: "big data driven scheduling technology for intelligent manufacturing system," "ultra-precision machining technology for complex surfaces," "development of fully integrated wearable multi-functional sensors," "bionic soft robot," "thermal protection technology for hypersonic vehicle," "manned/unmanned aerial vehicle cooperative control technology," and "smart grid operation and dispatch technology." There are also three other fronts that are newly emerging: "driverless system based on 5G technology," "underwater unmanned vehicles and their warship-load technology," and "flexible electronic manufacturing technology." Table 2.1.2 shows the annual publication rate of core patents and related papers from 2014 to 2019. "Driverless system based on 5G technology" and "underwater unmanned vehicles and their warship-load technology" are the most significant directions of patent disclosure in recent years.

(1) Driverless system based on 5G technology

Driverless technology is an intelligent technology that combines environmental perception, decision planning, and automatic control, and can be operated by a system or device in the form of an automobile, aircraft, ship, and so on. The integration of "networking + intelligent" technology and industrial development is the most promising way to realize driverless technology. In recent years, 5G technology has become a key technology for networking and intelligent development due to its high speed, precise ranging and sensing capabilities, and low-latency communication. Current mainstream driverless technology relies on an individual vehicle's independent perception ability. Moreover, such a technology requires a series of sensors (e.g., expensive cameras, lidar, millimeter wave radar, ultrasonic sensors, inertial navigation, and satellite navigation) and can only sense the range of visibility. In the case of inclement weather and rapid changes in light, it is difficult for individual technique such as cameras or lidar to perform robust perception, and it has difficulties in synchronizing time and space. Aside from complex computing tasks, in-vehicle computing platforms for driverless technology are also expensive, have limited processing power, and cannot be easily mass produced on a large scale. Meanwhile, the disadvantages of 4G technology include limited communication capabilities; inability to provide sufficient data rate support for high-definition maps, virtual reality, and augmented reality applications; and inability to meet road safety requirements of low latency and high reliability. The combination of 5G and driverless system is a research frontier and hot issue in the field of driverless. Its main applications include internet of vehicles, remote control, edge computing, and building connections between individuals and everything in the environment, among others.

(2) Underwater unmanned vehicles and their warship-load technology

Compared with other types of underwater detection

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	Driverless system based on 5G technology	137	106	0.77	2018.6
2	Underwater unmanned vehicles and their warship-load technology	536	2 413	4.50	2016.6
3	Flexible electronic manufacturing technology	671	5 047	7.52	2016.0
4	Big data driven scheduling technology for intelligent manufacturing system	26	24	0.92	2018.2
5	Ultra-precision machining technology for complex surfaces	76	259	3.41	2016.2
6	Development of fully integrated wearable multi-functional sensors	119	487	4.09	2017.1
7	Bionic soft robot	30	244	8.13	2016.4
8	Thermal protection technology for hypersonic vehicle	73	171	2.34	2017.0
9	Manned/unmanned aerial vehicle cooperative control technology	49	210	4.29	2016.7
10	Smart grid operation and dispatch technology	133	686	5.16	2016.0

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	2014	2015	2016	2017	2018	2019
1	Driverless system based on 5G technology	1	0	3	8	30	95
2	Underwater unmanned vehicles and their warship-load technology	42	44	94	89	85	137
3	Flexible electronic manufacturing technology	60	83	84	106	121	112
4	Big data driven scheduling technology for intelligent manufacturing system	0	0	4	2	5	15
5	Ultra-precision machining technology for complex surfaces	5	14	10	14	11	14
6	Development of fully integrated wearable multi-functional sensors	6	8	18	36	34	17
7	Bionic soft robot	2	5	5	2	3	10
8	Thermal protection technology for hypersonic vehicle	2	5	6	17	16	21
9	Manned/unmanned aerial vehicle cooperative control technology	2	4	2	5	22	7
10	Smart grid operation and dispatch technology	9	29	18	22	14	22

equipment, underwater unmanned vehicles can be used as an important node of an unmanned underwater monitoring network due to their advantages, including strong survivability and high autonomy; moreover, such vehicles cannot be easily detected compared with other traditional detection methods. However, with the influence of complex environmental factors, such as seawater density, ocean currents, seabed topography, and landforms as well as the limitations of the bandwidth and transmission distance of underwater communication, the application efficiency of the underwater unmanned vehicles will be limited greatly. Research on underwater unmanned vehicle technology is mainly focused on the monomer adaptive tracking control in the complex ocean environments, underwater complex environment perception, autonomous task decision-making, and cross-platform communication network relay, among others. In order to broaden the application scenarios of such unmanned vehicles, it also emerges a series of exploratory research in unmanned vehicles' airdrop and shipboard deployment in the aspect of the application and deployment. The cooperative tracking and detection of an underwater unmanned vehicle cluster perform far better than those of the monomer tracking detection, which can maximize its platform advantages. Therefore, research on the collaborative networking control technology of an underwater unmanned vehicle cluster under the conditions of strong disturbance and asynchronous navigation will be the development trend of this research direction.

(3) Flexible electronic manufacturing technology

Flexible electronics is an emerging electronic technology that manufactures organic/inorganic thin-film electronic devices on flexible/stretchable substrates. With its unique flexibility/stretchable and highly efficient/low-cost manufacturing process, it has promising application prospects in the fields of information, energy, healthcare, and national defense; has opened up innovative electronic product applications, such as flexible display, wearable electronics, flexible energy, and smart e-skin; and is leading the technological revolution of the next generation of the electronics industry. Flexible electronics manufacturing can achieve large-area integration of nanoscale features, micro/nano-structures, and macroscale devices on complex surfaces or flexible substrates, involving the precise formation of functional interfaces of organic, polymeric, metal, nonmetal, and nano materials with remarkably different electrical and mechanical properties. It breaks through the limits of size, flexibility, and reliability of traditional microelectronics; faces the manufacturing technology revolution from "plane to curved surface," from "2D to 3D," and from "undeformable to large deformation." Currently, major technology development trends include: developing multiscale high-precision manufacturing methods for nanofeatures, micro/nano-structures, and meter-scale devices (i.e., large-area and precise manufacturing of organic or inorganic micro/nano-structures on nonplanar substrates with large deformation to meet demanding optical, electrical, and mechanical requirements; developing flexible micro/nano-structure design and manufacturing methods to meet the demanding requirements of the deformability of flexible electronics (deformation > 50%) and breaking through the deformation limit of traditional silicon-based devices (usually, its ductility does not exceed 2%); enhancing the design, manufacturing and integration reliability of flexible electronics to overcome the challenges brought by the features of flexible electronics (e.g., the serious mismatch between soft and hard materials, repeated bending and stretching, and multifunctional integration).

(4) Big data driven scheduling technology for intelligent manufacturing system

A typical intelligent manufacturing system is a human–machine integrated intelligent production system composed of human experts and intelligent machines, which is driven by large-scale personalized customization and supported by industrial big data, AI, industrial intelligent networking and other technologies. It serves as the core of intelligent manufacturing. Intelligent scheduling is one of the key technologies of intelligent manufacturing systems. Before the advent of big data technology, the production scheduling of manufacturing systems heavily relied on the accurate modeling and efficient algorithms. However, as product requirements and processes become more diverse, manufacturing systems become increasingly complex, and the traditional "causality + modeling + algorithm" model can hardly meet the demand. Big data technology provides a new way for solving this problem. Various kinds of manufacturing system data have been collected with the rapid development of information technology and automation technology, especially the extensive use of NC machine tools, sensors, data acquisition devices, and other intelligent devices with perception capabilities in the manufacturing system. Using big data technology to analyze and use the collected data to make intelligent scheduling become the research frontier in current manufacturing system field. The main research directions include human–cyber–physical fusion and knowledge generation of manufacturing system, big data driven accurate prediction of uncertainty information in manufacturing systems, dynamic scheduling of human–machine-material integration manufacturing system, cross-regional and cross-scale distributed production scheduling, joint model- and data-driven scheduling optimization decision, and digital twin enabled production scheduling.

(5) Ultra-precision machining technology for complex surfaces

With the rapid development of advanced technologies, such as microelectronics, aerospace, and advanced optics, there has been an increasing demand for ultra-precision manufacturing of high-performance, complex curved components to meet their high-quality service requirements, such as long life, high reliability, and light weight. Based on the generation theory and manufacturing method of ultra-precision complex surface, current studies on ultra-precision machining technology of complex surfaces are mainly focused on the investigation for generation mechanism of complex surfaces, material removal mechanism, surface accuracy controlling mechanism, and advanced tool design and manufacturing, in order to explore the evolution and forming law of ultra-precision complex surface components. Nowadays, dimensions of components have evolved towards extreme; the shapes and materials have become increasingly complicated and diversified, respectively; and there are mounting requirements to minimize surface and subsurface damages. Hence, new challenges have emerged regarding the ultra-precision processing technology of complex curved surfaces, and addressing such challenges has become an important demand and traction for manufacturing science with nanoscale precision. In the future, researches on ultra-precision machining technology of complex curved surfaces should be developed in the following two directions. The first direction is the development of new principles and new methods of ultra-precision creation of high-performance complex curved surfaces. By introducing the multi-energy field-assisted manufacturing mode, the coupling mechanism of stress, thermal, optical, and other multi-energy fields in the processing, and the basic law of material micro-fracture propagation are revealed to realize ultra-precision and low-damage manufacturing. The second direction involves design and manufacturing of ultra-precision equipment, as well as the construction of intelligent control system for high-performance, complex curved surface. This direction aims to study the design theory and manufacturing technology of ultra-precision equipment for complex curved surfaces; reveal the mutual restriction mechanisms among component features, equipment accuracy, and processing path; and realize controlled intelligent manufacturing with nanoscale precision.

(6) Development of fully integrated wearable multi-functional sensors

The development of flexible electronics and stretchable electronics technologies has provided solutions for realizing the demand for flexible and wearable sensing systems, respectively. The wearable multi-functional sensor devices can not only accurately convert environmental stimuli into electrical signals, but also have the advantages of high accuracy, good fit, good conformality, and high degree of stability, among others. Such devices are widely used in the fields of robot tactile perception, wearable health monitoring, and rehabilitation. At present, the development of wearable, multi-functional, integrated sensors mainly focuses on exploring multi-modal sensing mechanisms, stretchable material design and synthesis, multi-modal sensor structure design, and the efficient integration of multi-modal sensors. Research on multi-modal sensing enhancement mechanism aims to design different sensing principles and realize high sensitivity according to the demand of sensors to capture pressure, shear force, temperature, humidity, and other external information. The design and synthesis of stretchable materials is based on the development of functional sensing materials and substrate materials with flexibility and stretchability to achieve the extensibility of sensing units. Meanwhile, the development of multi-modal sensor structure design and high-efficiency fabrication schemes aims to achieve high stretchability of the sensing system through structural design. This research direction mainly includes stress separation structure design, hierarchical and array sensor layout structure design, and micronano structure high-efficiency controllable preparation technology. The efficient integration of multi-modal sensors includes packaging technology based on flexible or stretchable substrates, high-density sensor array signal anti-interference reading technology, and multi-modal sensor information intelligent fusion processing technology. In the future, research on wearable multi-functional integrated sensors should develop in the following directions: high sensitivity and high response speed of the sensing unit, integration of multi-modal sensors with high density and high spatial resolution, and adaptive and autonomous sensing of multi-functional integrated sensors.

(7) Bionic soft robot

Robotics has been widely used in various engineering applications in recent years. More complex, dynamic, and unstructured scenarios have put forward higher adaptability demands for robots. Bionic soft robotics, as a branch of robotics, endows robots with better flexibility, large deformability, and other biological features by imitating the soft structure of the organism, thereby allowing the robots to interact morphologically and adaptively with the unpredictable environment. The inherent properties of these soft robot materials can potentially reduce the complexity of machinery and control algorithms in an “intelligent” way and realize some complex behaviors and functions with a high degree of freedom. The current development of bionic robot technology mainly includes new smart soft materials, new actuation/function mechanisms, structure design of bionic soft robots, integration of actuation and perception, design and manufacturing integration technology, interactive control strategy and theory, and high energy density flexible battery technology. Although a series of exploration and development on bionic soft robots have been made in recent years, such studies are still in the preliminary stage of development compared with those biological intelligence. Future studies are expected to combine bionic soft robots with tissue engineering and artificial biology to create a biological hybrid system with unique perception, dynamic response, and mobility. In addition, the bionic soft robots are expected to integrate with humans and the environment more safely, and applied to more special application scenarios by accelerating the development of collaborative robots.

(8) Thermal protection technology for hypersonic vehicle

High-temperature aerodynamic heat (surface temperature greater than 1500 K) generated by hypersonic aircraft during high-speed flight (Mach number greater than 10) will seriously threaten the overall structural safety of an aircraft. Knowing how to design targeted thermal protection to solve the problem of high-temperature thermal ablation is one of the major key technologies in developing a hypersonic aircraft. Ablative heat protection is a type of heat protection technology that is widely used in super aircraft. This method is used to generate gas through the ablation of heat protection materials and reduce aerodynamic heat under the action of airflow. Nowadays, different countries around the world are developing high-performance and lightweight ablation-resistant coating materials, such as phenolic resin-based thermal insulation composites, ceramic/metal composite thermal functional gradient materials, alumina-reinforced thermal shielding materials, alumina-soluble modified thermal insulation materials, ultralight rigid thermal insulation materials, synthetic multi-density materials and other rigid thermal insulation materials, and flexible thermal insulation materials (i.e., new composite flexible thermal insulation felt and sewing flexible thermal insulation felt). With the emergence of various new heat-proof materials, the next issue for consideration would be the low-cost production technology of those materials, including raw materials, composite processes, and quality control. The main research direction includes: low-temperature curing/high-temperature use/long-life resins and prepregs using composite materials with hybrid fibers, the improvements to the automation of prepreg preparation, automated placement technologies for fibers or fabric reinforcements, and low-temperature curing, electron beam curing, and resin transfer molding and its derivative technologies.

(9) Manned/unmanned aerial vehicle cooperative control technology

Manned/unmanned aerial vehicle collaboration refers to the decision-making, planning, control, and perception between the manned-aircraft system and the unmanned aerial vehicle (UAV) system. Such a process not only involves independent calculations, storage, and processing but also achieves group collaboration through interaction and integration. On one hand, the UAV system currently does not have the ability to respond and handle accidents in real time. It is also unable to complete tasks autonomously, that is, when performing tasks, it needs to be operated and controlled by humans through the data link to ensure task completion and safe use. On the other hand, manned aerial vehicles (MAVs) and UAVs have natural advantages that complement each other in terms of platform capabilities (e.g., stealth, maneuverability, hang time, and combat radius), airborne sensor, and airborne weapon performance. Therefore, realizing the collaboration of high-end UAVs and advanced MAVs is a prioritized operational style that can be developed and implemented. This is an important approach in overcoming the deficiencies of MAVs and UAVs, and can greatly improve the combat effectiveness and battlefield survival capability of the cooperative system. Thus, it represents an important direction for the innovative development of future air combat models. Studies on manned/unmanned aerial vehicle cooperative control mainly focus on several directions. The first direction is multi-machine and multi-task allocation and overall formation optimization in a dynamic environment as well as collaborative situation awareness and information fusion. The second one is MAVs/UAVs cooperative route planning based on mission planning indicators, flight constraints, and battlefield environment. The third research direction is the human–computer interaction control based on the control technology of natural language understanding to realize the information exchange between manned and unmanned aerial vehicles. The fourth research direction is the application and research on the application of cluster heterogeneous multi-agent technology in cooperative decision-making of MAVs and UAVs.

(10) Smart grid operation and dispatch technology

In recent years, the increase in renewable energy penetration has magnified the uncertainty of power grids, the development trend of power electronics has continuously decreased the relative inertia of power grids, and the promotion of the power market has constantly strengthened the game among multimarket players, which make the secure operation of power grid face unprecedented challenges. At the same time, the coupling of power and other energy systems has continued to deepen, and the role of smart grids in the hub platform of the future large energy system has become increasingly prominent. Smart grid operation and dispatch technology adopts advanced sensing and measurement technology as well as control and decision-making methods to realize the secure, high-quality, economical, and green operation of a grid integrating bulk renewable energy through the interaction among the source, grid, and load. On the power source side, the variability of the renewable energy output is reduced through complementary power generation, thus the regulation capacity of traditional power plants is improved simultaneously. On the grid side, regional interconnection and auxiliary service transactions are adopted to achieve cross-regional balance and consumption. On the load side, through the construction of the microgrid and active distribution network, the demand side response is provided by the load integrator, or the supply and demand is balanced across more energy networks through power-to-X. Smart grid operation and dispatch technology presents the following development trends: the application of low-inertia smart grid dispatching operation and control theory to ensure the secure and stable operation of smart grids with high penetration of nonsynchronous machine power sources; new business patterns that encourage power generation manufacturers and users to provide auxiliary services to grids and encourage active consumption of renewable energy; the adoption of theoretical methods of data and model fusion to achieve intelligent decision-making in uncertain environments and improve the economic efficiency of smart grid operation and the utilization efficiency of renewable energy.

2.2 Interpretations for three key engineering development fronts

2.2.1 Driverless system based on 5G technology

Developing 5G technology-based driverless system has several advantages: it can increase the range of situational awareness, perceive the environment more accurately and effectively, and thus ensure driving safety; reduce the number of high-precision sensors deployed on a single vehicle, and thus minimize the cost of perception and calculation; realize real-time linkage between vehicles and roads, and thus increase road traffic efficiency and ease traffic congestion; and has a wealth of network applications, such as remote driving, vehicles platooning, automatic parking, speed guidance, accurate reminder of road conditions, and real-time sharing of high-definition video.

A driverless system based on 5G technology has several research directions. First, it can break through the limitations of driverless perception through collaborative perception. Under the support of 5G technology, it can help establish vehicle-to-vehicle, vehicle-to-tower, vehicle-to-lamp communication, and thus reduce the influence of strong sunlight, night, haze, rainstorm and other adverse environment on driving; perceive the vehicle information in all aspects of the intersection and realize the mutual "perspective" of surrounding vehicles. In this global perspective, reliance on single-vehicle sensors is minimized and the cost of the driverless system is reduced, but its applicability, reliability, and safety are improved. Second, the system can improve stability and real-time performance of remote control. The driverless remote control capability in a 5G environment is several times greater than that of 4G, and can effectively respond to the on-site situation. Edge computing support can also be provided by 5G network to enhance driverless technology. Here, the driverless system uploads its sensor information to the edge node via a 5G network and obtains driving decision results based on the powerful computing power of the edge node. Third, the system can enhance the communication ability of vehicles connected to many objects and thus realize the interconnection of information. Such enhanced connection enables traffic control departments to make intelligent decisions related to traffic resource dispatch and decision-making in the cloud, thereby improving the efficiency of public transportation.

Despite the advantages, a driverless system based on 5G technology faces two major challenges. The first challenge involves security challenges. Although 5G enables the convergence of computing and communication, the virtualization and software-defined capabilities of 5G technology also bring the risk in terms of security. It is more vulnerable to be attacked compared to previous telecommunications-specific devices, and its network stability is also more vulnerable. The second challenge has to do with the ubiquitous and unified high-precision space–time frame of reference. Autonomous driving places very high requirements on its own and on environmental positioning. Sub-meter or even centimeter-level high-precision positioning is an important factor that guarantees vehicle networking can carry out automatic vehicle driving and ensure decision-making safety. The information integration of collaborative perception must also be established within a unified space–time frame of reference. A high-precision space–time reference with seamless coverage must be established through 5G-global navigation statellite system, which provides the basis for the driverless system.

The top three countries with core patent disclosures and are at the engineering development front of “driverless systems based on 5G technology” are China, South Korea, and the United States, respectively. The top three countries in terms of citation frequency are the United States, China, and Germany, as shown in Table 2.2.1. The top three institutions with core patent disclosures are LG Group, Nippon Telegraph and Telephone Corporation, and HUAWEI, as shown in Table 2.2.2. Major countries and institutions with the most public core patents do not cooperate with each other.

2.2.2 Underwater unmanned vehicles and their warship-load technology

With the wide-ranging application of underwater unmanned vehicles in marine scientific observation and underwater target detection, such vehicles and their warship-load technologies have received extensive research attention, and a great deal of engineering practice work have been carried out. The tracking and detection of underwater unmanned vehicles in complex marine environments are difficult to perform under the strong disturbance effects of extreme environmental factors on the platform tracking and control. Currently, relevant studies have been carried out from the perspectives of sensor loading, complex environment perception, adaptive mission planning, and route planning. The underwater environment is complex and highly dynamic, and using only a single type of detection signal in such an environment has major limitations. Sensor loading is expanded from the perspective of the platform, and the multi-source data feature analysis is conducted based on deep learning methods. Then, the multi-source data fusion research is conducted so as to improve the platform’s perception of the complex marine environments. Referring to prior information and environmental perception, the underwater environment modeling is completed. Furthermore, the system featuring the adaptive tracking and detection of the underwater autonomous vehicle is combined with the detection task requirements and tracking target characteristics.

The development trend of the underwater unmanned vehicles involves performing tracking and detection tasks under the mode of cluster cooperative networking. The key task is to achieve certain dimensional consistency among multiple platforms. Consistency can be achieved by obtaining information from adjacent platforms or all platforms through a communication network, thus generating control commands

Table 2.2.1 Countries with the greatest output of core patents on “driverless system based on 5G technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	96	70.07%	82	77.36%	0.85
2	South Korea	15	10.95%	1	0.94%	0.07
3	USA	7	5.11%	22	20.75%	3.14
4	Japan	6	4.38%	0	0.00%	0.00
5	Germany	4	2.92%	1	0.94%	0.25
6	India	3	2.19%	0	0.00%	0.00
7	Sweden	2	1.46%	0	0.00%	0.00
8	Finland	1	0.73%	0	0.00%	0.00
9	Netherlands	1	0.73%	0	0.00%	0.00

Table 2.2.2 Institutions with the greatest output of core patents on "driverless system based on 5G technology"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	LG Group	South Korea	11	8.03%	0	0.00%	0.00
2	Nippon Telegraph and Telephone Corporation	Japan	6	4.38%	0	0.00%	0.00
3	HUAWEI	China	5	3.65%	11	10.38%	2.20
4	Xi'an University of Technology	China	5	3.65%	0	0.00%	0.00
5	Dajiang Innovations Technology Co., Ltd.	China	3	2.19%	27	25.47%	9.00
6	Shanghai Langbo Communication Technology Co., Ltd.	China	3	2.19%	0	0.00%	0.00
7	AT&T	USA	2	1.46%	16	15.09%	8.00
8	Fraunhofer	Germany	2	1.46%	1	0.94%	0.50
9	Guangdong Rongqi Intelligent Technology Co., Ltd.	China	2	1.46%	1	0.94%	0.50
10	Beihang University	China	2	1.46%	1	0.94%	0.50

through coordination strategies. Considering the underwater disturbance and communication delay, distributed collaborative research on underwater unmanned vehicles can be carried out. First, a distributed consistency protocol is designed to give the expected consistency variables, and then the mapping relationship is used to invert the required control coefficients. Finally, the collaborative design of multiple underwater unmanned vehicles is realized. Underwater unmanned vehicles can also be used as a support platform for surface ships or submarines, because their shapes and dimensions are similar to those of underwater weapons in the current military service. Meanwhile, the warship-load technology of underwater unmanned vehicles has expanded the applications of traditional underwater unmanned vehicles and simplified their deployment. Currently, numerous warship-load applications, such as self-propelled deployment using torpedo tubes, underwater pneumatic deployment, and air-drop deployment of warship-load underwater unmanned vehicle, have emerged in recent years.

Currently, the top three countries with core patent disclosures on the forefront of "underwater unmanned vehicles and their warship-load technology" engineering development are China, the United States, and Japan, and the top three countries with the highest average citations per paper are the United States, Italy, and Germany, as shown in Table 2.2.3. Greater cooperation is observed between the United States and Columbia, and cooperation is also noted between Italy and the Netherlands, between the United States and the Netherlands, and between Japan and Colombia, as shown in Figure 2.2.1. The top three institutions with the largest number of core patent disclosures are Harbin Engineering University, United States Navy, and China State Shipbuilding Corporation Limited, as shown in Table 2.2.4. No cooperation has been observed among the major institutions.

2.2.3 Flexible electronic manufacturing technology

As the feature size of transistors gradually approaches the limit, "beyond Moore's law" has been proposed recently from the perspective of functional integration; silicon-based microelectronics have developed to polymer-based flexible electronics; its application has expanded from information processing to optoelectronic devices, biosensing, human–computer interaction, and health care; and it is transforming the entire electronics manufacturing technology and industry. Systematic research on flexible electronic materials, devices, processes and equipment is the key to the realization of flexible electronics going from "lab" to "fab," and it is also the breakthrough and beachhead for the next generation of information industry. In 2018, the "American Manufacturing Innovation Network" identified flexible hybrid electronics manufacturing as the seventh theme; the European Union, the United Kingdom, South Korea, and Japan have all launched comprehensive plans to develop flexible electronic technologies/products.

Table 2.2.3 Countries with the greatest output of core patents on “underwater unmanned vehicles and their warship-load technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	196	36.57%	398	16.49%	2.03
2	USA	177	33.02%	1 587	65.77%	8.97
3	Japan	45	8.40%	67	2.78%	1.49
4	Germany	27	5.04%	155	6.42%	5.74
5	Russia	27	5.04%	11	0.46%	0.41
6	Colombia	20	3.73%	60	2.49%	3.00
7	UK	16	2.99%	63	2.61%	3.94
8	South Korea	16	2.99%	19	0.79%	1.19
9	Netherlands	5	0.93%	2	0.08%	0.40
10	Italy	4	0.75%	24	0.99%	6.00

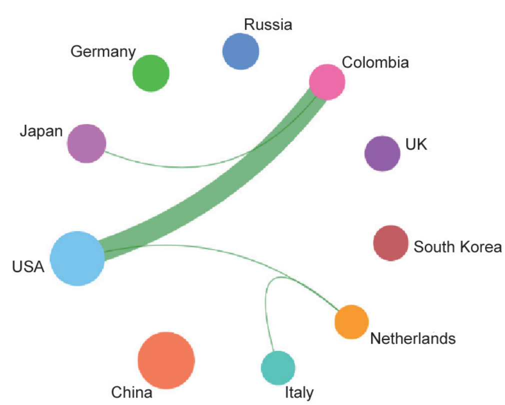

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “underwater unmanned vehicles and their warship-load technology”

Table 2.2.4 Institutions with the greatest output of core patents on “underwater unmanned vehicles and their warship-load technology”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Harbin Engineering University	China	110	20.52%	281	11.65%	2.55
2	United States Navy	USA	35	6.53%	80	3.32%	2.29
3	China State Shipbuilding Corporation Limited	China	16	2.99%	13	0.54%	0.81
4	Atlas Electronic GmbH	Germany	15	2.80%	142	5.88%	9.47
5	Boeing Company	USA	13	2.43%	19	0.79%	1.46
6	Raytheon Company	USA	12	2.24%	28	1.16%	2.33
7	Northwestern Polytechnical University	China	11	2.05%	9	0.37%	0.82
8	Adaptive Methods Inc.	USA	10	1.87%	25	1.04%	2.50
9	Subsea 7 Limited	UK	8	1.49%	29	1.20%	3.63
10	Kawasaki Heavy Industries, Ltd.	Japan	8	1.49%	7	0.29%	0.88

To break through the scale, flexibility, and reliability limits of traditional microelectronics and open up innovative/major applications of flexible electronic products, new materials, process mechanisms, and equipment principles of flexible electronic manufacturing must be systematically studied, and theoretical, technological, and equipment support for flexible electronics manufacturing must be provided. Major directions include the following: First, R&D and preparation of high-performance flexible electronic functional materials. Study on new principles and technologies for the preparation of functional materials, as well as surface and interface control of functional materials and polymers, and new methods for the preparation of nanocomposite functional fiber, nano-scale fiber, and low-dimensional functional materials. Second, high-efficiency low-temperature preparation of large-area flexible and dense film. Research on low-temperature vapor phase, liquid-phase film deposition technology, and printing technology of electrode, semiconductor, dielectric, and encapsulation layers on flexible substrates must be conducted, and the interfacial properties of heterogeneous films and their control methods under low-temperature processes must be explored. Third, multi-scale manufacturing of flexible micro/nano-structures. The application of flexible electronics often requires large-scale and large-area components, whereas flexible functional structures are developing toward micron and submicron line widths. Therefore, the patterning process of flexible electronics preferentially selects new printing technology and high-rate laser patterning technology or patterned sputtering deposition; however, its corresponding manufacturing accuracy and efficiency still need to be improved. Fourth, highly-efficient integration of flexible hybrid electronic systems. Flexible electronics has the characteristics of high and distributed integration, and the integration of materials with different physical and chemical properties and heterogeneous components with extremely different sizes inevitably lead to a common basic problem in the research and regulation of surface/interface effects. Fifth, design and reliability assurance of flexible electronic devices. The mechanical properties of flexible electronics, the interface strength of organic/inorganic materials, and the fatigue life of the entire system must be studied.

The top three countries with core patent disclosures on the forefront of “flexible electronics manufacturing technology” engineering development are China, the United States, and South Korea; the top three countries with the highest average citations per paper are France, the United States, and the Netherlands, as shown in Table 2.2.5. Among the top 10 countries with the largest number of publications, more cooperation is observed between China and the United Kingdom, and between the United States and South Korea, as shown in Figure 2.2.2. The top three institutions with the largest number of core patent disclosures are Toyobo Co., Ltd., Nissan Chemical Industry Co., Ltd., and Samsung Electronics Co., Ltd., as shown in Table 2.2.6. Among the major patent output organizations, cooperation is observed between Samsung Electronics Co., Ltd. and Korea Advanced Institute of Science and Technology, as shown in Figure 2.2.3.

Table 2.2.5 Countries with the greatest output of core patents in the engineering development front of “flexible electronic manufacturing technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	165	24.59%	292	5.79%	1.77
2	USA	152	22.65%	2 948	58.41%	19.39
3	South Korea	110	16.39%	217	4.30%	1.97
4	Japan	104	15.50%	423	8.38%	4.07
5	France	18	2.68%	432	8.56%	24.00
6	UK	17	2.53%	162	3.21%	9.53
7	Switzerland	10	1.49%	42	0.83%	4.20
8	Germany	8	1.19%	28	0.55%	3.50
9	Italy	8	1.19%	27	0.53%	3.38
10	Netherlands	7	1.04%	68	1.35%	9.71

Figure 2.2.2 Collaboration network among major countries in the engineering development front of "flexible electronic manufacturing technology"

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of "flexible electronic manufacturing technology"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Toyobo Co., Ltd.	Japan	22	3.28%	29	0.57%	1.32
2	Nissan Chemical Industry Co., Ltd.	Japan	18	2.68%	24	0.48%	1.33
3	Samsung Electronics Co., Ltd.	South Korea	16	2.38%	81	1.60%	5.06
4	Electronics and Telecommunications Research Institute	South Korea	14	2.09%	37	0.73%	2.64
5	Korea Advanced Institute of Science & Technology	South Korea	12	1.79%	17	0.34%	1.42
6	Intel Corp.	USA	10	1.49%	45	0.89%	4.50
7	Tsinghua University	China	10	1.49%	27	0.53%	2.70
8	MC10 Inc.	USA	9	1.34%	365	7.23%	40.56
9	University of California	USA	9	1.34%	86	1.70%	9.56
10	LG Group	South Korea	9	1.34%	44	0.87%	4.89

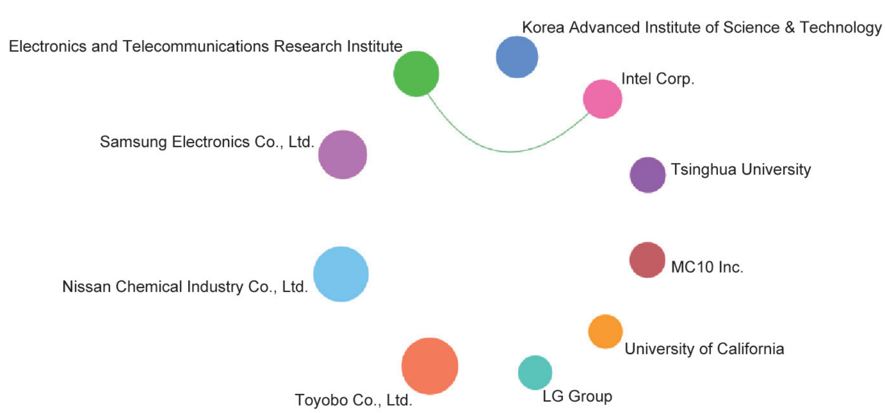

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of "flexible electronic manufacturing technology"

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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 information and electronic engineering field are summarized in Table 1.1.1, encompassing the sub-fields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. “Brain-inspired intelligent chips,” “edge computing,” and “adversarial learning” are among the popular topics published by *Clarivate*, and the seven other fronts are recommended by researchers.

The number of core papers published from 2014 to 2019 related to each front is shown in Table 1.1.2. Among them, “6G wireless transmission and network structure” is the most significant front in the number of core papers published in recent years.

(1) Brain-inspired intelligent chips

Brain-inspired intelligent chips, also known as brain-inspired chips (BICs), are a new type of information processing chips based on the basic principle of how human brains process information. They can be classified into brain-inspired computing chips (BICCs) and brain-inspired sensing chips (BISCs). BICCs are a new type of non-von Neumann information processing chips based on the basic principles of brain science for the development of the brain, such as general intelligence. Unlike acceleration platforms that provide proprietary algorithms, the BICC aims to process various complex unstructured pieces of information with low power consumption, high parallelism, high efficiency, versatility, robustness, and intelligence. BISCs are a new type of chips that use the basic principles of biological sensing and perception for information perception. As the signal input device of the BICC, the BISC provides highly sensitive, accurate, and high-speed sensing information for the BICC, effectively ensuring that the BICC can correctly perform intelligent processing, such as learning, memory, recognition, cognition, and decision-making. BICs are an emerging technology. Currently, no clear technical solution or research roadmap is available. Research teams from the United States, the United Kingdom, Germany, France, South Korea, Japan, Switzerland, Singapore, and China are actively exploring BIC solutions from various aspects, such as architecture, model,

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 intelligent chips	60	5 664	94.40	2016.1
2	Multi-scale spatial–temporal super-resolution medical imaging instruments	120	6 774	56.45	2015.5
3	Edge computing	492	32 594	66.25	2017.4
4	6G wireless transmission and network structure	22	750	34.09	2018.3
5	Carbon-based integrated circuits (ICs)	72	4 413	61.29	2015.8
6	Space–air–ground integrated navigation and positioning system	9	532	59.11	2016.2
7	Adversarial learning	216	10 725	49.65	2017.6
8	Principles and instrumentation of ultra-precision three-dimensional microscopy	83	2 909	35.05	2015.4
9	Program synthesis for cyber–physical systems (CPSs)	237	5 479	23.12	2015.7
10	Long-reach underwater wireless optical communication	55	2 875	52.27	2016.4

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	2014	2015	2016	2017	2018	2019
1	Brain-inspired intelligent chips	10	14	12	11	8	5
2	Multi-scale spatial–temporal super-resolution medical imaging instruments	38	28	21	24	7	2
3	Edge computing	15	27	57	119	178	96
4	6G wireless transmission and network structure	0	0	1	5	3	13
5	Carbon-based ICs	16	20	14	10	9	3
6	Space–air–ground integrated navigation and positioning system	1	3	1	1	3	0
7	Adversarial learning	6	10	13	54	91	42
8	Principles and instrumentation of ultra-precision three-dimensional microscopy	27	18	19	17	2	0
9	Program synthesis for CPSs	63	53	49	37	25	10
10	Long-reach underwater wireless optical communication	2	9	17	19	7	1

ICs, devices, coding and decoding, signal processing, design, process, integration, testing, and software. The BIC is the cornerstone of the development of brain-inspired general intelligence. It is particularly suitable for real-time and efficient solutions in uncertain and complex environments. It can enhance all aspects of life and promote the rapid development of various industries, such as agriculture, medical treatment, finance, and national defense.

(2) Multi-scale spatial–temporal super-resolution medical imaging instruments

Major diseases are often complicated by their occurrence and development mechanisms; therefore, the early warning and diagnosis of diseases (such as tumors) are still some of the major problems encountered today when human science and technology have made significant achievements. Medical imaging instruments exploit the interaction of electromagnetic waves (X-rays, positrons, or photons) or sound waves with the research object to obtain the time series information of disease-related structures, physiology, cells, or molecules on the macro-, meso-, micro-, and nano-scales. Macroscopic imaging systems that provide structural and physiological information such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, positron emission computed tomography (PET), and single-photon emission computed tomography have been widely used in clinical practice.

The ideal imaging instrument should be quantitative, have a high spatial–temporal resolution, and be able to obtain tissue structure information, physiological and metabolic information, molecular information, and even genetic information with high sensitivity and specificity, providing comprehensive aid to clinicians in the diagnosis and monitoring of diseases. Currently, governments, academia, and industries in many countries have attached significance to the development of such imaging instruments. “Molecular imaging,” “precision medicine,” and various “brain projects” all rely on the advancement of multi-scale spatial–temporal super-resolution medical imaging instruments. The primary research directions of multi-scale spatial–temporal super-resolution medical imaging instruments include the following: 1) to develop ultra-high temporal-resolved and spatial-resolved structural and functional imaging techniques as well as new methods of image processing and analysis, to provide new tools for disease diagnosis; 2) to develop a multi-parameter spatial–temporal dynamic simultaneous imaging system, reveal the correlation between monitoring parameters, infer the causal relationship in the pathophysiological response from the speed of the response of each parameter, and interpret the pathophysiological response mechanism; 3) to jointly use light, sound, electricity, magnetism, and other phenomena to develop *in vivo* high-resolution imaging theories and technologies encompassing multiple scales such as molecule, cell, tissue, and organ.

(3) Edge computing

The development of the Internet of Things (IoT) and mobile

Internet technologies has resulted in the explosive expansion of data on the edge of the network. The traditional cloud computing model can no longer satisfy the real-time, secure, and low-power requirements of big data processing. In this context, edge computing is increasing. Edge computing refers to a new computing paradigm that performs computing at the edge of the network. In contrast to cloud computing, edge computing can provide services at locations closer to the data sources, resulting in lower processing latency and higher privacy.

In recent years, edge computing has become popular in both academia and the industry. The team of Prof. Weisong Shi from Wayne State University in the United States defined edge computing for the first time in May 2016. In the same year, the Association for Computing Machinery (ACM) and Institute of Electrical and Electronics Engineers (IEEE) jointly initiated and sponsored a well-known edge computing conference, i.e., the ACM/IEEE Symposium on Edge Computing (SEC). Thereafter, important international conferences such as MobiCom and INFOCOM have included the topic of edge computing. Amazon released the Greengrass platform in 2017 to support the deployment of machine learning services on the edge. Subsequently, cloud platform providers such as Google, Microsoft, Alibaba Cloud, and Baidu released their edge computing platforms. In addition, open-source projects such as EdgeX and KubeEdge are actively being developed and have an important effect on the open-source community, academia, and the industry in terms of edge computing. In China, edge computing is developing at a fast rate. In November 2016, Huawei established the Edge Computing Consortium (ECC) together with many other companies. Internet companies, such as Alibaba and Tencent, and mobile operators, such as China Mobile, China Unicom, and China Telecom, are all actively planning edge computing strategies. Hikvision released the artificial intelligence (AI) cloud framework in 2017, focusing on edge computing for video surveillance. The research directions of edge computing primarily include edge computing systems and platforms, edge–cloud collaboration and scheduling, algorithms for edge intelligence, and innovative edge computing applications.

(4) 6G wireless transmission and network structure

6G is a new mobile communication technology aimed for application to the information society in 2030. 6G will introduce new key performance indexes and application scenarios, for example, full coverage, higher efficiencies of the spectrum, energy, and cost, and higher intelligence and security. To satisfy these requirements, 6G will rely on new enabling technologies. It is expected to have four types of new paradigm shifts: global coverage, full spectra, full applications, and high security. 6G will have the capability of ultra-high throughput in Tbps, ultra-high spectrum efficiency in kbps/Hz, ultra-low latency in microseconds, and coverage of 90% of the Earth. 6G will support heterogeneous applications.

The network autonomy and intelligent generation for the entire society, entire industry, and entire ecology will be investigated in the 6G network structure. The deep integration of data-centered information, communication, and data technologies and new green wireless networking technologies for multi-dimensional full-scene services will also be fully investigated. 6G wireless transmission technologies will include new waveforms, multiple access, channel codes, cell-free distributed massive multiple-input multiple-output (MIMO), and intelligent radio resource management. 6G will be an integrated wireless network covering space, land, and sea, which will include a land mobile communication network and satellite and unmanned aerial vehicle (UAV) communications. To further increase the data rate and connection density, full spectra that include sub-10 GHz, millimeter wave, terahertz, and optical spectrum will be used. The heterogeneous network, dozens of scenarios, large antenna elements, wide bandwidth, and new applications will generate large amounts of data. 6G will use AI and big data technologies to satisfy these requirements.

(5) Carbon-based integrated ohips

Carbon-based IC technology uses carbon nanotubes (CNTs) as the active layers of field-effect transistors (FETs). Because of the excellent room-temperature carrier mobility, extremely low intrinsic capacity, and extraordinary electrostatic characteristics of CNTs, next-generation FETs with higher performance, lower energy consumption, and better scalability can be constructed. Generally, carbon-based ICs benefit from the unique physical, electronic, chemical, and mechanical properties of novel nano-scaled materials, such as CNTs, and provide information-processing chips with excellent performance and low energy consumption, sensors with higher sensitivity and diverse forms, and communication systems-on-chips with higher working frequencies and faster speed. Thus, three-dimensional monolithic integration using these functional chips and processing systems with even higher performance can be constructed.

After two decades of fundamental research, a mature technology system on carbon-based ICs, including the synthesis of carbon-based materials, transport performance characterization, solid-state device physics, fabrication of complementary metal-oxide-semiconductor (CMOS) devices, and construction of fundamental ICs has evolved. The energy efficiency and high performance of carbon-based devices have been verified and preliminarily confirmed. Currently, carbon-based ICs have entered the engineering development phase, which focuses on the critical challenges, including the wafer-scale synthesis of materials, fabrication processes of carbon-based CMOS FETs at the advanced technology nodes, electronic design automation platform, and design flow of carbon-based ICs.

In July 2018, supported by the US Defense Advanced Research Projects Agency (DARPA)'s Electronics Resurgence Initiative program, a joint research group led by the Massachusetts Institute of Technology (MIT), Analog Devices, Inc., and the US Air Force Research Laboratory began using industrial standard design flow and fabrication processes to advance the engineering development of carbon-based ICs. In the same year, Peking University in China advanced the engineering development phase of carbon-based ICs at advanced technology nodes.

(6) Space–air–ground integrated navigation and positioning system

The space–air–ground integrated navigation and positioning system utilizes the global navigation satellite system (GNSS) as the core and also includes other techniques such as low Earth orbit (LEO) satellites, air–ground pseudolites, 5G, and other communication networks as well as various indoor and outdoor positioning sources. It aims to create unified management of spatiotemporal resources on networks and collaborative monitoring and processing on the cloud. The system, from underground to deep space is an integrated navigation and positioning network system with characteristics such as "ubiquitous," "accurate," "unified," "integrated," and "intelligent."

The following are the main research interests: 1) Research on the navigation and positioning sources of underground, ground, air, and LEO satellites with the aid of GNSS to form a space–air–ground augmented navigation network with an integrated communication and navigation system that is compatible with GNSS signals and has the characteristics of time and space unity. The aim is to realize ubiquitous indoor and outdoor seamless precise positioning, navigation, and timing (PNT) services. 2) Research on intelligent hybrid cloud positioning technologies. The heterogeneous multi-navigation source network is considered to be the main body, and the integration and cooperation with the IoT and 5G networks are strengthened. Individual and group capabilities in continuous and reliable PNT service are improved through intelligent processing of spatiotemporal big data. 3) Research on the operating system platform for networked location services and open standard protocol technology. The research is based on ubiquitous real-time precise positioning data and is supported by a holographic location map. The aim is to create a spatial intelligent location service in a multi-dimensional user spatial–temporal information association.

The construction of the space–air–ground integrated navigation and positioning system will result in the rapid development of PNT technology in China. This will widely integrate the PNT information with big data businesses and enhance the in-depth mining of space–time big data using AI technology. Furthermore, it will promote PNT technology into a more ubiquitous, integrated, and intelligent system.

(7) Adversarial learning

Adversarial learning involves exploring and exploiting the vulnerability of machine learning algorithms, weakens the security of machine learning systems through data perturbation, and simultaneously fill the loopholes of models through methods such as adversarial training to increase the robustness and generalization ability of machine learning algorithms in an adversarial environment. Adversarial learning can be applied to model uncertainty evaluation and neural network vulnerability detection in computer vision, natural language processing, unmanned driving systems, and other fields. Recent studies have shown its significant potential in accelerating deep learning training and increasing the robustness of AI systems. The research direction of adversarial learning primarily includes three aspects: adversarial attack, adversarial defense, and adversarial game. An adversarial attack involves the generation and optimization methods of adversarial noises, which can be divided into white-box and black-box attacks according to the knowledge of attackers on the target models. Adversarial defense involves increasing the robustness of models through noise detection and active defenses. An adversarial game involves methods that improve the performance of models through a game-style training process, such as the generative adversarial network that uses generators and discriminators to learn from each other. Physical attack, natural noise generation, and the acceleration of adversarial training are important development directions in adversarial learning. Physical attacks must eliminate the dependence of existing methods on simulated scenes and generate adversarial examples capable of attacking under different angles, distances, and lighting conditions in the actual world. To improve the naturalness of adversarial noises, the generative adversarial network must be used to map the adversarial examples to the manifold of the original images. Aiming at the poor generality and slow convergence of existing adversarial training methods, the learning framework of a generative adversarial network must be promoted to increase the robustness and generalization ability of multiple models in collaborative training, and accelerate the convergence of the training process.

(8) Principles and instrumentation of ultra-precision three-dimensional microscopy

The characterization accuracy of microscopic measurements represents the limit of today's micro-manufacturing capabilities. The new generation of micro-component and micro-system technologies has fully entered the era of three-dimensional integration, and the functional characterization of ultra-precision three-dimensional micro-structures has become the quality foundation and scientific frontier of competition in the global information industry. Optical microscopic measurements are non-contact measurements, and they have the advantages of high spatial resolution and no damage to samples. They are widely used in the manufacturing of high-sensitivity photodetectors, high-efficiency light-emitting diodes (LEDs), and high-integration micro-electrical system devices as well as to measure macro- and micro-composite structures of ultra-smooth surfaces in virtual reality (VR)/augmented reality (AR) systems. Ultra-precision three-dimensional micro-measurement is an indispensable method for nano-devices and micro-systems to continuously break through the performance limits. The main research directions encompass the innovative principles and methods of ultra-precision three-dimensional micro-measurement, three-dimensional reconstruction and visualization of measurement results, error analysis and measurement uncertainty evaluation, calibration of ultra-precision three-dimensional micro-measurement instruments, and traceability of measurement values. Development trends include: 1) high-precision characterization of functional geometric parameters of special-shaped microstructures; 2) online measurement and intelligent monitoring of key geometric parameters of products in complex industrial scenarios; 3) innovative integration of composite multi-mode parameter measuring instruments; and 4) breakthroughs in metrology theory of three-dimensional microscopy.

(9) Program synthesis for cyber–physical systems

CPSs are the future direction in the development of software and systems as cyber and physical spaces have become increasingly intertwined. In a CPS, components that sense, compute, communicate, and control are deeply integrated, and they cooperate to complete and optimize various capabilities and intelligent services. CPSs have many applications in various domains of the national economy, and they make software a fundamental infrastructure in the information era. Typically, many of these systems require strong guarantees of safety, reliability, security, and availability. The dominant approaches for the design of CPS are model-based design (MBD) and design-by-contract (DbC). With MBD, a complex system can be developed at different levels of abstraction, and the consistency between different models is guaranteed by abstraction and/or refinement. With DbC, a complex system can be composed of and/or decomposed into simpler components that may be described from different perspectives, and the consistency between component systems and the original system is established through contracts. However, the theoretical foundations for both MBD and DbC are still lacking, and designing correct models for complex CPS and automatically and efficiently generating reliable and correct codes from the evolving models remain significant challenges. For automatic code generation, the industrial community mostly uses simulation-based approaches, as represented by Simulink/Stateflow, while the academic community primarily uses approaches based on formal verification and synthesis. Simulation-based methods generate codes directly from graphical models; therefore, they are intuitive, efficient, and easy-to-use. However, they cannot guarantee the correctness and reliability of the generated codes. Approaches based on formal verification and synthesis first build formal models of a system and then conduct formal verification of the models to verify all requirements. Correct and reliable codes can then be generated from the verified models according to the refinement theory. This approach is currently more difficult to use and less scalable. The future trend is to combine techniques from these two methods to efficiently design, generate, and evolve safe and reliable control software for CPSs.

(10) Long-reach underwater wireless optical communication

Underwater wireless optical communication (UWOC) technology, which adopts light as a signal carrier for broadband underwater wireless communication, has the advantages of high bandwidth, small volume, low power consumption, low time latency, and high security. It has become one of the most important communication technologies that most countries in the world are competing to develop in the fields of subsea exploration, ocean monitoring, and underwater networking. The long-reach UWOC system is based on a high-power light source, highly sensitive detector, signal processing technology, and automatic acquisition, tracking, and pointing systems. Recent research has demonstrated the feasibility of UWOC with high data rates (e.g., several Gbps) and long transmission distances (e.g., more than 100 m). These studies demonstrated the significant potential of UWOC for the application of data exchange, simultaneous underwater illumination and communication, underwater positioning systems, internal communication among a swarm of underwater unmanned vehicles, and military fields. Although many challenges require to be addressed, UWOC is still an attractive alternative or complement to long-reach undersea communication.

To design and complete a long-reach UWOC system, research must be conducted on the unique characteristics of the undersea optical channel, which includes the inherent optical properties, volume scattering function, and other properties of the seawater, such as sea bubbles or turbulence. The link power budget is a key concern for UWOC owing to the heavy attenuation of light in seawater. Therefore, light sources with high power and excellent beam quality and ultra-sensitive receivers are desirable for the design of UWOC systems. In addition, the scattering of seawater and the multi-path effect will degrade the communication performance, which can be enhanced by appropriately designed signal processing technologies, e.g., channel coding, channel equalization, and diversity multiplexing. Furthermore, AI enables the UWOC system to learn from experiences in which the data cannot be accurately modeled, improve the system performance, and contribute to the intelligentization of UWOC systems.

1.2 Interpretations for three key engineering research fronts

1.2.1 Brain-inspired intelligent chip

Currently, no commonly accepted technical solutions and research roadmaps for BICs exist. Global research teams are exploring BICs from various aspects including architecture, models, ICs, devices, codes, signal processing, design, manufacturing, integration, testing, and software. The BIC architecture is the foundation. Owing to the complex spatio–temporal characteristics of the information coding of the brain, major foreign research teams have adopted the spatio–temporal fusion architecture to support the spiking neural network models with high spatio–temporal complexity. Classified by data expression, the BIC architecture is divided into digital, analog, and digital–analog hybrid architectures. The use of very large-scale ICs to implement neural network models to construct brain-inspired perception and computing systems was proposed by Carver A. Mead and others in the late 1980s. If the degree of deviation between the brain-inspired computing solution and the traditional von Neumann architecture are considered to be the standard, the levels of the solutions can be crudely categorized into program, architecture, circuit, and device from top to bottom. According to this, among several mainstream solutions, Spinnaker from the University of Manchester in the United Kingdom is a program-level representative, IBM’s TrueNorth, Intel’s Loihi, and Tsinghua University’s Tianjic are architecture-level representatives, BrainScaleS from the University of Heidelberg in Germany is a circuit-level representative, and Neurogrid from Stanford University in the United States is the device-level representative.

In addition to BICs based on silicon technology, BICs based on new nano-devices exist, such as resistive random access memory (RAM) and memristors (e.g., spin transfer torque RAM and phase-change memory). These types of the chip directly use specific device structures to emulate the electrical characteristics of biological neurons and synapses with a higher degree of integration, which is a very potential BIC solution. However, the current manufacturing process of large-scale neuromorphic devices is immature, and the consistency and reproducibility of devices are poor. Currently, no chips comparable to the scale of BICs based on silicon technology exist yet.

The key to BIC research includes the brain science principles that should be used for references, the expressing, storing, calculating, and transmitting of information in the BIC, and the use of chip and software to co-design to control, transfer, and manage information. The current mainstream BIC technologies include storage and calculation integration, event-driven, highly parallel, asynchronous, sparse coding, and hybrid integration. To take advantage of the coming golden decade of computer architecture development, the Turing computing architecture should be expanded, and BICs should be innovated and developed using the collaborative design of models, chips, and software.

Today, the development of narrow AI encounters problems, such as small or dirty data, uncertainty, new problems or incomplete knowledge, dynamic and complex environments, and multi-system and multi-modal complex systems. The most potential solution to these problems is to develop brain-inspired general intelligence. BICs are the cornerstone of brain-inspired general intelligence, which can enhance all aspects of life and comprehensively promote the rapid development of industries, agriculture, medical care, finance, and national defense.

The countries and institutions with the greatest output of core papers on brain-inspired intelligent chips are shown in Tables 1.2.1 and 1.2.2, respectively. The countries and institutions with the greatest output of citing papers on brain-inspired intelligent chips are shown in Tables 1.2.3 and 1.2.4, respectively. This research front has received much attention from academies and industries. The United States has a particularly strong research foundation, ranking first in core papers; China and Switzerland rank second and third, respectively. Among the top 10 institutions with the greatest output of core papers, 5 are from the United States, 3 from China, and 2 from Switzerland (Table 1.2.2). Currently, the United States and China have a larger degree of collaboration (Figure 1.2.1). As shown in Table 1.2.2, Swiss Federal Institute of Technology Zurich, University of Zurich, University of Michigan, and Purdue University are the leading institutions with the greatest output of core papers. In terms of institutional cooperation, Swiss Federal Institute of Technology Zurich has the closest cooperation with University of Zurich (Figure 1.2.2).

1.2.2 Multi-scale spatial–temporal super-resolution medical imaging instruments

The advent of CT has been recognized as a significant breakthrough since W.C. Rontgen discovered X-rays because it has marked a milestone in the integration of physics, electronics, computer science, and mathematics. Imaging can use self or endogenous signals, imaging molecular probes, and signals to qualitatively or quantitatively detect physiological and pathological changes in organisms. The research and development in medical imaging instruments

Table 1.2.1 Countries with the greatest output of core papers on “brain-inspired intelligent chips”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	38	63.33%	3 702	97.42	2016.3
2	China	13	21.67%	1 141	87.77	2017.2
3	Switzerland	8	13.33%	645	80.62	2015.2
4	Germany	6	10.00%	349	58.17	2016.5
5	South Korea	5	8.33%	430	86.00	2016.0
6	Japan	4	6.67%	645	161.25	2015.0
7	Singapore	4	6.67%	224	56.00	2017.0
8	UK	3	5.00%	488	162.67	2015.7
9	France	3	5.00%	432	144.00	2015.3
10	Qatar	2	3.33%	367	183.50	2016.5

Table 1.2.2 Institutions with the greatest output of core papers on "brain-inspired intelligent chips"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Swiss Federal Institute of Technology Zurich	8	13.33%	645	80.62	2015.2
2	University of Zurich	6	10.00%	525	87.50	2015.3
3	University of Michigan	4	6.67%	495	123.75	2016.8
4	Purdue University	4	6.67%	217	54.25	2016.2
5	Cornell University	3	5.00%	582	194.00	2015.3
6	IBM Almaden Research Center	3	5.00%	478	159.33	2015.0
7	Tsinghua University	3	5.00%	340	113.33	2018.0
8	Southwest University	3	5.00%	157	52.33	2017.0
9	Arizona State University	3	5.00%	156	52.00	2016.0
10	Chinese Academy of Sciences	3	5.00%	126	42.00	2017.3

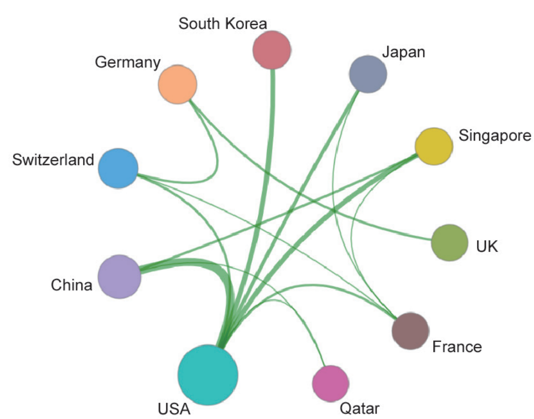

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "brain-inspired intelligent chips"

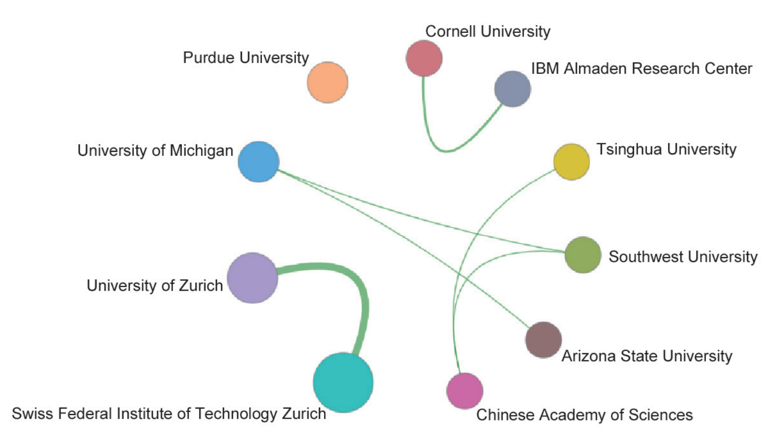

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "brain-inspired intelligent chips"

Table 1.2.3 Countries with the greatest output of citing papers on “brain-inspired intelligent chips”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	1 287	29.14%	2018.4
2	China	1 262	28.58%	2018.7
3	South Korea	316	7.16%	2018.7
4	UK	267	6.05%	2018.3
5	Switzerland	242	5.48%	2017.8
6	Germany	240	5.43%	2018.5
7	France	188	4.26%	2018.2
8	Japan	186	4.21%	2018.7
9	India	150	3.40%	2018.8
10	Singapore	142	3.22%	2018.5

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

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	178	16.95%	2018.8
2	Swiss Federal Institute of Technology Zurich	151	13.87%	2017.5
3	Tsinghua University	123	11.29%	2018.3
4	University of Zurich	105	9.64%	2017.2
5	Seoul National University	105	9.64%	2018.4
6	Huazhong University of Science and Technology	82	7.53%	2018.7
7	University Chinese Academy of Sciences	73	6.70%	2018.9
8	Purdue University	71	6.52%	2018.3
9	Peking University	70	6.43%	2018.6
10	National University of Singapore	66	6.06%	2018.5

have the dual characteristics of the scientific frontier and comprehensive intersection. With the aid of imaging instruments, human beings continue to extend and expand their capabilities in temporal and spatial resolution, recognition, and interpretation. Imaging technology can be considered to have contributed significantly to promoting the development of medicine and life sciences. Malignant tumors and cardiovascular and cerebrovascular diseases are the two types of diseases that cause the highest human mortality. The development of science and technology advances higher requirements for the diagnosis and early warning of these diseases, which is difficult with traditional imaging instruments. The discovery of new phenomena and the development of optimization, detection, high-speed acquisition, and signal processing technologies have resulted in new ideas in the development of imaging instruments.

The development trends of medical imaging instruments are as follows:

(1) The development of new measurement techniques for super temporal resolution, super spatial resolution, and super sensitivity. Medical imaging instruments can conduct qualitative and quantitative research on biological processes in a living state and perform real-time, dynamic, non-invasive imaging of biological and pathological changes in the organism. A high temporal resolution, high spatial resolution, and high sensitivity are essential for medical imaging instruments. Ultra-fast MRI, ultrasound imaging, low-dose CT, PET imaging, and ultra-optical diffraction-limited microscopic imaging instruments are all research targets.

(2) The development of multi-scale, multi-modal, and multi-parameter *in vivo* measurement technologies. Comprehensively determining the pathophysiological state

of tumors based on the changes in a single physiological index is difficult; an imaging instrument that can perform a comprehensive evaluation of multiple pathophysiological parameters is urgently required. Multi-tracer PET imaging instruments and fingerprint MRI technologies that can simultaneously image multiple physiological parameters are some of the development directions being undertaken, and multi-color fluorescence imaging instruments can realize the simultaneous visualization of multiple structures.

(3) The development of new imaging instruments incorporating AI. Since its emergence, AI has experienced two lows and three waves. With the development of algorithms, computing power, and big data, AI, particularly in machine learning algorithms, has developed rapidly. Deep learning, which is one of the fields of machine learning, has developed more rapidly. Imaging instruments will be deeply integrated with AI, and a new generation of imaging instruments will appear. In 2020, the College of Optical Science and Engineering of Zhejiang University and the US National Institutes of Health jointly published a paper titled "Rapid image deconvolution and multiview fusion for optical microscopy" in *Nature Biotechnology*. In this paper, a new technology of fluorescence microscope image deconvolution and multiview image fusion is proposed to increase the post-processing efficiency of fluorescence microscope image by tens or even thousands of times. A month after the publication of the paper, the technology was rated as one of the top ten advances in microscopic imaging technology in the world.

(4) The development of new principle imaging instruments and advance to areas that people cannot reach. In 2016, *Nature* published an article on polarized nuclear imaging technology, which uses MRI technology to achieve nuclear imaging; therefore, the image has both the functional information of nuclear medicine images and the high-resolution characteristics of MRI imaging.

The distribution of the main output countries of the core papers in the engineering research front of multi-scale spatial–temporal super-resolution medical imaging instruments is shown in Table 1.2.5. Research on medical imaging instruments in the United States has a strong foundation, and the number of core papers from there accounts for more than half of the global total. Those from Gemany accounts for approximately 15% of the core papers globally. Switzerland, France, Italy, and the United Kingdom are almost evenly divided. China's international cooperation target is primarily the United States (Figure 1.2.3). Table 1.2.6 shows that the institutions producing core papers are relatively centralized. Among the institutions that published no less than four core papers, apart from the Paul Scherrer Institute, all others are well-known universities in the field of medical imaging, including Harvard University, MIT, Swiss Federal Institute of Technology Zurich, University of California at Berkeley, and University of California at Davis. An interesting phenomenon was observed in the connection of core-paper output institutions: Two research institutions in Switzerland, Swiss Federal Institute of Technology Zurich and Paul Scherrer Institute, cooperate the most closely (Figure 1.2.4). For the

Table 1.2.5 Countries with the greatest output of core papers on "multi-scale spatial–temporal super-resolution medical imaging instruments"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	63	52.50%	3 478	55.21	2015.6
2	Germany	17	14.17%	1 192	70.12	2015.5
3	Switzerland	11	9.17%	881	80.09	2015.9
4	France	10	8.33%	443	44.30	2016.0
5	Italy	9	7.50%	402	44.67	2015.8
6	UK	9	7.50%	398	44.22	2015.4
7	Netherlands	8	6.67%	615	76.88	2015.4
8	Australia	8	6.67%	314	39.25	2015.4
9	Spain	7	5.83%	728	104.00	2016.0
10	China	7	5.83%	467	66.71	2015.3

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “multi-scale spatial–temporal super-resolution medical imaging instruments”

Table 1.2.6 Institutions with the greatest output of core papers on “multi-scale spatial–temporal super-resolution medical imaging instruments”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Swiss Federal Institute of Technology Zurich	7	5.83%	633	90.43	2015.7
2	MIT	7	5.83%	400	57.14	2015.7
3	Paul Scherrer Institute	4	3.33%	237	59.25	2015.5
4	University of California, Berkeley	4	3.33%	202	50.50	2016.2
5	Harvard University	4	3.33%	179	44.75	2015.8
6	University of California, Davis	4	3.33%	175	43.75	2016.0
7	Spanish National Research Council	3	2.50%	327	109.00	2017.3
8	California Institute of Technology	3	2.50%	240	80.00	2015.7
9	University of Texas at Austin	3	2.50%	228	76.00	2016.0
10	University of Geneva	3	2.50%	204	68.00	2016.3

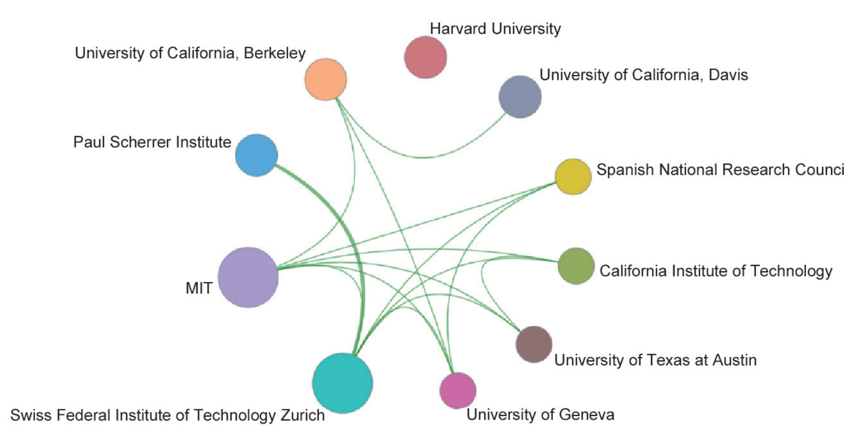

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “multi-scale spatial–temporal super-resolution medical imaging instruments”

number of citing core papers (Tables 1.2.7 and 1.2.8), the United States accounted for more than 30%, China also performed well with more than 14%, Germany had more than 10%, and the distribution of other countries is basically the same as that of the producing countries, indicating that China is clearly on the same level with the top countries in the field of medical imaging.

1.2.3 Edge computing

The key research problem in edge computing is the design of an edge–cloud collaboration framework and real-time processing techniques for big data to address the problems of high latency, poor security, and high power consumption in cloud computing. In recent years, edge computing has received increasing interest in both academia and the industry. In 2016, ACM and IEEE jointly initiated and sponsored a well-known edge computing conference, i.e., the ACM/IEEE SEC. Amazon released the Greengrass platform in 2017 to support the deployment of machine learning services on the edge. Subsequently, cloud platform providers such as Google, Microsoft, Alibaba Cloud, and Baidu released their edge computing platforms. In addition, open-source projects such as EdgeX and KubeEdge have been actively developed and have a significant effect on the open-source community as well as in academia and the industry.

Table 1.2.7 Countries with the greatest output of citing papers on “multi-scale spatial–temporal super-resolution medical imaging instruments”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	2 229	30.48%	2017.8
2	China	1 060	14.49%	2018.3
3	Germany	870	11.89%	2017.9
4	UK	673	9.20%	2017.9
5	France	524	7.16%	2018.0
6	Australia	343	4.69%	2018.0
7	Canada	343	4.69%	2018.1
8	Italy	336	4.59%	2017.8
9	Switzerland	324	4.43%	2017.9
10	Netherlands	320	4.38%	2017.9

Table 1.2.8 Institutions with the greatest output of citing papers on “multi-scale spatial–temporal super-resolution medical imaging instruments”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	214	17.48%	2018.2
2	California Institute of Technology	139	11.36%	2018.0
3	Nanyang Technological University	130	10.62%	2018.1
4	Harvard University	121	9.89%	2017.8
5	MIT	102	8.33%	2018.0
6	Stanford University	90	7.35%	2017.7
7	University of Toronto	90	7.35%	2017.7
8	University of Illinois	88	7.19%	2017.8
9	University of Chinese Academy of Sciences	87	7.11%	2018.5
10	University of California, Berkeley	83	6.78%	2017.8

The research on edge computing primarily includes the following aspects:

(1) Edge computing systems and platforms

Edge computing is encountering the challenges of high hardware and software heterogeneity, low reliability, and limited resources. The existing cloud computing architecture cannot satisfy the application requirements of high reliability, low latency, and adaptiveness for dynamics. Therefore, customized edge computing systems and platforms for different application scenarios must be designed to address key problems such as the flexible customization of edge services, efficient use of distributed computing resources, and achieving low latency and high reliability.

(2) Edge–cloud collaboration and scheduling

Cloud computing and edge computing have their advantages and disadvantages. Cloud computing has the advantages of strong computing power and high reliability, while edge computing has the advantages of low latency and high privacy. Edge–cloud collaborative computing combines the advantages of the two computing paradigms. In addition, edge devices are highly heterogeneous in terms of computing and storage capabilities. Therefore, edge computing systems must perform edge–cloud collaborative task scheduling to improve system performance according to task categories, device computing capabilities, network bandwidth, etc. The key research concerns include achieving coordinated scheduling of tasks between cloud centers and edge devices and achieving seamless and efficient computing migration.

(3) Algorithms for edge intelligence

Efficiently implementing AI and machine learning algorithms on edge devices with limited resources is challenging. Therefore, the adaptive optimization of edge intelligence algorithms must be studied to reduce the resource overhead while maintaining the accuracy of the algorithm. Additionally, the customization of edge intelligence algorithms under specific application scenarios on demand should be studied.

(4) Innovative applications of edge computing

The development of edge computing technology is closely related to important edge computing applications. Based on edge computing platforms and key technologies such as edge–cloud collaboration scheduling and edge intelligence algorithms, we can realize a series of key applications such as smart video surveillance, autonomous vehicles, smart factories, and smart structural health monitoring. In developing these applications, we can refine the edge computing system architecture, create a breakthrough in a series of key technologies, and further discover potential challenges and opportunities.

The main output countries of core papers on edge computing are shown in Table 1.2.9. Edge computing has attracted much interest from academia and the industry. The number of core papers in China accounts for approximately 50% of the world's output. The core papers in the United States account for approximately 30%, the United Kingdom and Canada each account for approximately 10%. China cooperates primarily with the United States, the United Kingdom, and Canada, and the cooperation among other countries is relatively balanced

Table 1.2.9 Countries with the greatest output of core papers on "edge computing"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	234	47.56%	15 171	64.83	2018.0
2	USA	135	27.44%	10 674	79.07	2017.5
3	UK	60	12.20%	3 594	59.90	2017.4
4	Canada	53	10.77%	3 201	60.40	2017.6
5	South Korea	31	6.30%	2 668	86.06	2017.3
6	Italy	30	6.10%	1 211	40.37	2017.0
7	Finland	28	5.69%	1 976	70.57	2017.2
8	Australia	28	5.69%	1 905	68.04	2017.5
9	India	27	5.49%	1 250	46.30	2017.5
10	Germany	26	5.28%	2 356	90.62	2016.3

(Figure 1.2.5). The institutions producing core papers are also relatively concentrated (Table 1.2.10 and Figure 1.2.6). Among the top three institutions with the highest output of core papers, i.e., Beijing University of Posts and Telecommunications, Xidian University, and Huazhong University of Science and Technology, all of them are focusing on the research on mobile edge computing. They also conduct research on edge computing in specific scenarios such as the Internet of Vehicles and intelligent video analysis. In terms of the number of citing papers (Table 1.2.11), China accounts for approximately 40%. Among the top 10 citing paper output institutions, 9 institutions are from China (Table 1.2.12), indicating that China's institutions are very active in the field of edge computing.

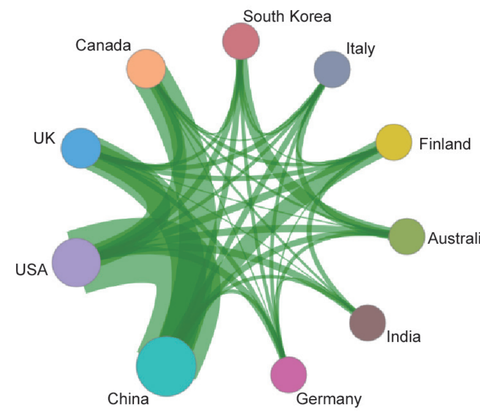

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "edge computing"

Table 1.2.10 Institutions with the greatest output of core papers on "edge computing"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Beijing University of Posts and Telecommunications	28	5.69%	1 480	52.86	2017.8
2	Xidian University	23	4.67%	1 270	55.22	2018.2
3	Huazhong University of Science and Technology	18	3.66%	1 070	59.44	2018.2
4	King Saud University	18	3.66%	657	36.50	2018.2
5	Dalian University of Technology	17	3.46%	968	56.94	2018.2
6	University of Electronic Science and Technology of China	16	3.25%	985	61.56	2018.1
7	University of Oslo	15	3.05%	1 397	93.13	2018.0
8	Nanjing University	15	3.05%	1 285	85.67	2018.2
9	Aalto University	14	2.85%	1 105	78.93	2017.3
10	Guangdong University of Technology	14	2.85%	833	59.50	2018.1

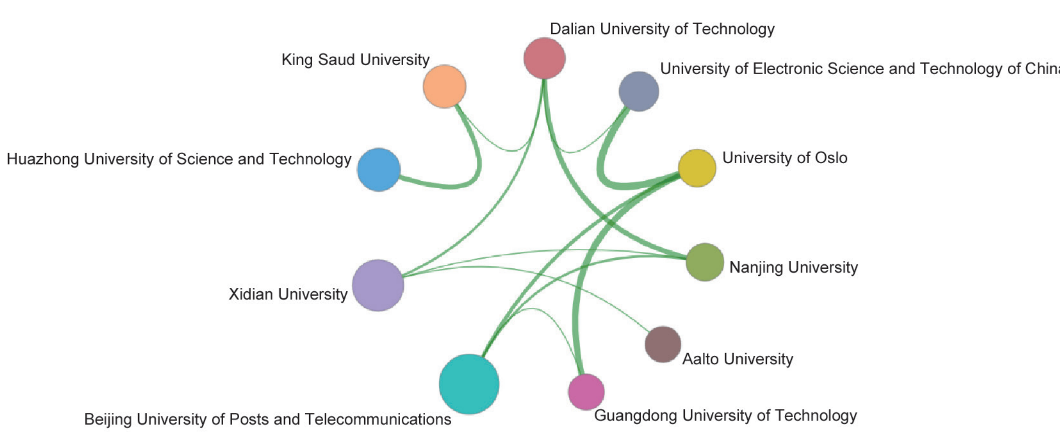

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "edge computing"

Table 1.2.11 Countries with the greatest output of citing papers on "edge computing"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	6 559	39.83%	2018.9
2	USA	2 738	16.63%	2018.7
3	UK	1 201	7.29%	2018.7
4	Canada	1 006	6.11%	2018.7
5	India	932	5.66%	2018.7
6	South Korea	870	5.28%	2018.8
7	Italy	774	4.70%	2018.6
8	Australia	693	4.21%	2018.9
9	Spain	602	3.66%	2018.6
10	Germany	581	3.53%	2018.4

Table 1.2.12 Institutions with the greatest output of citing papers on "edge computing"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Beijing University of Posts and Telecommunications	633	20.77%	2018.7
2	Chinese Academy of Sciences	382	12.54%	2018.8
3	Xidian University	287	9.42%	2019.0
4	University of Electronic Science and Technology of China	264	8.66%	2018.9
5	Tsinghua University	260	8.53%	2018.8
6	Huazhong University of Science and Technology	240	7.88%	2018.9
7	King Saud University	236	7.75%	2019.1
8	Southeast University	203	6.66%	2018.9
9	Zhejiang University	189	6.20%	2018.8
10	Shanghai Jiao Tong University	181	5.94%	2018.7

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, encompassing the sub-fields 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, the "development of extreme ultraviolet (EUV) light sources for IC chip nanolithography," "integrated wireless communications and sensing technology," "design and implementation of intelligent robot cluster cooperation systems," and "terahertz key devices and ultra-high-speed wireless transmission applications" are recommended by researchers, and the other six fronts are published based on the analysis of *Derwent Innovation* of *Clarivate*.

The annual disclosure of core patents involved in the 10 development fronts from 2014 to 2019 is shown in Table 2.1.2.

(1) Development of EUV light sources for IC chip nanolithography

Semiconductor IC chips, the core of the high-end manufacturing industry, have a significant effect on all aspects of modern human life. According to Moore's law, the minimum node linewidth of the IC chip has decreased to 1 nm. An important factor affecting the node of nanolithography is the wavelength of the nanolithography light source. Currently, the prevailing nanolithography machines use deep ultraviolet (DUV) light sources, which can attain a linewidth of 7 nm through multiple

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	Development of EUV light sources for IC chip nanolithography	121	980	8.10	2014.4
2	Integrated wireless communications and sensing technology	299	1 113	3.72	2016.4
3	Design and implementation of intelligent robot cluster cooperation systems	243	1 094	4.50	2016.2
4	VR/AR near-eye display technology	156	1 869	11.98	2017.5
5	Optical frequency combs for precision measurement and time/frequency metrology	156	573	3.67	2016.2
6	Integration of the massive MIMO antenna array and radio frequency (RF)	158	843	5.34	2016.9
7	Autonomous environment perception and scene cognition technology for intelligent mobile robots	70	71	1.01	2017.5
8	Solid-state vehicle-mounted phased-array light detection and ranging (LiDAR)	47	367	7.81	2018.2
9	Terahertz key devices and ultra-high-speed wireless transmission applications	145	534	3.68	2016.3
10	Distributed network security and management based on blockchain	125	332	2.66	2018.5

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	2014	2015	2016	2017	2018	2019
1	Development of EUV light sources for IC chip nanolithography	24	20	21	10	4	9
2	Integrated wireless communications and sensing technology	24	28	46	51	59	58
3	Design and implementation of intelligent robot cluster cooperation systems	4	9	8	26	46	66
4	VR/AR near-eye display technology	7	9	22	25	38	52
5	Optical frequency combs for precision measurement and time/frequency metrology	13	20	19	21	22	36
6	Integration of the massive MIMO antenna array and RF	18	15	24	21	36	38
7	Autonomous environment perception and scene cognition technology for intelligent mobile robots	1	7	8	9	32	13
8	Solid-state vehicle-mounted phased-array LiDAR	1	2	2	5	9	28
9	Terahertz key devices and ultra-high-speed wireless transmission applications	16	15	17	18	39	23
10	Distributed network security and management based on blockchain	0	0	1	12	33	79

exposures. The latest nanolithography machines use EUV light sources, which can attain a linewidth of 7 nm through a single exposure and a linewidth of 1 nm through crafts improvement. Therefore, EUV nanolithography machines are superior to DUV nanolithography machines in terms of linewidth, efficiency, and product yield. These make the development of EUV light sources the key to a new generation of large-scale industrial applications.

EUV is an extreme ultraviolet radiation with wavelengths of 10–121 nm. To date, two main methods exist to obtain an EUV light source: laser produced plasma (LPP) and discharge produced plasma (DPP). LPP primarily uses an Nd:YAG laser to generate a pre-pulse to bombard the droplet-shaped tin (Sn) target to form a sub-micron-grade mist; subsequently, the main pulse laser output from 10 kW CO_2 laser bombards sub-micron Sn mist to form high-temperature, high-density plasma to generate the EUV radiation. Compared with DPP, LPP does not damage the electrode and produces relatively small optical debris. These make the LPP the mainstream solution for an EUV light source.

With the improvement in the accuracy of IC chip processing, nanolithography machines have increasingly higher requirements for the performance of EUV light sources. To attain the 3-nm nanolithography technology node, the average power of the EUV light source must be increased to the kilowatt level. In addition, the application of metal gadolinium (Gd) targets and the research on free-electron lasers are expected to obtain short wavelength and high average power, thereby breaking through the current nodes of nanolithography.

(2) Integrated wireless communications and sensing technology

The integrated wireless communications and sensing technology refers to a high-level integration of advanced technologies in the field of communications and sensing in terms of hardware architecture and algorithm design by sharing the fundamental infrastructure and time–frequency–space resources of wireless communication systems. This technology can create the cooperation and joint design of communication and sensing by utilizing the high-throughput and low-latency information interaction of wireless communication systems. Moreover, this technology breaks the traditional pattern of the isolated design of communication and sensing, achieves the future communication requirements of ultra-high rate, ultra-low delay, and ultra-high reliability, realizing centimeter-level accuracy positioning capabilities and ultra-high fine-grained sensing abilities. The integrated wireless communications and sensing technology has become a new driving force for the evolution of communication systems, transformation of industrial technologies, and upgradation of the smart society.

Research and development in the field of integrated wireless communications and sensing technology are still in its infancy. The mainstream technical route focuses on utilizing new opportunities created by wireless communication systems, such as large-scale antenna arrays, ultra-dense networking, new multiple access technologies, and full spectra, and establishing the collaboration and symbiosis of communication and sensing to maximize the spectrum efficiency and reduce hardware costs. Based on the foundation and current scenario, the future research directions of integrated technology of wireless communications and sensing are as follows: constructing multi-level, multi-functional, and intelligent networks of integrated communication and sensing, including the function of positioning, sensing, and imaging; establishing the mechanism of interaction and cooperation between communication and sensing in highly dynamic scenarios; and designing information fusion and resource collaboration technologies suitable for high-dimensional, large-scale, and ultra-heterogeneous networks.

(3) Design and implementation of intelligent robot cluster cooperation systems

Intelligent robot cluster cooperation systems are complex systems that are composed of several robots with certain autonomy to accomplish tasks for a common goal. They are commonly used in the application scenarios of robot cluster collaborative manufacturing, wharf and warehouse logistics, unmanned system swarm collaborative area search, etc. Generally, different types of systems are distinguished by the architecture, working environment, and mission of robot clusters. Robots can be heterogeneous, homogeneous, or even cross-domain combinations. For example, the air–ground cooperation of UAVs can achieve an efficient target search. Depending on the differences in tasks and environmental factors, the architecture, collaboration relationship, network topology, control mode, etc., may have significant differences. For example, in the workshop environment, a communication network to support the information interconnection and intercommunication between the dispatching center and a robot can be easily set up, and a robot in a field environment primarily accomplishes information exchange and sharing through a self-organizing mobile wireless network. The main technical directions of intelligent robot cluster cooperation systems include cluster architecture design, communication and networking technology, perception and navigation positioning technology, task planning and decision-making technology, robot collaborative movement, and operation control technology. On one hand, with the expansion of the cluster scale and operation space, perception, planning, decision-making, control, and other aspects are exhibiting a development trend with “distributed” features. On the other hand, to satisfy the requirements of diverse complex tasks and gain higher environmental adaptability, the cluster cooperative work of robots will maintain the development trend of intelligence and autonomy and will have a higher self-organization cooperation ability and higher work efficiency when performing various complex tasks.

(4) VR/AR near-eye display technology

VR/AR near-eye display devices are considered to be the display terminals of personal mobile equipment of the future. Depending on whether the display device is optically see-through or not, near-eye displays are categorized as VR (non-see-through) and AR (see-through) systems. Near-eye display equipment frequently includes a micro-display chip, an optical imaging system, and a head tracking system. Micro-display chips primarily involve liquid crystal on silicon (LCOS), digital light processor, organic light-emitting diode (OLED), and micro-LED technologies. The optical imaging system includes a micro-projector, optical waveguide, optical free-form surface elements, and other optical technologies. Head tracking involves simultaneous localization and mapping technologies.

The near-eye display technology will develop in the direction of lightweight, high resolution, high brightness, and large fields of view (FOVs). The key technologies include the following aspects. In the micro-display technology, LCOS, micro-LED, OLED, laser scanning, and other display technologies with high resolution and high brightness will be developed. In optical imaging systems, the waveguide technology is the main technical method of making the display device similar to ordinary glasses, and the main development direction is a highly uniform and highly efficient image transmission in a surface-relief grating waveguide, holographic waveguide, and liquid crystal polymer grating waveguide. The foldable optical system, FOV splicing technology, free-form lens imaging, and imaging with holographic optical elements will also be under development to achieve an ultra-thin and large FOV in near-eye displays. To solve the dizziness problem caused by the vergence-accommodation conflict of human eyes in near-eye display stereo vision, light field near-eye displays, zoom lenses, and near-eye holographic display technology will be explored for multi-focal plane or continuous focal plane imaging.

(5) Optical frequency combs for precision measurement and time/frequency metrology

An optical comb (optical frequency comb) generates a spectrum composed of equally distanced frequency lines with a stable phase relationship. It bridges the optical and microwave bands, can enable ultra-precious time–frequency metrology, and dramatically promotes the accuracy of time–frequency measurements.

The optical clock based on optical frequency combs (or the optical atomic clock) has exhibited uncertainty in frequency/time measurement <1E-18, demonstrating a few physical quantities with the highest measurement accuracy. Optical frequency combs have also demonstrated significant potential in gravitational wave detection, basic physical constant testing and attosecond ultrafast science, and technical applications such as ultra-broadband communications, low-noise optical-microwave sources, and high-precision spectroscopy.

Currently, locked optical frequency combs include techniques based on femtosecond mode-locked lasers, electro–optical modulation, and novel optical frequency combs based on micro-cavities and other components. Femtosecond mode-locked optical frequency combs have been commercialized, but they are limited by their structural complications and high cost; such a technical solution is still difficult for mass fabrication. The electro–optical modulation frequency comb is still not ready for engineering applications owing to the immaturity of noise suppression technology with a wide optical spectrum bandwidth. The advanced Kerr comb technology based on optical micro-cavities developed in recent years can achieve self-reference locking while maintaining very low noise, with a compact and simple structure; additionally, it can operate at ultra-low power consumption and is compatible with current CMOS processes, which further enables its chip-level mass production. DARPA (USA) and the H2020 plan (European Union) are vigorously developing this chip-level optical comb technology, aiming to occupy the commanding heights of this time metrology technology. In the future, this technology will result in progress in applications such as high-resolution navigation, high-accuracy metrology, high-speed communication, and intelligent sensing.

(6) Integration of the massive MIMO antenna array and RF

In 5G base stations, with the application of massive MIMO antenna array techniques, passive antennas become active and are integrated with remote radio units to become active antenna units. The integrated antennas, because of their stability and reliability, outperform conventional antennas in reducing the damage to the connectors of the feeding lines, improving the appearance of the antenna, and upgrading the installation convenience. However, in 5G terminals, because the communication protocols are becoming increasingly complex, the order of MIMO must be improved. Moreover, the terminals are becoming more compact, thinner, lighter, and more integrated. Therefore, much higher integration of the antennas and RF is required.

In the evolution of antenna and RF integration, several technical trends require much attention: 1) Shared aperture and decoupling designs are required for compact massive MIMO antenna arrays because, in practical scenarios, the number of antennas and their operating frequency bands continues to increase while their sizes shrink. 2) Antennas are integrated with passive feeding networks, components, and active amplifiers. New forms of antenna systems are emerging, such as cable-less antennas, antenna filter units, plastic antenna elements, and active antennas, to improve the integration level and reduce loss. 3) Antenna-in-package and antenna-on-chip designs are becoming increasingly popular in the millimeter wave frequency band. In higher frequency bands, the size of the antenna (array) is significantly reduced to the level of package and die. Therefore, many silicon- or carbon-based novel antenna arrays that are integrated with active RF chips as well as baseband chips with the aid of advanced circuit and packaging techniques, making the antenna an on-chip component. 4) As the frequency increases and the RF front end becomes highly integrated with antenna elements, no external interface for the device under test may be required. Conventional conductive measurements for the transmitter and receiver must be conducted over the air. Furthermore, in the process of research and design, packaging and testing, antennas onboard or chips must be measured over the air. Passive parameters, RF performance, and radiation performance for multiple ports must be obtained with better efficiency since hundreds or thousands of antenna elements are used. Since active antennas are installed at the base station, their measurements should also be considered.

(7) Autonomous environment perception and scene cognition technology for intelligent mobile robots

An intelligent mobile robot acquires the multi-modal information of the dynamic environment through its multi-sensor system, establishes a dynamic environment model based on an analysis of effective information, and realizes the understanding and cognition of a dynamic scene. Intelligent mobile robots can successfully complete tasks such as autonomous positioning, environment exploration, and autonomous navigation because of their good adaptive capabilities to an environment during long-term operation. Intelligent mobile robots have broad application prospects in military, industry, agriculture, commerce, transportation, logistics, etc. For example, in the fight against COVID-19, service robots with autonomous mobile capabilities have contributed significantly to medical treatment, distribution, inspection, and other fields to reduce human contact.

The future research directions of autonomous environment perception and scene cognition technology for intelligent mobile robots include the following: 1) integrating multiple sensing data deeply, building a detection system covering all space and time, improving the ability of the sensing system, and providing a more reliable decision basis for intelligent mobile robots; 2) transfer learning to transfer the knowledge obtained from a limited training dataset to different scenarios and different tasks in an open environment, enhancing the long-term autonomous environment adaptability for mobile robots effectively; 3) excavating and analyzing the associations between objects, and between objects and scenes to enable the mobile robot to obtain the cognition of the scene category level and then select the models and parameters corresponding to the scene recognition results for relocation and scene understanding; 4) extracting knowledge automatically to build relationships from massive multi-source heterogeneous data, understand high-level semantic information, and effectively combine with application scenarios to realize the leap from perception intelligence to cognitive intelligence for mobile robots.

(8) Solid-state vehicle-mounted phased-array LiDAR

LiDAR refers to a system that uses laser-beam transmission and reception to realize obstacle detection and ranging. Owing to its long-range and high-precision detection characteristics, it is an important technical approach to realizing three-dimensional sensing. LiDAR primarily applies to automobile autonomous driving, robotics, geographic mapping, and atmospheric exploration. Auto-driving is a key market for LiDAR. As one of the most important sensors in the sensing terminal of an automatic driving system, LiDAR has two core functions. First, the three-dimensional environment model around the car can be obtained using laser beam scanning, and the surrounding vehicles and pedestrians can be accurately detected using relevant algorithms. Second, by comparing real-time global and high-precision maps, navigation and enhancement of the vehicle positioning accuracy can be realized.

The image mapping methods for LiDAR primarily include mechanical rotation scanning and solid-state scanning. Currently, most available LiDAR systems on the market use rotating mechanical devices for beam scanning. The representative products are Velodyne's HDL-64E and HDL-32E, which have been used by most well-known driverless car manufacturers (such as Google, Baidu, and Volvo). The entire scanning device rotates at a certain rate and continuously emits and detects laser pulses during the rotation. Owing to the inherent limitations of the mechanical rotation scanning mechanism, the scanning rate of the beam is limited, the practicability is low, and the complexity and cost of the system are high. Recently, researchers have begun to focus on another type of laser radar technology: an all-solid-state beam scanning system. Because it contains no macro-moving, it has good durability and reliability, which satisfies the requirements of automatic driving for solid-state, miniaturized, and low-cost LiDAR.

As the main scheme for all-solid-state beam scanning, an optical phased array (OPA) is composed of several transmitting and receiving units. Using external electrical control, an OPA can independently control various characteristics, such as light intensity and phase, of light emitted by different units. To realize beam scanning, based on the interference effect of coherent light, multi-beam interference can be enhanced in the specified direction by tuning the phase and amplitude distribution of different elements in the array, while interference in other directions can be canceled. Many methods and corresponding material platforms are available to realize OPAs. The early proposed scheme based on an AlGaAs waveguide array cannot achieve a large Lagrange invariant, resulting in an extremely small scanning angle. Moreover, the deflection efficiency of phased arrays based on liquid crystal technology is low at large angles, and the response time is generally in the order of milliseconds, which cannot satisfy the requirements of specific application scenarios such as automatic driving. Owing to its compatibility with CMOS technology, silicon-based photonic integration technology provides a low-cost solution for chip-scale solid-state LiDAR systems. As the core components of the solid-state LiDAR system, silicon-based integrated OPAs have been widely studied in recent years because of their solid-state beam scanning ability. Silicon-based integrated OPAs have the advantages such as fast scanning speed (MHz), high pointing accuracy (in the order of 0.1°), and good controllability (both high-density scanning of the target area and sparse scanning in other areas). Comparing the current development status of silicon-based integrated OPA to practical application requirements, many key technical problems remain to be solved. The future development direction includes the following aspects. First, the generation, modulation, and amplification of the laser sources should be integrated and packaged into a single chip with an optical phased array. Second, we must solve the problem of crosstalk between adjacent antennas in a high-density waveguide array, break through the technology of high modulation efficiency, low insertion loss, low amplitude chirp, and high-speed on-chip phase modulation, and achieve the required field of view and angle resolution in both the horizontal and vertical directions. Third, the degraded interference of background stray light, the directionality of the target reflected light, and the detection of weak light signals on the chip must be solved.

(9) Terahertz key devices and ultra-high-speed wireless transmission applications

Terahertz key devices and ultra-high-speed wireless transmission applications include two components: key functional devices and high-speed communication. The key functional devices of the terahertz frequency band primarily include the mixer, amplifier, frequency multiplier, modulator, antenna, transmission line structure, and channelized components. Terahertz high-speed communication uses terahertz signals as carrier waves for applications such as communications, data transmission, and networking. Its main applications are space high-speed communications, aviation massive data transmission, and backhaul links in the later 5G or 6G period. With the intensification of human society informatization, the data show that the average household broadband access rate has increased to 30 Mb/s, and the popularization of mobile 4G terminals has increased the average personal mobile network access to 100 Mb/s. Therefore, the transmission of large amounts of data and the seamless coverage of space, sky, and Earth will become the driving force of technology in the future. Currently, although the terahertz communication technology has the initial technical conditions for application, the system cost is still significantly high, and a low cost, mass production, and integrated terahertz communication system technology must be achieved. Therefore, terahertz communication integration and monolithic systems, terahertz high-power and high-efficiency key components, terahertz intelligent beams, and terahertz high-robustness adaptive capture and tracking technology are all technologies to be urgently realized in the future. With the breakthrough of these technologies, terahertz communication technology can be soon commercially popularized. The development trend in terahertz communication technology can be summarized as follows: higher frequency band, higher rate, smaller volume, lower power consumption, lower cost, and seamless connection of space and Earth.

(10) Distributed network security and management based on blockchain

Distributed network security and management based on blockchain involves building a set of trusted, transparent, and autonomous network operations and information security protection systems and accomplishing the leap of network security and management concepts from isolated points to systems using blockchain technology, which integrates many geographically dispersed, status-equal, and rule-clear network nodes. In this system, nodes are no longer solitary points but autonomous collaborative units under rules. Each node has self-protection capabilities and inputs and outputs security services. The unsafe state of any node will not be spread to other nodes; therefore, internal and external threats can be effectively blocked. The main technical directions of this front include systematic collaborative protection, trusted identity verification, access control and authority management, data confirmation and security, and privacy protection. These directions integrate the advantages of blockchain technology in network architecture, consensus rules, smart contracts, and data management to solve the problems encountered in network security and management. The development trend in the this field has two main directions: One is to provide users with application services to solve security problems in vertical application fields, such as for IoT application scenarios providing solutions for identity management, timestamp services, data protection, and single-point fault tolerance. The other is to provide basic protocols or algorithms for hardware facilities to improve the underlying security protection capabilities.

2.2 Interpretations for three key engineering development fronts

2.2.1 Development of EUV light sources for IC chip nanolithography

An EUV light source is the core component of a nanolithography machine, and its short wavelength can effectively reduce the node linewidth of IC chips. Currently, LPP sources are primarily used in commercial EUV nanolithography machines. An EUV-LPP light source is primarily composed of a main-pulse laser, pre-pulse laser, beam transmission system, Sn droplet target, Sn collector, collecting mirror, target chamber, etc. The main-pulse laser uses a high-power CO_2 laser combined with multistage amplifiers. After the beam transmission system, the main-pulse and pre-pulse generated by different lasers are focused on the collecting mirror. Sn droplets with a diameter of 20–30 μm are successively bombarded by the pre-pulse and main-pulse, transformed into a high-temperature Sn plasma radiating a 13.5-nm EUV light source, which is focused to the middle focal point by collecting mirrors.

The main objectives of EUV light source research are to determine target materials with short wavelengths, create new methods of effectively eliminating debris, and obtain a high conversion efficiency. In the process of searching for short-wavelength targets, note that Gd produces strong narrow-band resonance radiation at 6.7 nm, which is similar to Sn at 13.5 nm. It is highly likely to become an ideal target for a 6.7-nm light source in the future, which can greatly improve the nanolithography accuracy. However, the problem of debris is still the main factor that limits the conversion efficiency of EUV light sources in large-scale production. Currently, two main methods of reducing debris exist: applying double-pulse laser radiation and combining inert gases or hydrogen with an external magnetic field. In addition, satisfying the requirements of high average power and long-term stability for industrial mass production requires an in-depth study.

For the development of EUV light sources for IC Chip nanolithography, the core patents of the main producing countries, main producing institutions, and the cooperation network among major countries are shown in Tables 2.2.1, Table 2.2.2, and Figure 2.2.1, respectively. The top three countries in terms of core patent disclosures and citations are Japan, the United States, and China, among which the United States occupies a leading position in citations. The cooperation network among countries is concentrated in the United States, Japan, and Germany. The top three core patent producers are ASML Netherlands B.V., Komatsu Ltd., and Carl Zeiss SMT GmbH. The major institutions have no cooperative relationship amongst themselves.

Research on EUV nanolithography in China began relatively late. Some teams from the China Academy of Sciences and some universities are engaged primarily in related research. The existing technology accumulation in China and the industrial foundation of China are not yet mature.

2.2.2 Integrated wireless communications and sensing technology

The continuous evolution of wireless communication systems from 1G to 5G has resulted in a qualitative leap in communication capabilities as well as the gradual enhancement of sensing accuracy. Mutual integration and promotion are occurring between wireless communications and sensing. With the further development of large-scale antenna arrays, ultra-dense networking, new multiple access techniques, full spectra as well as the enabling of reconfigurable intelligent surface and AI, integrated wireless

Table 2.2.1 Countries with the greatest output of core patents on "development of EUV light sources for IC chip nanolithography"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	40	33.06%	219	22.35%	5.48
2	USA	26	21.49%	663	67.65%	25.50
3	China	23	19.01%	23	2.35%	1.00
4	Germany	16	13.22%	70	7.14%	4.38
5	Netherlands	14	11.57%	20	2.04%	1.43
6	South Korea	1	0.83%	1	0.10%	1.00

Table 2.2.2 Institutions with the greatest output of core patents on "development of EUV light sources for IC chip nanolithography"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	ASML Netherlands B.V.	Netherland	36	29.75%	668	68.16%	18.56
2	Komatsu Ltd.	Japan	14	11.57%	180	18.37%	12.86
3	Carl Zeiss SMT GmbH	Germany	13	10.74%	54	5.51%	4.15
4	Ushio Denki Kabushiki Kaisha	Japan	8	6.61%	9	0.92%	1.13
5	Harbin Institute of Technology	China	7	5.79%	1	0.10%	0.14
6	Semiconductor Manufacturing International (Shanghai) Co., Ltd.	China	6	4.96%	12	1.22%	2.00
7	IHI Corporation	Japan	4	3.31%	12	1.22%	3.00
8	Institute of Optics and Electronics, Chinese Academy of Sciences	China	4	3.31%	5	0.51%	1.25
9	Kansai University	Japan	4	3.31%	1	0.10%	0.25
10	Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences	China	3	2.48%	3	0.31%	1.00

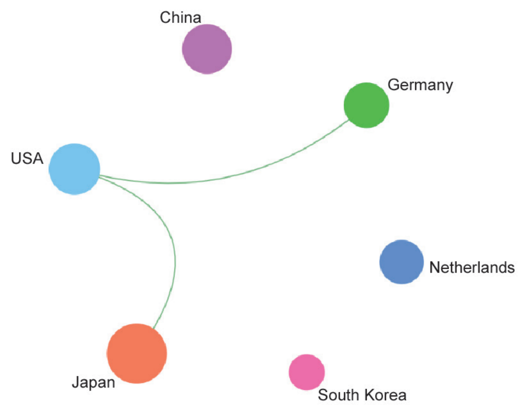

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “development of EUV light sources for IC chip nanolithography”

communications and sensing technology has become the leading direction in the field of wireless communications and sensing.

The integrated wireless communications and sensing technology refers to a high-level integration of advanced technologies in the field of communications and sensing in terms of hardware architecture and algorithm design by sharing the fundamental infrastructure and time–frequency–space resources of wireless communication systems. This technology can realize the cooperation and joint design of communication and sensing using the high-throughput and low-latency information interaction of wireless communication systems. Moreover, this technology breaks the traditional pattern of the isolated design of communication and sensing, achieves the future communication requirements of ultra-high rate, ultra-low delay, and ultra-high reliability, and realizes the centimeter-level accuracy positioning capabilities and ultra-high fine-grained sensing abilities.

Currently, the applications of integrated wireless communications and sensing technology are emerging in the fields of the Internet of Vehicles, intelligent transportation, and industrial network systems. In the future, the integrated wireless communications and sensing technology will become a new driving force for the evolution of communication systems, the transformation of industrial technologies, and the upgradation of smart societies. The integrated wireless communications and sensing technology will focus on the construction of a multi-level, multi-functional, and intelligent integrated network that includes functions of communication, positioning, sensing, and imaging. Future research will be devoted to revealing the coupling relationship among transmission, sensing, and control, improving the overall performance of the system in terms of communication and sensing, establishing the mechanism of interaction and cooperation between communication and sensing in highly dynamic scenarios, and designing information fusion and resource collaboration technologies suitable for high-dimensional, large-scale, and ultra-heterogeneous networks.

China, South Korea, and the United States are the top three countries to produce core patents in the engineering development of integrated wireless communication and perception technology (Table 2.2.3). The top three institutions of producing core patents are LG Electronics Inc. in South Korea, Qualcomm Incorporated in the United States, and Samsung Electronics Co., Ltd. in South Korea (Table 2.2.4). LG Electronics Inc. focuses primarily on mobile terminals, wearable smart devices, smart robots, and TV sets using wireless IP. Qualcomm Incorporated focuses on improving the performance of wireless communication systems using sensing technologies, including the sensing of channel and signal characteristics. The research directions of Samsung Electronics Co., Ltd. are broad, involving the application of integrated wireless communication and sensing technologies in intelligent transportation, smart homes, and equipment monitoring. The cooperation network of countries primarily involves China and the United States (Figure 2.2.2). There is no cooperation among the main institutions.

2.2.3 Design and implementation of intelligent robot cluster cooperation systems

The design and development of intelligent robot cluster cooperation systems involve complex technical systems, which are based on single robot technology and have multi-system, multi-level, and multi-disciplinary comprehensive integration as the core. They rely on network system construction for interconnection and AI technology for task empowerment. This involves the comprehensive application of subject knowledge in electromechanical systems, communication networks, operation research and scheduling, AI, and cybernetics. They are common in the application scenarios of robot cluster collaborative manufacturing, wharf and

Table 2.2.3 Countries with the greatest output of core patents on "integrated wireless communications and sensing technology"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	182	60.87%	332	29.83%	1.82
2	South Korea	56	18.73%	159	14.29%	2.84
3	USA	27	9.03%	480	43.13%	17.78
4	Japan	17	5.69%	28	2.52%	1.65
5	Sweden	3	1.00%	7	0.63%	2.33
6	Finland	2	0.67%	62	5.57%	31.00
7	Malaysia	1	0.33%	4	0.36%	4.00
8	Ireland	1	0.33%	1	0.09%	1.00
9	Germany	1	0.33%	0	0.00%	0.00
10	UK	1	0.33%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "integrated wireless communications and sensing technology"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	LG Electronics Inc.	South Korea	13	4.35%	31	2.79%	2.38
2	Qualcomm Incorporated	USA	11	3.68%	347	31.18%	31.55
3	Samsung Electronics Co., Ltd.	South Korea	5	1.67%	139	12.49%	27.80
4	Beijing University of Posts and Telecommunications	China	3	1.00%	28	2.52%	9.33
5	State Grid Corporation of China	China	3	1.00%	25	2.25%	8.33
6	Telefonaktiebolaget LM Ericsson	Sweden	3	1.00%	7	0.63%	2.33
7	University of Electronic Science and Technology of China	China	3	1.00%	5	0.45%	1.67
8	Toyota InfoTechnology Center Co., Ltd.	Japan	3	1.00%	4	0.36%	1.33
9	Sony Corporation	Japan	3	1.00%	0	0.00%	0.00
10	China Academy of Telecommunications Technology	China	2	0.67%	24	2.16%	12.00

warehouse logistics, unmanned system cluster collaborative search, and rescue. They have a very important function in the development strategy of intelligent manufacturing and AI in China. They are important carriers of the leading-edge technology of AI, such as autonomous intelligent systems and swarm intelligence. With the rapid development of AI and communication network technology, the autonomy and intelligence of robots will continue to improve in the future, the scale of robot clusters will increase, and the cost will continue to decrease. Efficient operation mode will promote the wide application of intelligent robot cluster cooperation systems, and human production and lifestyle will undergo significant changes.

An intelligent robot cluster cooperation system is primarily used to perform complex tasks with a large spatial distribution and various operation links. Such systems are often used in the fields of manufacturing, logistics, and transportation. For example, heterogeneous robots such as processing and transport robots can form a robot cluster collaborative production manufacturing system, which can significantly increase the production efficiency and degree of automation and intelligence of production and manufacturing. However,

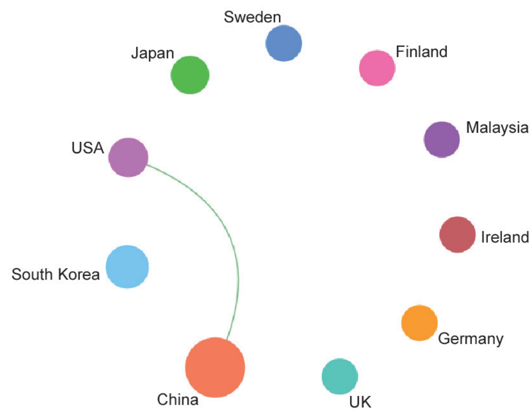

Figure 2.2.2 Collaboration network among major countries in the engineering development front of “integrated wireless communications and sensing technology”

e-commerce enterprises such as Jingdong, Cainiao, and Amazon have established intelligent warehousing systems with transport robots as the basic work units; this significantly increases the operational efficiency of the logistics system. Other typical applications include cooperative area search, target detection, or other complex tasks using various homogeneous or heterogeneous unmanned system clusters composed of UAVs, unmanned ground vehicles, and unmanned surface vehicles. The United States, Russia, the United Kingdom, France, and other countries have formulated long-term development plans to develop various robot cluster systems. With the expansion of cluster scale and working spaces and the continuous expansion of application scope, the robot cluster collaborative operation system presents the development trend of distributed, intelligent, and autonomous in terms of architecture, perception, planning, decision-making, and control.

Table 2.2.5, Table 2.2.6, and Figure 2.2.3 show the main producing countries, main output institutions, and cooperation network among major countries, respectively. China, the United States, and Japan rank in the top three in the number of core patent disclosures and citations, among which China occupies an absolute leading position in terms of patent disclosure and citations. The Boeing Company, Hangzhou Dianzi University, and Xidian University are the top three major producers of core patents. The United States and Saudi Arabia cooperate to a certain extent, but the main institutions have no cooperative relationship. China’s relevant scientific research institutions are primarily institutions of higher learning, focusing on multi-robot collaborative path planning, distributed motion control, and other basic methods and technologies. The scientific research institutions in the United States and Japan are primarily large international companies, whose research primarily focuses on the application of multi-robot cooperation technology in specific industrial fields. For example, the technological invention of the Boeing Company in the United States involves actual operation tasks, such as multi-robot cooperation to operate on the workpiece surface, and human–robot collaboration to perform fuselage assembly in a complex operation environment. The technology invention of Toshiba Co., Ltd. of Japan adopts displacement measurement and external force estimation to realize multi-robot collaborative cargo handling operations.

Table 2.2.5 Countries with the greatest output of core patents on “design and implementation of intelligent robot cluster cooperation systems”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	85	75.89%	122	47.47%	1.44
2	USA	7	6.25%	27	10.51%	3.86
3	Japan	6	5.36%	66	25.68%	11.00
4	South Korea	3	2.68%	20	7.78%	6.67
5	Saudi Arabia	3	2.68%	9	3.50%	3.00
6	Germany	3	2.68%	0	0.00%	0.00
7	Canada	1	0.89%	15	5.84%	15.00
8	Italy	1	0.89%	1	0.39%	1.00
9	France	1	0.89%	0	0.00%	0.00
10	India	1	0.89%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “design and implementation of intelligent robot cluster cooperation systems”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations
1	The Boeing Company	USA	4	3.57%	3	1.17%
2	Hangzhou Dianzi University	China	3	2.68%	5	1.95%
3	Xidian University	China	3	2.68%	2	0.78%
4	Shunde Polytechnic	China	3	2.68%	1	0.39%
5	Toshiba Corporation	Japan	2	1.79%	40	15.56%
6	Beihang University	China	2	1.79%	24	9.34%
7	Saudi Arabian Oil Company	Saudi Arabia	2	1.79%	6	2.33%
8	Southeast University	China	2	1.79%	6	2.33%
9	Shanghai University	China	2	1.79%	4	1.56%
10	Hangzhou Siasun Robot and Automation Co., Ltd.	China	2	1.79%	3	1.17%

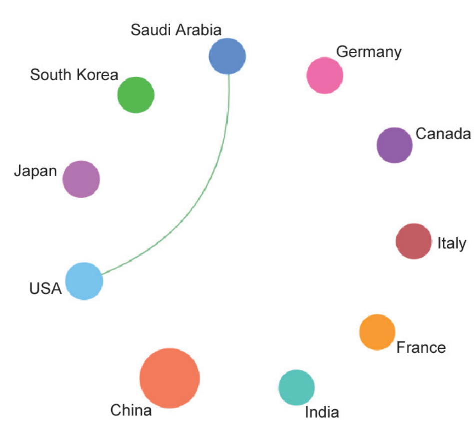

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “design and implementation of intelligent robot cluster cooperation systems”

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III. Chemical, Metallurgical, and Materials Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts determined by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Tables 1.1.1 and 1.1.2. The topics of “smart nanomedicine for cancer therapy,” “preparation of novel high-performance porous biomaterials for bone repair,” “development and application of next-generation advanced electronic components based on two-dimensional materials,” “efficient and robust synthesis of solar fuels,” and “non-aqueous potassium-ion batteries with high energy density” are based on core papers provided by *Clarivate*. The other five are recommended by experts or were selected by analyzing data from the *Web of Science*. Basic research on energy, especially pertaining to “efficient and robust synthesis of solar fuels,” remains highly topical, and the number of core papers covering this topic has exhibited a general trend of increase. Furthermore, basic research on lithium batteries/capacitors and industrial technologies employing these devices have attracted significant attention.

(1) Smart nanomedicine for cancer therapy

Cancer is among the diseases with the highest mortality rates. Traditional clinical treatments for cancers include chemotherapy, radiotherapy, immunotherapy, and gene therapy. To improve the clinical performance of these therapies while minimizing adverse side effects, nanomedicines—new theranostic agents based on nanotechnology—have been gradually applied in the precise diagnosis and treatment of cancers. Smart nanomedicines have been rationally designed and developed using different biocompatible materials, such as proteins, lipids, polymers, and organic/inorganic nanomaterials with multiple biological functions. Smart nanomedicines can prospectively exhibit simultaneous responses to exogenous stimuli (e.g., light, temperature, ultrasound, magnetic field) and the stimuli in the microenvironment of tumors (pH, reductants, enzymes, reactive oxygen species, and ATP). These responses improve

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Smart nanomedicine for cancer therapy	190	27 890	146.79	2015.7
2	High-energy-density and fast-charging battery–capacitor hybrid energy storage systems	177	27 040	152.77	2016.0
3	Metallurgy and materials processes in high magnetic fields and fabrication of functional materials	139	5 431	39.07	2015.8
4	Preparation of novel high-performance porous biomaterials for bone repair	161	13 121	81.50	2015.8
5	Development and application of next-generation advanced electronic components based on two-dimensional materials	86	15 572	181.07	2015.9
6	Efficient and robust synthesis of solar fuels	77	6 893	89.52	2017.6
7	Non-aqueous potassium-ion batteries with high energy density	52	8 710	167.50	2017.0
8	Ceramic materials for the radome of hypersonic missiles	94	4 140	44.04	2015.7
9	Quantum materials and devices with artificial structures	167	12 065	72.25	2015.5
10	Welding fluxes geared toward high-heat-input applications	115	2 954	25.69	2015.6

Table 1.1.2 Annual number of core papers for the top 10 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Smart nanomedicine for cancer therapy	37	51	51	29	20	2
2	High-energy-density and fast-charging battery–capacitor hybrid energy storage systems	31	48	31	28	31	8
3	Metallurgy and materials processes in high magnetic fields and fabrication of functional materials	34	33	29	24	13	6
4	Preparation of novel high-performance porous biomaterials for bone repair	32	43	30	34	20	2
5	Development and application of next-generation advanced electronic components based on two-dimensional materials	21	15	21	15	10	4
6	Efficient and robust synthesis of solar fuels	0	4	7	21	26	19
7	Non-aqueous potassium-ion batteries with high energy density	1	5	5	24	16	1
8	Ceramic materials for the radome of hypersonic missiles	21	23	22	20	6	2
9	Quantum materials and devices with artificial structures	44	50	33	23	15	2
10	Welding fluxes geared toward high-heat-input applications	23	35	30	21	6	0

the specificity, controllability, and intelligence of nanoparticles for tumor-specific imaging, targeted drug delivery, and precise cancer treatment. Currently, the primary research in this field has been aimed at achieving the following objectives: developing new biocompatible nanomaterials or self-assembly of materials for nanomedicines, stimuli-responsive intelligent nanomedicines for specific cancers and controllable drug release, smart nanoprobes for intelligent tumor imaging and cancer diagnosis, new strategies for developing cancer theranostics for smart nanomedicines, and exploring systemic metabolism and toxicity of smart nanomedicines.

(2) High-energy-density and fast-charging battery–capacitor hybrid energy storage systems

The lithium-ion capacitor (LIC) is a representative high-energy-density and fast-charging battery–capacitor hybrid energy storage system. The energy storage excellent performance of the LIC has both of lithium-ion batteries (LIBs) and a supercapacitor. As a novel energy storage device, the LIC combines the high energy density of LIBs with the high power density and long cycle life of a supercapacitor. The type and structure of the electrode materials, cathode and anode matching, and the potential window of the LIC influence its energy density, power density, and cycle life. At present, most cathode materials for LICs are activated carbon materials with the characteristics of electric double-layer energy storage. Meanwhile, the anode materials are mostly carbon-based with the function of lithium-ion deintercalation. However, the capacity and potential of the carbon materials limit the energy density of devices employing carbon-based electrodes. The use of transition metal oxides, pre-lithiation of the anode materials, and the use of organic electrolytes can render the energy density of LICs comparable to that of LIBs; however, the cycle life and power density of the LIC system must be further improved to be comparable to that of supercapacitors. Therefore, designing and developing new types of high-energy-density electrode materials, tailoring the surface/interface structure of electrode materials, optimizing the process for matching the cathode and anode materials, and achieving miniaturized, flexible, and transparent devices are important research directions for the future development of high-performance LICs.

(3) Metallurgy and materials processes in high magnetic fields and fabrication of functional materials

Improving the service performance of metallic materials and imparting new functions to materials are the major requirements for sustainable development and are also the main challenges in the fields of metallurgy and materials science. A high magnetic field (exceeding 2 T) is usually difficult to achieve with permanent magnets and ordinary electromagnets; it renders a variety of exceptional properties in terms of force, heat, and energy. The efficient coordination of these effects offers significant potential for the design and fabrication of functional metallic materials, and provides a new approach for innovation in metallurgy and material preparation. Multidisciplinary research into metallurgy and materials processes in high magnetic fields is currently trending toward the following objectives: research on the experimental equipment for material preparation and performance testing, measurement of the physical properties of high-temperature metal melts, theoretical research on alloy solidification, development of metallurgical technology, and the design of new metal-based functional materials. It is exceedingly crucial to clarify the effects of synergism and competitive mechanisms involving various phenomena in high magnetic fields on metallurgical and material processes.

(4) Preparation of novel high-performance porous biomaterials for bone repair

With rapid economic development and the aging global population, the number of cases of bone trauma has witnessed a significant increase. Therefore, regenerative medicine is faced with a major challenge; the development of novel bone repair biomaterials is driven by rapidly increasing clinical needs. Bone repair materials with porous structures are required to facilitate the ingrowth of blood vessels, which is critical for bone tissue repair. Scaffolds prepared by 3D printing technology can be used to construct complex shapes matching the bone defect. Furthermore, accurate control of the internal pore structure can be achieved to meet clinical needs. 3D-printed porous scaffolds are usually limited to a single material. Current research is trending toward the development of composites of different types of materials that afford control of the desired scaffold parameters—pore size and type, degradation rate, and mechanical strength—to achieve the most effective bone repair. In addition, constructing fine structures such as nerve and blood vessel networks to reproduce the complex and diverse functions of bone tissue is another goal in the 3D printing of porous bone repair scaffolds. And recent years have witnessed significant progress in the development of bone repair materials, where new bone biomaterials have been designed based on the studies of the interaction of cell materials at the cellular and molecular levels. These studies have led to the development of new technologies for the fabrication of novel bone repair materials with “active repair function” and “tissue microenvironment responsive characteristics” by the accurate control of the chemical composition and nano–micro structure.

(5) Development and application of next-generation advanced electronic components based on two-dimensional materials

Next-generation electronic devices are crucial for developing advanced electronic and photonic integrated circuit technology and realizing miniaturization and integration of high-performance communication and Lidar and electronic warfare systems. Two-dimensional advanced electronic devices afford higher speed, efficiency, and integration, as well as a lower power cost, which should drive a wave of electronic innovation in the near future. The United States and Europe have already focused on two-dimensional advanced electronic devices. Since 2017, particularly the Defense Advanced Research Projects Agency (DARPA) of United States has directed their focus toward advanced devices and materials through the Electronics Resurgence Initiative to attain a technological edge over the rest of the world. Current technology in China is competitively comparable to cutting-edge international developments. Facing unprecedented development opportunities, China also needs to strengthen basic research and development (R&D) and engineering, provide deep research on the preparation and technical problems related to key materials, and establish an independent innovation system. The key challenges are as follows: wafer-scale growth of high-quality single-crystal two-dimensional materials, including graphene, two-dimensional transition metal dichalcogenides, two-dimensional ferromagnetic materials; large-scale nondestructive transfer and hetero-structure integration technology; mechanism of multi-physical-field coupling for high-performance control and manipulation of electronic devices.

(6) Efficient and robust synthesis of solar fuels

Solar energy is a clean, abundant, and renewable power source with tremendous potential. Harnessing solar energy to produce fuels that can be used by human beings is one of the effective ways to solve the global energy crisis and environmental problems. Inspired by natural photosynthesis, solar fuel refers to the use of renewable energy, specifically solar energy, to convert CO_2 and H_2O into chemical fuels (e.g., H_2, CH_3OH). This can be realized in two general ways: One is to use solar energy to decompose H_2O to produce H_2 and O_2 through photo(electro)catalysis and combine H_2 and CO_2 to produce CH_3OH; the other is the direct reduction of CO_2 to CH_3OH by photo(electro)catalysis. This process can achieve zero carbon emissions and is also the main pathway to achieve low-carbon energy. Considering the non-renewable nature of fossil fuels and the increasing demand for energy, the realization of solar fuel is bound to become an important part of the energy structure in the future. Two key catalytic approaches are employed in the process of solar fuel synthesis; the first is utilizing efficient, inexpensive, and stable catalysts for water decomposition/CO_2 reduction by photo(electro) catalysis, with an energy conversion efficiency exceeding 80%, and the other is using inexpensive and highly selective catalysts for the hydrogenation of carbon dioxide to methanol. To improve the conversion efficiency of water splitting into hydrogen/CO_2 reduction, the selectivity and stability of the catalysts and coupling of the two key catalytic technologies are the main research directions in this field.

(7) Non-aqueous potassium-ion batteries with high energy density

Potassium is one of the most abundant elements in the earth's crust and is widely distributed. Its physical and chemical properties are similar to those of lithium, which makes potassium-ion batteries a useful supplement to LIBs. Similar to the working principle of LIBs, charge and discharge processes in potassium-ion batteries are realized by the reversible intercalation and desorption of potassium ions between the positive and negative electrodes. The radius of the potassium ion is larger than that of the lithium ion, while its migration speed is lower in the bulk phase of the material. This leads to a deficiency in the electrochemical performance of the potassium-ion battery. Therefore, the development of anode and cathode materials with stable structures that can undergo reversible insertion and deinsertion has become a key scientific and technological problem to be addressed. At present, the development of cathode materials has mainly focused on Prussian blue, combined with studies of layered transition metal oxide cathodes with high theoretical specific capacity and polyanion cathode materials with high voltage and stability. The primary anode materials are the intercalation/deintercalation and alloy-type anode materials. Although they have certain defects, improved electrochemical performance of modified electrodes can be achieved by element doping, surface coating, and nano-sizing. Research on electrolytes has been mainly aimed at matching the electrolyte and electrode materials. With the advancement of research, potassium-ion batteries are expected to become beneficial complements to LIBs for use in low-speed electric vehicles and large-scale energy storage.

(8) Ceramic materials for the radome of hypersonic missiles

Advanced high-temperature thermoresistant ceramic materials with unique properties are generally used in extreme environments, such as those encountered in prolonged supersonic flight, re-entry flight, crossover flight in the aerosphere, and rocket propulsion. The development of advanced radome materials is one of the key objectives for achieving advanced hypersonic missiles. With the escalating flying speeds of missiles, radome ceramic materials must withstand increasingly harsh working environments. In addition to the various static and dynamic loads, ceramic materials also need to withstand the ablation and corrosion induced by high-temperature, high-pressure, and high-speed airflows. Consequently, ceramic materials for radomes must exhibit excellent mechanical and dielectric properties, resistance to ablation, oxidation, and thermal shock, and an appreciable molding processability to ensure a high transmission power and low aiming error. At present, the advancement of several national key projects is mainly hampered by the lack of advancement in heat-resistant ceramics and their composites. This constraint arises from the insufficient comprehension of the fundamental issues involved in key ceramic processing technologies. The lack of advancement is also attributed to the restricted development of raw materials, such as high-purity ultra-fine ceramic powders/precursors, and major equipment for these processes. Ceramic materials undergo long-term thermo-mechanical coupling ablation; therefore, future efforts should be focused on developing new ceramic fibers and related composites with higher ablation resistance and excellent wave transparency, geared toward achieving improved high-temperature dielectric stability. For large-sized, thin-walled, special-shaped components, it is necessary to develop efficient forming techniques for near-net-size materials. Moreover, dense wave-transmitting ceramic coatings functional at higher temperatures are essential for the porous wave-transparent structural components of radomes.

(9) Quantum materials and devices with artificial structures

Artificially structured quantum materials and devices are novel kinds of semiconductor materials and devices designed and manufactured on the nanoscale via various physical or chemical means. The intriguing properties of these materials mainly originate from the special structures rather than the intrinsic characteristics of the materials. At present, studies on artificial structural quantum materials and devices have focused on the atomic-scale manipulation of defects in two- dimentional materials, design of artificial multiple quantum wells, and periodic structures of superlattices in semiconductor heterostructures. By combining first-principles calculations with micro-machining technology, artificial structural quantum devices with novel functions have been developed by controllable defect doping, and growth of artificially designed structures on the atomic, molecular, or nano scale. The key research targets for developing artificial structural quantum materials and devices are as follows: 1) determining how to precisely and arbitrarily control the thickness of quantum wells/barriers and their multiple stacks; 2) deepening the understanding of the mechanism of interaction between photons, phonons, and electrons in semiconductor quantum dot structures; and 3) comprehending the inherent laws of electron transport, optical transitions, and quantum energy states. The strategic requirements are geared toward further integrating and developing new artificial structural quantum devices, such as highly sensitive mid-infrared detectors, quantum cascade lasers, and superluminescent diodes, by combining high-precision artificial semiconductor microstructures and atomic pattern processing technology.

(10) Welding fluxes geared toward high-heat-input applications

Thick-plate products, such as steel for shipbuilding and offshore engineering, steel for pressure vessels, and steel for hydropower and nuclear power, are of considerable technological importance with high added value. These materials are the “heavy implements of a large country,” and having an independent supply and using these materials to meet extreme needs reflect the comprehensive strength of a nation’s industrial development strategy and safety. The welding efficiency of these materials has become a bottleneck, restricting the construction of thick-plate products. The manufacture of thick-plate products has been enabled by the wide application of large heat input welding, which affords high efficiency and low cost. From existing research, oxide metallurgy technology is a key point for large heat input welding for thick plates. Domestic R&D for the enhancement of the features of high-grade welding consumables must be improved. The core challenge for obtaining welding consumables from high-strength thick steel plates using a large heat input and high-grade welding materials is to achieve a deeper understanding of the metallurgical welding process, such as flux/slag decomposition, the oxygen gaining mechanism, and alloying element transition of the welds. The welding pool reaction thermodynamics and dynamics model should take into account the evolution process of welding slag structure, alloy element transition, inclusion dissolution and precipitation, which will lead to control over the microstructure of weld metal. This essential regulation is of great significance to consolidate the oxide metallurgy foundation of thick plate large heat input welding and have high performance materials.

1.2 Interpretations for three key engineering research fronts

1.2.1 Smart nanomedicine for cancer therapy

Cancer is a serious threat to human health, with high morbidity and mortality rates. To date, various therapeutic methods, including radiotherapy, chemotherapy, immunotherapy, photodynamic therapy, and gene therapy have been widely used in clinical research and cancer therapy. Cancer therapy has entered the era of precision targeted therapy, with the emergence of smart nanomedicine as a strategy for cancer diagnosis and/or treatment. Smart nanomedicines, as an offshoot of nanoscience and nanotechnology, are geared toward circumventing the various adverse side effects of traditional therapeutics associated with drug delivery, drug enrichment, and systemic toxicity. Smart medicines are also sensitive to exogenous or endogenous stimuli and afford the targeted release and enrichment of sensors or drugs at tumor sites to enhance the biological effects of these agents for cancer diagnosis and cancer treatment.

The following are the main research frontiers for smart nanomedicine: 1) improving the therapeutic effect of traditional chemotherapeutics with the assistance of nanotechnology. Under this objective, various biocompatible materials (e.g., nucleic acids, proteins, lipids) have been designed and developed for producing nanomedicines through chemical conjugation, physical packaging, or supermolecular self-assembly of small-molecule drugs or macromolecule drugs (e.g., nucleic acid drugs, protein drugs, antibodies). Such materials can enhance the stability of drugs and reduce their systemic toxicity. For example, the U.S. Food and Drug Administration-approved albumin-paclitaxel conjugate nano-drug, Abraxane®, is clinically used in the treatment of non-small cell lung cancer and other malignant tumors, affording a significant decrease in the toxicity of paclitaxel to normal organs during cancer therapy. The nanomedicine Doxil® with PEGylated liposomes greatly improved the therapeutic effect of the loaded doxorubicin. 2) Developing specific smart nanomedicines for cancer therapy and their controllable release. Antibody-drug conjugates (ADCs), also known as intelligent biological bombs, exhibit highly active targeting ability for cancers. In January 2020, the National Medical Products Administration of China approved the target nanomedicine Kadcyla® for HER2 positive breast cancer patients, thereby achieving a 50% reduction in recurrence and all-cause mortality in comparison with the use of the trastuzumab HER2 monoclonal antibody. By further using exogenous triggers (e.g., light, temperature, ultrasonic, magnetic field) and endogenous environmental triggers (e.g., pH, Red/Ox, enzymes, ATP), the entrapment of smart nanomedicines in nanomaterials can be maintained during circulation. Meanwhile, drug release can be triggered under certain endogenous or exogenous conditions at tumor sites and the maximum concentration for optimal therapy can be rapidly achieved, resulting in reduced systemic toxicity. 3) Developing smart nanoprobes for tumor imaging and cancer diagnosis, with focus on tumor-specific targeting and multiple modes of precise cancer diagnosis. Numerous specific targeting moieties, including nucleic acid aptamers, antibodies, peptides, and specific small donor molecules, have been conjugated to nanomaterials to develop high-contrast fluorescent nanoprobes, Raman nanoprobes, radionuclide-labeled nanoparticles, and quantum dots to achieve direct tumor diagnosis and surgical navigation. 4) Developing new strategies for synthesizing nanomedicines and theranostics for cancer therapy. Through precise rational design, nanomedicines combined with imaging agents and drugs have been optimized to achieve precise, image-guided tumor treatment. Emerging strategies for cancer therapeutics include targeting nanorobots, *in-vivo* self-assembled nanostructures, and protein nanoreactors for cancer theranostics. 5) Avoiding systemic metabolism and toxicity of nanomedicines. The blood circulation, enrichment, tumor cell penetration, and biological metabolism of nanomedicines with different sizes, morphologies, and surface properties differ from those of traditional drugs. Detailed evaluation of the health safety, therapeutic risk, and toxicological mechanism of nanomedicines will be beneficial for achieving safe clinical cancer therapy.

Among 190 core papers, 67 review papers have been published thus far. The paper titled “Cancer nanomedicine: Progress, challenges and opportunities” published by Harvard Medical School in 2017 received more than 1500 citations. By reviewing core papers focusing on the concept of “smart nanomedicine for cancer therapy” published since 2014, the main countries and institutions involved in this research field are compiled in Tables 1.2.1 and 1.2.2, respectively. The collaboration between major countries and institutions is shown in Figures 1.2.1 and 1.2.2, respectively, where China, the United States, and South Korea are the top three countries for publication in this field. Among the institutions with the highest output of papers in this field, the Chinese Academy of Sciences ranked No. 1. As shown in Figure 1.2.1, China and the United States boast the greatest number of collaborations, and the collaboration networks between France and Italy, the United States and Singapore are also well developed. Figure 1.2.2 demonstrates that the Chinese Academy of Sciences along with the University of Chinese Academy of Sciences and the National Center for Nanoscience and Technology of China are the institutions with the most active collaborations. According to Table 1.2.3, the core papers are most cited by the researchers from China, the United States, and India in a descending order. The top two institutions with the largest number of citing papers are the Chinese Academy of Sciences and the University of Chinese Academy of Sciences (Table 1.2.4).

1.2.2 High-energy-density and fast-charging battery–capacitor hybrid energy storage systems

With the gradual depletion of fossil energy in recent years, the alteration of the energy structure and advancement in the development and large-scale use of new energy technologies have been incorporated into the medium- and long-term development strategies of countries globally. The rapid development of new energy vehicles and smart electronic devices requires energy storage devices capable of fast charging, with high energy density, high power density, and long life. Therefore, there is an urgent need to improve the energy density and power density of energy storage systems to achieve longevity.

Electrochemical energy storage is one of the most effective methods of storing electrical energy, owing to its flexibility, high energy conversion efficiency, and easy maintenance. Thus far, LIBs have been the most successfully developed

Table 1.2.1 Countries with the greatest output of core papers on “smart nanomedicine for cancer therapy”

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	102	53.68%	12 767	125.17	2015.9
2	USA	66	34.74%	12 137	183.89	2015.6
3	South Korea	14	7.37%	1 977	141.21	2015.2
4	Singapore	9	4.74%	909	101.00	2015.2
5	Italy	7	3.68%	1 068	152.57	2015.1
6	Spain	6	3.16%	703	117.17	2015.8
7	India	6	3.16%	570	95.00	2016.2
8	France	5	2.63%	852	170.40	2015.0
9	Portugal	5	2.63%	566	113.20	2016.2
10	Canada	5	2.63%	452	90.40	2015.8

Table 1.2.2 Institutions with the greatest output of core papers on “smart nanomedicine for cancer therapy”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	39	20.53%	4 923	126.23	2015.8
2	University of Chinese Academy of Sciences	15	7.89%	2 284	152.27	2016.0
3	Soochow University	14	7.37%	1 520	108.57	2015.9
4	Harvard University	12	6.32%	4 310	359.17	2016.0
5	National Center for Nanoscience and Technology of China	7	3.68%	716	102.29	2015.9
6	Xiamen University	6	3.16%	1 056	176.00	2016.8
7	Massachusetts Institute of Technology	5	2.63%	1 916	383.20	2014.4
8	National Institute of Biomedical Imaging & Bioengineering, National Institutes of Health	5	2.63%	878	175.60	2016.4
9	Seoul National University	5	2.63%	774	154.80	2014.6
10	University of North Carolina at Chapel Hill	5	2.63%	577	115.40	2015.0

electrochemical energy storage technology. However, the limited kinetics of the chemical reactions of the constituents and the reaction mechanisms of LIBs make it difficult to achieve high power density and long life. In contrast, while supercapacitors boast of these characteristics, they cannot provide high capacity and energy density. The LIC is a special energy storage system that combines LIB-type electrodes and capacitor-type electrodes. Thus, LICs have a high energy density close to that of LIBs and the high-power characteristics of supercapacitors.

Recent years have witnessed a rapid development in battery–capacitor energy storage systems based on LIBs and supercapacitors. Research on electrochemical energy storage materials and devices is an interdisciplinary field involving

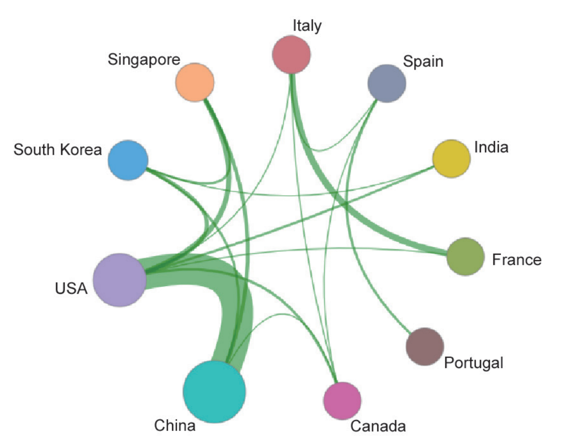

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “smart nanomedicine for cancer therapy”

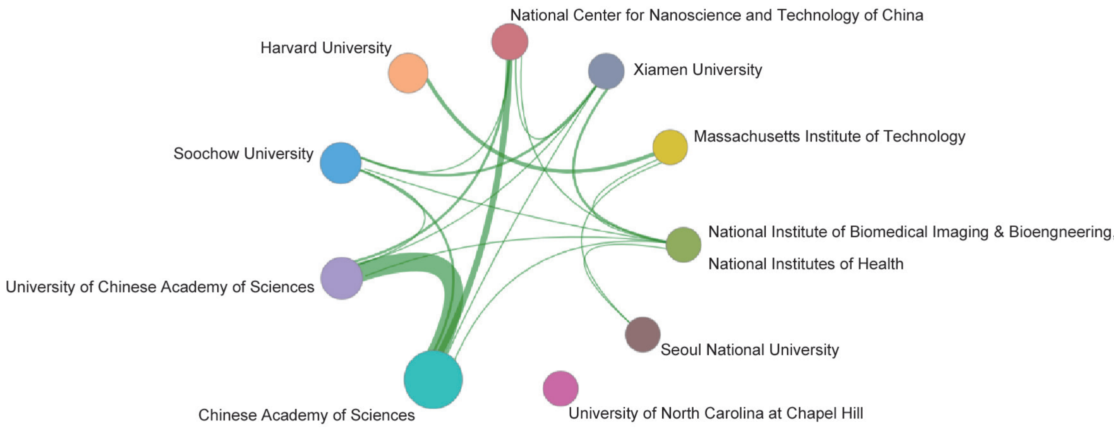

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "smart nanomedicine for cancer therapy"

Table 1.2.3 Countries with the greatest output of citing papers on "smart nanomedicine for cancer therapy"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	10 396	50.47%	2018.1
2	USA	3 673	17.83%	2017.8
3	India	1 146	5.56%	2018.1
4	South Korea	898	4.36%	2018.0
5	Germany	726	3.52%	2018.0
6	Spain	680	3.30%	2017.9
7	Iran	679	3.30%	2018.3
8	Italy	663	3.22%	2017.8
9	UK	619	3.01%	2018.0
10	France	567	2.75%	2017.8

Table 1.2.4 Institutions with the greatest output of citing papers on "smart nanomedicine for cancer therapy"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	1 792	30.43%	2018.0
2	University of Chinese Academy of Sciences	716	12.16%	2018.1
3	Soochow University	483	8.20%	2017.7
4	Shanghai Jiao Tong University	440	7.47%	2018.2
5	Zhejiang University	386	6.56%	2018.3
6	Sichuan University	368	6.25%	2018.0
7	Jilin University	364	6.18%	2018.1
8	Fudan University	364	6.18%	2018.1
9	University of Science and Technology of China	340	5.77%	2018.4
10	Harvard University	335	5.69%	2017.8

materials science, physics, chemistry, and metallurgy, and is wide-ranging and relatively complex. The following are the principal research hotspots in the field: 1) the development of new electrode materials to improve the energy density of these systems. Research on new battery-type electrode materials has mainly focused on high-capacity metal oxide materials, such as Li–Ni–Mn–O and Nb_2O_5. Meanwhile, pseudocapacitive materials are often used for capacitor-type electrode materials instead of carbon materials such as MXenes and MoO_3. Surprisingly, with some new electrode materials, the energy density and power density of LICs can reach 92.3 Wh/kg and 1100 W/kg, respectively. 2) Developing nanostructured electrode materials. Designing, tailoring, and preparing nanomaterials with different morphologies and structures that can be modified by applying an electromagnetic field, coating, element doping, or surface/interface design can afford enhanced kinetic characteristics of electrochemical reactions, and higher specific surface area and conductivity of electrode materials. The improved characteristics result in the enhanced power density and cycle performance of LICs. Moreover, the high wettability and ion/electron transport properties of three-dimensional integrated electrodes offer distinct advantages for improving the performance of LICs. 3) The development of new electrolytes to improve the electrochemical performance and safety of LICs. The primary characteristics of electrolytes to be considered are their voltage window ranges, ionic conductivities, thermal stabilities, and compatibility with electrode materials. In 2015, *Science* reported a “water-in-salt” electrolyte; the unique electrolyte displayed good thermal stability and a high voltage resistance in battery–capacitor systems. Based on the high power density, this electrolyte effectively improves the energy density of water-based battery-capacitors. 4) Diversification and functionalization of battery–capacitors. High energy density, high power density, and long-life energy storage devices will have broad application prospects in smart/wireless electronic devices and optoelectronic devices. Therefore, the future will witness a great demand for flexible, foldable, and even transparent battery–capacitor devices. In addition, high-capacity sodium ion capacitors with fast electrochemical reaction kinetics will have broad prospects.

The main countries involved in research and the institutions publishing core papers covering the concept of “high-energy-density and fast-charging battery–capacitor hybrid energy storage systems” since 2014 are listed in Tables 1.2.5 and 1.2.6, respectively; the collaboration between major countries and institutions is outlined in Figures 1.2.3 and 1.2.4. China, the United States, and South Korea are the top three countries, while the Chinese Academy of Sciences ranked No. 1 with the highest output of core papers. As shown in Figure 1.2.3, China and the United States boast the greatest number of collaborations. The core papers are most cited by the researchers from China, the United States, and South Korea in a descending order (Table 1.2.7). The Chinese Academy of Sciences, together with the University of Chinese Academy of Sciences, are the institutions with the greatest output of citing papers (Table 1.2.8). Research from Gleb Yushin at the Georgia Institute of Technology and Yi Cui of Stanford University is highly advanced. The 2016 review titled “Electrochemical capacitors: Mechanism, materials, systems, characterization and applications” by Yongyao Xia of Fudan University received more than 1300 citations in the last five years.

Table 1.2.5 Countries with the greatest output of core papers on “high-energy-density and fast-charging battery–capacitor hybrid energy storage systems”

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	95	53.67%	13 859	145.88	2016.4
2	USA	58	32.77%	11 617	200.29	2016.0
3	South Korea	15	8.47%	2 212	147.47	2015.6
4	Germany	11	6.21%	1 821	165.55	2016.4
5	Canada	11	6.21%	1 461	132.82	2016.5
6	Japan	9	5.08%	912	101.33	2015.0
7	Singapore	7	3.95%	1 468	209.71	2015.0
8	Australia	7	3.95%	957	136.71	2015.9
9	UK	5	2.82%	703	140.60	2016.8
10	France	5	2.82%	587	117.40	2014.8

Table 1.2.6 Institutions with the greatest output of core papers on "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	18	10.17%	2 129	118.28	2016.0
2	Fudan University	8	4.52%	1 757	219.62	2017.0
3	Tsinghua University	8	4.52%	908	113.50	2017.6
4	Nanyang Technological University	7	3.95%	1 468	209.71	2015.0
5	Nanjing University	7	3.95%	768	109.71	2015.6
6	Brookhaven National Laboratory	7	3.95%	535	76.43	2015.0
7	Stanford University	6	3.39%	1 375	229.17	2016.0
8	Argonne National Laboratory	6	3.39%	830	138.33	2016.8
9	University of Chinese Academy of Sciences	6	3.39%	769	128.17	2017.7
10	University of Waterloo	5	2.82%	894	178.80	2017.0

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "high-energy-density and fast-charging battery–capacitor hybrid energy storage system"

1.2.3 Metallurgy and materials processes in high magnetic fields and fabrication of functional materials

High-efficiency green metallurgy and material preparation technologies can improve the service performance of structural metallic materials and afford novel functional materials. These materials constitute the major needs of China's high-end equipment manufacturing, aerospace, energy, and other industries, as well as the core of the research in the fields of metallurgy and materials. Magnetic fields, especially high magnetic fields (exceeding 2 T), are difficult to achieve with permanent magnets and ordinary electromagnets. As a non-contact extreme physical field, high magnetic fields can act on matter on the atomic scale. This interaction can result in various enhanced effects, such as Lorentz force, thermoelectric magnetic force (a special

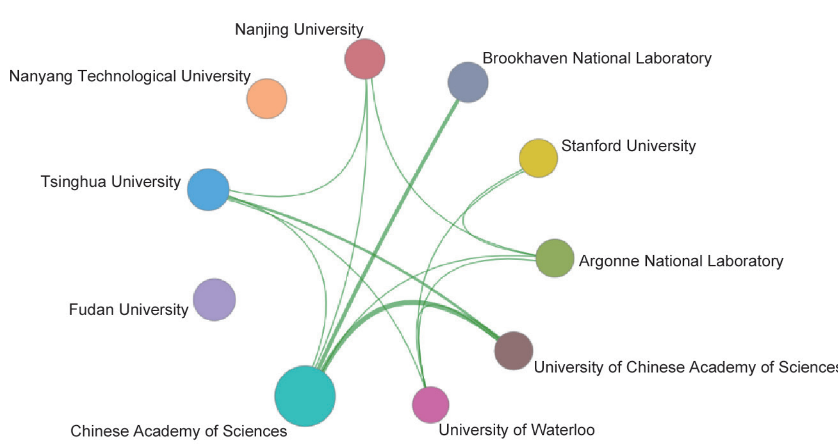

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "high-energy-density and fast-charging battery–capacitor hybrid energy storage system"

Table 1.2.7 Countries with the greatest output of citing papers on "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	12 484	53.07%	2018.3
2	USA	3 670	15.60%	2018.1
3	South Korea	1 584	6.73%	2018.2
4	Germany	1 238	5.26%	2018.1
5	Australia	891	3.79%	2018.3
6	India	818	3.48%	2018.3
7	Japan	707	3.01%	2018.2
8	Canada	592	2.52%	2018.3
9	Singapore	544	2.31%	2017.8
10	UK	534	2.27%	2018.3

Table 1.2.8 Institutions with the greatest output of citing papers on "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	1 687	29.39%	2018.2
2	University of Chinese Academy of Sciences	644	11.22%	2018.3
3	Tsinghua University	588	10.24%	2018.1
4	University of Science and Technology of China	427	7.44%	2018.4
5	Central South University	407	7.09%	2018.0
6	Nankai University	389	6.78%	2018.1
7	Harbin Institute of Technology	328	5.71%	2018.2
8	Nanyang Technological University	322	5.61%	2017.6
9	Huazhong University of Science and Technology	321	5.59%	2018.0
10	Peking University	318	5.54%	2018.3

kind of Lorentz force), magnetic force, magnetic torque, magnetic dipole-dipole interactions, or magnetization energy on materials. These effects provide unique methods for controlling the solidification of metallic materials, which is the key issue in metallurgy and material preparation. Therefore, exploiting these effects offers the possibility of new innovations in metallurgy and material fabrication for achieving novel functional materials.

In recent years, metallurgy and material processes employing high magnetic fields have been regarded as both prospective and strategic research undertakings globally. The Japan Science and Technology Agency has formulated a special research project for the "Development of New Materials under High Magnetic Field Conditions," and the National High Magnetic Field Laboratory of the United States has carried out a series of studies on high-temperature superconducting materials, alloy materials, and composite materials in high magnetic fields. France, the United Kingdom, Germany, and other countries have also carried out similar studies. Since 2000, independent research teams have been established in numerous universities and institutes in China, mainly focusing on the solidification behavior of metallic materials. After nearly 20 years of accumulation, they have successfully developed a series of special experimental apparatuses that are operational under high-magnetic-field conditions. Furthermore, they achieved considerable experimental and theoretical advancements in terms of the transfer behavior of fluid flow, solute migration, heat transfer, and the effects of these processes on microstructure evolution during the solidification of metallic materials in high magnetic fields.

Prospective studies in this field should address the following: 1) equipment for material preparation and performance testing in a high-magnetic-field environment, where such equipment should be reliable and have comprehensive functions for material preparation, physical property analysis, microstructural analysis, and performance monitoring. 2) Measurement of physical properties of metals at high temperatures in high magnetic fields. The physical properties include the electrical conductivity, viscosity, magnetic susceptibility, diffusion coefficient, contact angle, and phase transition temperature, which are the bases for the quantitative analysis of the various force and energy effects of high magnetic fields. Analyzing these parameters will provide a framework for addressing other major fundamental issues pertaining to high magnetic fields. 3) Theoretical studies on the solidification of alloys in high magnetic fields, including fluid flow behavior, solute diffusion and migration, solid/liquid interface stability, and crystal growth. These theories are the basis for determining the mechanisms by which the magnetic field exerts these effects. Moreover, the design of metallurgy-controlling techniques using a high magnetic field is influenced by these theories. 4) Development of novel high magnetic field-controlled metallurgy technologies. The key points are the application of high magnetic fields to melt treatment, liquid forming, casting, directional solidification, liquid phase sintering, and other traditional metallurgy and material preparation processes for preparing metallic materials in a "non-contact" manner. The objective is to regulate the solidification structure of materials via an effective and green approach. 5) Design and fabrication of novel functional metallic materials. High-intensity magnetic field metallurgy and material preparation technology can aid in developing high-performance functional materials with properties such as magnetostriction, magnetic storage, and permanent magnetism, along with thermoelectric, magnetocaloric, and magneto-optical properties. Materials with special structures such as gradient distribution, anisotropy, and second-phase enhancement can also be obtained.

The main countries and institutions conducting research on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials" are listed in Tables 1.2.9 and 1.2.10, respectively. The collaboration between major countries and institutions is shown in Figures 1.2.5 and 1.2.6. China, the United States, Iran, and Germany are the top four countries with the most publications in this field. Among the institutions with the highest output of papers, Shanghai University is ranked No. 1. As shown in Figure 1.2.5, China and the United States have the greatest number of collaborations, and the collaboration networks between China and Germany, China and France, China and Iran, Iran and Australia, and France and Tunisia are also well developed. Figure 1.2.6 demonstrates that the most active collaboration among institutions involves Shanghai University, Aix-Marseille University, French National Centre for Scientific Research, and the Chinese Academy of Sciences. As shown in Table 1.2.11, the top three countries with the highest output of citing papers are China, the United States, and Germany, while Table 1.2.12 demonstrates that Northeastern University, the Chinese Academy of Sciences, and Babol Noshirvani University of Technology are the top three institutions that employ the core literature as their references.

Table 1.2.9 Countries with the greatest output of core papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	61	43.88%	1 870	30.66	2015.8
2	USA	20	14.39%	799	39.95	2016.1
3	Iran	19	13.67%	1 438	75.68	2017.6
4	Germany	19	13.67%	1 242	65.37	2015.4
5	France	18	12.95%	473	26.28	2014.9
6	Australia	10	7.19%	498	49.80	2016.2
7	Japan	8	5.76%	296	37.00	2015.9
8	India	8	5.76%	247	30.88	2015.9
9	Tunisia	6	4.32%	165	27.50	2014.3
10	Russia	6	4.32%	149	24.83	2016.0

Table 1.2.10 Institutions with the greatest output of core papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Shanghai University	17	12.23%	382	22.47	2015.5
2	Babol Noshirvani University of Technology	12	8.63%	1 230	102.50	2018.3
3	Northeastern University	10	7.19%	277	27.70	2015.4
4	Chinese Academy of Sciences	8	5.76%	181	22.62	2015.4
5	French National Centre for Scientific Research	7	5.04%	188	26.86	2014.4
6	University of Science and Technology Beijing	4	2.88%	135	33.75	2015.8
7	Dalian University of Technology	4	2.88%	115	28.75	2014.8
8	Aix-Marseille University	4	2.88%	93	23.25	2014.5
9	Xi'an Jiaotong University	3	2.16%	252	84.00	2017.7
10	Public Authority for Applied Education & Training	3	2.16%	222	74.00	2018.0

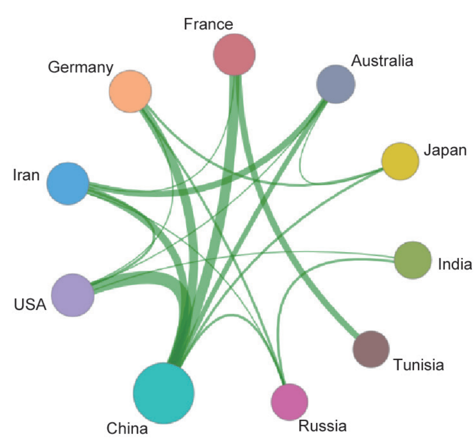

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

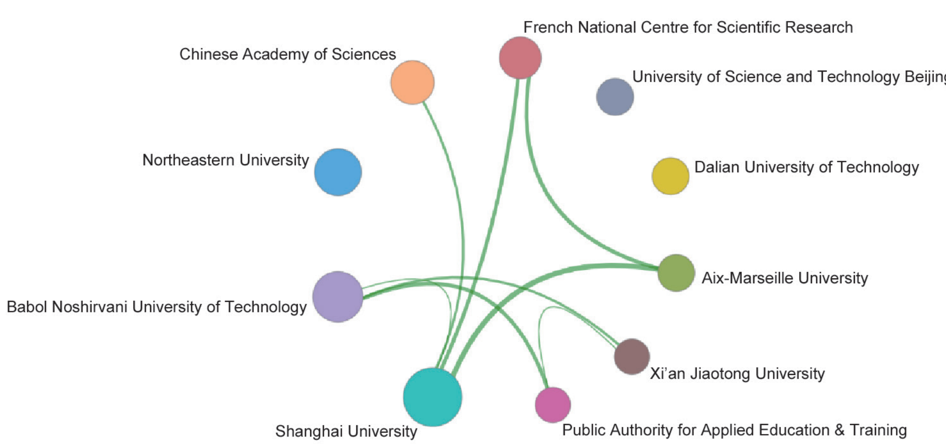

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

Table 1.2.11 Countries with the greatest output of citing papers on “metallurgy and materials processes in high magnetic fields and fabrication of functional materials”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	1 678	35.01%	2018.1
2	USA	643	13.42%	2018.0
3	Germany	352	7.34%	2017.9
4	Iran	347	7.24%	2018.6
5	France	333	6.95%	2017.7
6	Japan	282	5.88%	2018.0
7	India	259	5.40%	2018.2
8	Russia	257	5.36%	2017.9
9	Saudi Arabia	225	4.69%	2018.4
10	Pakistan	215	4.49%	2018.5

Table 1.2.12 Institutions with the greatest output of citing papers on “metallurgy and materials processes in high magnetic fields and fabrication of functional materials”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Northeastern University	224	17.23%	2017.8
2	Chinese Academy of Sciences	177	13.62%	2018.0
3	Babol Noshirvani University of Technology	133	10.23%	2018.8
4	Shanghai University	130	10.00%	2017.8
5	Ton Duc Thang University	128	9.85%	2019.1
6	Islamic Azad University	96	7.38%	2018.6
7	Jilin University	90	6.92%	2018.0
8	University of Wollongong	89	6.85%	2018.7
9	University of Science and Technology Beijing	81	6.23%	2018.3
10	Russian Academy of Sciences	76	5.85%	2017.9

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. “All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology” and “precision etching of semiconductors” are based on the patents provided by *Derwent Innovations Index*. The other eight are recommended by experts. Of the ten fronts, four are interdisciplinary of chemical/environmental/energy/materials/metallurgical science and engineering (i.e., “degradation and recycling of waste plastics,” “all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology,” “multi-scale, multi-dimensional, *in-situ* dynamic analysis technology,” and “refined sorting technology and equipment for multiple-composite solid waste”); four fronts are about metallurgy (“manufacturing technology for new-generation shipbuilding steel,” “high-temperature titanium alloy system and parts for aviation,” “low-cost and high-quality additive forging for key components of major equipment,” and “super-bearing steel with high cleanliness and heavy refined structure”); and two of the fronts are about materials research (“precision etching of semiconductors” and “development of smart materials and technology with high adaptability for intelligent manufacturing equipment"). The annual number of core patents falling under "multi-scale, multi-dimensional, *in-situ* dynamic analysis technology" and "low-cost and high-quality additive forging for key components of major equipment" witnessed a rapid increase (Table 2.1.2). Technologies for environmental applications, such as "degradation and recycling of waste plastics" rank as No. 1, and patents falling under "refined sorting technology and equipment for multiple-composite solid waste" have 13.69 citations per patent, which is the highest among all top 10 fronts.

(1) Degradation and recycling of waste plastics

The rapid development of the plastics industry has led to large quantities of waste plastics. The existing treatments for waste plastics by disposal in landfills, incineration, or

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Degradation and recycling of waste plastics	627	649	1.04	2017.0
2	All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology	818	3 706	4.53	2016.0
3	Manufacturing technology for new-generation shipbuilding steel	595	2 590	4.35	2015.0
4	Precision etching of semiconductors	546	5 028	9.21	2014.6
5	Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology	954	802	0.84	2018.4
6	High-temperature titanium alloy system and parts for aviation	410	713	1.74	2016.5
7	Low-cost and high-quality additive forging for key components of major equipment	967	4 369	4.52	2017.7
8	Super-bearing steel with high cleanliness and heavy refined structure	656	3 916	5.97	2015.4
9	Development of smart materials and technology with high adaptability for intelligent manufacturing equipment	1 223	6 469	5.29	2016.6
10	Refined sorting technology and equipment for multiple-composite solid waste	807	11 049	13.69	2016.6

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

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Degradation and recycling of waste plastics	38	47	57	92	199	153
2	All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology	93	90	83	103	144	166
3	Manufacturing technology for new-generation shipbuilding steel	74	60	64	75	78	76
4	Precision etching of semiconductors	82	56	65	60	59	52
5	Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology	5	4	27	108	176	628
6	High-temperature titanium alloy system and parts for aviation	49	54	65	83	73	69
7	Low-cost and high-quality additive forging for key components of major equipment	21	49	76	186	275	348
8	Super-bearing steel with high cleanliness and heavy refined structure	78	100	84	91	57	107
9	Development of smart materials and technology with high adaptability for intelligent manufacturing equipment	89	123	234	233	254	216
10	Refined sorting technology and equipment for multiple-composite solid waste	49	46	101	143	190	189

discarding lead to serious environmental pollution and resource wastage. Tremendous efforts have been expended to degrade and recycle waste plastics. As one approach, low-cost and degradation-controllable biodegradable plastics should be developed, where these plastics can eventually be decomposed by natural microorganisms and re-enter the ecosystem in the form of CO_2 and water. In another approach, technologies have been developed for converting waste plastics into regenerative plastics, energy, or small-molecule chemicals by using machinery, heat, solvents, and other methods. The key points in this approach include developing high-efficiency and high-selectivity catalytic systems, green and mild solvent systems, and efficient product separation techniques. New recyclable plastics comprising recyclable monomers and reversible dynamic bonds have been considered. Future development strategies should focus on application-oriented closed-loop and upgraded recycling technologies to maximize resource utilization and environmental protection. For applications in which the collection of waste plastics is difficult, plastics that biodegrade quickly and harmlessly under the environmental conditions of waste are in high demand. For applications in which waste plastics are easy to collect, efforts should be strengthened to achieve efficient clean recovery and high-value utilization of waste plastics and recyclable plastics with good performance.

(2) All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology

Electrochemical energy storage systems afford the ability to track load changes and offer high response speed, accurate control, and the dual functions of bi-directional regulation and peak shaving and valley filling. Thus, these systems are an important peak-shaving power supply. Solid-state lithium batteries are characterized by high specific energy, safety, and long life. LICs have significant advantages such as high power, a wide operational temperature range, and fast response. By exploiting the innovation of polymer solid-state lithium batteries and lithium capacitors, a novel integrated all-climate electrochemical energy storage system with high energy and high power can be achieved. Current research is mainly focused on: 1) developing solid electrolyte and cobalt-free cathodes; 2) industrial production of key materials for cobalt-free solid-state batteries; 3) preparation engineering technology for solid-state electrodes and solid-state single cells; 4) rapid lithium-ion storage technology; 5) precise and controllable pre-lithium and new ultra-low-temperature compounding techniques; and 6) efficient and intelligent integration and demonstration of dual-source energy storage systems.

(3) Manufacturing technology for new-generation shipbuilding steel

Iron and steel are the most critical structural materials for shipbuilding. The properties of these materials are directly related to the advanced technology, service life, and safety and reliability of ships. For large vessels, the United States initially proposed the development of new-generation high-strength low alloy (HSLA) hull steel. Currently, easily weldable high-strength series, such as HSLA80, HSLA100, HSLA115, and HSLA130 steels, are employed for ship construction. For underwater applications, Russia has developed a structural hull steel for pressure shell with a yield strength of 1175 MPa to be employed in vessels that can dive to depths exceeding 650 m. With the development of large-scale and deep-diving ships, hull structural steel requires high strength, high toughness, and must be easily weldable. Three advanced research areas should be considered: 1) smelting technology of ultra-low-carbon clean steel, 2) new-generation thermo mechanical control process (TMCP) based on ultra-fast cooling technology, and 3) matching welding materials and welding technology for shipbuilding.

(4) Precision etching of semiconductors

Semiconductor materials and technology play a central role in the fields of computers, communications, and electronics, and are also the cornerstones in the development of social informatization. Precision etching is the core technology in the semiconductor industry and the foundation of advanced manufacturing processes. The performance of semiconductor devices is directly influenced by the etching precision. The precision of etching techniques is an important index for evaluating the level of development of the semiconductor industry. Etching is a chemical or physical method that selectively removes material, and current etching processes can be divided into wet and dry etching. The etching quality is evaluated by the direction, selectivity, rate, and uniformity of etching. In the large-scale production of semiconductors, precision etching requires high reliability to ensure appreciable continuity and low defect rates. Wet etching, which affords high selectivity, is generally used for grinding, polishing, cleaning, and removing corrosion from traditional silicon-based semiconductors. Meanwhile, dry etching, with anisotropic features, can be used to construct the fine structure of integrated circuits. With improvements in the semiconductor manufacturing process and the demand for semiconductors with a smaller critical size, etching processes must afford high selectivity, high stability, and anisotropy. Furthermore, there is a rapid development in new third-generation semiconductor materials, such as silicon carbide and gallium nitride. Thus, etching processes must be adapted to the novel characteristics of these new materials to achieve devices that are operational under high-temperature, high-radiation, and high-power conditions. Owing to the requirements for small size, high integration, and new materials for integrated circuits, precision etching can be employed to improve the processing reliability. Precision etching can also afford breakthroughs in resolution through innovative approaches to optimize the working medium for etching, strengthen control of the etching process, and explore new etching principles. Finally, precision etching would definitely contribute to the semiconductor industry and information society.

(5) Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology

Multi-scale (nanometer to centimeter), multi-dimensional (2D, 3D, 4D), *in-situ* dynamic analysis using the synchrotron radiation source at the national large scientific facility in China is an advanced frontier characterization technique with high temporal and spatial resolution. This high-performance technique allows the *in-situ*, dynamic, real-time observation of the formation and evolution of microstructures or defects in novel materials during the preparation process. Microstructural evolution and damage to materials under simulated extreme service environments can also be monitored. Quantitative data on the temporal evolution of the microstructure of materials or related information (such as the chemical composition) can also be acquired. This technology has become a powerful tool for revealing the relationships between material composition, microstructure, processing, and service performance, as the elucidation of these relationships is critical for addressing scientific issues in material research. For example, multi-scale, multi-dimensional, *in-situ* dynamic analysis technology can be employed to study the microstructural evolution and mechanisms of damage in a series of advanced metallic materials used for the key components of major equipment (such as aeroengine blades, lunar rover cantilever beams, and icebreaker propellers) during the preparation and processing steps. Corresponding changes under simulated, complex, extreme service environments (extremely high/low temperature or alternating temperature, corrosion, or the coupling of these factors) can also be monitored, which is critical for developing physical models of the materials and improving the service performance and safety of the key components of those major equipment. Further development of this technology is geared toward: 1) the design and construction of *in-situ* devices for material preparation using coupled external multi-fields, and for evaluating the performance of these materials under extreme service conditions; 2) the development of high spatial/temporal resolution and high-precision synchrotron radiation X-ray methodology, as well as automatic data analysis technology; 3) the development and joint applications of techniques using coupled X-ray methods, such as synchrotron radiation X-ray imaging, diffraction, fluorescence, and scattering.

(6) High-temperature titanium alloy system and parts for aviation

Owing to their excellent properties, especially high specific strength and fatigue resistance, high-temperature titanium alloys are widely used in aerospace applications, such as aero engine room, heat shield, casing, turbine disk, high pressure compressor blade and disk. It is important to develop new alloy components and technologies for synthesizing and processing high-temperature titanium alloys. Such technologies include casting, forging, powder metallurgy, and 3D printing. Ingots prepared by multiple processes exhibit better microstructures and mechanical properties than those prepared using a single process. High-temperature titanium alloys, mainly comprise the α-phase and β-phase, under different strengthening modes and phase transitions, and afford equipment with a service temperature of up to 480 °C; this can be further extended to 550–650 °C with the addition of trace alloying elements. Advanced studies on high-temperature titanium alloys for aviation have focused on: 1) the size, shape, and content of the α-phase, β-phase, enhanced phase, and α_2-phase, to improve the stability of the microstructure of high-temperature titanium alloys;

2) developing joint-preparation technologies for large ingots, while controlling the microstructure of the α-flake structure, α-equiaxial structure, and the transformation matrix of the β structure. This was aimed at achieving higher-temperature applications by exploiting the high plasticity and good thermal stability of these alloys; 3) using the directional solidification technology to prepare columnar or single crystal blade billets of high temperature titanium alloy with excellent properties; 4) using the finite element model to determine the proper size of the α_2-phase and the critical transition point based on the composition of high-temperature titanium alloys to achieve appreciable thermal strength and stability. This approach is crucial for providing theoretical support for developing high-performance, high-temperature titanium alloys for aviation.

(7) Low-cost and high-quality additive forging for key components of major equipment

Heavy forgings are the core components of major equipment and play an indispensable role in national defense security and the national economy. Conventionally, to manufacture a heavy component of up to hundreds of tons, a super-large steel ingot is required. Unfortunately, owing to the size effect of solidification, heavy forgings derived from ingots weighing hundreds of tons always have severe defects, such as macro-segregation and shrinkage. These defects severely deteriorate the quality and performance of the forgings. Consequently, the homogeneous manufacture of heavy forgings has become an urgent issue of global concern. Three-dimensional printing has been used to manufacture large components, such as titanium alloy large integral main bearing structural parts, where the performance of these components may be comparable to that of forgings. However, for iron-based and nickel-based materials, 3D printing has always been limited in terms of economy and reliability compared to traditional forging methods. In recent years, China has played a leading role in the use of metal additive forging to manufacture high-quality heavy forgings. This technology combines the advantages of traditional forging with emerging additive manufacturing, enabling the low-cost and high-quality manufacturing of heavy components for energy and electricity applications. At present, metal additive forging is in the preliminary stages and is used for engineering applications in wind power, hydropower, nuclear power, and other fields. It is noteworthy that the research and application of this technology are in the initial stage. Meanwhile, the key restrictions to the large-scale application of metal additive forging include: 1) lack of prepare methods for base elements with the appropriate size for different alloy systems; 2) lack of efficient techniques for cleaning and activating the surface of the base elements; 3) lack of methods for breaking and decomposing the oxidation film during interface bonding; and 4) underdeveloped additive forging of heavy components for superalloys, titanium alloys, and special stainless steels. The following approaches are recommended for solving the above problems: 1) establishing general technical standards for metal additive forging, determining the evaluation system and application criteria for components manufactured by additive forging, and expanding this technology as the cutting-edge technique for developing heavy component limit manufacturing globally; 2) exploring efficient methods for cleaning and activating the alloy surfaces, developing special surface treatment equipment and intelligent production lines for additive forging, and replacing traditional large steel ingots with high-quality and low-cost additive forging billets; 3) further developing additive forging techniques for large-scale and homogenous material systems for heavy gas turbine disks, nuclear power/hydrogenation pressure vessels, and high-quality mold steels, developing and assessing the sample pieces, and delineating technical specifications.

(8) Super-bearing steel with high cleanliness and heavy refined structure

Bearing steels are recognized as steels with the highest requirements for material quality, known as “the king of steel.” High-end bearings are mainly used in aero-engines, marine equipment, high-speed trains, shield machines, computer numerical control machine tools, and wind power. Service life and reliability are the key elements of bearings. First, new steel materials with high cleanliness, good homogeneity, and adequate microstructures are required to circumvent the early failure of bearings, insufficient strength and toughness, and poor wear resistance problems. Second, comprehensive system standards should be established for bearing steels, such as regulating the oxygen content or Ti content of bearing steel. The third area is developing advanced metallurgical technology for bearing steel, including new refining and continuous casting techniques. This is very important for preventing the problem of large discrete inclusions, especially in the case of large ingots. Field-enhanced refining, continuous casting, solidification, and remelting processes, such as electromagnetic refining, new electromagnetic continuous casting, continuous casting heavy reduction, large ingot solidification with field control, and magnetically controlled electroslag remelting technology, are expected to provide high cleanliness, ultra-fine, high homogenization, and high service performance of bearing steel.

(9) Development of smart materials and technology with high adaptability for intelligent manufacturing equipment

Developing intelligent manufacturing equipment is an important driving force for achieving intelligent manufacturing technology. Intelligent manufacturing integrates advanced manufacturing, digital control, modern sensing, and artificial intelligence, and has functions such as perception, learning, decision-making, and execution. Compared with traditional manufacturing equipment, intelligent manufacturing equipment with high adaptability can be used to realize customized and multi-purpose production. Intelligent manufacturing equipment can actively receive external information and conduct independent analysis and execution to adapt to complex processing environments and procedures during manufacturing with different materials, different material types, or different processes. Thus, a large number and volume of sensors and actuators with multiple functions are required for such equipment. Smart materials respond quickly, and simultaneously possess the functions of sensors and actuators. These features enable miniaturization, diversification of functions, and afford simple structures of intelligent manufacturing equipment, thereby improving the adaptability and reliability of the equipment. Smart materials have a high response speed, generate a strong driving force, and their performance can be tailored to the requirements. They can respond to external stimuli, including temperature and humidity, pH, gas, mechanical force, and light, which endows the structures with intelligence. These features meet the requirements of intelligent manufacturing trends and have received immense attention. Smart materials have been applied in high-sensitivity sensors, flexible robot drives, mechanical vibration control, self-detection and self-repair of damage to structural equipment, equipment working status detection, and other manufacturing fields. Nevertheless, research on smart materials used in intelligent manufacturing equipment is still in its infancy and requires further development. On one hand, it is necessary to develop smart materials with higher response speed, greater driving force and driving stroke, and lower requirements for operation in the working environment. On the other hand, it is essential to combine a variety of smart materials to form smart structures to improve the range of use and work performance from the perspective of engineering design.

(10) Refined sorting technology and equipment for multiple-composite solid waste

Multiple-composite solid wastes (MCSWs) are mainly decommissioned products, including electronic waste, spent batteries, waste organic composite materials, waste textiles, and waste packaging. The distinct characteristics, such as complex phase composition and structure, complex phase-to-phase interface, and dual attributes of being a resource as well as an environmental burden, are significantly different from those of traditional industrial waste and other solid wastes. Consequently, the refined sorting of MCSWs is essential for efficient recycling of its resources. Existing waste separation technologies are generally based on traditional mineral separation and metallurgical principles. These separation techniques combine multidisciplinary theories regarding materials, the environment, machinery, and intelligent control. The major demands of the recycling industry market are promoting refined separation for short-cut resource recycling and material utilization, advanced green manufacturing for the entire product chain, and significant improvement of resource utilization and environmental protection. Efficient and refined sorting of multiple-composite solid wastes, precise interface identification and dissociation, and so on, can be achieved by addressing the following technical requirements: 1) developing techniques for *in-situ* nondestructive testing and precise identification of the MCSW interface; 2) developing a full spectrum database of the characteristics of complex materials and multi-dimensional algorithms for accurate identification and sorting; 3) high-efficiency mechanical–physical coupling to enhance dissociation and control at the multi-phase interface; 4) enhanced field control for MCSWs separation technology and equipment; 5) developing integrated treatment technology and equipment for typical MCSWs intelligent identification-interface dissociation-sorting; 6) generating green products via resource recycling and developing “green evaluation” methods and standards for the entire industry chain, i.e., technology–environment–economy; coupling intelligent, green, and precise multi-phase interface control for the entire chain by constructing innovative technological systems.

2.2 Interpretations for three key engineering development fronts

2.2.1 Degradation and recycling of waste plastics

The global cumulative production of plastics has reached 8.3 billion metric tons since the advent of the mass production of plastics in the 1950s, of which 6.3 billion metric tons have become waste, causing great harm to the ecosystem. However, because of the immaturity and high cost of the existing recycling technology, only approximately 9% of the waste plastics can be recycled, and the rest are mostly disposed of by direct incineration, storage in landfills, or discarding; this leads to serious secondary pollution and resource waste. Therefore, developing green and efficient processes for degrading and recycling waste plastics is highly desired.

On one hand, research for developing biodegradable plastics is required to enable plastics to eventually return to nature in the form of CO_2 or water, catalyzed by natural microorganisms; however, this is only applicable in disposal fields where the plastics are difficult to collect. On the other hand, waste plastics can be recycled by four techniques: 1) physical recycling, which often causes a decline in the mechanical properties of the materials because of thermo-mechanical effects, leading to poor performance and low value of the regenerated plastics; 2) biological recycling, which is not yet practical because of the low efficiency of biological enzymes; 3) energy recycling, which usually requires large investment in equipment, and may produce secondary pollution during the recycling process; this process is only suitable for heavily polluted waste plastics; 4) chemical recycling, which has attracted significantly higher attention because plastics can be degraded into useful chemicals through pyrolysis and solvolysis. However, it is hindered by limitations, such as harsh reaction conditions, complex products, and difficulties in product separation and reuse of chemical reagents. At present, recycling is mainly applied to thermoplastics via physical recycling. In comparison, thermoset plastics are difficult to degrade because of their stable three-dimensional network structure; only the reinforcing fibers can be recycled. The recovery of the resin is still in the laboratory stage. Studies on the degradation and recycling of waste plastics include: 1) the development of high-efficiency and high-selectivity chemical degradation catalysts; 2) green and mild solvent systems as well as high-efficiency product separation technologies; 3) novel recyclable plastics with recyclable monomers or reversible dynamic bonds; and 4) low-cost and completely biodegradable plastics.

Future development strategies should focus on application-oriented, closed-loop, and upgrading recycling technologies. Biodegradable plastics should be used in applications where waste plastics are not easy to collect. The impact of environmental factors on the biodegradation of plastic should be considered. Biodegradable plastics that can be rapidly and harmlessly degraded in abandoned environments are in high demand. For applications in which waste plastics are easy to collect, efforts should be strengthened to achieve efficient and clean recovery and to develop technologies for the high-value utilization of waste plastics, including the direct recycling of hybrid plastics, upcycling of waste plastics, and direct conversion of waste plastics to functional/high-performance materials. In addition, recyclable plastics with appreciable thermal stability and mechanical properties are highly desired.

Recycled thermoplastics mainly include polyethylene (PE), polypropylene (PP), polyvinvyl chloride (PVC), polystyrene (PS), and polyethyleneterephthalate (PET). Chinese companies such as Kingfa Sci. & Tech. Co., Ltd. and Longfu Recycling Energy Scientech Co., Ltd., generally use physical recycling to produce regenerative products. Mitsubishi Heavy Industries, Ltd., Kawasaki Heavy Industries, Ltd., JBI Inc., and SITA UK employ chemical recycling and have commercialized pyrolysis technology for oil refining; PET depolymerization has been commercialized by Teijin Ltd., Dupont, Hoechst, and other industries. Recycling of thermoset plastics and composites by physical methods is also used in China. Only a few Chinese companies use chemical pyrolysis to recycle reinforced composite materials. Shanghai Jiao Tong University developed pyrolysis technology and apparatus with completely independent property righs. Three Japanese carbon fiber recycling companies, Toray, Toho Tenax, and Mitsubishi Rayon, and the US companies Carbon Conversions Inc. and MIT LLC, have achieved carbon fiber recycling. Biodegradable plastics include polylactic acid (PLA), poly(butyleneadipate–co–terephthalate) (PBAT), and poly(butyl acrylate) (PBA). Kingfa Sci. & Tech. Co., Ltd. and Xinjiang Blue Ridge Tunhe Chemical Industry Joint Stock Co., Ltd. of China, Natureworks of the United States and BASF of Germany have developed advanced technologies and products. In recent years, China and Chinese enterprises have produced more patents in this field, but have received little attention (Tables 2.2.1 and 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on “degradation and recycling of waste plastics”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	566	90.27%	409	63.02%	0.72
2	South Korea	27	4.31%	14	2.16%	0.52
3	Japan	11	1.75%	30	4.62%	2.73
4	Austria	6	0.96%	76	11.71%	12.67
5	USA	6	0.96%	34	5.24%	5.67
6	India	2	0.32%	17	2.62%	8.50
7	Germany	1	0.16%	57	8.78%	57.00
8	Luxembourg	1	0.16%	4	0.62%	4.00
9	Turkey	1	0.16%	4	0.62%	4.00
10	UK	1	0.16%	2	0.31%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on “degradation and recycling of waste plastics”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Qingyuan Hengjin Plastic Co., Ltd.	China	16	2.55%	4	0.62%	0.25
2	Anhui Guosheng New Material Co., Ltd.	China	12	1.91%	0	0.00%	0.00
3	Jiangsu Jinwo Machinery Co., Ltd.	China	9	1.44%	14	2.16%	1.56
4	Zhangjiagang City Yili Machinery Co., Ltd.	China	8	1.28%	9	1.39%	1.13
5	Jiangxi Fengdi New Materials Co., Ltd.	China	6	0.96%	0	0.00%	0.00
6	Jieshou Rongfa Renewable Resources Co.	China	6	0.96%	0	0.00%	0.00
7	EREMA Engineering Recycling Maschinen und Anlagen GmbH	Austria	5	0.80%	70	10.79%	14.00
8	Fujian Eagle Gifts Craft Production Co., Ltd.	China	5	0.80%	3	0.46%	0.60
9	Shandong Yusu Pipe Co., Ltd.	China	5	0.80%	1	0.15%	0.20
10	Anhui Zhonglu Environment Protection Equipment Technology Co., Ltd.	China	5	0.80%	0	0.00%	0.00

2.2.2 All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology

With the advantages of low investment and a short construction period, electrochemical energy storage systems have been developed and rapidly promoted in the fields of peak valley price arbitrage, new energy grid connection, and power system auxiliary services. Market-oriented energy storage policies will help promote the market share of electrochemical energy storage to the 100 billion CNY level. At present, LIBs are widely used in new energy power generation. However, the low-temperature discharge capability of traditional LIBs is poor, which makes it difficult to achieve all-climate systems. Moreover, thermal runaway easily occurs under high-temperature abuse conditions. All-climate functional electrochemical energy storage systems based on polymer solid-state lithium battery and lithium capacitor technology are characterized by high specific energy, high safety, a wide operational temperature range, long life, and fast response, making them ideal electrochemical energy storage systems.

A polymer solid-state lithium battery is a battery in which traditional liquid electrolytes are replaced by solid-state electrolytes. The solid-state electrolyte effectively prevents fires and explosions caused by abnormal use of commercial LIBs, such as in situations that induce short-circuiting or pinning. The solid-state electrolyte can also match the high energy density of the lithium anode. Thus, higher energy density can potentially be achieved while meeting the application requirements for high safety. Polymer solid electrolytes have good film-forming ability, high toughness, good compatibility with lithium metal anodes, and are easily produced and processed on a large scale. In 2011, a polymer lithium metal battery with a polyethylere oxide (PEO) solid electrolyte, developed by Bollore Company in France, with an energy density of 170 Wh/kg and good safety performance, was applied in Bluecar and was used in automobile sharing services. In 2015, the Qingdao Institute of Bioenergy and Bioprocess Technology of the Chinese Academy of Sciences developed a polycarbonate-based polymer solid electrolyte. The material has a wider electrochemical window (~4.5 V) and can match the properties of the cathode material, with a higher voltage. The energy density (300 Wh/kg) of solid-state lithium batteries has improved greatly, and the comprehensive performance of these batteries has steadily improved.

The LIC is an asymmetric capacitor in which the charging and discharging principles for the positive and negative electrodes differ. The design of these capacitors exploits the principle of double-layer capacitors and electrochemical lithium storage. The structure combines the negative material of the LIB and the positive material of the electric double-layer capacitor, which greatly improves the energy density relative to that of the traditional electric double-layer capacitor while maintaining high-power characteristics. At present, domestic LICs are in the R&D stage, while foreign LIC manufacturers are active in Japan. Several enterprises, such as JM Energy, FDK Energy, TAIYO YUDEN, ACT Company, and SKEM have initiated batch production. Recently, Maxwell in the United States also developed an LIC with a monomer electrostatic capacity of 2200 F and voltage of 3.8 V, with an energy density of 12 Wh/kg (24.2 Wh/L). Qingdao Institute of Bioenergy and Bioprocess Technology of the Chinese Academy of Sciences successfully developed an LIC with a maximum monomer capacity of 3500 F and voltage of 4 V, with an energy density of 55.9 Wh/L (20.5 Wh/kg). The first pilot production line for LICs in China was designed and constructed.

Japan, China, and South Korea have the largest number of published core patents, with Japan ranking No. 1 with 43.28% and 6.22 citations per patent (Table 2.2.3). It can be seen from Table 2.2.4 that Japanese companies have the absolute "say on patents," with 6/10 of the main institutions publishing core patents. China has more international cooperation with other countries (Figure 2.2.1).

2.2.3 Manufacturing technology for new-generation shipbuilding steel

Shipbuilding steel refers to the hull structural steel employed in military surface ships (such as destroyers and cruisers) and underwater submarines (such as conventional powered submarines and nuclear-powered submarines), as well as minesweepers. Shipbuilding steel is generally produced

Table 2.2.3 Countries with the greatest output of core patents on "all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	354	43.28%	2 201	59.39%	6.22
2	China	235	28.73%	562	15.16%	2.39
3	South Korea	111	13.57%	322	8.69%	2.90
4	Colombia	57	6.97%	271	7.31%	4.75
5	USA	39	4.77%	336	9.07%	8.62
6	Germany	18	2.20%	40	1.08%	2.22
7	France	3	0.37%	20	0.54%	6.67
8	Belgium	3	0.37%	0	0.00%	0.00
9	Kenya	2	0.24%	9	0.24%	4.50
10	Singapore	2	0.24%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Toyota Jidosha KK	Japan	76	9.29%	302	8.15%	3.97
2	Idemitsu Kosan Co., Ltd.	Japan	56	6.85%	233	6.29%	4.16
3	TDK Corporation	Japan	28	3.42%	185	4.99%	6.61
4	Samsung Electronics Co., Ltd.	South Korea	28	3.42%	183	4.94%	6.54
5	LG Chem Ltd.	South Korea	28	3.42%	70	1.89%	2.50
6	Furukawa Kikai Kinzoku KK	Japan	22	2.69%	18	0.49%	0.82
7	Panasonic Intellectual Property Management Co., Ltd.	USA	21	2.57%	92	2.48%	4.38
8	Hitachi Ltd.	Japan	19	2.32%	89	2.40%	4.68
9	Seiko Epson Corporation	Japan	16	1.96%	130	3.51%	8.13
10	Korea Institute of Industrial Technology	South Korea	14	1.71%	14	0.38%	1.00

in small batches, must meet various specifications and high requirements, and is characterized by slow updates. Moreover, it is essential for shipbuilding steel to display sufficient strength and toughness and excellent workability, while resisting corrosion by seawater. All countries worldwide have strict requirements on the quality of ship steel, not only in terms of the chemical composition and mechanical properties, but also quality control during the production process.

With the development of manufacturing technologies such as ultra-pure smelting, micro-alloying, controlled rolling, and cooling, and to improve the welding properties and reduce the welding cost of ship steel, the United States developed a new generation of HSLA ship-hull steel. They implemented the industrial production of HSLA80 steel and HSLA100 steel after carrying out the industrial TMCP and accelerated cooling tests with Japanese steel enterprises in the 1980s. In the early the 1990s, HSLA65, HSLA115, and HSLA130 steels were developed and applied to the main housing, aircraft deck, trestle deck, and the key structural parts of surface ships to further reduce the weight and lower the center of gravity for new aircraft carriers. HSLA hull steel, based on low-carbon ferrite steel or ultra-low-carbon bainite steel, has a lower carbon content and excellent weldability and low-temperature toughness compared with the conventional quenched and tempered hull

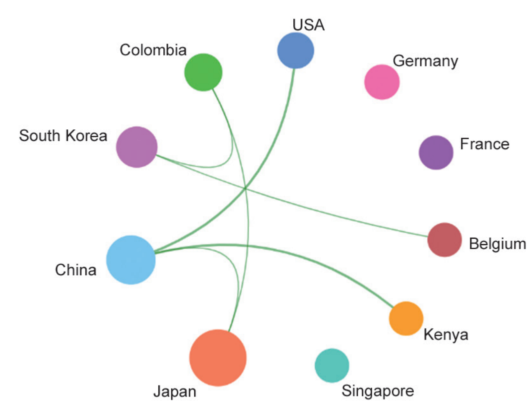

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology”

steel. Copper aging treatment and precipitation strengthening are used to compensate for the strength loss caused by carbon reduction. This type of steel can be welded at 0 °C without preheating, which greatly simplifies shipbuilding processes, and it represents the development trend for new-generation structural hull steel. Many advanced countries worldwide have also developed new ship steel: Russia developed AB series steel, with a yield strength of 1 175 MPa; Japan developed NS110 steel, with a yield strength of 1 078 MPa; and France developed HLES100 steel, with a yield strength of 980 MPa. The United Kingdom and Australia have also developed HSLA steels with strength and toughness equivalent to those of US HY100 steel.

High performance remains the main pursuit of new-generation shipbuilding steel. It is crucial to enhance its overall characteristics, such as strength, shape, toughness, and anti-explosion performance, as well as anti-brittle damage, anti-seawater corrosion, and anti-fatigue properties. Strict specifications and dimensions are required for ship plate steel, and the use of this steel affords finished products with higher quality. High surface quality is required, with no surface defects and a compact and uniform surface oxide scale. Much attention has been paid to tailoring the composition of high-strength structural steels and strengthening methods, such as precipitation strengthening with nanoscale precipitates based on conventional alloying, and to improving the theories and methods. Balanced improvement of the service and welding performance has received much more attention, along with high strength and toughness.

Asian countries, especially China, witnessed rapid development during the last 30 years. The countries and institutions with the greatest output of core patents on "manufacturing technology for new-generation shipbuilding steel" since 2014 are listed in Tables 2.2.5 and 2.2.6, respectively. The collaborative network among major countries focusing on "manufacturing technology for new-generation shipbuilding steel" is illustrated in Figure 2.2.2. According to Table 2.2.5, the majority of the core patents were published by the top five countries (China, Japan, South Korea, the United States, and Germany). China's output of core patents accounted for 40.67% of the total, and Japan ranked second, with their output accounting for 38.66%. Patents from Japan had the highest number of citations (1 374), and the percentage of citations reached 53.05%, far exceeding those of other countries. The average citation rates for France and the United States ranked among the highest worldwide. According to Table 2.2.6, the top 10 institutions with the greatest output of core patents are five Chinese companies, three Japanese companies, and two South Korean companies. The top three of the 10 are all Japanese companies. In the development of new-generation shipbuilding steel, considerable attention should be paid to the development trends in Japan, the United States, and Germany, especially Japanese enterprises. As illustrated in Figure 2.2.2, only Germany, Sweden, and South Korea collaborated in the development of new-generation shipbuilding steel.

Table 2.2.5 Countries with the greatest output of core patents on "manufacturing technology for new-generation shipbuilding steel"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	242	40.67%	404	15.60%	1.67
2	Japan	230	38.66%	1374	53.05%	5.97
3	South Korea	40	6.72%	98	3.78%	2.45
4	USA	23	3.87%	231	8.92%	10.04
5	Germany	17	2.86%	133	5.14%	7.82
6	Russia	7	1.18%	3	0.12%	0.43
7	France	6	1.01%	71	2.74%	11.83
8	UK	5	0.84%	5	0.19%	1.00
9	Netherlands	3	0.50%	26	1.00%	8.67
10	Sweden	3	0.50%	21	0.81%	7.00

Table 2.2.6 Institutions with the greatest output of core patents on "manufacturing technology for new-generation shipbuilding steel"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Nippon Steel & Sumikin Stainless Steel Corporation	Japan	82	13.78%	582	22.47%	7.10
2	JFE Steel Corporation	Japan	74	12.44%	403	15.56%	5.45
3	Kobe Steel Ltd.	Japan	50	8.40%	226	8.73%	4.52
4	Baoshan Iron & Steel Co., Ltd.	China	22	3.70%	38	1.47%	1.73
5	Posco Co., Ltd.	South Korea	17	2.86%	45	1.74%	2.65
6	Nanjing Iron & Steel Co., Ltd.	China	12	2.02%	28	1.08%	2.33
7	Angang Steel Co., Ltd.	China	12	2.02%	17	0.66%	1.42
8	Hyundai Motor Co., Ltd.	South Korea	8	1.34%	29	1.12%	3.63
9	Tangshan Iron and Steel Group Co., Ltd.	China	8	1.34%	4	0.15%	0.50
10	China State Shipbuilding Co., Ltd.	China	7	1.18%	3	0.12%	0.43

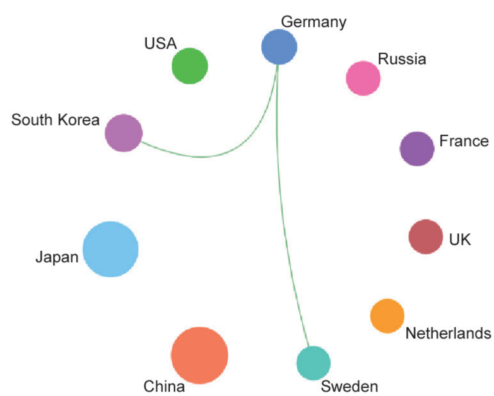

Figure 2.2.2 Collaboration network among major countries in the engineering development front of "manufacturing technology for new-generation shipbuilding steel"

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IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in top 12 engineering research fronts

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

Among these 12 research fronts, emerging research fronts include "renewable synthetic fuel," "on-site conversion and efficient utilization of petroleum resources," and "digital nuclear reactor and power plant intelligent simulation systems." "Advanced nuclear spent fuel reprocessing and nuclear fuel recycling," "fracture diagnosis and evaluation methods," "study of mantle plume-related ore deposits of critical metals," and "theory and technology for safe direct combustion of low-concentration gas" represent further developments in existing research fields. The research front of "fluidized mining of deep solid mineral resources and its process control mechanism" is revolutionizing the mining industry. The fronts of interdisciplinary integration include "basic theory and method for intelligent drilling," "solar photovoltaic thermal (PV/T) coupling system based on nano phase change materials (nano-PCMs)," "security of intelligent grid cyber-physical systems," and "Z-pinch driven inertial fusion mechanism based on pulse power technology."

The number of core papers published annually from 2014 to 2019 for each of the top 12 engineering research fronts is listed in Table 1.1.2.

(1) Renewable synthetic fuel

Increasing concerns regarding energy security and CO_2 emission require a widespread use and development of renewable energy, which is also the key to address issues of energy storage, climate change and to achieve sustainable development worldwide. Although the installed renewable power capacity, from sources such as solar and wind power,

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	Renewable synthetic fuel	87	14 388	165.38	2016.4
2	Advanced nuclear spent fuel reprocessing and nuclear fuel recycling	21	333	15.86	2016.0
3	On-site conversion and efficient utilization of petroleum resources	10	579	57.90	2016.6
4	Basic theory and method for intelligent drilling	44	257	5.84	2018.5
5	Solar PV/T coupling system based on nano-PCMs	44	1 753	39.84	2016.8
6	Security of intelligent grid cyber-physical systems	28	1 182	42.21	2016.8
7	Digital nuclear reactor and power plant intelligent simulation systems	4	43	10.75	2016.2
8	Z-pinch driven inertial fusion mechanism based on pulse power technology	45	1 433	31.84	2016.1
9	Fracture diagnosis and evaluation methods	98	3 238	33.04	2016.0
10	Study of mantle plume-related ore deposits of critical metals	8	442	55.25	2015.4
11	Theory and technology for safe direct combustion of low-concentration gas	122	951	7.80	2017.5
12	Fluidized mining of deep solid mineral resources and its process control mechanism	28	961	34.32	2016.2

Table 1.1.2 Annual number of core papers published for the top12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Renewable synthetic fuel	0	26	23	20	14	4
2	Advanced nuclear spent fuel reprocessing and nuclear fuel recycling	0	9	5	5	2	0
3	On-site conversion and efficient utilization of petroleum resources	0	2	2	4	2	0
4	Basic theory and method for intelligent drilling	0	1	3	4	12	15
5	Solar PV/T coupling system based on nano-PCMs	1	5	11	13	12	2
6	Security of intelligent grid cyber-physical systems	3	4	4	9	2	6
7	Digital nuclear reactor and power plant intelligent simulation systems	0	1	1	2	0	0
8	Z-pinch driven inertial fusion mechanism based on pulse power technology	0	17	14	8	5	1
9	Fracture diagnosis and evaluation methods	0	38	30	21	7	2
10	Study of mantle plume-related ore deposits of critical metals	2	3	1	2	0	0
11	Theory and technology for safe direct combustion of low-concentration gas	0	15	21	30	19	19
12	Fluidized mining of deep solid mineral resources and its process control mechanism	0	9	8	9	0	2

is increasing dramatically, their seasonal and intermittent features limit the direct integration of renewable energy into power grids. One strategy to overcome this is to develop renewable synthetic fuels, which converts CO_2 into stable, storable, and high-energy-density liquid fuels such as alcohols, ethers, and hydrocarbons using renewable energy sources. Renewable synthetic fuels can be utilized in power plants, internal combustion engines, aero engines, gas turbines, etc. The CO_2 released by using these fuels can be captured from the environment and reduced into renewable synthetic fuels again, thus forming a carbon-neutral energy cycle. In the field of renewable synthetic fuels, major technological approaches include electrocatalytic, photocatalytic, photoelectrocatalytic, and chemical reductions of CO_2 to fuel. This research front is focused on determining methods to improve product selectivity, conversion efficiency, and production rate.

(2) Advanced nuclear spent fuel reprocessing and nuclear fuel recycling

The world is facing a major challenge in the coordinated development of energy and environmental protection, and the situation regarding energy conservation and emission reduction is serious. As a clean, efficient, and large-scale means of energy production, nuclear energy has received considerable attention from international communities. The development and utilization of nuclear energy must be supported by nuclear fuel. The sustainable development of nuclear energy requires the continuous recycling of nuclear fuel through reprocessing, so that unburned fuel can be fully utilized, and the newly generated nuclear fuel can be used effectively. Furthermore, this recycling ensures that other valuable nuclides can be used. The nuclear fuel cycle represents the entire process that involves the preparation of nuclear fuel before it is injected into the reactor, combustion of the fuel in the reactor, and post-processing of the nuclear fuel. The various processing procedures after nuclear fuel is discharged from the reactor comprise the post-nuclear fuel cycle. These procedures include intermediate storage of spent fuel, nuclear fuel reprocessing, preparation and recycling of recovered fuel, radioactive waste treatment, and final disposal. Among these, nuclear fuel reprocessing is the most critical step. The main task of nuclear fuel reprocessing is to separate the fission products from spent fuel using chemical treatment methods; recover and purify valuable fissionable substances, such as ^{235}U and ^{239}Pu, and turn them into fuel elements; and return these elements to nuclear power plants (thermal reactors or fast reactors) for use, which can increase the utilization rate of nuclear fuel and save a considerable amount of uranium resources. This process can also help extract transuranium elements and fission products to advance the application of isotopes in the medical and aerospace industries. The reprocessing of spent fuel significantly reduces the toxicity and volume of radioactive waste that requires final geological disposal and promotes safe disposal. Therefore, reprocessing is of great significance to the sustainable development of nuclear energy. At the same time, nuclear fuel reprocessing technology is a typical dual-use sensitive technology that is strictly restricted by the international Nuclear Non-Proliferation Treaty. Development of the reprocessing technology is an important indicator of the overall national strength and international status of a country.

(3) On-site conversion and efficient utilization of petroleum resources

Research on on-site conversion and efficient utilization of petroleum resources comprises the integration of thermophysics, thermochemistry, materials science, and other multi-disciplinary areas; the transformation of low-grade resources into high-grade energy underground; and advanced research on the upgrade of high-viscosity crude oil and oil shale using *in-situ* conversion technology, which is expected to greatly increase the recovery rate or energy conversion rate and provide cutting-edge technology to deal with future structural changes in petroleum resources. The technology for *in-situ* upgrading of heavy oil has advanced from steam stimulation to steam flooding, steam assisted gravity drainage (SAGD), and fire flooding. In recent years, multi-media steam flooding technology has been developed. This technology is being further developed to include the application of highly active and universally applicable catalyst systems that allow the modification and viscosity reduction reactions of heavy oil to occur at a lower temperature, while simultaneously achieving ideal modification and viscosity reduction effects for different heavy oils. The shale oil underground *in-situ* conversion technology involves a physical and chemical process that uses horizontal well electric heating lightening technology to continuously heat the organic-rich shale interval to lighten multiple types of organic matter. Such a breakthrough in shale oil underground *in-situ* conversion technology would aid the development and utilization of shale oil resources and ensure long-term stability and an even higher production of crude oil. Promoting the *in-situ* conversion and efficient utilization of petroleum resources and realizing breakthroughs in commercialization are of great significance in the future development of the world petroleum industry.

(4) Basic theory and method for intelligent drilling

Drilling is a key aspect of the discovery, exploration, and exploitation of oil and gas resources. However, existing drilling technology cannot meet the development requirements of complex oil and gas resources in terms of economy, safety, efficiency, and environmental protection. The application of smart technology in the field of oil and gas exploration and development has become the development trend of the petroleum industry. Major international oil companies are actively implementing various intelligent oil and gas exploration and development strategies. Therefore, a new generation of drilling technology must be developed. Intelligent drilling is a transformative technology that integrates big data, artificial intelligence, information engineering, downhole control engineering, and other theories and technologies. Advanced drilling, closed-loop control, precise guidance, and intelligent decision-making are realized through the application of surface automatic drilling rigs, downhole intelligent actuators, intelligent monitoring, decision-making technologies, etc. This is expected to greatly improve the drilling efficiency and reservoir encountering rate. In addition, this will help reduce drilling costs and significantly increase the single-well production and recovery efficiency of complex oil and gas reservoirs.

The basic theories and methods of intelligent drilling mainly involve intelligent characterization of the drilling environment, intelligent perception of drilling conditions, intelligent decision-making of drilling schemes, and intelligent control of drilling parameters. The intelligent characterization of the drilling environment can realize fine characterization of the drilling environment and the physical properties of the reservoir, which is the basis for the realization of intelligent drilling monitoring, diagnosis, decision-making, and regulation. Intelligent perception of drilling conditions uses intelligent monitoring and data transmission technologies to realize real-time analysis and acquisition of geological and engineering parameters and provide dynamic data support for intelligent drilling engineering. The intelligent decision-making of the drilling plan is based on the integration and processing of geological engineering data, revealing the cooperative response mechanism between the geological engineering parameters and objective functions such as drilling rate, cost, and risk. In addition, it helps optimize and determine engineering parameters and construction plans. Intelligent control of drilling parameters is based on an integrated coordination mechanism between drilling parameters. It utilizes the intelligent control theory to achieve intelligent control of drilling parameters such as well trajectory, wellbore pressure, and fluid performance.

(5) Solar PV/T coupling system based on nano-PCMs

Based on the temperature characteristics of solar PV cells, the solar PV/T coupling system can consider both solar PV power generation and thermal energy conversion. While increasing electrical power generation, it can produce a certain amount of thermal energy. Currently, it is one of the most efficient methods for solar energy conversion and utilization. The use of nano-PCMs in PV/T systems can effectively control the operating temperature of the PV cells, with a high energy storage density and a fast heat storage and release speed, which is important for the efficient large-scale application of solar energy.

The main research topics include the micro-mechanisms of electricity and heat cogeneration for solar cells and optimization of the energy conversion process, new solar PV/T modules and their temperature characteristics, PV/T packaging with nano-PCMs, novel heat transfer mechanisms in nano-PCM energy storage and heat dissipation, the thermal characteristics of the PV/T coupling system using nano-PCMs, and the characteristics of electricity and heat cogeneration.

The combination of nano-PCMs and PV/T systems is important for realizing systematic solar thermoelectric conversion and improving energy efficiency. Research on and development of high-efficiency solar PV/T components and systems that integrate electricity and heat generation to meet the electricity, heating, and cooling loads of buildings and neighborhoods are receiving attention in the field of high-efficiency solar energy conversion and applications. Solar PV/T coupling systems are also an important energy source for future low-carbon cities, green buildings, and zero-energy buildings. Combined with nano-PCMs, PV/T technology can realize effective regulation and a stable energy supply for building energy systems.

(6) Security of intelligent grid cyber–physical systems

A smart grid cyber–physical system includes a power network, an information network, and a power grid cyber–physical network. It facilitates the real-time perception, dynamic control, and information service of smart grids based on distributed intelligent sensors and communication networks. The security of smart grid cyber–physical systems focuses on the security of the information network and physical network as well as the risk of coupling the two networks. Power grids can be attacked by injecting false information through sensing devices. Therefore, the security problem of cyber–physical systems can limit the power grid security. Various cyber–physical system attack strategies and corresponding risk and vulnerability evaluation methods have been investigated previously. In addition, a test platform has been established for security assessment. Considering the dynamic propagation of the risk in cyber–physical systems, it is vital to conduct in-depth research on the risk propagation and evolution mechanism. Moreover, advanced network security technologies should be developed to strengthen the defenses of the information network, reduce risk, and resist cyber-attacks. Furthermore, future research should focus on the establishment of cyber-security situational awareness platforms, which will be used to identify risk events and simulate risk propagation processes. Big data and situational prediction techniques can be combined to predict cyber-physical system security and guarantee the safe and reliable operation of cyber-physical systems in an actual environment.

(7) Digital nuclear reactor and power plant intelligent simulation systems

The development of a numerical reactor system refers to the entire process of providing a high-confidence expert reference database for the modeling of reactor operating conditions, the development of high-confidence numerical simulation software systems, and the establishment of virtual reactors for reactor engineering design, performance optimization, operating economy, safety, and reliability, based on the rapid development of high-performance computer systems. Using high-fidelity numerical methods and high-precision models, direct multi-physics simulations of the core design can be achieved, and more accurate calculation results can be obtained, improving the design margins from professional models and interprofessional interfaces, improving the safety and economy of design schemes and promoting reactor operation flexibility. In addition, the test project and scale can be optimized, thereby shortening the research and development cycle and reducing research and development costs. If high-fidelity numerical methods and high-precision models were used for the optimization of reactor operation, the competitiveness of nuclear power in the energy supply system can be enhanced.

Digitization/intelligence refers to the development of a digital design system integrating model research and development, engineering design, and comprehensive verification. Based on design data and new-generation intelligent technologies such as the Internet of Things, big data, and virtual reality, it realizes automated engineering design, intelligent computational analysis, and visualization of results and projects. In addition, it supports a multi-specialty, multi-project, fully collaborative, standardized digital construction system. Focusing on business scenarios such as nuclear power plant operation, maintenance, overhaul, decommissioning, and training, research is being conducted on key applications, such as production management, configuration management, intelligent monitoring and diagnosis, and intelligent robots in nuclear power plant operations. Other avenues of research include building digital twin power plants based on 3D simulation and virtual reality technologies, realizing the one-to-one mapping between the panoramic space of nuclear power plants and the real environment, and forming a digital twin with perception, analysis, decision-making, and execution capabilities. A database regarding the full life cycle of nuclear power plants should also be constructed. The integration of smart nuclear energy systems is being studied to realize nuclear power generation, nuclear energy supply at the site, and intelligent scheduling and management of various aspects of nuclear energy utilization, such as heat, nuclear energy, sea water desalination, and nuclear energy hydrogen production.

(8) Z-pinch driven inertial fusion mechanism based on pulse power technology

Controllable fusion energy is the ideal clean energy of the future. The main techniques to realize this energy are magnetic and inertial confinement. For the inertial confinement, the fusion energy is obtained by supplying the heating energy directly or indirectly onto the fusion target, compressing the target, and then realizing thermonuclear ignition and combustion under the inertial constraint of internal explosive motion. Key technologies related to this front include driving sources with high heating power, repetition rate, and stability; the structural design of the implosion chamber and the fusion target; optimization of the design of the ignition method; high-efficiency energy conversion; and Tritium cycle and extraction. The fast Z-pinch technology is based on pulse power technology. Therefore, it can realize high-efficiency energy conversion from the electric energy storage of the driver to kinetic energy or X-ray radiation energy of the Z-pinch load. It is expected to help realize the repetitive operation of the driver, which will provide a powerful energy source for driving inertial confinement fusion and inertial fusion energy. The inertial confinement driven by the Z-pinch is a complex multi-scale and multi-physical process. Current experimental techniques are not capable of directly achieving fusion ignition. Numerical simulation is an important means to study the physical problems of Z-pinch driven inertial confinement fusion. In the future, numerical simulation tools will be further developed and improved to conduct research on the physics of the whole process and associated key problems.

(9) Fracture diagnosis and evaluation methods

Fractures are the main spaces for the storage and circulation of oil and gas. Hydraulic fracturing occupies a high proportion of the production stimulation measures of low-permeability oil and gas reservoirs, and it is the main method for improving oil and gas recovery. Therefore, it is necessary to conduct research on fracturing diagnosis and evaluation methods to clarify the actual shape and parameters of fractures under current reservoir conditions. According to test results, and to compensate for the differences between theory and practical applications, the principles of hydraulic fracturing design are adjusted to ensure that the fracture parameters calculated by the fracturing model are in good agreement with the actual ones, which will further improve the applicability of the fracturing design plan. At the same time, this reduces fracturing investment and improves the effect of fracturing reconstruction. Although fracturing pressure fitting, tracers, production logging tools, micro-seismic fracture monitoring, micro-deformation fracture monitoring, and other methods have been used to diagnose and evaluate fractures for decades, little is known about them today and there are knowledge gaps pertaining to the complex shape, length, width, height, and distribution of diversion capacity. Owing to the characteristics of storage and hydraulic fracturing parameters, it is particularly important to accurately understand the fracture length and fracture orientation to optimize the overall development of low-permeability oilfields. In the future, research on fracture diagnosis and evaluation technology should be strengthened, as it is an important basis for deepening our understanding of fractures, correcting fracture prediction models, optimizing fracturing design and well pattern deployment, and ultimately helping oilfield developers optimize oilfield and single-well development plans to enhance the economic benefits.

(10) Study of mantle plume-related ore deposits of critical metals

A mantle plume links the mass and energy exchange between the core, mantle, and crust, thus providing a long-term and steady material base for various critical metal mineralizations. Plume-related magmatic sequences are found to host some specific types of mineralization, such as mafic-ultramafic layered intrusions and Fe-Ti-V oxide (Co and Sc), Ni-Cu-PGE (platinum group element) sulfides and Cr-Ti-Fe oxides deposits, komatiite and related Cu-Ni sulfides deposits, peralkaline complex-carbonatites and Nb-Ta-Zr-REE deposits. In contrast, metals in the crust are transported and further concentrated by hydrothermal convection, which is activated by thermal anomalies induced by a mantle plume. This leads to the formation of hydrothermal ore deposits that are indirectly related to mantle plumes, such as Mn-Co ores, Carlin-style gold deposits, and tellurium ore deposits associated with the Emeishan large igneous provinces (LIPs). Previous research has identified the following key controlling factors in plume-related critical metal mineralization: structure of the plume, magma source, crystal fractionation, crustal contamination and liquid immiscibility, magma replenishment, mingling/mixing, and intrusion processes. Although the key metal mineralization related to mantle plumes is gaining an increasing amount of attention, its theoretical framework has not been established yet, and the understanding of the key controlling factors still needs to be improved. Notably, there are two Permian LIPs in China, which host various types of critical metal deposits and thus provide rare opportunities for us to reveal the genetic links between mantle plumes and critical metal mineralization and establish a systematic theory of critical metal metallogeny. Therefore, in addition to previous case studies on individual deposits, emphasis should be placed on research on the metallogenic sequence of key metals in mantle plumes, which will contribute to building an integrated theoretical system for critical metal mineralization associated with mantle plumes.

(11) Theory and technology for safe direct combustion of low-concentration gas

Methane is the second largest greenhouse gas after CO_2, accounting for approximately 20% of global greenhouse gas emissions. The concentration of methane in the atmosphere is much lower than that of CO_2, but the global warming potential (GWP) of methane is 25 times that of the same amount of CO_2. According to the GWP, the methane emissions of the coal and oil energy industries are equivalent to more than 10 billion tons of CO_2, and the reduction of methane emissions in the energy industry is of great significance to environmental protection. As of 2018, the utilization rate of low-concentration coal mine gas with a concentration between 6% and 30% is only approximately 28%, and the utilization rate of ultra-low-concentration gas (including ventilation gas) with a concentration less than 6% is only 2%. Exploring the utilization technology of low-concentration gas, especially ultra-low-concentration gas, is the key to solving the problem of low gas utilization rate. For the combustion (oxidation) utilization of ultra-low-concentration gas and ventilation gas, research groups from various countries have proposed different thermal storage oxidation technologies, such as the thermal flow reversal reactor technology in the United States, the catalytic flow-reversal reactor technology in Canada, the catalytic gas turbine technology in Australia, the thermal regeneration oxidation technology in Germany, and the monolithic honeycomb catalytic oxidation technology in Germany. Some progress has been made, but the proportion of ultra-low-concentration gas in coal mines is large (more than 70% of the total gas emissions), and the gas concentration is low (< 6%). Furthermore, the concentration fluctuates greatly and crosses the explosion boundary range, and the content of impurities is high (dust, water vapor, and impurity gas). Therefore, the realization of safe transportation of explosive gas, efficient removal of impurity components, and efficient direct combustion (oxidation) of ultra-low-concentration gas is crucial for industrial application.

(12) Fluidized mining of deep solid mineral resources and its process control mechanism

The exploitation of deep solid resources faces high stress, high well temperature, and high well depth. Fluidized mining of deep solid mineral resources involves injecting a leaching solution into a deep ore deposit via injection wells to allow the leaching solution and targeted minerals to react. Then, the leaching solution containing soluble metallic ions is lifted to the surface. Finally, metallic products are obtained via solvent extraction electrowinning. Studies in this research area aim to develop an innovative green mining method and a regulation mechanism of deep solid mineral resources, promote mining reform, and eventually provide a reference for safe and efficient mining of deep solid resources.

There are several research topics in this area such as exploring the inlay interaction between the *in-situ* pore structure and valuable minerals of deep solid resources to realize a clear representation of deep mining environments and studying the law of multi-scale seepage of solution under high-temperature and high-pressure conditions deep underground. Other research avenues include detecting the leaching reaction mechanism of metallic minerals under multi-physics effects and building a model to describe the response of *in-situ* mineral dissolution and precipitation to pore structure evolution. Furthermore, a mathematical model of leachable evaluation and prediction of deep solid mineral resources has been developed, and an ameliorated technology system for deep-ground solution seepage and leaching reaction has been built.

The future development of this research front will include non-disturbed detection of multi-scale pore structures during the deep fluidized leaching process, coupling of deep pore structure, solution seepage, and leaching reaction, well-net setups and seepage intelligent controls of deep fluidized leaching, and other future research interests, to eventually achieve a breakthrough in the theory of fluidized mining of deep solid resources and the equipment for this technology.

1.2 Interpretations for four key engineering research fronts

1.2.1 Renewable synthetic fuel

There is an urgent need to develop zero-carbon and carbon-neutral energy technologies to sustainably develop the world's infrastructure. George Andrew Olah, the Nobel Prize winner in Chemistry, discussed the concept and drawbacks of hydrogen economy in his book *Beyond Oil and Gas: The Methanol Economy* in 2006, and further proposed a promising idea, namely to create a renewable energy resource by converting CO_2 from both nature and industry into carbon-neutral alcohol and ether fuels. In 2018, four academicians of the Chinese Academy of Sciences, published a perspective in *Joule* (Joule, 2018, 2, 1925–1949), where they pointed out that the key to utilizing solar energy is to convert it into stable, storable, and high-energy-density chemical fuels, which is also the concept of renewable synthetic fuel.

Owing to the potential to address the energy and environmental challenges, renewable synthetic fuels have attracted increasing attention in recent years. Major economies, including China, the United States, Europe, Japan, and South Korea are all pursuing researches in this field. The Department of Energy of the United States established 46 Energy Frontier Research Centers, which support the study of solar power generation and solar-to-fuel conversion technology. In 2010, it established the Joint Center for Artificial Photosynthesis (JCAP) with Caltech, University of California campuses in Irvine and San Diego, the Lawrence Berkeley National Laboratory, and the SLAC National Accelerator Laboratory, which is the largest research program dedicated to the advancement of solar fuel generation science and technology. In 2020, the JCAP started to investigate the solar-fuel reactor system in order to convert CO_2 into liquid fuel driven by solar energy at a large scale. The European Union and South Korea also established the Energy-X and KCAP programs, aiming to achieve the cyclic utilization of carbon energy on a CO_2 basis. According to a report by BOSCH, renewable synthetic fuels will be widely used in Europe by 2050, which could reduce CO_2 emissions by 2.8 billion tons (approximately three times the annual CO_2 emissions in Germany).

In June 2019, the China Association for Science and Technology announced a list of the top 20 scientific and engineering technical problems of 2019 which play a guiding role in scientific and technological innovation, of which the development of renewable synthetic fuel is one of the foremost scientific problems. Domestic scientific research institutions represented by Tsinghua University, the University of Science and Technology of China, the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, and Shanghai Jiao Tong University have also been committed to this field for a long time. Currently, the major technological paths include electrocatalytic, photocatalytic, photoelectrocatalytic, and chemical reductions of CO_2 to fuel. However, each of these remains at the experimental exploration stage, and a number of technical bottlenecks need to be overcome before industrial application is possible. Significant further work on the reaction mechanism, catalytic materials, and reactor systems is required to greatly improve the product selectivity, conversion efficiency, and production rate in order to promote the practical application of this technology.

The top three countries with the greatest output of core papers on “renewable synthetic fuel” are the United States (37), China (31), and Canada (10), and the corresponding citations per paper reach 185, 222, and 123, respectively, as listed in Table 1.2.1. Among the major countries with publications on this research front, there is a large amount of cooperation among the United States, China, and Canada, as shown in Figure 1.2.1. The top two institutions with the greatest output of core papers are Stanford University (8) and the Chinese Academy of Sciences (6), as given in Table 1.2.2. Out of the top 10 institutions by publication volume, there is a large amount of cooperation among Stanford University, SLAC National Accelerator Laboratory, the University of Toronto, the University of Science and Technology of China, and Chinese Academy of Sciences, as demonstrated in Figure 1.2.2. The top three countries with the greatest output of citing papers are China (4 818), the United States (1 580), and Japan (523), as presented in Table 1.2.3. The top three institutions with the greatest output of citing papers are the Chinese Academy of Sciences (860), the University of Chinese Academy of Sciences (351), and the University of Science and Technology of China (239), as shown in Table 1.2.4.

Table 1.2.1 Countries with the greatest output of core papers on “renewable synthetic fuel”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	37	42.53%	6 863	185.49	2016.7
2	China	31	35.63%	6 896	222.45	2016.6
3	Canada	10	11.49%	1 238	123.80	2017.3
4	Japan	8	9.20%	1 642	205.25	2015.1
5	South Korea	7	8.05%	1 044	149.14	2016.1
6	France	6	6.90%	721	120.17	2015.8
7	Netherlands	5	5.75%	1 054	210.80	2015.2
8	Saudi Arabia	4	4.60%	2 011	502.75	2016.2
9	Spain	3	3.45%	391	130.33	2015.7
10	Germany	3	3.45%	277	92.33	2016.7

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “renewable synthetic fuel”

Table 1.2.2 Institutions with the greatest output of core papers on "renewable synthetic fuel"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Stanford University	8	9.20%	1 070	133.75	2017.4
2	Chinese Academy of Sciences	6	6.90%	1 314	219.00	2016.8
3	Leiden University	5	5.75%	1 054	210.80	2015.2
4	Tokyo Institute of Technology	5	5.75%	837	167.40	2015.2
5	SLAC National Accelerator Laboratory	5	5.75%	604	120.80	2018.0
6	University of Toronto	5	5.75%	563	112.60	2017.6
7	University of Science and Technology of China	4	4.60%	1 396	349.00	2015.8
8	Brookhaven National Laboratory	4	4.60%	1 040	260.00	2016.0
9	University of Delaware	4	4.60%	643	160.75	2016.2
10	University of California, Berkeley	4	4.60%	394	98.50	2017.2

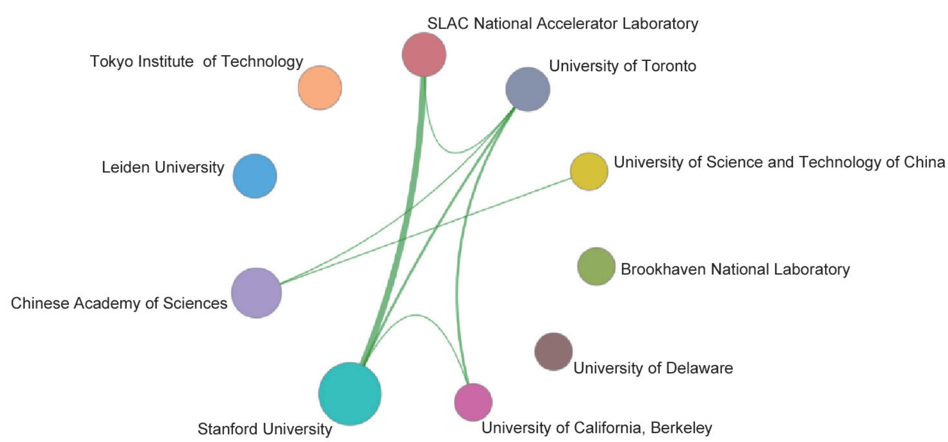

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "renewable synthetic fuel"

Table 1.2.3 Countries with the greatest output of citing papers on "renewable synthetic fuel"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	4 818	49.96%	2018.4
2	USA	1 580	16.38%	2018.3
3	Japan	523	5.42%	2018.1
4	Germany	501	5.19%	2018.3
5	South Korea	415	4.30%	2018.4
6	Australia	392	4.06%	2018.5
7	Canada	335	3.47%	2018.5
8	India	326	3.38%	2018.4
9	UK	266	2.76%	2018.3
10	France	253	2.62%	2018.3

Table 1.2.4 Institutions with the greatest output of citing papers on “renewable synthetic fuel”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	860	33.17%	2018.4
2	University of Chinese Academy of Sciences	351	13.54%	2018.5
3	University of Science and Technology of China	239	9.22%	2018.4
4	Tianjin University	186	7.17%	2018.4
5	Jiangsu University	146	5.63%	2018.0
6	Tsinghua University	140	5.40%	2018.4
7	Beijing University of Chemical Technology	140	5.40%	2018.7
8	Fuzhou University	138	5.32%	2018.0
9	Nanyang Technological University	137	5.28%	2018.4
10	Wuhan University of Technology	132	5.09%	2017.9

1.2.2 Advanced nuclear spent fuel reprocessing and nuclear fuel recycling

Nuclear fuel reprocessing is divided into two categories depending on whether it is conducted in an aqueous medium: water reprocessing and dry reprocessing. Water reprocessing comprises the chemical separation and purification processes in aqueous solutions such as precipitation, solvent extraction, and ion exchange, while dry reprocessing consists of processes, such as the fluorination volatilization process, high-temperature metallurgical treatment, high-temperature chemical treatment, the liquid metal process, the molten salt electrolysis process, and other chemical separation methods in an anhydrous state. Dry reprocessing has advantages in terms of processing high burnup spent fuel, especially fast reactor spent fuel, but is relatively difficult to implement and is still an important research direction at present.

Traditional spent fuel water reprocessing, e.g., the Plutonium uranium recovery by extraction (Purex) process, is currently used for the reprocessing of spent fuel in nuclear power plants. However, owing to its deep burnup, higher radioactivity, and high fission product content, spent fuel reprocessing in nuclear power plants is more focused on separating key elements such as neptunium and technetium more reliably and efficiently, and, through the separation of high radioactive nuclei and transmutation, to shorten the volume and storage duration for better environmental compatibility. In order to adapt to future requirements, thermal reactor spent fuel reprocessing plants will be reliable, safe, and economical. For this reason, research on and development of reprocessing technology, equipment, control, etc. are still under way. Further research on the post-treatment process includes improvements to the Purex process, such as simplifying the process flow, reducing investment costs, and using salt-free reagents to reduce waste generation.

In France, Areva developed the COEX process. In accordance with so-called non-proliferation considerations, the process does not produce pure Pu products, but produces U-Pu mixed products. It is said that this product is beneficial to the manufacture of mixed oxide fuel, but this is a controversial topic. The United States developed the UREX+ process, which separates U, Tc, and I, and the remaining products (including Pu) in the high-level radioactive waste liquid undergo further separation. Separation–transmutation is a strategic measure to minimize nuclear waste. In this method, the minor actinides (MAs) and long-lived fission products (LLFPs) are first separated from the high-level radioactive waste generated by the reprocessing of spent fuel. Then, the MAs and LLFPs are made into targets and transmuted in a transmuter (fast reactor or accelerator driven sub-critical system) to transform the long-lived MAs and LLFPs into short-lived or stable nuclides, in order to reduce the volume and long-term toxicity of high-level radioactive waste that requires geological disposal. Russia has rebuilt RT-1 and continues to reprocess the spent fuel. Meanwhile, the RT-2 plant can also reprocess the spent fuel.

In terms of the research and development of advanced main processes, based on the newly-built experimental platform of Nuclear Fuel Reprocessing Radiochemical Experimental

Facility, in 2015, the China Institute of Atomic Energy successfully completed a 100-hour thermal experiment of continuous operation of the advanced process, and comprehensively obtained the key process indicators such as process flow fragment purification, uranium-plutonium yield, and uranium-plutonium separation. Furthermore, it highlighted the trend in the data of key elements, such as neptunium and technetium in the process, and investigated the stability and reliability of the process.

Regarding the separation process of high-level radioactive waste liquid, Tsinghua University developed the trialkylphosphine oxide process in the 1970s. After 160 hours of radioactive verification, the conditions for a pilot-scale test were prepared. The next step is to conduct research on the separation of high-level radioactive waste liquids in the reprocessing of power reactor fuel.

In recent years, several domestic research institutions and universities have successfully conducted basic and applied research on different separation technologies, such as the chemical processes of actinides, the separation and extraction processes of neptunium, the separation of new actinium and lanthanum, and the separation of strontium and cesium. These institutions have also aimed to develop thorium-based molten salt reactors and conducted preliminary research on dry post-processing technology. Furthermore, they have researched electrolytic refining and the separation of uranium and rare earths, ionic liquid separation of rare earths, and supercritical CO_2 extraction and separation of uranium.

In addition to the water separation process, another direction of research abroad is the research and development of the dry separation process as a candidate for advanced reprocessing. As nuclear fuel burnup further increases, spent fuel will become more radioactive, which may make it difficult for organic solvent-based water reprocessing. As a result, dry post-processing, which was studied by various countries in the 1960s and the 1970s, has become an active research field after approximately 20 years. Countries that are currently actively developing dry reprocessing techniques include the United States, Russia, Japan, France, India, and South Korea.

Dry reprocessing is a high-temperature chemical process, and the most promising method is the molten salt electrolytic refining method for metal fuel and oxide fuel. Compared with water reprocessing, the advantages of dry reprocessing are as follows: The inorganic reagents used have good high-temperature resistance and radiation resistance. In addition, the process flow is simple, and the equipment structure is compact. Furthermore, the equipment has good economic efficiency, and the recycling of reagents reduces waste generation. Moreover, Pu and MAs are recycled together, which helps prevent nuclear proliferation. However, dry reprocessing technology is difficult to implement. The strong irradiation of the components requires the entire process to be operated remotely, and the atmosphere needs to be strictly controlled to prevent hydrolysis and precipitation. Furthermore, the structural materials must have good high-temperature resistance, radiation resistance, and corrosion resistance.

As shown in Table 1.2.5, 30 core papers have been published in this direction, and the countries with the largest number of core papers are the United States, the United Kingdom, France, Germany, and China. It can be seen from Table 1.2.6 that the organizations that have published the largest number of core papers on this research topic are the French Alternative Energies and Atomic Energy Commission, the Joint Research Center of the European Commission, and the Korea Atomic Energy Research Institute. From the cooperation network among the top 10 core paper publishing countries (Figure 1.2.3), it can be seen that France, Germany, and the United Kingdom have frequent cooperation, and China and the United States have some cooperation. As demonstrated in Figure 1.2.4, out of the top 10 institutions by publication volume, there is a large amount of cooperation among French Alternative Energies and Atomic Energy Commission, Joint Research Center of the European Commission, Central Laboratory, Forschungszentrum Juelich, and Karlsruhe Institute of Technology; Korea Atomic Energy Research Institute, South Korea University of Science and Technology, and Ulsan National Institute of Science and Technology also have close cooperation on this front. The top five countries with the greatest output of citing papers are the United States, China, India, France, and Germany, as presented in Table 1.2.7. The top institutions with the greatest output of citing papers are the Chinese Academy of Sciences, French Alternative Energies and Atomic Energy Commission, University of Chinese Academy of Sciences, University of Tokyo, and Idaho National Laboratory, as shown in Table 1.2.8.

Table 1.2.5 Countries with the greatest output of core papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	5	23.81%	92	18.40	2016.0
2	UK	4	19.05%	94	23.50	2016.2
3	France	4	19.05%	78	19.50	2015.2
4	Germany	4	19.05%	75	18.75	2016.5
5	China	3	14.29%	67	22.33	2016.7
6	South Korea	3	14.29%	39	13.00	2015.7
7	India	3	14.29%	34	11.33	2016.7
8	Japan	2	9.52%	29	14.50	2016.0
9	Spain	1	4.76%	11	11.00	2016.0
10	Russia	1	4.76%	11	11.00	2015.0

Table 1.2.6 Institutions with the greatest output of core papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	French Alternative Energies and Atomic Energy Commission	4	19.05%	78	19.50	2015.2
2	Joint Research Center of the European Commission	3	14.29%	61	20.33	2016.0
3	Korea Atomic Energy Research Institute	3	14.29%	39	13.00	2015.7
4	Central Laboratory	2	9.52%	52	26.00	2015.5
5	Forschungszentrum Juelich	2	9.52%	52	26.00	2015.5
6	Karlsruhe Institute of Technology	2	9.52%	52	26.00	2015.5
7	Government of India Department of Atomic Energy	2	9.52%	24	12.00	2017.0
8	University of Utah	2	9.52%	24	12.00	2015.5
9	South Korea University of Science and Technology	2	9.52%	23	11.50	2016.0
10	Ulsan National Institute of Science and Technology	2	9.52%	23	11.50	2016.0

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

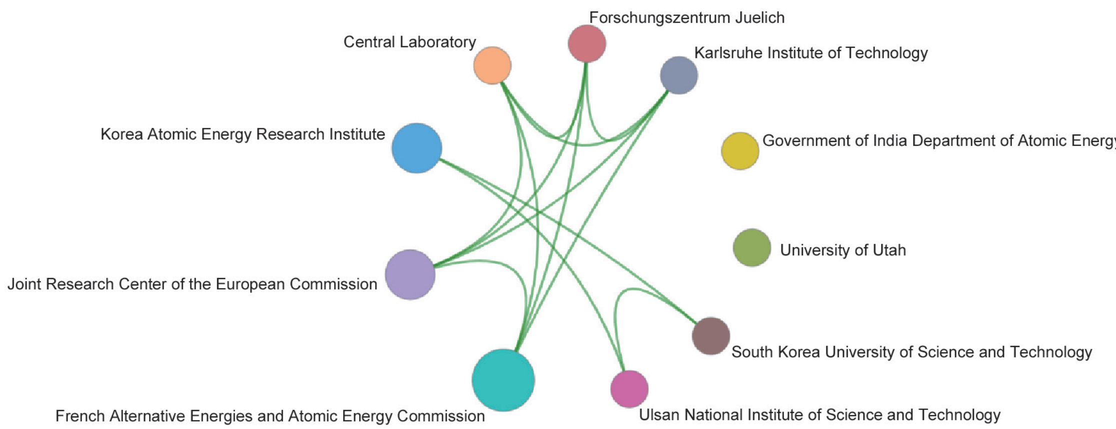

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

Table 1.2.7 Countries with the greatest output of citing papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	78	21.91%	2018.5
2	China	70	19.66%	2018.4
3	India	38	10.67%	2018.4
4	France	35	9.83%	2017.6
5	Germany	31	8.71%	2017.9
6	Japan	22	6.18%	2018.2
7	UK	22	6.18%	2017.9
8	Russia	21	5.90%	2017.9
9	South Korea	17	4.78%	2018.1
10	Spain	15	4.21%	2018.1

Table 1.2.8 Institutions with the greatest output of citing papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	29	18.12%	2018.7
2	French Alternative Energies and Atomic Energy Commission	17	10.62%	2017.0
3	University of Chinese Academy of Sciences	17	10.62%	2018.7
4	University of Tokyo	15	9.38%	2018.2
5	Idaho National Laboratory	15	9.38%	2018.2
6	Bhabha Atom Research Center	15	9.38%	2018.3
7	Homi Bhabha National Institute	14	8.75%	2018.5
8	Indira Gandhi Center for Atomic Research	13	8.12%	2018.2
9	North China Electric Power University	9	5.62%	2017.7
10	Forschungszentrum Juelich	9	5.62%	2017.6

1.2.3 On-site conversion and efficient utilization of petroleum resources

As the degree of exploration and development increases, the quality of petroleum resources is deteriorating. The remaining oil in old oilfields is extremely dispersed, and the development of crude oil is approaching the limit of profitability. A large amount of shale oil is difficult to flow and produce and faces common problems of efficient resource utilization. Flow and extraction are common challenges in the efficient use of these resources. Research on on-site conversion and efficient utilization of petroleum resources refers to the integration of thermophysics, thermochemistry, materials science, and other multi-disciplines to transform low-grade resources into high-grade energy underground. It also refers to advanced research on *in-situ* upgrading of high-viscosity crude oil and oil shale *in-situ* conversion technology, which is expected to greatly increase the recovery rate or energy conversion rate and provide cutting-edge technology to deal with future structural changes in petroleum resources.

The technology for *in-situ* upgrading of heavy oil has advanced from steam stimulation to steam flooding, SAGD, and fire flooding. In recent years, multi-media steam flooding technology has been developed, and this technology is being furthered by developing highly active and universally applicable catalysts. The system enables the modification and viscosity reduction reactions of heavy oil to occur at a lower temperature and, at the same time, achieve the ideal modification and viscosity reduction effects for different heavy oils.

Shale oil underground *in-situ* conversion involves a physical and chemical process that uses horizontal well electric heating lightening technology to continuously heat the organic-rich shale interval to lighten multiple types of organic matter. This advancement in shale oil underground *in-situ* conversion technology would help in the development and utilization of shale oil resources and ensure the long-term stability and even higher production of domestic crude oil. Promoting the *in-situ* conversion and efficient utilization of petroleum resources and realizing commercial breakthroughs are of great significance to improving China's crude oil self-sufficiency and the future development of the world's petroleum industry.

Relevant papers in this area are published primarily by China, the United States, India, and other countries, as given in Table 1.2.9. The foremost institutions include the Chinese Academy of Sciences, the University of Chinese Academy of Sciences, and Anna University, as listed in Table 1.2.10. In terms of international cooperation, Malaysia has cooperated with India, Canada with Turkey, and China with the United States (Figure 1.2.5). Close collaberation exists between Ann University and the University of Malaya; Gachon University, the Korea Advanced Institute of Science and Teahnology, and the Korea Institute of Energy Research; the Chinese Academy of Sciences and the University of Chinese Academy of Sciences (Figure 1.2.6). Moreover, the papers are cited primarily by countries such as China, the United States, and India, and by institutions such as the Chinese Academy of Sciences, the University of Chinese Academy of Sciences, and the University of Toronto (Tables 1.2.11 and 1.2.12).

Table 1.2.9 Countries with the greatest output of core papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	3	30%	105	35	2017.0
2	USA	2	20%	68	34	2016.5
3	India	1	10%	201	201	2016.0
4	Malaysia	1	10%	201	201	2016.0
5	South Korea	1	10%	90	90	2015.0
6	Germany	1	10%	49	49	2018.0
7	Canada	1	10%	47	47	2017.0
8	Turkey	1	10%	47	47	2017.0
9	Iran	1	10%	32	32	2015.0
10	Spain	1	10%	28	28	2018.0

Table 1.2.10 Institutions with the greatest output of core papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	2	20%	64	32	2017
2	University of Chinese Academy of Sciences	2	20%	64	32	2017
3	Anna University	1	10%	201	201	2016
4	University of Malaya	1	10%	201	201	2016
5	Gachon University	1	10%	90	90	2015
6	Korea Advanced Institute of Science and Technology	1	10%	90	90	2015
7	Korea Institute of Energy Research	1	10%	90	90	2015
8	Max Planck Society	1	10%	49	49	2018
9	Ruhr University of Bochum	1	10%	49	49	2018
10	Istanbul Technical University	1	10%	47	47	2017

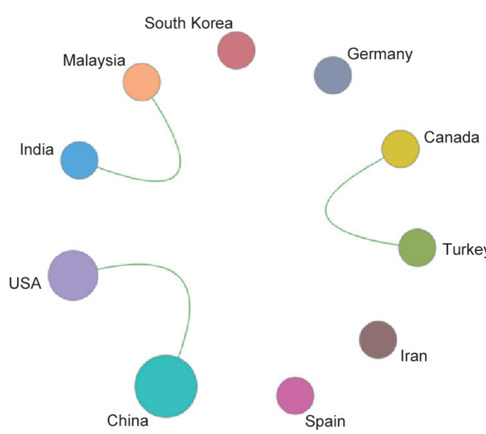

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "on-site conversion and efficient utilization of petroleum resources"

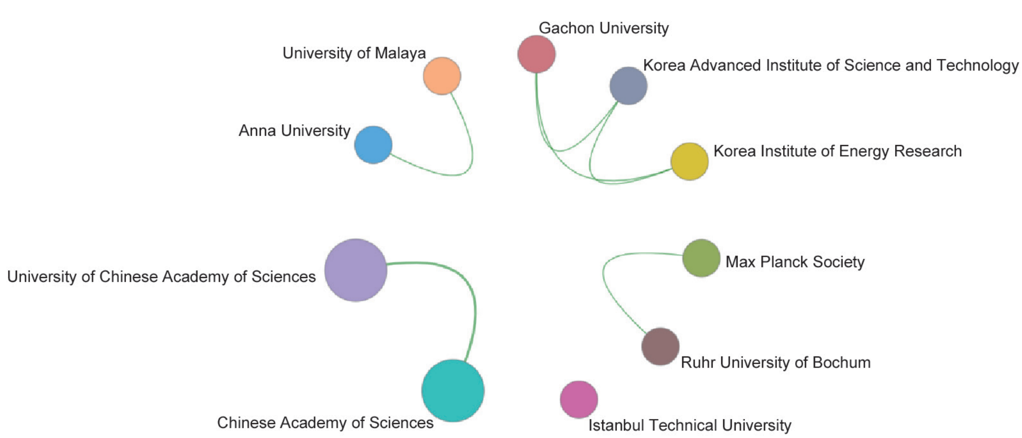

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "on-site conversion and efficient utilization of petroleum resources"

Table 1.2.11 Countries with the greatest output of citing papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	199	38.72%	2018.8
2	USA	75	14.59%	2018.1
3	India	37	7.20%	2018.5
4	South Korea	35	6.81%	2017.8
5	Canada	34	6.61%	2018.4
6	Iran	29	5.64%	2018.1
7	Spain	22	4.28%	2018.5
8	Brazil	22	4.28%	2018.6
9	UK	21	4.09%	2017.9
10	Japan	18	3.53%	2018.5

Table 1.2.12 Institutions with the greatest output of citing papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	59	32.24%	2018.8
2	University of Chinese Academy of Sciences	39	21.31%	2018.7
3	University of Toronto	11	6.01%	2018.7
4	Korea Advanced Institute for Science and Technology	10	5.46%	2016.9
5	Xiamen University	10	5.46%	2018.9
6	Zhengzhou University	9	4.92%	2019.4
7	Dalian University of Technology	8	4.37%	2018.9
8	University of North Carolina	8	4.37%	2016.9
9	Texas A&M University	8	4.37%	2017.6
10	Harbin Institute of Technology	7	3.83%	2019.4

1.2.4 Basic theory and method for intelligent drilling

As the core driving force of today's technological revolution and industrial innovation, intelligent technology has become crucial. The application of smart technology in the field of oil and gas exploration and development has become an important trend in the development of the petroleum industry. Major international oil companies such as Schlumberger and Halliburton are actively implementing the strategic layout of intelligent oil and gas exploration and development. Drilling is a key part of the discovery, exploration, and exploitation of oil and gas resources. Intelligent drilling technology is a transformative technology that integrates big data, artificial intelligence, information engineering, downhole control engineering, and other theories and technologies. This is expected to greatly improve the drilling efficiency and reservoir drilling encountering rate. Furthermore, this technology can reduce drilling costs and significantly increase the single-well production and recovery efficiency of complex oil and gas reservoirs.

The intelligent characterization of the drilling environment can provide a precise description of the drilling environment working conditions and the physical properties of the reservoir, which is the basis for the realization of intelligent drilling monitoring, diagnosis, decision-making, and regulation. The eDrilling Company has established a virtual wellbore to provide early warnings of gas invasion and well kick. Sinopec realized the direct characterization of rock physical properties using the amplitude variation with offset inversion method. The focus of research in this area is 3D geological modeling, drilling process visualization, and digital twin simulation.

Intelligent perception of drilling conditions is based on intelligent monitoring and data transmission technologies. It combines artificial intelligence algorithms, realizes real-time analysis and collection of geological and engineering data, and provides dynamic data support for the realization of intelligent drilling engineering. At present, King Fahd University of Petroleum and Minerals in Saudi Arabia has achieved a high-precision prediction of the rate of penetration (ROP) using neural network technology. Northeast Petroleum University in China used the improved back-propagation algorithm to predict the friction factor of the drill string to overcome individual differences in the friction factor. The main research trends in this area are the response mechanism of downhole monitoring devices, automatic diagnosis of risks in wells, and early warning theory.

The intelligent decision-making of the drilling plan is based on the integration and processing of geological engineering data, revealing the cooperative response mechanism between the geological engineering parameters and objective functions such as drilling rate, cost, and risk. Moreover, it helps optimize and determine engineering parameters and construction schemes. Drilling efficiency, construction cost, and drilling risk are the most important objective functions of intelligent decision-making. At present, Saudi Aramco analyzes the response of drilling parameters to changes in lithology in real time and obtains optimal control parameters through algorithms such as gradient search. The China Petroleum Engineering Institute proposed a bit selection database, which realized bit selection based on formation information. Research on multi-source data fusion, geological engineering model reconstruction, and intelligent coordinated control strategies for all drilling conditions will effectively promote the development of intelligent decision-making technology for drilling. The main research trend of intelligent decision-making is the two-way efficient real-time transmission of massive data, and the closed-loop optimization theory of downhole control parameters.

Intelligent control of drilling parameters is based on an integrated coordination mechanism between drilling parameters. It utilizes the intelligent control theory to achieve intelligent control of drilling parameters such as well trajectory, wellbore pressure, and fluid performance. The Halliburton fracturing parameter intelligent control system uses real-time measurement and an adaptive rate control algorithm to intelligently adjust the pump speed to achieve uniform fracturing. Intelligent control of drilling engineering parameters is a key component to realize intelligent drilling. The closed-loop control of ROP, intelligent steering drilling, and wellbore stability will become the focus of future research.

According to Table 1.2.13, the countries with the largest number of core papers on this research topic are China, Iran, and Australia. The percentage of core papers on this topic in each country other than China, Iran, and Australia is less than 10%. The percentage of Chinese core papers is 38.64%. The each country with the most citations of core papers in this direction is Iran, and the one with the most citations per core paper is Malaysia. Table 1.2.14 shows that Amirkabir University of Technology in Iran and Southwest Petroleum University in China have the largest number of core papers on this research topic, each with a fraction of more than 10%, while each of the other institutions has published less than 10% of the total papers. The core papers from the Amirkabir University of Technology are cited most frequently, and the core papers University of Technology Malaysia have the most citations per paper.

From Figure 1.2.7, it can be seen that China, Iran, the United States, and Australia cooperate more with other countries in this field. According to Figure 1.2.8, collaborative research among institutions is mainly carried out by Amirkabir University of Technology, University of Tehran, Iran Petroleum University of Technology, Islamic Azad University, and Sharif University of Technology, each of which has cooperative relations with three other institutions.

According to Table 1.2.15, the countries with the largest number of citing papers on this research topic are China, Iran, and Vietnam. The percentage of citing papers in China exceeds 30%. It can be seen from Table 1.2.16 that the institutions with the largest number of papers on this research topic are Duy Tan University, Amirkabir University of Technology, University of Technology Malaysia, and Ton Duc Thang University, with the percentage of citing papers written by each university exceeding 10%.

Table 1.2.13 Countries with the greatest output of core papers on “basic theory and method for intelligent drilling”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	17	38.64%	66	3.88	2018.7
2	Iran	15	34.09%	155	10.33	2018.1
3	Australia	5	11.36%	31	6.20	2018.8
4	Malaysia	3	6.82%	45	15.00	2018.7
5	USA	3	6.82%	37	12.33	2019.3
6	Saudi Arabia	2	4.55%	20	10.00	2018.5
7	France	2	4.55%	18	9.00	2019.0
8	South Africa	2	4.55%	12	6.00	2018.5
9	UK	2	4.55%	11	5.50	2018.0
10	Canada	2	4.55%	9	4.50	2019.5

Table 1.2.14 Institutions with the greatest output of core papers on “basic theory and method for intelligent drilling”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Amirkabir University of Technology	5	11.36%	79	15.80	2019.0
2	Southwest Petroleum University	5	11.36%	21	4.20	2018.8
3	University of Tehran	4	9.09%	23	5.75	2017.5
4	Iran Petroleum University of Technology	3	6.82%	43	14.33	2016.7
5	Islamic Azad University	3	6.82%	26	8.67	2016.7
6	Sharif University of Technology	3	6.82%	21	7.00	2019.3
7	University of Technology Malaysia	2	4.55%	38	19.00	2019.0
8	King Fahd University of Petroleum and Minerals	2	4.55%	20	10.00	2018.5
9	Chiba University	2	4.55%	2	1.00	2019.0
10	China University of Geoscience	2	4.55%	2	1.00	2019.0

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “basic theory and method for intelligent drilling”

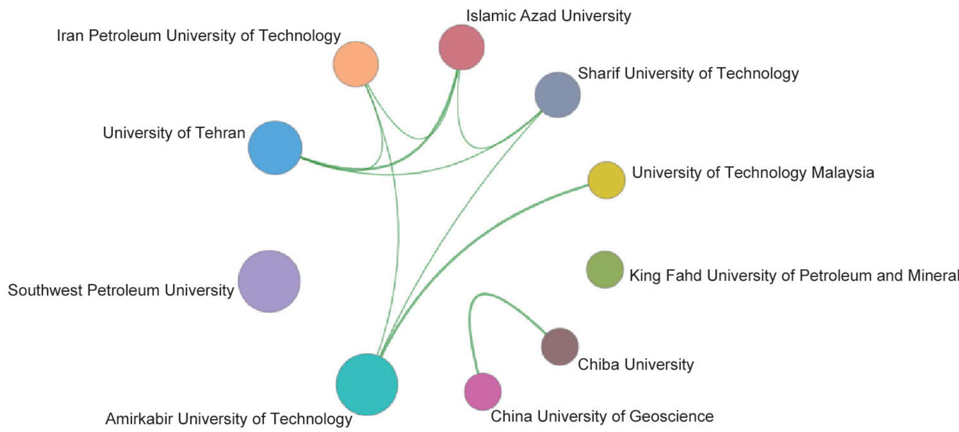

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "basic theory and method for intelligent drilling"

Table 1.2.15 Countries with the greatest output of citing papers on "basic theory and method for intelligent drilling"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	158	31.29%	2018.9
2	Iran	98	19.41%	2018.8
3	Vietnam	70	13.86%	2018.9
4	Malaysia	48	9.50%	2019.0
5	USA	36	7.13%	2019.2
6	Saudi Arabia	32	6.34%	2019.3
7	UK	17	3.37%	2018.9
8	Australia	16	3.17%	2018.9
9	Canada	11	2.18%	2018.3
10	Greece	10	1.98%	2019.1

Table 1.2.16 Institutions with the greatest output of citing papers on "basic theory and method for intelligent drilling"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Duy Tan University	55	17.57%	2018.8
2	Amirkabir University of Technology	47	15.02%	2018.8
3	University of Technology Malaysia	42	13.42%	2019.0
4	Ton Duc Thang University	36	11.50%	2019.2
5	Central South University	31	9.90%	2019.0
6	Islamic Azad University	25	7.99%	2018.8
7	King Fahd University of Petroleum and Minerals	24	7.67%	2019.4
8	Southwest Petroleum University	17	5.43%	2018.9
9	China University of Petroleum	16	5.11%	2018.7
10	Shahrood University of Technology	10	3.19%	2018.8

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 tabulated 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.

Of these top 12 development fronts, "development of a three-dimensional imaging system for Earth observation" and "key technologies for future electric grids with a high proportion of renewable energy" are emerging fronts. Further developments in existing research fields include "key technologies for controlled nuclear fusion engineering testing reactor," "nuclear spent fuel reprocessing and nuclear fuel recycling," "nuclear battery technology and applications," "seismic data acquisition and processing technology based on compressed sensing," and "system for undisturbed detection of multi-scale pore structures in deep mining processes." "All-solid-state lithium battery with high energy density, long life, and controllable interface" is a revolutionary front. The fronts of interdisciplinary integration include "key technologies for coupling electric vehicles and the smart grid," "intelligent monitoring and early-warning information collection system for coal mine disasters," "research and development of three-dimensional prospecting technology for solid mineral resources," and "research on oil and gas intelligent drilling system and tools."

The numbers of core papers published each year from 2014 to 2019 for the top 12 engineering development fronts are listed in Table 2.1.2.

(1) Key technologies for coupling electric vehicles and the smart grid

Electric vehicles use batteries and electric motors to replace the power system of conventional oil engine vehicles. Their application can effectively reduce dependence on oil resources and reduce urban environmental pollution. At the same time, the charging load of electric vehicles can be adjusted in a certain margin in time and location. Then, the charged electric vehicles can be used as mobile energy

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	Key technologies for coupling electric vehicles and the smart grid	59	4 228	71.66	2014.7
2	Key technologies for controlled nuclear fusion engineering testing reactor	29	113	3.90	2016.7
3	Development of a three-dimensional imaging system for Earth observation	35	400	11.43	2016.0
4	Intelligent monitoring and early-warning information collection system for coal mine disasters	271	5 438	20.07	2015.7
5	Key technologies for future electric girds with a high proportion of renewable energy	473	1 933	4.09	2016.6
6	All-solid-state lithium battery with high energy density, long life, and controllable interface	65	357	5.49	2016.8
7	Nuclear spent fuel reprocessing and nuclear fuel recycling	56	118	2.11	2015.8
8	Nuclear battery technology and applications	139	1 008	7.25	2015.9
9	Research and development of three-dimensional prospecting technology for solid mineral resources	62	690	11.13	2016.0
10	Seismic data acquisition and processing technology based on compressed sensing	224	2 158	9.63	2015.7
11	Research on oil and gas intelligent drilling system and tools	201	3 836	19.08	2015.3
12	System for undisturbed detection of multi-scale pore structures in deep mining processes	352	5 338	15.16	2015.7

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	2014	2015	2016	2017	2018	2019
1	Key technologies for coupling electric vehicles and the smart grid	9	3	3	15	6	4
2	Key technologies for controlled nuclear fusion engineering testing reactor	1	5	6	0	5	9
3	Development of a three-dimensional imaging system for Earth observation	6	9	10	3	4	3
4	Intelligent monitoring and early-warning information collection system for coal mine disasters	59	76	54	47	33	2
5	Key technologies for future electric grids with a high proportion of renewable energy	35	33	50	107	84	113
6	All-solid-state lithium battery with high energy density, long life, and controllable interface	10	5	4	8	15	20
7	Nuclear spent fuel reprocessing and nuclear fuel recycling	1	5	7	6	12	9
8	Nuclear battery technology and applications	7	18	18	23	27	22
9	Research and development of three-dimensional prospecting technology for solid mineral resources	10	14	15	13	10	0
10	Seismic data acquisition and processing technology based on compressed sensing	70	42	40	35	36	1
11	Research on oil and gas intelligent drilling system and tools	84	46	30	17	23	1
12	System for undisturbed detection of multi-scale pore structures in deep mining processes	81	95	65	59	51	1

storage resources to support the establishment of the smart grid. Therefore, the coupling of electric vehicles and the smart grid is considered to be the key factor affecting and promoting the development of the two technologies. This can not only significantly reduce the impact of large-scale electric vehicle charging load on the grid, but also reduce the investment and operation cost of the grid and improve the ability of the smart grid to incorporate renewable energy sources.

The main technical directions of electric vehicle and smart grid coupling include the following: integration technology to integrate the charging and discharging devices and power stations for electric vehicles; the optimized layout and evaluation technology of electric vehicle charging and discharging facilities, considering the integration of transportation and the power grid; large-scale orderly electric vehicle charging control technology and secure, intelligent management of the power grid; business model, communication and data security protection; dispatch control technology for the interaction between electric vehicles and the power grid (V2G); large-scale electric vehicle charging behavior analysis and charging guidance technology based on data mining and artificial intelligence; and cascade utilization technology of electric vehicle power batteries.

With the increasing number of electric vehicles, electric vehicle charging operators and users will realize orderly charging and V2G through intelligent charging and discharging facilities, participate in the optimization of the smart grid operation and the competition of the power market, and help provide considerable regulatory resources for smart grid.

(2) Key technologies for controlled nuclear fusion engineering testing reactor

Nuclear fusion energy, which is clean and abundant, is regarded as the best energy source to fundamentally solve the energy crisis in the future. At present, research on different types of fusion experiment devices around the world indicates that the superconducting tokamak, a type of magnetic confinement nuclear fusion device, such as the International Thermonuclear Experimental Reactor (ITER) and the China Fusion Engineering Test Reactor (CFETR), is the device that is most likely to generate electricity. The ITER program represents an international nuclear fusion research and engineering megaproject and the world's largest magnetic confinement fusion (MCF) device. The machine assembly was launched on 28 July 2020. The construction of the facility is expected to be completed in 2025, and the initial plasma experiments will begin as scheduled. This will be the culmination of the research on tokamaks. China, as one of ITER program's seven members, will continue international cooperation with the ITER research group and assimilate the technology of nuclear fusion experimental reactors. CFETR, designed and developed independently by China, acts as a bridge between the ITER and the fusion demonstration reactor. The implementation of these measures will put China at the forefront of the world's research on the key engineering technology for nuclear fusion experimental reactors.

(3) Development of a three-dimensional imaging system for Earth observation

Three-dimensional imaging for land resource prospecting aims to visualize big data with space-time information, which is obtained by satellite technology, space technology, and land exploration technology. This technology mainly uses satellite remote sensing, satellite geophysics, airborne geophysical exploration, aerial remote sensing, ground infrared spectrum, ground geochemistry, ground geophysical exploration, and other multi-level Earth observation big data obtained using satellite technology, and presents Earth observation big data with space–time information in the form of three-dimensional images using computer technology. This enables the basic problems encountered in geological surveys and in mineral resource exploration and assessment to be solved.

This method optimizes and integrates the data by applying Earth observation big data to geological surveys. At the same time, it displays the results of Earth exploration in the form of three-dimensional images, which is convenient for the use of different types of users. In the future, the establishment of a three-dimensional space–time Earth observation big data system with time information can use data from the past, analyze the current situation, and better understand the rules of geology to ensure the safety of a country's geology and national resources and energy.

(4) Intelligent monitoring and early-warning information collection system for coal mine disasters

An intelligent monitoring and early-warning information collection system of coal mine disasters includes a monitoring network, an early warning system, and a data acquisition and processing module, which cooperate with each other to ensure the safety of underground coal mine operations. Effective monitoring and early warning of coal mine hazards are important to ensure normal coal mine production and the safety of miners. Based on different hazard sources, the system can be divided into five major hazard monitoring and early warning systems: gas, mine pressure and roof, coal dust, water, and fire monitoring systems.

First, the systems of the Internet of Things should be established in coal mines to realize digital and intelligent mining. Intelligent perception systems for major sources of danger and accurate early warning systems should be developed. Second, a unified framework and data standard format for coal mine hazard monitoring and early warning systems should be provided. Finally, hidden danger identification, early warning, and intelligent control should be realized by adopting the data fusion method, the data mining technology, prediction models, and space analysis technology.

(5) Key technologies for future electric grids with a high proportion of renewable energy

It is difficult for the existing power grid system based on fossil energy to promote the development of an environmentally friendly society and continuously support future economic growth. The general trend is to tackle this problem by forming modes of energy consumption that are based on renewable energies, such as solar, wind, and water energy, and thereby build a new power grid with a high proportion of renewable energy as the main feature.

The fluctuation, intermittence, and uncertainty of renewable energies cause a great number of theoretical and technical challenges when planning future power grid with a high proportion of renewable energy. The main technical directions of research are the establishment of a probabilistic theoretical system of high-proportion power system flexibility, analysis theory for stability of the electronic power system, basic theory and planning of the security boundary of the electricity distribution system, simulation of panoramic power grid operation, AC/DC hybrid transmission grid planning, and the efficient and optimized operation of the AC/DC hybrid system.

In the future, research could be further refined and extended to cover the sending and receiving ends of a grid connection with a high proportion of renewable energy and the connection itself. In addition, solar thermal power generation technology and energy storage technology could be important research directions, considering the fact that these technologies may have an important impact on the structure of future power systems.

(6) All-solid-state lithium battery with high energy density, long life, and controllable interface

Lithium-ion batteries are widely used in electronic devices, electric vehicles, and grid storage, but they are severely hindered by the safety issues induced by flammable liquid/gel electrolytes. All-solid-state lithium batteries utilizing solid electrolytes as a substitute for the problematic liquid electrolytes can not only eliminate/alleviate safety problems but also help employ lithium anode or sulfur/oxygen cathode materials with a higher energy density. Solid-state electrolytes can be divided into inorganic electrolytes, solid polymer electrolytes, and plastic crystal electrolytes. Inorganic electrolytes possess a high ionic conductivity comparable to that of liquid electrolytes, but the large interfacial impedance and inadequate stability hamper their practical applications. Solid polymer electrolytes have been in development since the early 2000s, but, currently, the limited room-temperature ionic conductivity of these electrolytes render them unsuitable for practical application. Plastic crystal electrolytes have high ionic conductivities and improved interfacial properties, which are promising for industrial evaluation. Solid polymer electrolytes and plastic crystal electrolytes may be applied on certain occasions in the short term, but the application of solid inorganic electrolytes is desirable in the long term. Polymer plastic crystal electrolytes can be prepared by employing a polymer as the backbone and a plastic crystal as the conducting material. By adjusting the concentration of the lithium salt in the interface layer, it is expected that the interface can be effectively controlled while ensuring the overall conductivity, so as to achieve a solid-state battery with high energy density and long life.

(7) Nuclear spent fuel reprocessing and nuclear fuel recycling

The whole process of preparation, burning during reactor operation, and subsequently reprocessing of nuclear fuel is called the nuclear fuel cycle, which is mainly comprised of three major links. The first is the industrial processing the nuclear fuel before it is used in a nuclear reactor, which includes uranium (thorium) mining, processing, enrichment, and nuclear fuel assembly processing and manufacturing. The second link is the use of the fuel in the reactor to obtain nuclear energy or produce new fission nuclides, etc. The third link involves reprocessing and disposing the nuclear fuel (called "spent fuel") discharged from the reactor, including the intermediate storage and reprocessing of spent fuel, and the processing and final disposal of spent radioactive wastes.

The reactor is the central link of the nuclear fuel cycle. Thermal reactors are a mature and widely used technology worldwide. The fast reactor is the preferred next-generation reactor for nuclear energy development. When fissile nuclear fuel is consumed, this reactor converts more ^{238}U into ^{239}Pu to realize the proliferation of nuclear materials. At the same time, it can also incinerate and transmutate long-lived high-level radioactive waste in the spent fuel of a pressurized water reactor, which greatly reduces the environmental risk of long-term geological storage of high-level radioactive wastes.

Spent fuel reprocessing is at the core of the back end of nuclear fuel cycle. Its purpose is to process the spent fuel components discharged from nuclear power plants, separate and recover unburned uranium and newly generated plutonium, and process radioactive wastes to meet disposal requirements. Reprocessing is divided into a wet process (also known as water process) and a dry process, according to the existing state of spent fuel when it undergoes the prior main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purex process converts the spent fuel elements of the reactor into an aqueous solution of nitric acid after proper pretreatment, and then organic solvents are used for extraction and separation to recover nuclear fuel and remove fission products. Dry reprocessing has certain advantages for processing high burnup spent fuels, especially fast reactor spent fuels, which is currently an important research direction.

(8) Nuclear battery technology and applications

A nuclear battery system (radioisotope power supply) is a device that converts the energy generated in the process of radioisotope decay into electrical energy. It has a long working life, good environmental adaptability (adaptable to no-light, extremely cold, high-voltage, and other environments), high energy density, high reliability, and is maintenance-free during its lifetime. It is widely used in space exploration, terrestrial extreme environmental area monitoring, deep-sea monitoring, and other fields. The battery system is a key technical bottleneck restricting deep-space exploration and deep-sea deployment and control tasks. There are more than ten types of nuclear battery systems, of which the most mature technology with the widest range of applications is the temperature difference nuclear battery system.

The main research directions pertaining to the thermoelectric nuclear battery system are focused on the production of radioisotope materials, the development of modular heat sources, high-efficiency thermoelectric conversion, heat source safety testing and evaluation, and power supply reliability testing and evaluation, for which radioisotope raw materials are the prerequisite and are important for the development, production, and application of nuclear battery systems. The development of new and efficient thermoelectric conversion material systems and conversion devices has always received a considerable amount of interest in the development of thermoelectric nuclear battery systems. In addition, the materials of the different shell layers of the thermoelectric nuclear battery system influence the internal heat conduction of the battery, the safety of the heat source, the reliability of the power supply, etc., and advancements in terms of key materials, structural design, and manufacturing processes are still needed.

The development trend of thermoelectric nuclear battery systems mainly lies in improving the efficiency of thermoelectric conversion devices and developing high-power and high-efficiency thermoelectric nuclear battery systems. With regard to high-efficiency conversion technology (such as Stirling conversion technology and thermo-photoelectric conversion technology, etc.), improving the maturity of this technology and developing high-power and high-efficiency temperature difference nuclear battery systems is the focus.

(9) Research and development of three-dimensional prospecting technology for solid mineral resources

Three-dimensional prospecting technology for solid mineral resources aims to develop a method for rapid and efficient prospecting using an integrated space–air–ground prospecting approach. This can be achieved by using satellite remote sensing, unmanned aerial vehicle (UAV) hyperspectral remote sensing, airborne geophysical exploration, infrared spectroscopy for land surface and drill core samples, geophysical and geochemical exploration of the land surface, shallow drilling technology, and other modern exploration techniques.

Based on traditional mineral resource prospecting techniques and with the application of modern technology, three-dimensional prospecting technology aims to modernize solid mineral resource exploration and keep up with the forefront of ming technology in the world. The main technical approaches include combining modern mineral deposit theory with modern technology; integrating aerospace, aviation, and ground exploration; selecting important exploration target areas by means of space remote sensing and geophysical techniques; optimizing the exploration target area using hyperspectral remote sensing; determining drilling positions using infrared spectroscopy and ground geophysical and geochemical exploration in target areas; and verifying target areas using shallow drilling technology.

Based on the rapid development of satellite remote sensing technology and UAV technology, three-dimensional prospecting is expected to advance into an intelligent and automatic technology that integrates communication, artificial intelligence, and geophysical–geochemical–remote sensing prospecting.

(10) Seismic data acquisition and processing technology based on compressed sensing

Traditional seismic data acquisition and processing are based on the Fourier transform of regular sampling, which cannot reconstruct ideal results for datasets with a significant amount of missing data. At the same time, the sampling rate requirements must be met, which adds considerable difficulty for actual applications. Seismic data acquisition and processing technology based on compressed sensing effectively combines the acquisition of seismic data in practical scenarios and compression in data processing. The seismic data acquisition points can be flexibly arranged according to the design of the sampling matrix and are no longer limited. Compared to traditional regular and high-density sampling, the aforementioned compressed sensing technique can help overcome the limitations of the traditional method with respect to sampling frequency. Furthermore, it uses the sparsity of seismic signals to realize the reconstruction of missing data, which greatly reduces the sampling cost and time, improves the work efficiency, and enables the large-scale development of density seismic exploration. In other words, the use of compressed sensing technology for seismic data acquisition can greatly reduce the workload of field acquisition, reduce expenditure, and restore and reconstruct high-precision data to complete the geological exploration task. In the future, relevant methods based on the compressed sensing theory should be applied to actual production to improve the production efficiency and continue to mitigate the problems encountered.

(11) Research on oil and gas intelligent drilling systems and tools

Intelligent drilling is a combination of big data, artificial intelligence, downhole control engineering, and other theories and technologies. It achieves advanced detection and completion of oil and gas drilling, closed-loop control, precision guidance, and transformative technology for intelligent decision-making through surface automatic drilling rigs, downhole intelligent actuator devices, intelligent drilling and completion fluids, and intelligent monitoring and decision-making systems. The intelligent drilling system is mainly composed of intelligent surface equipment, downhole tools, completion and fracturing equipment, and an integrated system platform.

Intelligent ground equipment will effectively reduce personnel input, improve drilling efficiency, and reduce drilling risks and costs. The main intelligent ground equipment which should be developed in the future includes automated drilling rigs, integrated driller control systems, drill floor robots, and intelligent pressure control systems. Intelligent downhole tools can provide technical support for rock breaking, real-time acquisition of downhole data, efficient data transmission, precise drilling guidance, and closed-loop control. The development trend of downhole tools includes smart drill bits, smart drill pipes, smart steering drilling systems, smart sensors, and underground microchips. The development of intelligent completion fracturing equipment will enable infinite-level fracturing and intelligent oil and gas development. The development trend of equipment includes infinite-level intelligent fracturing devices, downhole temperature and pressure monitoring and control devices, wireless communication intelligent fracturing casing, and downhole production dynamic monitoring systems. An intelligent drilling and completion integrated system platform is key to realizing intelligent monitoring, diagnosis, and decision-making in drilling engineering. Drilling data management systems, drilling digital twin simulation systems, expert analysis and decision systems, and remote operation support systems will become the development trend of intelligent drilling and completion integrated systems.

(12) System for undisturbed detection of multi-scale pore structures in deep mining processes

In complicated conditions where high crustal stress is encountered in deep mining, high osmotic pressure, high temperature, and severe mining disturbances, the undisturbed system can realize visualized detection, refined dynamic pore structure characterization, and advanced disaster warning of deep deposits via multi non-disturbed detection technologies, thereby guaranteeing the efficiency and safety for deep mining operations.

Major research interests include developing dynamic refined characterization theories of deep deposit structures; exploring real-time accurate positioning and identification methods for deep high-stress compaction regions; constructing a precise positioning and identification model of pores and cracks in multiple stope regions; conducting studies on the non-disturbed identification of pore structure in the time and frequency domains under deep mining dynamic loading; exploring the intelligent identification of mineral deposits based on 3D concentrated inversion technology; and constructing a database of deep deposit intelligent identification and detection data.

This front is focused on *in-situ* fidelity sampling and structure detection of deep mineral deposits, dynamic interaction of multi-scale pore structures under deep mining disturbances, deep irregular rock mechanic behavior detection and characterization, and other key technologies. This system for undisturbed detection of multi-scale pore structures in deep mining processes will provide hardware support for the transparency of the structure and process of China's mining of deep mineral resources.

2.2 Interpretations for four key engineering development fronts

2.2.1 Key technologies for coupling electric vehicles and the smart grid

The coupling of electric vehicles and smart grid is a key factor affecting and promoting the development of the two technologies. It can not only significantly reduce the impact of large-scale electric vehicle charging load on the grid, but also reduce the investment and operation cost of the grid and help incorporate renewable energy sources into the smart grid.

In 2019, about 2.2 million new energy vehicles were sold worldwide, which represented a year-on-year increase of 10%. The market share of new energy vehicles increased from 2.1% to 2.5%, of which, pure electric vehicles accounted for 74%, with a year-on-year increase of 5%, and plug-in hybrid vehicles accounted for 26%, with a year-on-year decrease of 5%. In 2019, the production and sales of new energy vehicles in China were 1.242 million and 1.206 million, respectively. Of these figures, the production and sales of pure electric vehicles reached 1.02 million and 0.972 million, respectively. The production and sales of plug-in hybrid electric vehicles were 0.22 million and 0.232 million, respectively

According to the latest data released by the International Energy Agency, the number of public charging points for electric vehicles worldwide increased by 60% in 2019, which exceeded the sales of electric vehicles, with 60% of the increase coming from China. By the end of 2019, the total number of public charging piles and private charging piles in China reached 1.219 million, which represented a year-on-year increase of 50.8%.

As listed in Table 2.2.1, the countries with the largest number of core patents published in this field are the United States, Germany, and Japan, with the United States and Germany ranking first and second, accounting for 66.10% and 10.17% of the total number of the core patents, respectively. The proportion of core patents published by Japan was 8.47%.

As tabulated in Table 2.2.2, NIO USA Inc., Qualcomm Inc., and the Witricity Corporation are the institutions with the largest number of core patents published on this research topic, having 19, 7, and 5 core patents, respectively. As shown in Figure 2.2.1, Germany, South Korea, and Switzerland have a greater level of cooperation in this field. Germany collaborates with the largest number of countries as it cooperates with South Korea and Switzerland. As depicted in Figure 2.2.2, on this research front, Witricity Corporation has a strong cooperative relationship with Qualcomm Inc. and Delta Electronics, Inc., so do Better Place GmbH and Renault SAS.

2.2.2 Key technologies for controlled nuclear fusion engineering testing reactor

Compared with the currently used types of energy and the clean energies that are being developed, nuclear fusion energy is an ideal future strategic energy source owing to its safety, economy, durability, and environmentally friendly characteristics. MCF is the use of a specific morphological magnetic field to confine the ultrahigh temperature plasma composed of free electrons and light nuclei, such as deuteron and tritium in a limited volume, which promotes the production of a large number of nuclear fusion reactions under control, and releases energy. At present, there are three types of MCF devices worldwide: tokamak, stellarator, and reversed-field pinch. Each of these has its own advantages and disadvantages. However, a tokamak can most easily get close to fusion conditions and is being developed the fastest. Both the ITER and CFETR are based on tokamak technology to realize fusion energy.

Table 2.2.1 Countries with the greatest output of core patents on “key technologies for coupling electric vehicles and the smart grid”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	39	66.10%	3 684	87.13%	94.46
2	Germany	6	10.17%	114	2.70%	19.00
3	Japan	5	8.47%	124	2.93%	24.80
4	New Zealand	3	5.08%	188	4.45%	62.67
5	Switzerland	2	3.39%	113	2.67%	56.5
6	China	2	3.39%	26	0.61%	13.00
7	South Korea	1	1.69%	18	0.43%	18.00
8	Sweden	1	1.69%	10	0.24%	10.00
9	France	1	1.69%	8	0.19%	8.00
10	UK	1	1.69%	3	0.07%	3.00

Table 2.2.2 Institutions with the greatest output of core patents on "key technologies for coupling electric vehicles and the smart grid"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	NIO USA Inc.	USA	19	32.20%	148	3.50%	7.79
2	Qualcomm Inc.	USA	7	11.86%	770	18.21%	110.00
3	Witricity Corporation	USA	5	8.47%	2789	65.96%	557.80
4	Auckland UniServices Ltd.	New Zealand	3	5.08%	188	4.45%	62.67
5	Better Place GmbH	Switzerland	2	3.39%	344	8.14%	172.00
6	GM Global Technologies Operations Inc.	USA	2	3.39%	65	1.54%	32.50
7	Toyota Motor Co., Ltd.	Japan	2	3.39%	60	1.42%	30.00
8	Nissan Motor Co., Ltd.	Japan	2	3.39%	31	0.73%	15.50
9	Delta Electronics, Inc.	USA	1	1.69%	2086	49.34%	2086.00
10	Renault SAS	France	1	1.69%	271	6.41%	271.00

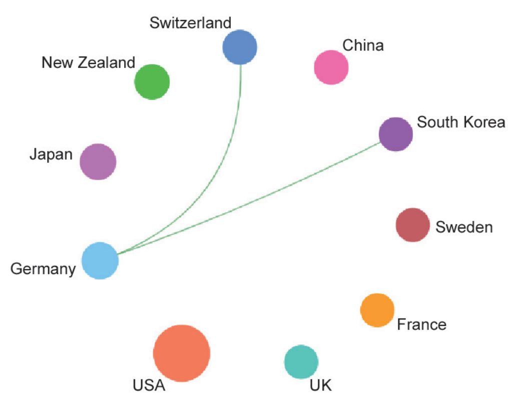

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "key technologies for coupling electric vehicles and the smart grid"

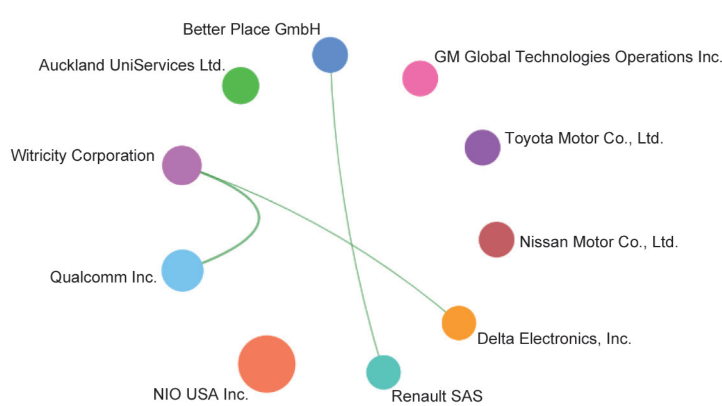

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "key technologies for coupling electric vehicles and the smart grid"

In recent years, significant progress has been made in the field of controllable nuclear fusion. The ITER program, the largest and most far-reaching international scientific project in the world, is jointly undertaken by the European Union, China, South Korea, Russia, Japan, India, and the United States. The ITER program will integrate the main scientific and technological achievements of controlled MCF research and realize the first controlled thermonuclear fusion experimental reactor in the world, which is comparable with a practical future fusion reactor scale, and can solve the key problems that are hindering progress toward fusion power stations. The successful implementation of the ITER program will fully verify the scientific and engineering feasibility of the development and utilization of fusion energy, which is the key step for human controlled thermonuclear fusion research to be practical.

The United States, Japan, the European Union, South Korea, and other major countries and regions have formulated detailed fusion energy development routes. Furthermore, they have built and developed their own next generation of devices and conducted relevant research related to ITER.

China is vigorously supporting the MFC research community to actively participate in the construction and experiments of ITER, promoting the corresponding domestic physical and engineering technology research, and supporting the independent design of CFETR with the goal of obtaining fusion energy. At present, the physical and engineering conceptual design has also been completed in China's self-designed CFETR, and the full construction of CFETR will begin in due course.

The top three countries for core patent disclosure are the United Kingdom, China, and United States. The percentage of core patens published by the United Kingdom and China both are 37.93% (Table 2.2.3). The top three institutions with the highest number of core patents are Tokamak Energy Ltd., the Hefei Institutes of Physical Science of the Chinese Academy of Sciences, and the China National Nuclear Corporation (Table 2.2.4). There is some cooperation between the China National Nuclear Corporation and Beijing Leyfond Vacuum Technology Co., Ltd., as well as between Advanced Research Corporation and the West Virginia University (Figure 2.2.3).

2.2.3 Development of a three-dimensional imaging system for Earth observation

Three-dimensional imaging for land resource prospecting arises from photography. This technique has undergone rapid development because of the progress in computer graphics and image processing technology. Owing to the maturity of aerospace and land exploration technology and rapid access to data obtained from satellite remote sensing, satellite geophysics, airborne geophysical exploration, aerial remote sensing, ground infrared spectrum, ground geochemistry, and ground geophysical exploration, the practical application of space–air–ground three-dimensional imaging for land resource prospecting has finally become possible.

In the 1950s, the US National Aeronautics and Space Administration developed a three-dimensional global elevation model using radar systems. Currently, Google Inc. has a complete 3D map of the Earth (i.e., Google Earth) based on satellite remote sensing images and a three-dimensional elevation model. Three-dimensional imaging has become a major function in many industries, such as UAVs. In July 2017, the Aerospace Information Research Institute, the largest aerospace research institute under the Chinese Academy of Sciences, was established. In November 2019, China launched the Gaofen-7 satellite, which is capable of providing a 1:10 000

Table 2.2.3 Countries with the greatest output of core patents on "key technologies for controlled nuclear fusion engineering testing reactor"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UK	11	37.93%	91	80.53%	8.27
2	China	11	37.93%	10	8.85%	0.91
3	USA	2	6.90%	4	3.54%	2.00
4	South Korea	2	6.90%	1	0.88%	0.50
5	Russia	2	6.90%	1	0.88%	0.50
6	Japan	1	3.45%	6	5.31%	6.00

Table 2.2.4 Institutions with the greatest output of core patents on "key technologies for controlled nuclear fusion engineering testing reactor"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Tokamak Energy Ltd.	UK	11	37.93%	91	80.53%	8.27
2	Hefei Institute of Physical Sciences, Chinese Academy of Sciences	China	4	13.79%	2	1.77%	0.50
3	China National Nuclear Corporation	China	2	6.90%	0	0.00%	0.00
4	Japan Atomic Energy Agency	Japan	1	3.45%	6	5.31%	6.00
5	Advanced Research Corporation	USA	1	3.45%	3	2.65%	3.00
6	West Virginia University	USA	1	3.45%	3	2.65%	3.00
7	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	China	1	3.45%	2	1.77%	2.00
8	Seoul National University R&DB Foundation	South Korea	1	3.45%	1	0.88%	1.00
9	All-Russia Research Institute of Automatics	Russia	1	3.45%	0	0.00%	0.00
10	Beijing Leyfond Vacuum Technology Co., Ltd.	China	1	3.45%	0	0.00%	0.00

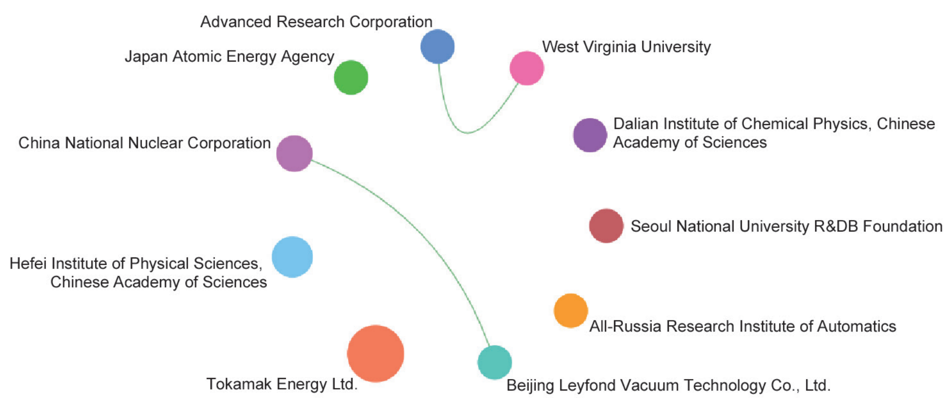

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of "key technologies for controlled nuclear fusion engineering testing reactor"

scale satellite three-dimensional imaging that contributed to the successful three-dimensional imaging of Mount Qomolangma (Mount Everest) in May 2020.

Significant progress has been made in three-dimensional imaging in many countries, and there are connections among these countries. The technical difficulties associated with three-dimensional imaging include the cooperative use of multi-source data and accurate visualization of data, and more studies for this technique are required.

The top three countries with the most published core patents for three-dimensional imaging for land resource prospecting are China (21), the United States (7), and Germany (4). China has the highest percentage (60%) of published core patents and the highest citations (196) for the published core patents. The top three countries with the highest citations per patent are Sweden (27), the United States (16.5), and Germany (10.5) (Table 2.2.5). Institutions with the most published core patents include the Beijing Institute of Technology (5), Lessmueller Lasertechnik GmbH (2), Changchun Institute of Optics, Fine Mechanics and Physics (2), Nanjing University of Science and Technology (2), and Harbin Institute of Technology (2). The institutions with the highest number of citations are Boeing Corporation (44), Lessmueller Lasertechnik GmbH (28), the Beijing Institute of Technology (27), General Electric Company (27), and Zhejiang Sci-Tech University (27) (Table 2.2.6).

Table 2.2.5 Countries with the greatest output of core patents on "development of a three-dimensional imaging system for Earth observation"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	21	60.00%	196	49.00%	9.33
2	USA	7	20.00%	116	29.00%	16.57
3	Germany	4	11.43%	42	10.50%	10.50
4	Japan	2	5.71%	19	4.75%	9.50
5	Sweden	1	2.86%	27	6.75%	27.00

Table 2.2.6 Institutions with the greatest output of core patents on "development of a three-dimensional imaging system for Earth observation"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Institute of Technology	China	5	14.29%	27	6.75%	5.40
2	Lessmueller Lasertechnik GmbH	Germany	2	5.71%	28	7.00%	14.00
3	Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences	China	2	5.71%	26	6.50%	13.00
4	Nanjing University of Science and Technology	China	2	5.71%	21	5.25%	10.50
5	Harbin Institute of Technology	China	2	5.71%	13	3.25%	6.50
6	Boeing Corporation	USA	1	2.86%	44	11.00%	44.00
7	General Electric Company	USA	1	2.86%	27	6.75%	27.00
8	Zhejiang Sci-Tech University	China	1	2.86%	27	6.75%	27.00
9	KLA-Tencor Corporation	USA	1	2.86%	21	5.25%	21.00
10	Nova Measuring Instruments Ltd.	USA	1	2.86%	17	4.25%	17.00

2.2.4 Intelligent monitoring and early-warning information collection system for coal mine disasters

Based on safety monitoring requirements and early warning of an intelligent fully mechanized mining face, this system studies the real-time monitoring and early warning of five major disasters: water, fire, gas, mine pressure, and dust hazards. Through a comprehensive evaluation model, safety index analysis and early warning of the working face area can be realized, which can guarantee security for the intelligent control of the fully mechanized working face and provide real-time monitoring and analysis data for the safety warning and control of the disaster. It is an important part of the intelligent working face safety warning and control system.

Effective monitoring and early warning of hazards in underground coal mines are important for normal production and the safety of miners.

With the development of the complete equipment technology of fully mechanized faces, the number of intelligent fully mechanized faces is increasing. However, the environmental safety monitoring and management of intelligent fully mechanized faces are still in the stages where they rely on over-limit alarms, manual connections, and verbal warnings. Taking the five aforementioned major coal mine disasters as an example, and considering the situation from the perspectives of basic analysis of data sources, disaster analysis methods, and monitoring analysis results, the status quo of environmental safety monitoring and early warning on working faces is as follows:

(1) Analysis of basic data sources: The analysis process requires manual intervention. The basic data cannot be acquired automatically, and the subjective uncontrollability of human interference cannot be eliminated. Furthermore, the analysis results cannot be produced in real time.

(2) Disaster analysis method: Isolated analysis of water, fire, gas, mineral pressure, and dust, without the overall layout of the working face, integrated analysis, and early warning based on each disaster monitoring.

(3) Results of disaster monitoring and analysis: Most results are in the form of research reports, and research results are submitted for the analysis of staged production processes. Thus, it is impossible to conduct safety analysis, safety tracking, and safety guarantee for the entire production cycle of the working face.

The development trends of this front include: First, establish the Internet of Things in coal mines, build digital and intelligent mines, develop intelligent perception systems of major sources of danger, and establish accurate early warning systems. Second, provide a unified framework and data standard format for coal mine hazard monitoring and early warning systems. Third, establish mine hidden danger identification, early warning, and intelligent control by means of the data fusion method, data mining technology, prediction models, and space analysis technology.

As can be seen from Table 2.2.7, patents related to this development front are mainly concentrated in the United States and China, which account for 94% of all patents. The United States also ranks first in the world in terms of citations and percentage of citations. China ranks second in the world with 39 published patents. Table 2.2.8 lists the major institutions at the forefront of this development front. The results show that the numbers of patents published by Honeywell International Inc. and Johnson Controls Technology Co. are the two highest, accounting for approximately 25% of the global number of patents. As illustrated in Figure 2.2.4, China, the United States, New Zealand, India, and the Czech Republic have established cooperation networks.

Table 2.2.7 Countries with the greatest output of core patents on “intelligent monitoring and early-warning information collection system for coal mine disasters”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	216	79.70%	4 546	83.60%	21.05
2	China	39	14.39%	660	12.14%	16.92
3	Canada	5	1.85%	90	1.66%	18.00
4	Netherlands	4	1.48%	96	1.77%	24.00
5	South Korea	2	0.74%	28	0.51%	14.00
6	United Arab Emirates	1	0.37%	29	0.53%	29.00
7	Czech Republic	1	0.37%	29	0.53%	29.00
8	India	1	0.37%	22	0.40%	22.00
9	Germany	1	0.37%	19	0.35%	19.00
10	New Zealand	1	0.37%	18	0.33%	18.00

Table 2.2.8 Institutions with the greatest output of core patents on “intelligent monitoring and early-warning information collection system for coal mine disasters”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Honeywell International Inc.	USA	48	17.71%	1 274	23.43%	26.54
2	Johnson Controls Technology Co.	USA	22	8.12%	344	6.33%	15.64
3	Emerson Electric Co.	USA	16	5.90%	545	10.02%	34.06
4	Google Inc.	USA	15	5.54%	431	7.93%	28.73
5	EcoFactor Inc.	USA	14	5.17%	214	3.94%	15.29
6	Senseware Inc.	USA	10	3.69%	89	1.64%	8.90
7	Trane International Inc.	USA	8	2.95%	131	2.41%	16.38
8	Philips Lighting Holding BV	USA	4	1.48%	96	1.77%	24.00
9	Gree Electric Appliances, Inc. of Zhuhai	China	4	1.48%	80	1.47%	20.00
10	Siemens Corp.	USA	3	1.11%	39	0.72%	13.00

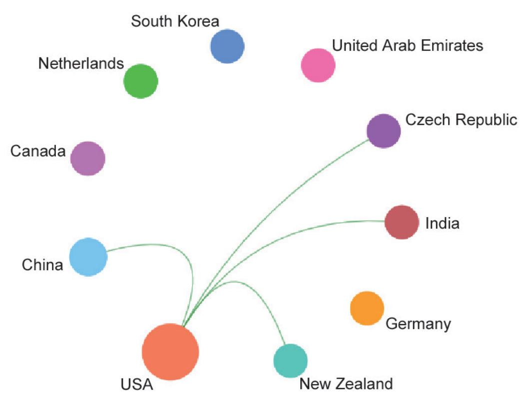

Figure 2.2.4 Collaboration network among major countries in the engineering development front of “intelligent monitoring and early-warning information collection system for coal mine disasters”

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V. Civil, Hydraulic, and Architectural Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering, construction materials, transportation engineering, architecture, HVAC, municipal engineering, surveying and mapping engineering, and hydraulic engineering. The following research fronts were recommended by experts: "smart city and smart basin integrated sensing based on geospatiotemporal big data," "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes," "urban spatial analysis and optimization methods based on big data," "ventilation theory for adaptive thermal comfort and indoor air quality," and "multiscale prediction of dynamic hazard evolution for underground engineering." The five remaining fronts were identified using the co-citation clustering method applied to the top 10% of highly cited papers, and they were confirmed by experts. Table 1.1.2 presents annual statistical data on the core papers published between 2014 and 2019 that are relevant to these top 10 research fronts.

(1) Smart city and smart basin integrated sensing based on geospatiotemporal big data

Integrated sensing is an important foundation for the realization of smart cities and smart basins. In smart cities and smart basins, ubiquitous smart sensors achieve the comprehensive perception of physical cities and physical watersheds and detect the core system of urban operations and watershed management in real time, thereby seamlessly connecting digital cities and digital watersheds with physical cities and physical watersheds. The real-time geospatiotemporal big data are then used to provide users with intelligent services. Developing trends in this research front include: 1) construction methods for the

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	Smart city and smart basin integrated sensing based on geospatiotemporal big data	36	924	25.67	2017.0
2	Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes	40	1 271	31.78	2016.3
3	Urban spatial analysis and optimization methods based on big data	58	2 461	42.43	2017.1
4	Ventilation theory for adaptive thermal comfort and indoor air quality	544	16 740	30.77	2016.6
5	Multiscale prediction of dynamic hazard evolution for underground engineering	93	2 297	24.70	2017.5
6	Nano-engineered concrete materials in civil engineering	74	3 995	53.99	2017.2
7	Urban planning and design to reduce the urban heat island effect	188	6 975	37.10	2016.9
8	Performance evolution and durability design principles for materials and structures on highways and for track engineering	56	1 584	28.29	2017.5
9	Formation mechanisms and changing trends of extreme hydrologic events	238	9 287	39.02	2016.5
10	Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior	105	3 319	31.61	2017.3

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 fronts	2014	2015	2016	2017	2018	2019
1	Smart city and smart basin integrated sensing based on geospatiotemporal big data	2	5	5	10	8	6
2	Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes	11	5	4	6	8	6
3	Urban spatial analysis and optimization methods based on big data	5	5	4	20	12	12
4	Ventilation theory for adaptive thermal comfort and indoor air quality	69	97	88	102	92	96
5	Multiscale prediction of dynamic hazard evolution for underground engineering	6	7	6	19	24	31
6	Nano-engineered concrete materials in civil engineering	3	6	11	19	20	15
7	Urban planning and design to reduce the urban heat island effect	21	23	30	44	29	41
8	Performance evolution and durability design principles for materials and structures on highways and for track engineering	6	3	5	5	16	21
9	Formation mechanisms and changing trends of extreme hydrologic events	26	46	46	41	50	29
10	Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior	5	14	10	22	27	27

integrated sensing infrastructure systems of smart cities and smart basins to realize the large-scale interconnection of monitoring resources and the coordination of multi-source heterogeneous sensing resources; 2) city and basin sensing methods based on integrated sensing infrastructure; and 3) integrated management and real-time analysis methods for the geographic spatial-temporal big data of smart cities and smart basins. Between 2014 and 2019, 36 core papers relevant to this research front were published. These papers received 924 citations, with an average of 25.67 citations per paper.

(2) Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes

Offshore engineering structures such as harbor wharfs, breakwaters, oil production platforms, submarine pipelines, sea-crossing bridges and tunnels, and offshore wind power foundations confront severe operating environments and high safety risks. Under the action of winds, waves, currents, and earthquakes, the pore water pressure increases, and the effective stress decreases in the foundation of the seabed, which can lead to the strength-weakening and liquefaction of the seabed soil. At the same time, the action of waves and currents can scour the seabed foundation. Moreover, structural movements under the action of dynamic loads can also cause changes in the pore water pressure and effective stress in the seabed soil, complicating the bearing capacity of the seabed foundation. The coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes are thus a key issue for the safety and durability of offshore engineering structures. The main problems to be solved include the following: 1) the mechanism and evolution law of the strength-weakening and liquefaction of different seabed foundations (gravel, sand, soft clay, etc.) under the action of different periodic cyclic loads such as waves, earthquakes, and structural motion; 2) elastoplastic constitutive models that consider the processes of strength-weakening, liquefaction, and excess pore pressure dissipation and consolidation after the liquefaction and re-liquefaction of seabed soil under the action of cyclic loads; 3) scouring models of different seabed foundations that account for seepage effects under the action of waves and currents; 4) coupled numerical models and efficient and reliable numerical simulation methods for the nonlinear dynamic analysis of cyclic load–marine structure–seabed foundation systems; and 5) basic theory and experimental technology for physical model tests to investigate the bearing capacity of cyclic load–marine structure–seabed foundation systems. Between 2014 and 2019, 40 core papers relevant to this research front were published. These papers received 1271 citations, with an average of 31.78 citations per paper.

(3) Urban spatial analysis and optimization methods based on big data

With the development of Internet technologies, the paradigm of urban spatial analysis is being transformed by the emergence of new big data that are geo-referenced, such as cell phone data, public transport tap-in/out data, and social media check-ins. The advantages of this type of data include its large size, fine resolution, and wide coverage. These data record various human behaviors across time and space with a new level of precision, thereby forming new pipelines for us to observe, perceive, and interpret cities and their transformation. Spatial analysis and optimization based on urban big data are frontiers in urban studies and practices. The institutes leading the relevant research are located in the West in developed countries or districts, such as the United States, the United Kingdom, and the European Union, and in rapidly developing countries and areas, such as China. Developed countries typically maintain more comprehensive research systems and networks with the solid establishment of theory, methods, and applications, whereas rapidly developing countries, particularly China, are notable for the large size of their urban big data, which is attributable to their large populations, optimism toward new technologies, and good software and hardware facilities. Between 2014 and 2019, 58 core papers relevant to this research front were published, and these papers received 2461 citations, with an average of 42.43 citations per paper.

(4) Ventilation theory for adaptive thermal comfort and indoor air quality

The concept of ventilation theory for adaptive thermal comfort and indoor air quality refers to the idea that when a person is in a naturally ventilated environment, the thermal acceptability of his or her body increases due to its thermal adaptation. Because natural ventilation can provide better indoor air quality, a balance can be achieved between energy conservation and comfort. The main research directions in this front include: 1) the physiological and psychological mechanisms of human thermal adaptability in building environments; 2) effects and prediction models for thermal comfort caused by exposure experiences and thermal adaptation; 3) indoor air quality assessments in naturally ventilated environments and passive building environments; and 4) design methods for naturally ventilated environments and passive building environments. This research front has maintained a high level of activity in recent years. Extensive field surveys have been conducted in various climate zones worldwide, enriching adaptive thermal comfort theory and improving the prediction accuracy of human thermal comfort in naturally ventilated buildings. Natural ventilation, artificial airflow, and personalized comfort equipment have been used to replace traditional air conditioning and heating equipment in specific seasons and spaces in order to reduce the dependence of buildings on traditional energy and to integrate human development with nature. Between 2014 and 2019, 544 core papers relevant to this research front were published, and these papers received 16 740 citations, with an average of 30.77 citations per paper.

(5) Multiscale prediction of dynamic hazard evolution for underground engineering

At present, the construction of underground structures is developing rapidly. Many of these structures are large in scale and may encounter complex geological environments as well as hazard threats induced by strong earthquakes, active fault zones, and seismic liquefaction. Such threats pose a serious challenge to the science and technology of disaster prevention and mitigation in geotechnical and underground engineering. The multiscale prediction of dynamic hazard evolution for underground engineering is based on a combination of interdisciplinary subjects, including geotechnical earthquake engineering, structural dynamics, and multiscale science, and on the construction of multiscale dynamic analysis models that cover the macro- and meso-space scales and time effect scales. The aim is to reveal not only the integral dynamic response characteristics of underground structures at the macro-scale but also the dynamic damage mechanisms of critical joints at the meso-scale when subjected to strong earthquakes. The ultimate goal is to realize the multiscale prediction of the entire process of dynamic hazard evolution for underground engineering under high seismic intensity and adverse site conditions and thus to provide a scientific basis and technical support to improve disaster prevention and mitigation for underground structures. The main research directions in this front include: longitudinal seismic design theory for long and large tunnels, multiscale analysis methods for massive nonlinear seismic responses in underground structures, physical experimental simulations of the effects of strong earthquakes and nonuniform seismic spatial variations, dynamic response analysis of complex underground structures with sharp stiffness transitions, and dynamic hazard simulations for underground engineering in adverse sites, such as liquefaction sites and active fault zones. Trends suggest that future developments will include: the damage mechanisms of underground engineering under strong earthquakes and design countermeasures, seismic mitigation technologies and structural measures for underground structures, and rational and unified performance-based concepts for the seismic design of underground structures. Furthermore, optimizing the combination of seismic countermeasures and mitigation measures and adapting them to the seismic response characteristics of underground engineering under complex and adverse geological conditions remains one of the most challenging and urgent problems in this front. Between 2014 and 2019, 93 core papers relevant to this research front were published, and these papers received 2297 citations, with an average of 24.70 citations per paper.

(6) Nano-engineered concrete materials in civil engineering

The need for concrete materials that meet increasingly strict requirements is being expressed in modern civil engineering; however, traditional single- or multi-performance improvements at the macro-scale can barely meet this need. Multi-scale micro-nano-structure regulation and function upgrades are one of the feasible ways to improve the performance of concrete materials for modern civil engineering. Nanomaterials enable the nano-optimization of cementing gels to regulate the micro-nano-structure of concrete materials. Chemical coordination and hybridization with cement-based materials can be realized by doping organic functional groups. Moreover, nonreactive nanoparticles can regulate the early hydration progress of cement to refine its molecular structure, while some nanoparticles with reactive surface properties can be used as strong nano-bridges to coordinate and complex with cementing gels. The nano-regulation and optimization of cementing gels can significantly improve the toughness and durability of concrete materials with very low dosages. Moreover, introducing nanomaterials can provide traditional concrete materials with new functions for performance optimization. Through doping or surface infiltration, some nanomaterials can equip concrete materials with electrical conductivity and self-cleaning abilities. Piezoelectric nanoparticles can introduce intelligent perception to concrete materials, while physicochemical self-healing can be initiated by nano-functionalized healants in concrete materials. Nanomaterial-based functional improvements in concrete materials can thus meet the integrated structural and functional requirements of modern civil engineering. Theoretical analysis and numerical simulation are critical to achieving designable nano-engineered concrete materials. Nanomaterial-based optimization strategies for concrete materials can be established through computational chemistry at the nano-scale. Big data-based modeling can contribute to the elaboration of the effects of nanoparticles on concrete materials. In this way, the top-level design and rational doping theory of high-performance and multifunctional nano-engineered concrete can be achieved. Theoretical analysis, numerical simulation, and nano-dispersion technologies should be combined in order to realize nano-regulation, nano-functionalization, and nano-design in concrete. Between 2014 and 2019, 74 core papers relevant to this research front were published, and these papers received 3995 citations, with an average of 53.99 citations per paper.

(7) Urban planning and design to reduce the urban heat island effect

In urban development, the temperature of the urban surface and canopy is higher than that of nearby rural areas. This phenomenon is called the urban heat island effect. The heat island effect is influenced by many factors including the urban morphology, land surface, air pollution, and anthropogenic heat. In the context of global climate change, the heat island effect further exacerbates abnormal weather phenomena, such as heat waves, and health risks to urban populations such as respiratory distress and heat stroke, resulting in adverse effects on urban climate and human comfort. Research on health-and-comfort oriented urban planning and design has been emphasized in international academic papers. The research on urban heat islands and microclimates involves the research fields of architecture, urban planning, and landscapes. The main technical measures are usually categorized as meso-scale or micro-scale. At the meso-scale are urban wind corridor planning analyses based on land use and development intensity, quantitative studies of the heat island effect based on high-resolution remote sensing technology, and green space ecological planning to mitigate the urban heat island using geographic information systems. At the micro-scale are the application of computational fluid dynamic technology for wind and heat simulation to optimize urban space planning and architectural design research and park or green space and urban street tree landscape designs to improve human comfort and mitigate heat risks. The urban block grid fineness method is a key technology for addressing the resolution reduction of the meso- and micro- scales. Other measures applied to urban heat islands include urban climate strategies, the innovation of sustainable urban developments, urban morphology, green design for heat risk management, and the prediction of the impact of urban development intensity on pollution diffusion and the energy consumption of urban agglomerations. Between 2014 and 2019, 188 core papers relevant to this research front were published, and these papers received 6975 citations, with an average of 37.10 citations per paper.

(8) Performance evolution and durability design principles for materials and structures on highways and for track engineering

Pavement material and structures are damaged by repetitive traffic loads and cyclic environmental disincentives and then deteriorate gradually over their in-service life. The concepts of behavioral evolution and durability-based design principles for pavement materials and structures refer to the evolution of pavement structures and materials and the development of fundamental design theory and methodology for durable pavement design. The main research areas in this front include: 1) using multi-scale theoretical analysis, numerical simulations, and experimental tests (both laboratory and field) to reveal the in-service behavioral evolution of pavement materials and structures and quantitatively describing their performance; 2) using modifiers to improve the durability of pavement materials; 3) considering the real stress/strain state of structures and the bimodular properties (different compression-tension properties) of materials to develop more accurate pavement design procedures; 4) developing more reliable pavement structure design models based on monitoring the long-term performance of pavement; and 5) optimizing pavement structures and conducting preventive maintenance to enhance the durability and service life of pavement. Potential research prospects include: 1) investigating the behavioral evolution of pavement materials and structures under the coupled effects of multiple factors based on the long-term performance monitoring and accelerated pavement testing; 2) developing highly efficient modifiers to improve the binder-aggregate interface bonding and the overall mechanical properties of pavement materials; and 3) developing a harmonious analysis of the mechanical properties and the structural mechanical responses of pavement materials based on the in-service behavior of pavement material and structure. Between 2014 and 2019, 56 core papers relevant to this research front were published. These papers received 1584 citations, with an average of 28.29 citations per paper.

(9) Formation mechanisms and changing trends of extreme hydrologic events

Extreme hydrologic events are hydrologic events that occur with a small probability of occurrence but a strong impact in a particular region and within a certain time scale, for which the hydrological variables deviate significantly from their normal values. Extreme hydrologic events are multi-dimensional nonlinear systems that are influenced by climate, underlying surfaces, human activities, and other factors. Their formation mechanism is therefore highly complex. In recent years, the intensity and frequency of extreme hydrologic events caused by global climate change have increased, and the consequently increased risk of flood and drought has become a major challenge for humans. The formation mechanisms and changing trends of extreme hydrologic events under the impact of global change have become top issues in current research. Main research trends include: 1) the impact of the interaction of climate–vegetation–hydrology–human activity on extreme hydrologic events; 2) trend detection, changing attributes, and future scenarios of extreme hydrologic events given the impacts of natural climate variability and human activities; 3) climate–hydrologic bidirectional coupling models and multi-scale extreme hydrologic process simulations in changing environments; and 4) risk assessment of, multi-dimensional regulation of, and comprehensive responses to extreme hydrologic events. In the future, the formation mechanisms and changing trends of extreme hydrologic events in complex environments should be investigated via a multi-disciplinary approach based on climate, hydrology, geography, management, etc., using three-dimensional total factor monitoring and scientific experiments, multi-source data fusion and assimilation, ensemble simulation of physical models with artificial intelligence (AI), and other new technologies. Between 2014 and 2019, 238 core papers relevant to this research front were published. These papers received 9287 citations, with an average of 39.02 citations per paper.

(10) Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior

The rapid development of human society has produced a growing demand for energy. With improvements in all types of technical engineering systems, the exploitation of energy resources has gradually reached the deep part of the earth. In recent years, the exploitation of shale gas, hot dry rock, coalbed methane, and combustible ice have seen an upsurge. However, deep rock masses are found in complicated geological environments with high temperature and high stress, and their mechanical behaviors are more complex than those of shallow rock masses. Affected by coupled fluid–thermal–chemical–mechanical effects, the key parameters of deep rock masses, including their mechanical strength, deformation mechanisms, and permeability characteristics, are not well explained by traditional theories. Meanwhile, catastrophic problems, such as rock bursts, induced seismicity, large deformations of soft rocks, and wall instabilities in complex strata, occur frequently in deep mining. Catastrophic mechanisms thus require further investigation. To better explore the effects of deep energy mining disasters and further improve the control of the mechanical behaviors of deep rock masses, the following research aspects should be given special attention: the multi-field coupling mechanisms of complex fractured rock masses; the mechanisms, processes, and evaluation of deep, dynamic disasters; the physical and mechanical properties, deformation, and failure characteristics of deep rock masses; and the influence of deep, complex structures on the physical and mechanical properties of rock masses. Between 2014 and 2019, 105 core papers relevant to this research front were published. These papers received 3319 citations, with an average of 31.61 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Smart city and smart basin integrated sensing based on geospatiotemporal big data

Integrated sensing is an important foundation for the realization of smart cities and smart basins. In smart cities and smart basins, ubiquitous smart sensors realize the comprehensive perception of physical cities and physical watersheds and detect the core system of urban operations and watershed management in real time, thereby seamlessly connecting digital cities and digital watersheds with physical cities and physical watersheds. The real-time geospatiotemporal big data are then used to provide users with intelligent services. With the development of smart cities and smart basins, urban and basin sensing has gradually developed from isolated online sensing to multi-network integrated sensing.

Currently, the major research topics concerning smart city and smart basin integrated sensing include:

(1) Construction methods for integrated sensing infrastructure systems of smart cities and smart basins, such as 1) new technologies for the large-scale interconnection of monitoring resources between cities and river basins, including mass sensor network communication, heterogeneous sensor access, sensor network resource management, sensor network service composition, streaming data mining analysis, and geographic information interoperability; and 2) new collaborative methods for multi-source heterogeneous sensing resources, such as sensor information modeling, observation capability evaluation, collaborative monitoring, data fusion of point and surface observations, and on-demand focused services;

(2) City and basin sensing methods based on integrated sensing infrastructure, including 1) multi-scale comprehensive perception indices, common technology and standard systems, seamless spatial perception methods of urban agglomeration and watershed surface elements; 2) multi-scale intelligent light field video imaging and analysis methods; 3) fine scene space-time perception and online monitoring methods; and 4) the multi-scale synthesis of city and watershed sensing service methods; and

(3) The integrated management and real-time analysis of geographic spatiotemporal big data from smart cities and smart basins, including integrated expression methods of multi-source real-time geographic information, fusion and organization methods for real-time geographic information, flexible service methods for real-time geographic information, and deep mining methods for geographic spatial-temporal big data.

As shown in Table 1.1.1, between 2014 and 2019, 36 core papers concerning “smart city and smart basin integrated sensing based on geospatiotemporal big data” were published, with each paper being cited an average of 25.67

times. The top five countries in terms of output of core papers on this topic are China, the United States, Malaysia, Iran, and Australia (Table 1.2.1). China is one of the most active countries, having published 27.78% of the core papers. The five countries with the highest citations per paper were South Korea, the United States, Turkey, Malaysia, and Switzerland. The papers published by Chinese authors were cited 19.80 times per paper on average, which indicates that there is an opportunity for improvement by Chinese scholars on this front. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation was observed among the most productive top 10 countries.

The five institutions that published the most core papers were Chinese Academy of Sciences (China), China Institute of Water Resources and Hydropower Research (China), Canik Basari University (Turkey), the National University of Malaysia (Malaysia), and the University of Hong Kong (China) (Table 1.2.2). The top two institutions in terms of widely cited publications are the Chinese Academy of Sciences and the China Institute of Water Resources and Hydropower Research. Both institutions are leaders in the application of AI techniques for urban flood warning and catchment flood forecasting to prolong the leading time and increase the forecasting accuracy. As illustrated in Figure 1.2.2, the ten most productive institutions have conducted collaborative studies in this regard.

Table 1.2.1 Countries with the greatest output of core papers on “smart city and smart basin integrated sensing based on geospatiotemporal big data”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	10	27.78%	198	19.80	2017.4
2	USA	6	16.67%	299	49.83	2016.7
3	Malaysia	5	13.89%	234	46.80	2017.0
4	Iran	5	13.89%	124	24.80	2017.2
5	Australia	5	13.89%	111	22.20	2017.2
6	UK	4	11.11%	59	14.75	2018.2
7	Turkey	3	8.33%	148	49.33	2016.0
8	South Korea	2	5.56%	148	74.00	2016.0
9	Switzerland	2	5.56%	72	36.00	2016.0
10	Iraq	2	5.56%	64	32.00	2018.0

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “smart city and smart basin integrated sensing based on geospatiotemporal big data”

Table 1.2.2 Institutions with the greatest output of core papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	3	8.33%	98	32.67	2018.0
2	China Institute of Water Resources and Hydropower Research	3	8.33%	38	12.67	2017.0
3	Canik Basari University	2	5.56%	140	70.00	2015.5
4	National University of Malaysia	2	5.56%	68	34.00	2017.0
5	University of Hong Kong	2	5.56%	54	27.00	2015.5
6	University of Tehran	2	5.56%	52	26.00	2016.5
7	Razi University	2	5.56%	49	24.50	2018.5
8	University of Southern Queensland	2	5.56%	47	23.50	2018.0
9	Islamic Azad University	2	5.56%	39	19.50	2018.5
10	Huazhong University of Science and Technology	2	5.56%	38	19.00	2018.5

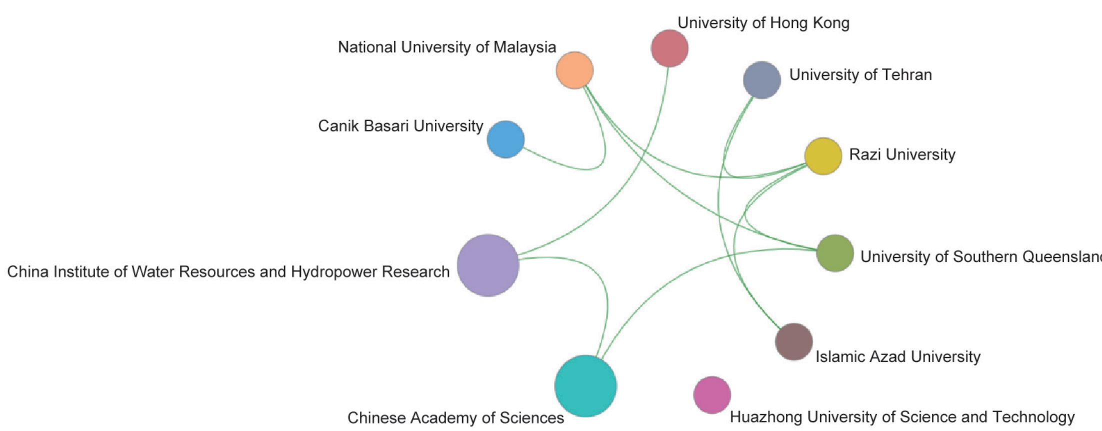

Figure 1.2.2 Collaboration network among institutions in the engineering research front of "smart city and smart basin integrated sensing based on geospatiotemporal big data"

As shown in Table 1.2.3, the five most active countries in terms of paper citations were China, Iran, the United States, Vietnam, and Australia. The top five institutions in terms of citations of core papers were Ton Duc Thang University (Vietnam), Duy Tan University (Vietnam), University of Tehran (Iran), University of Tabriz (Iran), and the University of Southern Queensland (Australia) (Table 1.2.4). China ranked first in terms of the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this topic.

Summarizing the above statistical data, in terms of research trends concerning "smart city and smart basin integrated sensing based on geospatiotemporal big data," compared with their foreign counterparts, Chinese scholars have performed well and are gradually becoming leaders in the field.

1.2.2 Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes

Offshore engineering structures such as seaport wharfs, breakwaters, oil production platforms, submarine pipelines, cross sea bridges, subsea tunnels, and offshore wind power foundations confront severe operating environments and elevated safety risks. Under the action of wind, waves, currents, and earthquakes, the pore water pressure increases,

Table 1.2.3 Countries with the greatest output of citing papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	258	24.86%	2018.7
2	Iran	165	15.90%	2018.8
3	USA	151	14.55%	2018.4
4	Vietnam	84	8.09%	2019.3
5	Australia	73	7.03%	2018.8
6	India	63	6.07%	2018.5
7	South Korea	62	5.97%	2018.5
8	Turkey	50	4.82%	2018.3
9	Malaysia	47	4.53%	2018.6
10	Canada	46	4.43%	2018.7

Table 1.2.4 Institutions with the greatest output of citing papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Ton Duc Thang University	63	17.36%	2019.2
2	Duy Tan University	47	12.95%	2019.5
3	University of Tehran	40	11.02%	2018.3
4	University of Tabriz	33	9.09%	2018.8
5	University of Southern Queensland	31	8.54%	2018.4
6	Chinese Academy of Sciences	27	7.44%	2018.3
7	Huazhong University of Science and Technology	27	7.44%	2018.7
8	University of California, Santa Barbara	25	6.89%	2018.0
9	Hohai University	25	6.89%	2019.0
10	Ilia State University	23	6.34%	2019.1

and the effective stress decreases in the foundation of the seabed. This can lead to the strength-weakening and liquefaction of the seabed soil. At the same time, the action of waves and currents can scour the seabed foundation. In addition, structural movements under the action of dynamic loads can also change the pore water pressure and effective stress in the seabed soil, complicating the bearing capacity of the seabed foundation. The coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes are key issues for the safety and durability of offshore engineering structures.

The dynamic responses of seabed foundations and their coupling effect with structures are core problems in the coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes. There are three types of response models for seabed foundations: the Laplace, diffusion, and Biot consolidation equations. Both the Laplace and diffusion equations assume that the soil skeleton is not deformable and consider the pore fluid to be either incompressible or compressible. The coupling effect between the soil skeleton and pore fluid is not considered in either model. The Biot consolidation equation assumes that the soil skeleton is deformable, the pore fluid is compressible, and the fluid motion satisfies Darcy's law. Moreover, it considers the acceleration of both the soil skeleton and the pore fluid. Although the coupling effect of the soil skeleton and pore fluid are considered in the Biot consolidation equation, the constitutive model of the seabed soil is limited in the elastic range. In modelling the coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes, most methods apply various dynamic actions on the structure as loads and do not consider the response effect of the seabed foundations under dynamic actions.

The main topics to be addressed in this field include the following:

(1) The mechanisms and evolution of the strength-weakening and liquefaction of different seabed foundations (gravel, sand, soft clay, etc.) under the action of different periodic cyclic loads such as waves, earthquakes, and structural motions;

(2) An elasto-plastic constitutive model that accounts for the processes of strength-weakening, liquefaction, and excess pore pressure dissipation and consolidation after the liquefaction and re-liquefaction of different types of seabed soil under the action of cyclic loads;

(3) Scouring models of different seabed foundations that consider seepage effects under the action of waves and currents;

(4) Coupled numerical models for the nonlinear dynamic analysis of cyclic load–marine structure–seabed foundation systems and efficient, reliable numerical simulation methods; and

(5) Basic theory and experimental technology to test physical models to investigate the bearing capacity of cyclic load–marine structure–seabed foundation systems.

As listed in Table 1.1.1, between 2014 and 2019, 40 core papers concerning "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes." On average, each paper was cited 31.78 times. The top five countries in terms of core-paper output were China, Australia, Denmark, the United Kingdom, and the Netherlands (Table 1.2.5). China was the most active country in this front, producing 57.50% of the core papers. The top five countries in terms of the average number of citations per paper were the Netherlands, the United States, Denmark, the United Kingdom, and Mexico. In terms of core-paper citations, papers published by Chinese authors were cited 26.87 times per paper on average, indicating that researchers in China are gradually gaining attention. As illustrated by the international collaborative network depicted in Figure 1.2.3, relatively close cooperation was observed between China, Australia, and the United Kingdom.

As listed in Table 1.2.6, the five institutions publishing the highest number of core papers were Griffith University (Australia), Technical University of Denmark (Denmark), Hohai University (China), Chinese Academy of Sciences (China), and Shanghai Jiao Tong University (China). In recent years, researchers from Griffith University have conducted in-depth, systematic studies on the dynamic responses of seabed foundations under the action of waves and currents, while researchers from the Technical University of Denmark have

Table 1.2.5 Countries with the greatest output of core papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	23	57.50%	618	26.87	2016.7
2	Australia	19	47.50%	491	25.84	2016.8
3	Denmark	12	30.00%	458	38.17	2015.7
4	UK	10	25.00%	350	35.00	2016.5
5	Netherlands	5	12.50%	230	46.00	2014.8
6	Belgium	3	7.50%	80	26.67	2017.7
7	USA	2	5.00%	79	39.50	2014.0
8	Turkey	2	5.00%	33	16.50	2017.0
9	Mexico	1	2.50%	28	28.00	2016.0
10	Norway	1	2.50%	17	17.00	2018.0

conducted research on seabed scouring around pipelines and vertical circular cylinders under the action of waves and currents. As illustrated in Figure 1.2.4, the top 10 institutions have cooperated closely.

The five countries with the most citations of core papers were China, the United Kingdom, Australia, Norway, and the United States (Table 1.2.7). The five institutions with the most citations of core papers were Hohai University (China), Shanghai Jiao Tong University (China), Griffith University (Australia), Technical University of Denmark (Denmark), and Ocean University of China (China) (Table 1.2.8). China ranked first in terms of both the number of published core papers and the number of citations of core papers, indicating that Chinese researchers have paid close attention to this research front.

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

Table 1.2.6 Institutions with the greatest output of core papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Griffith University	16	40.00%	411	25.69	2016.8
2	Technical University of Denmark	12	30.00%	458	38.17	2015.7
3	Hohai University	10	25.00%	224	22.40	2017.6
4	Chinese Academy of Sciences	7	17.50%	241	34.43	2015.6
5	Shanghai Jiao Tong University	7	17.50%	185	26.43	2016.6
6	Deltares	5	12.50%	230	46.00	2014.8
7	University of Bradford	5	12.50%	125	25.00	2017.6
8	Zhejiang University	3	7.50%	54	18.00	2018.7
9	Ningbo University	3	7.50%	52	17.33	2017.7
10	University of Dundee	2	5.00%	86	43.00	2014.5

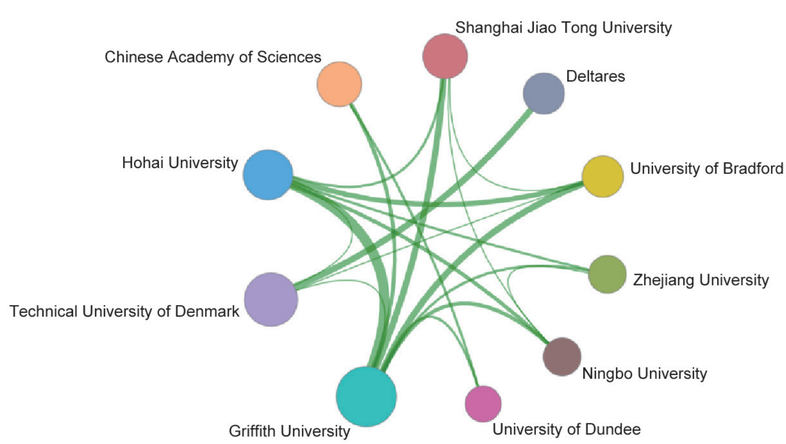

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

Table 1.2.7 Countries with the greatest output of citing papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Country	Citing papers	Proportions of citing papers	Mean year
1	China	327	38.97%	2018.3
2	UK	109	12.99%	2018.0
3	Australia	101	12.04%	2017.7
4	Norway	68	8.10%	2018.3
5	USA	62	7.39%	2018.2
6	Denmark	61	7.27%	2017.6
7	Netherlands	27	3.22%	2016.7
8	Italy	25	2.98%	2018.5
9	France	20	2.38%	2018.3
10	Spain	20	2.38%	2017.7

Table 1.2.8 Institutions with the greatest output of citing papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hohai University	70	17.07%	2018.4
2	Shanghai Jiao Tong University	60	14.63%	2017.8
3	Griffith University	52	12.68%	2017.9
4	Technical University of Denmark	41	10.00%	2017.4
5	Ocean University of China	37	9.02%	2018.2
6	University of Western Australia	32	7.80%	2017.3
7	Chinese Academy of Sciences	30	7.32%	2017.4
8	Zhejiang University	26	6.34%	2018.6
9	Dalian University of Technology	24	5.85%	2017.8
10	Norwegian University of Science and Technology	20	4.88%	2018.2

1.2.3 Urban spatial analysis and optimization methods based on big data

With the development of internet technologies, the paradigm of urban spatial analysis is being transformed by the emergence of new big data that are geo-referenced, such as cell phone data, public transport tap-in/out data, and social media check-ins. The advantages of this type of data include its large size, fine resolution, and wide coverage. These data record various human behaviors across time and space with a new level of precision, thereby forming new pipelines for us to observe, perceive, and interpret cities and their transformation. Spatial analysis and optimization based on urban big data are thus frontiers for urban studies and practices.

Three domains of urban studies are involved in this front. The first is urban observation based on human behavior data, which enables our understanding of the spatial characteristics of urban elements and improves the sensitivity of the statues of various urban sub-systems, such as populations, workplaces, public service, and transport. This domain has been well explored. The second domain is urban diagnosis and performance evaluation. On the basis of human behavior data, research in this domain evaluates urban performance, including commuting and the work–life balance, population distribution, and accessibility, in terms of urban sufficiency and equality. The output of such studies is strongly related to urban optimization. Most of these efforts, however, have not yet produced applications as they have focused on problem detection and methodological developments without a convergent form for applications. The third domain is the reformation of the relevant urban theory. This reformation has been enabled by the discovery and definition of new rules of urbanization with the intelligent simulation, integration, and prediction of urban systems and their transformation. Research in this domain is still limited, but it has been widely recognized as an essential direction.

A new era of urban science and research is now being encouraged by the availability of urban big data. The main focus of current efforts is to bridge research and practice using various emerging technologies for spatial analysis and optimization. The ultimate aim of such efforts is to facilitate smart cities with theoretical innovations of the new urban science.

The institutions leading the relevant research are located in the West in developed countries or districts, such as the United States, the United Kingdom, and the European Union and in rapidly developing countries and areas, such as China. Developed countries typically maintain more comprehensive research systems and networks with the solid establishment of theory, methods, and applications, whereas rapidly developing countries, particularly China, stand out for the large size of their urban big data due to their population size, optimism regarding new technologies, and good software and hardware facilities.

The world-leading institutions in this front include the Massachusetts Institute of Technology (e.g., Media Lab), University College London (e.g., the Centre for Advanced Spatial Analysis and Urban Dynamic Lab), Swiss Federal Institute of Technology in Zurich (e.g., Future City Lab), Alan Turing Institute, Google, Twitter, and Microsoft. The leading institutes in China include Tongji University (e.g., China Intelligent Urbanization Co-creation Centre for High-Density Regions), University of Chinese Academy of Sciences, Tsinghua University, Peking University, Alibaba, Tencent, Huawei, and Jingdong. Universities are the majority among these institutes because of their interdisciplinary advantage in incorporating urban planning, geography, computer science, geographical information science, etc., in a new urban science, which has led to their dominance in this research. As a complement to this research, technology companies utilize their data sources and advanced facilities for data storage, computation, and real-time applications via their internet platforms.

Thanks to the complementary advantages of diverse sectors, the forms of cooperation on this front vary greatly. The main types include multi-sector cooperation across many universities, governments, associations, and enterprises (e.g., China Intelligent Urbanization Co-creation Centre for High-Density Regions), cross-university cooperation (e.g., Alan Turing Institute), and institute–enterprise cooperation (e.g., CAUPD-Alibaba Future City Lab).

As listed in Table 1.1.1, between 2014 and 2019, 58 core papers concerning "urban spatial analysis and optimization methods based on big data" were published, and on average each paper was cited 42.43 times. The top five countries in terms of core-paper output were China, the United States, Norway, Australia, and the United Kingdom (Table 1.2.9). As one of the leading research countries, China published 41.38% of the core papers on this research front. The top five countries in terms of the average number of citations per paper were the United Kingdom, Switzerland, Singapore, Norway, and the United States. On average, the papers published by Chinese authors received 49.54 citations per paper, which is slightly above the overall average. From the perspective of cooperation networks between countries (Figure 1.2.5), close cooperation has been observed among the most productive ten countries particularly between the United States and China.

The five institutions producing the most core papers on this front are Wuhan University (China), Norwegian University of Science and Technology (Norway), Sun Yat-Sen University (China), Peking University (China), and Arizona State University (USA) (Table 1.2.10). Wuhan University is the leader in the fields of spatial analysis with big data and the measurement, computation, and redefinition of urban structures and their transformation. The Norwegian University of Science and Technology is a pioneer in the research of environmental sensing and smart sustainable urbanization supported by the Internet of Things (IoT), information and communication technology, and other emerging technologies. From the perspective of cooperation network among the leading institutions (Figure 1.2.6), collaborative studies have been conducted by the top 10 most productive institutions on this front, except for the Norwegian University of Science and Technology.

The top five countries in terms of citations of core papers are China, the United States, the United Kingdom, Spain, and Australia (Table 1.2.11). The top five institutions in terms of

Table 1.2.9 Countries with the greatest output of core papers on "urban spatial analysis and optimization methods based on big data"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	24	41.38%	1189	49.54	2017.4
2	USA	14	24.14%	856	61.14	2016.5
3	Norway	6	10.34%	425	70.83	2017.0
4	Australia	6	10.34%	110	18.33	2018.0
5	UK	5	8.62%	704	140.80	2015.2
6	Netherlands	5	8.62%	106	21.20	2017.4
7	Spain	4	6.90%	215	53.75	2016.2
8	Japan	4	6.90%	158	39.50	2016.5
9	Switzerland	3	5.17%	244	81.33	2014.7
10	Singapore	3	5.17%	217	72.33	2016.3

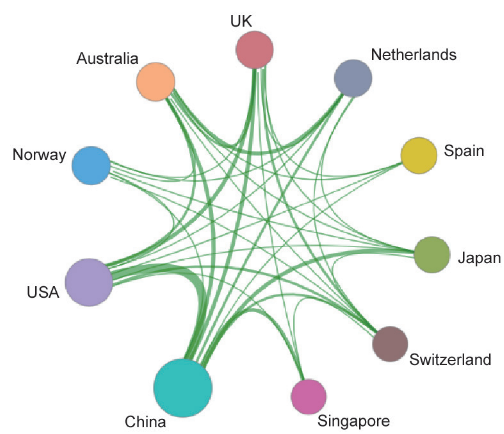

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "urban spatial analysis and optimization methods based on big data"

Table 1.2.10 Institutions with the greatest output of core papers on "urban spatial analysis and optimization methods based on big data"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Wuhan University	5	8.62%	180	36.00	2017.4
2	Norwegian University of Science and Technology	4	6.90%	333	83.25	2017.5
3	Sun Yat-Sen University	4	6.90%	183	45.75	2017.2
4	Peking University	3	5.17%	172	57.33	2016.3
5	Arizona State University	3	5.17%	114	38.00	2015.3
6	Texas State University	3	5.17%	67	22.33	2017.0
7	Chinese Academy of Sciences	3	5.17%	49	16.33	2017.7
8	University College London	2	3.45%	593	296.50	2014.0
9	Kyungpook National University	2	3.45%	237	118.50	2016.5
10	Nanyang Technological University	2	3.45%	199	99.50	2016.0

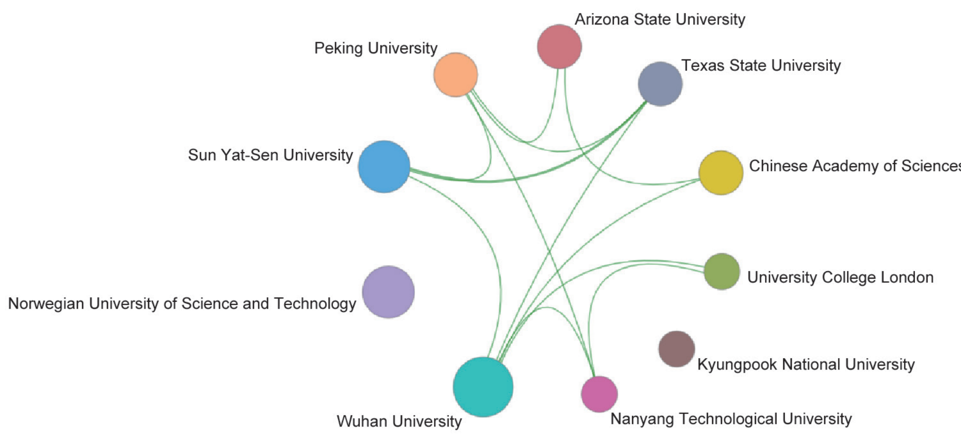

Figure 1.2.6 Collaborative network among major institutions in the engineering research front of “urban spatial analysis and optimization methods based on big data”

Table 1.2.11 Countries with the greatest output of citing papers on “urban spatial analysis and optimization methods based on big data”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	842	35.56%	2018.4
2	USA	510	21.54%	2018.1
3	UK	208	8.78%	2018.2
4	Spain	144	6.08%	2018.2
5	Australia	131	5.53%	2018.2
6	Italy	129	5.45%	2018.0
7	France	114	4.81%	2018.1
8	Germany	78	3.29%	2018.1
9	Japan	74	3.13%	2017.9
10	Canada	70	2.96%	2018.1

citations of core papers are Chinese Academy of Sciences (China), Wuhan University (China), Massachusetts Institute of Technology (USA), Sun Yat-Sen University (China), and Peking University (China) (Table 1.2.12). China ranked first in terms of the number of published core papers and citations of core papers, indicating that Chinese researchers have paid close attention to research performed on this front.

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including structural engineering, landscape and urban panning, transportation engineering, geotechnical and underground engineering, bridge engineering, construction materials, municipal engineering, hydraulic engineering, and geodesy and survey engineering. Among these development fronts, experts recommended the following: “planning and design technologies for public health emergency responses,” “deep-water detection of latent defects and treatment technologies for water conservancy projects,” “city information modeling,” “regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments,” “regulable design of ultra-high-performance concrete,” “technology and equipment

Table 1.2.12 Institutions with the greatest output of citing papers on "urban spatial analysis and optimization methods based on big data"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	101	19.77%	2018.0
2	Wuhan University	79	15.46%	2018.4
3	Massachusetts Institute of Technology	45	8.81%	2017.5
4	Sun Yat-Sen University	42	8.22%	2018.5
5	Peking University	42	8.22%	2018.3
6	University of Chinese Academy of Sciences	39	7.63%	2018.3
7	Zhejiang University	35	6.85%	2018.5
8	Tsinghua University	33	6.46%	2018.4
9	Microsoft Research Asia	32	6.26%	2016.4
10	Xidian University	32	6.26%	2018.1

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic, and architecture engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Planning and design technologies for public health emergency responses	38	22	0.58	2017.4
2	Intelligent construction technology and equipment for underground projects under extreme conditions	274	578	2.11	2017.5
3	Deep-water detection of latent defects and treatment technologies for water conservancy projects	90	181	2.01	2016.8
4	Design and construction technologies of earthquake-resilient structural systems	509	1 711	3.36	2016.2
5	City information modeling	150	418	2.79	2017.0
6	Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments	473	977	2.07	2016.5
7	Regulable design of ultra-high-performance concrete	15	17	1.13	2017.1
8	Precise positioning and safe navigation technology for high-speed trains	24	84	3.5	2017.0
9	Technology and equipment for leakage monitoring and in-situ repair for urban water supplies and drainage networks	177	233	1.32	2017.1
10	Earth observation and geospatial information processing technologies based on the blockchain	10	34	3.40	2018.8

for leakage monitoring and *in-situ* repair for urban water supplies and drainage networks," and "Earth observation and geospatial information processing technologies based on the blockchain." The remaining topics were identified from patent maps and then confirmed by experts. Table 2.1.2 presents annual statistical data on patents published between 2014 and 2019 related to these top 10 development fronts.

(1) Planning and design technologies for public health emergency responses

Urban planning and design can play a pivotal role in responses to public health emergencies involving space interventions since urban development has inevitable effects on human contact with infection sources, the mode of transmission and processes of infectious diseases, and the number of people who are susceptible via both ecological and social processes in the urban space. Although there are no wholly specific planning and design technologies for public health emergency responses, existing technologies for land use and urban ecology identification, the construction of the 3D urban physical space and environmental models, environmental pollution monitoring and assessment, etc. contribute to

Table 2.1.2 Annual number of patents published for the top 10 engineering development fonts in civil, hydraulic & architecture engineering

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Planning and design technologies for public health emergency responses	2	5	3	7	8	13
2	Intelligent construction technology and equipment for underground projects under extreme conditions	15	20	31	50	76	82
3	Deep-water detection of latent defects and treatment technologies for water conservancy projects	14	17	7	11	21	20
4	Design and construction technologies of earthquake-resilient structural systems	54	57	79	90	85	95
5	City information modeling	8	15	19	29	38	33
6	Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments	62	46	77	80	87	87
7	Regulable design of ultra-high-performance concrete	2	2	3	0	1	7
8	Precise positioning and safe navigation technology for high-speed trains	3	1	1	2	3	12
9	Technology and equipment for leakage monitoring and in-situ repair for urban water supplies and drainage networks	13	13	34	28	30	53
10	Earth observation and geospatial information processing technologies based on the blockchain	0	0	0	1	0	9

isolating infection sources and blocking disease transmission routes. The effects and capabilities of these technologies can be improved in terms of their pertinence to infectious diseases, disclosure of transmission mechanisms, provision of accurate predictions, and applicability to planning and design.

Furthermore, it is necessary to promote the research and development (R&D) of technology in this field in terms of three aspects: the big data-based analysis of the spatiotemporal behavior of residents and traffic, comprehensive construction of public health units, and comprehensive spatial layout of healthcare facilities based on social equity. With efforts focused on these aspects, the capability of the urban space to respond to public health emergencies will be improved, the planning and building of healthy cities be facilitated, and more scientific and reasonable planning and design strategies be formulated. The health of urban spaces has received increased attention due to the global COVID-19 pandemic, making the development and testing of planning and design technologies for public health emergency responses imperative for better planning and building of healthy cities. Between 2014 and 2019, 38 patents relevant to this research front were published. These patents received 22 citations, with an average of 0.58 citations per patent.

(2) Intelligent construction technology and equipment for underground projects under extreme conditions

The aim of this topic is the rapid, industrialized construction of underground projects under extreme conditions with little or no human intervention. Extreme conditions include extreme natural environments and ultra-complex geological conditions, for example, high altitude, high ground temperature, high ground stress, and high water pressure. To achieve this goal, intelligent techniques (e.g., design, production and processing, construction, operation and maintenance, and R&D) and automated, intelligent equipment should be developed. In extreme natural environments, the tolerance limits of personnel and equipment and the working efficiency of mechanical equipment decreases sharply. Meanwhile, eco-environmental protection regulations have become extremely strict. Nevertheless, in extremely complex geological conditions, chain geological disasters can occur very easily, causing major accidents. For rapid construction with little or no human intervention, the industrial construction capacity under extreme conditions must be dramatically improved. Improvement can be achieved by studying the essential theory and key techniques of intelligent construction methods and by developing intelligent equipment that can coordinate with humans and engage in self-directed learning. The main research interests on this front include the following: 1) basic theories for intelligent construction that integrates the acquisition, design, and construction steps of underground engineering; 2) basic digital design platforms and integrated, intelligent design systems; 3) digital, intelligent production and processing of lining structures; 4) geological disaster prediction, intelligent construction control, and the monitoring and detection of engineering quality under extreme conditions; 5) intelligent equipment capable of coordinating with humans and learning autonomously under extreme conditions; and 6) online monitoring, intelligent diagnosis, and automatic maintenance of underground engineering under extreme conditions.

At present, the development of intelligent construction technology and equipment for underground projects is focused on three aspects: 1) forming basic theories for intelligent underground engineering construction, 2) developing geological disaster prediction techniques under extreme conditions, and 3) studying and manufacturing intelligent construction equipment suitable for extreme conditions. Between 2014 and 2019, 274 patents relevant to this research front were published. These patents received 578 citations, with an average of 2.11 citations per patent.

(3) Deep-water detection of latent defects and treatment technologies for water conservancy projects

Water conservancy projects are important for the regulation of the spatial and temporal distribution of water resources and for the optimization of the allocation of water resources. Moreover, they play an important role in control engineering systems for river floods. Due to the aging of water conservancy project structures and consequent deterioration in their performance and the impact of environmental changes coupled with earthquakes and geological disasters, dangerous situations occur occasionally. The deep-water detection of latent defects and treatment technology has become a frontier in this field. Its core consists of underwater detection equipment, diving technology, and underwater operation technology.

The deep-water detection technologies primarily address underwater leakage detection, underwater structural defect detection, metal structure detection, and underwater exploration. In this case, the technical equipment is used for carrying, testing, and working on underwater projects, and it primarily consists of manned diving technologies and related equipment, manned submersible vehicles, unmanned diving equipment (underwater robots), and equipment for underwater detection, cleaning, cutting, welding, and other special underwater tasks. Underwater latent defects treatment technologies mainly address leakage treatment, structural reinforcement and defect treatment, metal structure anticorrosion treatment, and related construction technologies. In addition, it is necessary to conduct underwater inspection and dredging, gate sealing, and other treatment processes for water discharge and conveyance during project operations and reinforcements. The main areas of development on this front include the research and development of latent defects detection equipment for water conservancy projects under complex conditions in deep-water, high-precision positioning technology for deep-water environments and underwater detection and operation, high-resolution analytical technology for low-visibility environments, and repair and reinforcing materials and processes for deep-water environments. The deep-water detection of latent defects and treatment technology for water conservancy projects are important to ensuring the long-term safety of water conservancy projects. This front serves reservoir dams, sluices, gates and embankments, long-distance water diversions, transfer projects, etc. and has broad development prospects. Between 2014 and 2019, 90 patents relevant to this research front were published, and these patents received 181 citations, with an average of 2.01 citations per patent.

(4) Design and construction technologies of earthquake-resilient structural systems

Engineering structures are the most important elements of an earthquake-resilient city, the construction of which requires that engineering structures not only resist earthquakes and prevent damage but also have the ability to recover after an earthquake. An earthquake-resilient structure transforms the material nonlinear problem of a traditional system into a geometric nonlinear problem of a resilient structure. It forms a new recoverable functional system with controllable damage, concentrated elastic–plastic deformation, greater deformation capacity, and smaller residual deformation under strong earthquakes. There are three main types of earthquake-resilient structures: structural systems with rocking members, structural systems with self-centering members, and structural systems with replaceable components. At present, the development frontiers for the design and construction of earthquake-resilient structures are mainly focused on 1) new earthquake-resilient systems with coordinated mass-stiffness damping; 2) four-level seismic fortification objectives and multi-performance indicators; 3) direct displacement-based design methods for earthquake-resilient structures; 4) earthquake resilience technologies for non-structural components; and 5) rapid construction and post-quake recovery technologies for earthquake-resilient structures. Between 2014 and 2019, 509 patents were published on this topic with 1711 patent citations and an average of 3.36 citations per patent.

(5) City information modeling

City information modeling (CIM) is a digital platform at the city level that is an advance from building information modeling (BIM). CIM extracts and fuses data from BIM at the micro level, data from a geographic information system (GIS) at the macro level, and data captured by IoT to form a 3D city model and city-integrated information body that comprehensively depicts the dynamic reality of a city. More complete data models and the integration of city information are supported by the spatial features provided by GIS, detailed building characteristics supplied by BIM, and city dynamics obtained from the IoT. In addition to the vivid visualizations offered by its 3D city models, CIM provides feature data that cover various city components and that are available anywhere, anytime.

CIM has the capability to sense, analyze, share, compute, and judge in order to effectively address issues encountered during city development. It is able to simulate city operations and regulations. Furthermore, it can evaluate development strategies based on embedded data (models). Built on top of a solid information platform and enhanced by state-of-the-art techniques, including AI, big data analysis, and 3D modeling, CIM is able to more intelligently support urban planning, urban development, and urban governance. CIM is the core and foundation of smart city development and refined urban management.

Between 2014 and 2019, 150 patents relevant to this research front were published. These patents received 418 citations, with an average of 2.79 citations per patent.

(6) Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments

The extreme service environments of engineering structures include ultra-low temperatures, ultra-high temperatures, strong corrosion, strong radiation, strong magnetic fields, ultra-high pressure, strong vacuums, and complex loads. Such extreme environmental effects can lead to serious deterioration in the performance of cement-based materials in normal service and can seriously threaten the safety of engineering structures. With the expansion of the field of human exploration and the development of construction technologies, major countries have increased demand for extreme environmental engineering construction. Cement-based materials for extreme environments therefore have broad application prospects in many future extreme environment scenarios. Hence, it is necessary to study the evolution of the mechanical properties and durability of cement-based materials in extreme environments.

The microstructure of cement-based materials is closely related to their performance. To improve the safety and service life of cement-based materials in extreme environments, the development of a common microstructure regulation technologies based on the performance requirements of cement-based materials can be effective. To fulfill this goal, advanced testing and characterization methods combined with computer simulation technology should be adopted to study the evolution of the microstructural characteristics of cement-based materials in extreme environments at multiple scales in order to reveal deep-level deterioration and damage mechanisms. Corresponding multi-scale composite structure regulation methodologies have been proposed from the perspective of raw material optimization screening, mixed proportion optimization design, and micro-structure construction and design. In view of the structural performance requirements under different extreme environments, special attention should be given to the development of hydration processes for cement-based materials, the spatialtemporal distribution regulation of hydration products, calcium-silicate-hydrate micro and nano properties, pore structure optimization, and enhancement of the interface transition zone.

Between 2014 and 2019, 473 patents relevant to this research front were published. These patents received 977 citations, with an average of 2.07 citations per patent.

(7) Regulable design of ultra-high-performance concrete

Ultra-high-performance concrete (UHPC) has been one of the most innovative cement composite materials for the last 20 years. Its design and production are mainly based on the close packing of particles, which can be achieved by reducing the porosity, improving the microstructure, increasing the homogeneity, and increasing the toughness. Compared to conventional cement-based materials, UHPC has ultra-high strength, high toughness, and excellent durability. These superior properties make UHPC a good candidate to meet the requirements of lightweight, high rises, large spans, and high durability for civil engineering construction. Thus, it has great potential applications in bridges, anti-explosion structures, thin-walled structures, architectural ornaments, marine structures, and rehabilitated and strengthening members. By changing its internal components and modifying the preparation technology, key properties, including toughness, abrasion resistance, elastic modulus, repair compatibility, and resistivity, can be controlled, enabling its application for different aspects of civil engineering. Under the premise of fully understanding its material and microstructure characteristics, the wide and precise application of UHPC in various engineering fields can be achieved according to the engineering requirements. This can significantly enhance the safety, service life, and social sustainability of the structures.

Between 2014 and 2019, 15 patents relevant to this research front were published, and these patents received 17 citations, with an average of 1.13 citations per patent.

(8) Precise positioning and safe navigation technology for high-speed trains

The railways of China have entered the high-speed era, and it is of great significance to increase the running density of high-speed trains, improve transport efficiency, and ensure transport safety. Precise positioning and safe navigation technology for high-speed trains is the primary technical means of ensuring the safety and efficiency of high-speed railway transportation. This technology uses multi-sensor fusion methods to reliably and accurately measure the real-time position, speed, acceleration, and attitude of high-speed trains in order to ensure their safe navigation and motion blocks.

The precise positioning and safe navigation of high-speed trains require accurate, real-time performance. Owing to the complex changing environment of high-speed trains, a single sensor such as global navigation satellite system (GNSS), inertial navigation system, on-board speed radar, wheel speed encoder, or response beacon cannot guarantee the precise positioning of the train with sufficient spatial and temporal resolution across an entire area. For example, the accuracy of GNSS cannot be guaranteed in canyon areas and cannot even be located in tunnels, the positioning error of inertial navigation systems accumulates over time, and the spatial resolution of transponder beacons is insufficient. To ensure that the positioning of a train meets the accuracy requirements over the whole travel area, it is first necessary to select a sensor with sufficient observation accuracy and a sufficient sampling rate. Network real-time kinematic positioning, for example, can reach centimeter-level accuracy. Second, it is necessary to conduct joint observation using the above-mentioned multiple sensors in a unified spatial and temporal reference framework. Most importantly, an effective data fusion processing method, such as Kalman filtering and its derivative methods, is needed.

The technology also needs to meet reliability requirements. To guarantee reliability redundant communication channels and observation information are required. To reliably provide precise state information about trains, it is necessary to use observation anomaly detection methods to identify sensor faults and gross errors, to perceive abnormal jumps in train position, speed, acceleration, and attitude through state anomaly detection methods, and to use robust estimation methods.

In the future, high-speed trains will travel at even greater speeds. The key research directions in this field are as follows: precision positioning that integrates multiple high-dynamic sensors; resilient positioning, navigation, and timing of high-speed trains; observation, and state anomaly detection and processing by multiple high-dynamic sensors.

Between 2014 and 2019, 24 patents relevant to this research front were published, and these patents received 84 citations, with an average of 3.5 citations per patent.

(9) Technology and equipment for leakage monitoring and *in-situ* repair for urban water supplies and drainage networks

The efficient application of technologies and equipment for leakage monitoring and *in-situ* remediation of pipelines could greatly alleviate socioeconomic stresses by reducing the average leak duration. Based on the real-time monitoring of the pressure and flowrate of water distribution networks by the supervisory control and data acquisition system, the whole scheme for leakage identifying, locating, and repairing processes could be established by model-driven and data-driven methods. The current data-driven leakage monitoring method is confronting with the challenge of accurately identifying leakages with specific supervising history data that is limited in quantity and quality, whereas the challenge to the steady or transient model-driven leakage monitoring method lies in the validation of the hydraulic model, optimization of the monitoring location, and identification of the leakage characteristics in the surveillance area. With the rapid development of the IoT and AI technology, the integration of data-driven modelling techniques and high-performance equipment for leakage detection represent the main future trend in this field. In contrast, the leakage monitoring technology for drainage systems is still in a preliminary stage and is limited by problems such as the difficulty of installation and cumbersome preservation of the monitoring devices, unstable data acquisition for tracking the level and flowrate in pipelines, and low precision of the hydraulic model. Accordingly, the key scientific research on cutting-edge technologies in this field may include the development of leakage monitoring devices, the technology of leakage identification and location via the statistical analysis of the monitoring data, and the establishment of highly accurate hydraulic models and their validation. Regarding *in-situ* remediation techniques coordinated with the pipe rehabilitation supporting measures, the main techniques include local rehabilitation, rehabilitation dominated by polyolefin material, cured-in-place pipe (CIPP), and rehabilitation with liquid solidified material. Due to the potential significant economic and social benefits, trenchless rehabilitation is gaining increasing attention.

Between 2014 and 2019, 177 patents relevant to this research front were published, and these patents received 233 citations, with an average of 1.32 citations per patent.

(10) Earth observation and geospatial information processing technologies based on the blockchain

Earth observation and geospatial information processing technologies based on the blockchain are development frontiers in the field of surveying and mapping engineering. These frontiers are oriented to the distributed processing requirements of earth observation data and geospatial information. The techniques adopt a blockchain data structure, distributed node consensus algorithm, encrypted data transmission and access technology, intelligent contract data operation mode, and other core technologies, and provide a new distributed processing infrastructure and computing paradigm for earth observation data and geospatial information. The main development directions include: 1) sharing technology for remote sensing data of earth observation based on the blockchain to prevent illegal tampering and the dissemination of remote sensing images and to control and use of remote sensing images; 2) user participation based on the generation of geospatial information and updating the technology based on the blockchain; and 3) distributed geographic information service systems based on the blockchain that provide location services for vehicles and unmanned aerial vehicles.

Between 2014 and 2019, 10 patents relevant to this research front were published. These patents received 34 citations, with an average of 3.4 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Planning and design technologies for public health emergency responses

As urbanization continues, changes in habitats and high population density have increased the occurrence and spread of infectious diseases in cities. Ecological impact processes, such as changes in land use, urban heat island effects, and alterations in food production characteristics, together with social impact processes brought about by changes in the population, built environment, and lifestyle have had a decisive impact on the prevalence of infectious diseases. For spatial interventions, urban planning and design can play a pivotal role in isolating the sources of an infection, blocking transmission routes, and protecting susceptible groups.

Although at present there are no planning and design technologies specifically for public health emergency responses, existing technologies for land use and urban ecology identification, the construction of 3D urban physical spaces and environmental models, and environmental pollution monitoring and assessment can be used to isolate infection sources and block transmission routes. Nevertheless, the applicability of these technologies has yet to be further explored, and there is opportunity for improvement in their pertinence to the analysis of public health emergency responses and the scientific validity of planning and design interventions. Details for each of these technologies are as follows:

(1) Land use and urban ecology identification

At present, urban land use and urban ecology identification systems have been established based on data collection and classification, analysis and summary, and storage and monitoring. These systems can provide clues about the areas where infectious disease pathogens may exist, but their accuracy and predictive ability are still insufficient. In the future, it will be necessary to adopt machine learning to analyze the evolution of land use from the perspective of historical development. In tandem with ecological analyses, future technologies need to be applied to reveal the possible risks and impacts of pathogen exposure caused by urban expansion and habitat changes and to predict the risk of public health emergencies.

(2) Construction of 3D urban physical spaces and environmental models

The existing 3D space virtual construction technology for whole cities or specific spatial objects, such as a campus, can explicitly demonstrate multi-temporal and multi-level urban spatial forms and environmental characteristics and provide essential support for the regulation of urban activities and projects (e.g., guiding tourists, municipal projects, and fire warnings). This technology may also serve as a critical basis for the study of the transmission characteristics of infectious diseases and for the formulation of space intervention programs.

(3) Environmental pollution monitoring and assessment

The current pertinent analytical technologies focus on soil, water, and air pollution, and most are composed of modules including detection or identification, analysis, assessment, and early warning. The R&D of future technologies needs to account for key places where the risk of acquiring infectious diseases is high (such as hospitals, supermarkets, live poultry trading markets, and transportation hubs) and comprehensively consider the interactive effects of multidimensional factors, with a view to provide positive insights for spatial planning and design.

Furthermore, efforts should be made to advance the R&D of technology in terms of the following three aspects in order to improve the capability of urban spaces to respond to public health emergencies, to facilitate the planning and construction of healthy cities, and to formulate more scientific and rational planning and design strategies. 1) The big data-based analysis of the spatiotemporal behavior of residents and traffic can help predict the modes of transmission and spread of diseases under different traffic organization and management patterns, thus providing support for new urban zoning for epidemic prevention. 2) The comprehensive construction of public health units can help complete community function nodes that can play a role in both normal conditions and epidemics on the basis of the “15-minute community life circle.” 3) The comprehensive spatial layout of healthcare facilities based on social equity will emphasize care for groups susceptible to infectious diseases (such as the elderly and children) so that healthcare facilities will be reasonably equipped to best treat them.

As listed in Table 2.1.1, 38 patents related to this topic were published between 2014 and 2019. The three countries that published the most patents were China, South Korea, and Japan (Table 2.2.1), with China contributing 86.84% of the patents. The average citations per patent of the Chinese patents was 0.52, demonstrating increased attention being paid to Chinese patents.

The five organizations that produced the most patents were GEOTWO Corporation (South Korea), Xi’an University of Science and Technology (China), Sanya China Remote Sensing Research Institute (China), China National Petroleum Corporation, and Anhui Science and Technology University (China) (Table 2.2.2). GEOTWO Corporation, a South Korea-based geographic information technology company, places one of its focuses on the research and development of urban land use monitoring and assessment technology. Xi’an University of Science and Technology focuses on developing technologies of land use monitoring and urban carbon emission measurement. Specializing in the measurement of vegetation net primary productivity, Sanya China Remote Sensing Research Institute develops most of its key technologies based on remote sensing data and machine learning models. As an organization dedicated to petroleum development and transportation, China National Petroleum Corporation has developed the technology to evaluate the environmental risks brought by oil longer conveying pipeline, providing an effective method to evaluate the impacts of related accidents on eco-system. The patented technology developed by Anhui Science and Technology University on land use status can simulate the pattern succession of land use. Though none of the technologies mentioned above are designed to directly respond to public health emergencies, they can not only serve as the technical basis for planning and design interventions, but also provide solutions and references for research and development of relevant analytical methods and technological tools in the future.

Table 2.2.1 Countries with the greatest output of patents on "planning and design technologies for public health emergency responses"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	33	86.84%	17	77.27%	0.52
2	South Korea	4	10.53%	5	22.73%	1.25
3	Japan	1	2.63%	0	0.00%	0.00

Table 2.2.2 Institutions with the greatest output of patents on "planning and design technologies for public health emergency responses"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GEOTWO Corporation	South Korea	2	5.26%	5	22.73%	2.50
2	Xi'an University of Science and Technology	China	2	5.26%	5	22.73%	2.50
3	Sanya China Remote Sensing Research Institute	China	1	2.63%	3	13.64%	3.00
4	China National Petroleum Corporation	China	1	2.63%	2	9.09%	2.00
5	Anhui Science and Technology University	China	1	2.63%	2	9.09%	2.00
6	Guangzhou Institute of Geography	China	1	2.63%	1	4.55%	1.00
7	ANA Company	South Korea	1	2.63%	0	0.00%	0.00
8	Anhui Chuanbai Technology Co., Ltd.	China	1	2.63%	0	0.00%	0.00
9	Anhui Provincial Academy of Environmental Sciences	China	1	2.63%	0	0.00%	0.00
10	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	China	1	2.63%	0	0.00%	0.00

2.2.2 Intelligent construction technology and equipment for underground projects under extreme conditions

In extreme natural environments, the tolerance limits of personnel and equipment and the working efficiency of mechanical equipment decrease sharply. Meanwhile, eco-environmental protection regulations have become extremely strict. Moreover, under extremely complex geological conditions, chain geological disasters can occur very easily, causing major accidents. Consider the Sichuan–Tibet railway and highway as examples. In these two projects, tunnel sections account for a large proportion of the total length and have a large burial depth, and the railway and highway pass through multiple highly active fault zones. They face significant geological problems, including high ground stress, rock burst, and the large deformation of soft rocks. These tunnel sections also have an ultra-high risk of encountering slope slides, rockfalls, and debris. Furthermore, the eco-environment along the railway and highway is sensitive and vulnerable due to particular environmental features of this region: huge changes in altitude, ultra-low temperatures on the plateaus in winter, and very high ground temperatures. The development of intelligent technology and equipment is thus urgent for their construction. The topic "intelligent construction and techniques to guarantee engineering health for the expressway into Tibet" was listed among the top 10 engineering and technical problems by the China Association for Science and Technology in 2020.

Studying and developing intelligent construction technologies and equipment for underground projects under extreme conditions are conducive to forming an intelligent industrial construction system. Such a system would encompass the entire industrial chain, including design, production and processing, construction and equipment, and operation and maintenance. It would also contribute to the promotion of new industries, new forms of business, and new modes and support the in-depth integration of industries related to underground engineering, which are cross-field, all-dimensional, and multi-level.

At present, the global underground engineering industry is developing effectively, but it faces problems such as the low level of standardization, informatization, and intelligence. A big gap remains between the underground engineering industry and advanced construction methods. With the development of a new scientific and technological revolution and ongoing industrial transformation, the new generation of information technology, represented by AI, big data, the IoT, and 5G, is accelerating in its penetration and assimilation into the underground engineering industry. To date, research interests concerning intelligent construction technology and equipment for underground engineering under extreme conditions include the following.

(1) Construction method. Traditional construction methods, such as NATM and ADECO-RS, use a dynamic feedback mechanism that continuously adjusts the construction scheme based on initial semi-empirical designs by constantly monitoring the excavation progress. Construction methods are now moving toward the integration of intelligent "acquisition–design–construction" with the development of emerging techniques for underground projects, including new sensing techniques, data transmission techniques, BIM/GIS, and information integration techniques.

(2) Design system. It comprises both digital design systems based on BIM/GIS and platforms that integrate information from the whole process, which is being developed to coordinate and unify design, manufacturing, construction, operation, and maintenance.

(3) Production and processing. Some studies are developing new production and processing techniques, including digital technical processes and the application of robots to digitalize and intellectualize the production of lining structures for underground projects. This may eventually lead to production factories with little or no human intervention.

(4) Intelligent construction. Studies on intelligent construction fall into two main categories. First, some studies have pursued detailed detection and intelligent control for geological disasters by developing intelligent prediction and control methods for geological disasters in underground projects under extreme conditions. Second, some studies focus on automating tunnel construction and reducing the number of on-site personnel and their workload with emerging techniques, such as the intelligent collection and feedback of construction site information, automatic stereo perception and positioning, digital twin platforms, expert remote diagnosis, intelligent detection, and project quality control.

(5) Intelligent equipment. Many intelligent devices are now being developed. They include intelligent equipment with man–machine coordination and an autonomous learning capacity, intelligent construction robots, automatically operational brain controllers, robotized equipment for environmental risk perception and precise operational control under extreme conditions, highly reliable intelligent and interconnected equipment, and intelligent and interconnected equipment for identifying and processing all types of geological environmental risk.

(6) Intelligent operation and maintenance. Studies of this topic include the online monitoring of the operation environment and structural health status of underground projects under extreme conditions, the intelligent diagnosis and maintenance of structural performance, accident prevention and rescue, and disaster alarms and control.

As listed in Table 2.1.1, 274 patents related to this topic were published between 2014 and 2019. The three countries that published the most patents were China, the United States, and Canada (Table 2.2.3). China contributed 91.97% of the patents. The average citations per patent of the Chinese patents was 1.62. As depicted in Figure 2.2.1, international cooperation on this topic has been rare among the top 10 core patent-output countries.

The five organizations that produced the most patents were the China Railway Group Limited, China University of Mining and Technology-Beijing, China Communications Construction Company Limited, State Grid Corporation of China, and Shandong University (China) (Table 2.2.4). Cooperation among these organizations is rare (Figure 2.2.2).

2.2.3 Deep-water detection of latent defects and treatment technologies for water conservancy projects

The research and development of deep-water detection and operation technologies originated in the field of marine engineering, to which they have been applied on a large scale. The traditional industrial powers are leaders in the research, development, and industrial production of such equipment.

The application environment of technologies such as deep-water detection, underwater operation, and repair of water conservancy projects differs substantially from the marine environment. The underwater detection, repair, and reinforcement techniques that are applicable to the marine environment cannot simply be transplanted and applied to newly introduced technologies. It is therefore necessary to

Table 2.2.3 Countries with the greatest output of patents on "intelligent construction technology and equipment for underground projects under extreme conditions"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	252	91.97%	408	70.59%	1.62
2	USA	15	5.47%	170	29.41%	11.33
3	Canada	2	0.73%	11	1.90%	5.50
4	Brazil	1	0.36%	0	0.00%	0.00
5	Japan	1	0.36%	0	0.00%	0.00
6	South Korea	1	0.36%	0	0.00%	0.00
7	Saudi Arabia	1	0.36%	0	0.00%	0.00

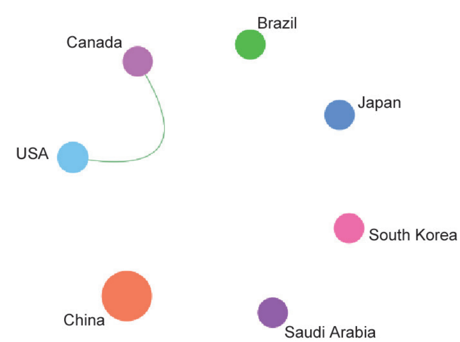

Figure 2.2.1 Collaboration network among countries in the engineering development front of "intelligent construction technology and equipment for underground projects under extreme conditions"

Table 2.2.4 Institutions with the greatest output of patents on "intelligent construction technology and equipment for underground projects under extreme conditions"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China Railway Group Limited	China	19	6.93%	16	2.77%	0.84
2	China University of Mining and Technology-Beijing	China	9	3.28%	12	2.08%	1.33
3	China Communications Construction Company Limited	China	7	2.55%	7	1.21%	1.00
4	State Grid Corporation of China	China	6	2.19%	6	1.04%	1.00
5	Shandong University	China	5	1.82%	12	2.08%	2.40
6	China University of Mining and Technology-Xuzhou	China	5	1.82%	10	1.73%	2.00
7	Southeast University	China	4	1.46%	16	2.77%	4.00
8	China Coal Technology & Engineering Group Corp	China	4	1.46%	5	0.87%	1.25
9	Chang'an University	China	4	1.46%	3	0.52%	0.75
10	Tongji University	China	3	1.09%	12	2.08%	4.00

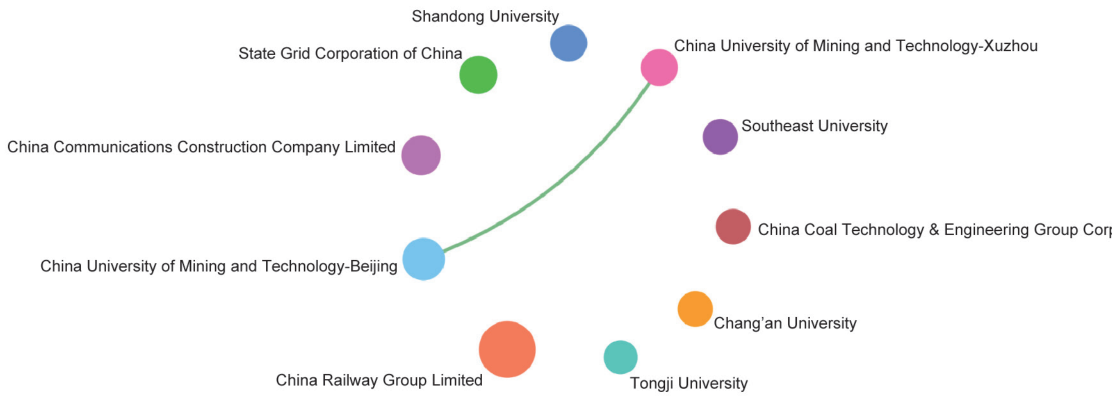

Figure 2.2.2 Collaboration network among institutions in the engineering development front of "intelligent construction technology and equipment for underground projects under extreme conditions"

produce renovations, improvements, and innovations in R&D according to the special water environments and boundary conditions of reservoir dams.

As one of the main tools for the exploration of the deep sea environment, remote-operated vehicles (ROVs) have played an important role in the exploitation of marine resources and scientific exploration of the deep sea and have long been a research focus of numerous countries. In recent years, ROVs have been used for search, dam detection, and safety inspections in reservoirs. Due to the special nature of the reservoir environment, the main application of ROVs to the water conservancy industry is observation class ROVs.

Abnormal leakages are a common issue in the operation of water conservancy projects. The existing underwater leakage detection and positioning technologies are mostly being applied experimentally in water conservancy projects. These technologies are applied in a limited manner with low accuracy, and at present they are the primary technical hurdle in the research on detection technologies for water conservancy projects.

Artificial diving operations are an irreplaceable means of underwater repair and reinforcement. The maximum depth of conventional air-diving operations is only 60 m, which does not meet the depth requirements of underwater operations for water conservancy projects. Although the most advanced conventional artificial diving can realize underwater detection and operation at depths of 100 m in deep-water environments, the artificial operation is inefficient, costly, and risky. Conventional artificial diving operations at depths exceeding 120 m remain impractical in terms of efficiency and cost, so saturated diving technologies have been adopted. To date, experiments have only been conducted at one high dam in Switzerland, and breakthroughs in adaptive equipment technology are urgently needed. It has become a priority to use ROVs, manned submersible vehicles, and other deep-water working platforms to develop unmanned operation technologies that can meet the needs of various underwater projects or to develop specialized saturated diving technologies that are suitable for the particular water environment of water conservancy projects with higher diving work efficiency, lower costs, and lower safety risks.

In environments with deep water, high head, and high flow velocity, work operations are difficult with low efficiency and high costs; moreover the applicability of underwater grouting and repair materials is poor, the process is complex, and it is difficult to guarantee the quality, inevitably affecting the repair efficacy. The research and development of new underwater repair materials and construction techniques that are convenient for underwater operations, reliable in quality, and rational in economy according to the special conditions and applications of the deep-water environment are therefore the main frontier areas that should be urgently developed. The problem of silting in front of deep-water dams resulting from the long-term operation of water conservancy projects or sudden disasters introduces great difficulties to the detection, care, and maintenance of underwater structures as well as the repair, opening, and closing of sluice gates. The existing desilting and dredging equipment and technologies domestically and abroad are mainly applicable to the clearing of sediment or small-particle aggregates in wide water areas at relatively shallow depths. It is difficult to effectively use them in narrow work environments, such as gates upstream of dams and flow channels with complex silt sediments. It is thus necessary to develop multi-functional desilting equipment and technologies suitable for water depths of over 100 m that can operate in narrow spaces and clean up complex siltation in layers (sedimentation) so as to ensure the long-term safe operation of water conservancy projects.

As listed in Table 2.1.1, 90 patents related to this topic were published between 2014 and 2019. The five countries that published the most patents were China, the United States, Brazil, the United Kingdom, and Norway (Table 2.2.5). Among these countries, China was at the forefront of development, contributing 90% of the patents. The average citations per patent of the Chinese patents was 2.21, demonstrating that Chinese patents are receiving increasing attention.

The five organizations that produced the most patents were the Power Construction Corporation of China, China National Offshore Oil Corporation, Shanghai Qere Ecological Technology Co., Ltd. (China), Zhejiang Institute of Hydraulics and Estuary (China), and Shandong University (China) (Table 2.2.6). Among the above organizations, the Power Construction Corporation of China is the only comprehensive construction corporation in China that provides water conservancy and electric power engineering and infrastructure planning, surveying and design, consulting and supervision, construction management, and investment and operation, and it has adopted "deep-water exploration and treatment technology for hidden hazards in water conservancy projects" as its core technology. China National Offshore Oil Corporation has applied deep-water exploration and operation technology to the field of marine engineering on a large scale.

Table 2.2.5 Countries with the greatest output of patents on "deep-water detection of latent defects and treatment technologies for water conservancy projects"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	81	90.00%	179	98.90%	2.21
2	USA	2	2.22%	0	0.00%	0.00
3	Brazil	2	2.22%	0	0.00%	0.00
4	UK	1	1.11%	1	0.55%	1.00
5	Norway	1	1.11%	1	0.55%	1.00
6	Japan	1	1.11%	0	0.00%	0.00
7	Mexico	1	1.11%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of patents on "deep-water detection of latent defects and treatment technologies for water conservancy projects"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Power Construction Corporation of China	China	4	4.44%	6	3.31%	1.50
2	China National Offshore Oil Corporation	China	3	3.33%	3	1.66%	1.00
3	Shanghai Qere Ecological Technology Co., Ltd.	China	2	2.22%	8	4.42%	4.00
4	Zhejiang Institute of Hydraulics and Estuary	China	2	2.22%	6	3.31%	3.00
5	Shandong University	China	2	2.22%	3	1.66%	1.50
6	China Communications Construction Company Limited	China	2	2.22%	1	0.55%	0.50
7	Shanghai Ocean University	China	2	2.22%	0	0.00%	0.00
8	Hohai University	China	2	2.22%	0	0.00%	0.00
9	Maoming Jinyang Tropical Pearl Boat Breeding Co., Ltd.	China	1	1.11%	14	7.73%	14.00
10	Guangdong Meixian Meiyan Mining Co., Ltd.	China	1	1.11%	12	6.63%	12.00

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VI. Environmental and Light Textile Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the field of environmental and light textile engineering (hereafter referred to as environmental engineering) 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 citation statistics for these research fronts and the annual number of core papers for each research front between 2014 and 2019 are summarized in Tables 1.1.1 and 1.1.2, respectively.

(1) Microinterfacial behavior and co-selection of antibiotic resistance genes in the environment

Environmental pollution caused by antibiotic resistance genes poses a direct threat to human health. However, the lack of large-scale quantitative studies on antibiotic resistance genes in most types of environments, and on humans and animal subjects, as well as the lack of data on resistance genes of potential co-selection reagents (such as fungicides and metals) have hindered the effective identification of environmental risks. It is therefore necessary to carry out detailed research on antibiotic resistance genes to reduce their potential environmental impacts. Among them, the migration, transformation, and fate of antibiotic resistance genes on environmental surfaces (microinterface behavior) and the interaction between antibiotic resistance genes and other resistance genes (co-selection mechanism) are the most important processes. Based on the existing literature, it is evident that natural system and human activities have a significant impact on the distribution of antibiotic resistance genes in the environment. Heavy metal resistance genes play an important role in the transmission of some antibiotic resistance genes; sewage treatment plants are one of the main sources of antibiotic resistance genes in the environment. Therefore, further studies on the effects and behavior patterns of these genes are required to guide risk-reduction actions.

(2) Microinterface behavior of combined pollution process

Consumption of coal, oil, and other energy resources, as well as continuous growth of industrial agglomeration and

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	Microinterfacial behavior and co-selection of antibiotic resistance genes in the environment	15	1 478	98.53	2015.7
2	Microinterface behavior of combined pollution process	57	3 400	59.65	2015.9
3	Catalytic performance of nanocomposites and their mechanism of action in wastewater treatment	66	3 083	46.71	2017.9
4	Pollution and toxicology of microplastics in environmental water	83	14 173	170.76	2015.9
5	Urban heat-island effect and urban planning	55	3 772	68.58	2015.8
6	Meteorology and sustainable development	26	1 172	45.08	2016.1
7	New spatial pattern and controlling factors of marine biological nitrogen fixation	26	1 326	51.00	2015.2
8	Precise dietary regulation technology based on intestinal flora intervention	80	12 040	150.50	2015.0
9	Degradation potential of dye-based industrial pollutants	274	20 097	73.35	2016.4
10	Ultra-low emission technology for pollution caused due to pulping and papermaking	2	105	52.50	2015.5

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	2014	2015	2016	2017	2018	2019
1	Microinterfacial behavior and co-selection of antibiotic resistance genes in the environment	3	2	8	1	1	0
2	Microinterface behavior of combined pollution process	16	10	10	10	8	3
3	Catalytic performance of nanocomposites and their mechanism of action in wastewater treatment	0	2	8	11	18	27
4	Pollution and toxicology of microplastics in environmental water	15	19	19	18	11	1
5	Urban heat-island effect and urban planning	12	9	15	14	5	0
6	Meteorology and sustainable development	6	4	7	2	5	2
7	New spatial pattern and controlling factors of marine biological nitrogen fixation	13	5	2	4	1	1
8	Precise dietary regulation technology based on intestinal flora intervention	20	14	13	8	6	2
9	Degradation potential of dye-based industrial pollutants	0	71	88	63	38	14
10	Ultra-low emission technology for pulping and papermaking pollution	0	1	1	0	0	0

extensive application of fertilizers and pesticides, has resulted in the release of several pollutants into the environment. This, in turn, has threatened the safety of agricultural products and the health of people. Pollutants in the environment do not occur singly; they exist in multiple forms and in various media simultaneously.

After entering the environment, pollutants undergo a series of physical/chemical/biological interfacial processes, such as adsorption/desorption, volatilization, reduction/oxidation, chemical precipitation/complexation/degradation, biological transformation/degradation and/or adsorption/transport via biological membranes. Because the environment is highly heterogeneous, pollutants always show interfacial and coupling effects, which make it difficult to predict their distribution, migration, and biological/ecological effects by using a single linear model. Thus, there is an urgent need to study the microinterface behavior of the composite fouling process, revealing the medium and coupling interface behavior mechanism, clarifying the environment pollutant migration process, and reducing their biological effects.

(3) Catalytic performance of nanocomposites and their mechanism of action in wastewater treatment

With the development of the social economy, water pollution has become increasingly serious. Based on environmental and health considerations, the top priority is to develop efficient wastewater treatment technologies, such as the use of nanomaterials. The high specific surface area of nanomaterials can expose more active sites, provide more reaction sites, and exhibit excellent performance in mechanical, thermal, optical, and electrical fields. Nanocomposites combine the advantages of a variety of nanomaterials. Through the design of raw materials, distribution of each component, and process conditions, the advantages of each component can be complemented and maximized, and therefore, the components can be utilized in a synergistic manner improving the overall catalytic performance. Research on the catalytic mechanism of nanocomposites is currently focused on the following aspects: 1) preparation of a composite material with strongly oxidizing free radicals and enhanced redox activity; 2) microstructure and performance of composite materials; 3) interface mechanism between various nanomaterials. Nanocomposites are widely used in the field of environmental restoration and for storing solar energy; their applications include: photocatalytic treatment of persistent organic pollutants, oxidation/reduction of heavy metal-ions, oxidative decomposition of pathogens, splitting of water for H_2 evolution, and CO_2 reduction. With the further development of technology, nanocomposite materials will also be used in emerging applications such the development of solar cells and biosensors. Therefore, in the future, joint efforts are required to develop more suitable nanocomposite materials so that they can be applied for the production of clean energy on a large scale, and ultimately achieve true sustainable development and the protection of the environment.

(4) Pollution and toxicology of microplastics in environmental water

Microplastics are plastic particles with a particle size of less than 5 mm. They are organic pollutants originating from various plastic products and easily migrate in the environment. Microplastics are highly toxic. Further, they can also adsorb other pollutants in enviornmental water, which enhances their toxic potential. Because of their small particle size, they are also easily ingested by zooplankton or passed along the food chain, accumulated and transferred in organisms, and produce irreversible toxic effects.

Microplastics have become a new type of pollutant worldwide, and the resulting environmental problems are becoming increasingly serious. The world's plastic production, consumption, and application areas are rapidly expanding. Due to the physical and chemical properties, plastics release toxic additives to water bodies, absorb hydrophobic organics, increase water toxicity, and pass through the food chain through biological predation. Therefore, the pollutants accumulated on the surface of microplastics can also be transmitted through the food chain and continuously enriched and amplified at different trophic levels, ultimately causing harm to human health. It is necessary to study the pollution and toxicology of microplastics in environmental water and identify solutions for microplastic treatment.

(5) Urban heat-island effect and urban planning

The urban heat-island (UHI) effect refers to the change in the thermal properties of the urban underlying surface (the contact surface between the bottom of the atmosphere and the ground), which is characterized by high temperatures in urban areas and relatively low temperatures in the suburbs. On the meteorological near-surface atmospheric isotherm map, the wide areas in the suburbs show little temperature change, analogous to a calm sea, while urban areas are high-temperature areas, like an island protruding from the sea. Because this type of island represents a high-temperature urban area, it is called an urban heat island.

The formation of UHIs is inseparable from urbanization. Microclimate changes caused by human activities are most significant in winter and during the night compared to the daytime; these are the most obvious characteristic of an urban climate. Many buildings and roads in urban areas constitute the underlying layers of cement, asphalt, and other materials. The thermal capacity and conductivity of these materials are much larger than those used in suburban areas; meanwhile, their reflectance to sunlight is low and the absorption rate is high. Therefore, during daytime, the surface temperature of the urban under layer is much higher than that of the suburbs. The heat-island effect results in the annual mean temperature in the city being higher than that in the suburbs by at least 1 °C. In summer, the temperature in some parts of the city is sometimes 6 °C higher than that in the suburbs. In addition, the dense and tall buildings block the air flow, reducing wind speed and increasing air pollution in the city.

The research front mainly focuses on the impact of the UHI effect, which should be fully considered in urban planning and design. Therefore, as urban development intensifies the heat-island effect, it is necessary to control the population and building density. In addition, management of urban water system must be considered to adjust to the changes in urban climate; effective urban water system management can achieve the purpose of decelerating the UHI.

Furthermore, to strengthen urban ventilation and reduce heat intensity in urban heat islands, it is necessary to widen the streets in the north-to-south direction when expanding or reconstructing new or old urban areas, respectively. In summary, it is very important to properly use the existing technology, control the rapid development of cities through reasonable planning, and fully consider and use meteorological factors in the development.

(6) Meteorology and sustainable development

Sustainable development is the kind of development that can meet the needs of the present without threatening the ability of future generations to meet their own needs. Its core is economic prosperity, social equity, and ecological security for generations. Meteorology has a unique position in achieving comprehensive, coordinated, and sustainable development. It involves the rational development and utilization of meteorological resources and plays an irreplaceable role in the protection of other natural resources and the ecological environment.

The concept of "meteorological resources" includes developing applicable technologies to strengthen research in the field of meteorology, and determines the optimal and limit value (or carrying capacity) of meteorological elements, such as wind, solar radiation, precipitation, among other meteorological resources.

At present, conventional energy sources are facing depletion. Meanwhile, environmental pollution and ecological deterioration, caused by energy production, are seriously impacting the living environment, prompting all countries to urgently consider optimal energy planning for sustainable development.

China has conducted various works in the fields of meteorology and sustainable development; increased attention has been paid to the technical research on, and development and usage of, renewable energy. Scientific and technological research in these fields of renewable energy has been identified as a priority area for scientific and technological development. It has been emphasized that attention should be paid to the optimization and adjustment of climate resources in sustainable development; these include research on the distribution, quantity, and quality of climate resources in a way that is beneficial to human utilization.

(7)New spatial pattern and controlling factors of marine biological nitrogen fixation

Marine biological nitrogen fixation refers to the transformation of atmospheric nitrogen into available biological ammonium. Marine biological nitrogen fixation can provide "new" sources of nitrogen that drive the assimilation and sequestration of marine carbon. It is critical for maintaining the ocean's primary productivity and the budget of carbon and nitrogen cycling.

Current research topics include the spatial and temporal distribution patterns, regulation mechanisms, and activity of nitrogen-fixing microorganisms in the global ocean and coastal waters. In the context of global environmental change (e.g., ocean warming, acidification) and the impact of human activities (e.g., atmospheric nitrogen deposition, land runoff), further exploration will improve our understanding of marine biological nitrogen fixation trends and their impact on ocean productivity and biogeochemistry.

Other topics pertaining to marine biological nitrogen fixation that merit investigation include geographical distribution patterns, nitrogen contribution to the coastal zone, and primary productivity and sustainability in typical offshore ecosystems such as mangroves, seagrass beds, and coral reefs. Furthermore, in deep-sea ecosystems, especially in cold seep and hydrothermal areas, research on the coupling of chemoautotrophs and biological nitrogen fixation should be research hotspots. Genomics, isotope tracing, and deep learning will play an important role and will be critical to the research field of marine biological nitrogen fixation in the future. Lastly, the development and application of ecological nitrogen-fixing bacterial agents for marine ecological engineering is also a significant research field.

(8) Precise dietary regulation technology based on intestinal flora intervention

Intestinal flora is the general term for microorganisms inhabiting the intestinal system, and it is closely related to human health and diseases. Healthy intestinal flora can protect the human body from pathogenic bacteria and participate in many physiological processes, including biological activity metabolism, immune regulation, and glucose and lipid metabolism. As the main nutrients in the diet, fats, proteins, and carbohydrates provide energy to the human body and have an important impact on the composition of the intestinal flora. An unreasonable dietary structure will result in an imbalance the intestinal flora, which is significantly related to the occurrence and development of obesity, depression, diabetes, and related metabolic diseases. At the same time, differences in individual genes, living habits, and living environment can also affect the intestinal flora; therefore, based on these conditions, it is important to set personalized dietary recommendations. A regulated regime aims to combine scientific dietary guidelines to provide personalized recommendations based on the nutritional needs of individuals and their intestinal flora to achieve disease prevention and control. Therefore, precise dietary regulation based on the intervention of intestinal flora is of great significance to improve human health.

(9)Degradation potential of dye-based industrial pollutants

The wanton discharge of dye-based industrial pollutants not only leads to excessive waste of resources, but also causes serious water pollution and environmental degradation threatening the living environment and health of humans. It is of great practical significance and application value to develop efficient and low-cost degradation and reuse technologies for dye-based industrial pollutants. Textile printing and dyeing wastewater contain a variety of harmful substances, such as reactive dyes. Dyes can absorb light, reduce the transparency of water, affect the growth of aquatic organisms and microorganisms, and are not conducive to water self-purification. Phthalein bronze and some azo dyes are highly toxic and can directly or indirectly threaten human health when they enter the biological food chain. Therefore, dye-based industrial pollution is an urgent global problem that needs to be addressed. Dye-based industrial pollutants mainly exist in the form of water mixtures. Due to the diversity of textile dyes and water pollutants, the main degradation and treatment methods, such as physical adsorption, chemical oxidation, and aerobic biological treatment, are generally inefficient and costly, as wastewater is difficult to reuse. At present, many countries are focusing on the degradation and reuse of dye-based industrial pollutants. The main research directions in this field focus on the design and preparation of fiber-based high-efficiency and low-cost dye-based pollutant degradation membranes, synthesis of novel materials, screening of microorganisms, and construction and engineering of physical–chemical–biological combined degradation systems.

(10) Ultra-low emission technology for pollution caused due to pulping and papermaking

Vast quantities of wastewater are inevitably generated during pulping and papermaking, which has made the protection of the ecological environment highly challenging. Recently, due to the shortage of water resources, environmental pressures have become more severe; thus, more stringent national and local standards have been issued, which have put forth stricter environmental protection requirements for the pulping and papermaking industries. In this case, ultra-low emission technology has become an important research direction for achieving clean and green pulping and papermaking.

Conventional technologies usually fail to achieve the standards of wastewater discharge, while the ultra-low emission of pollution from pulping and papermaking is a promising deep treatment approach to achieve this objective. At present, various technologies have been applied for attaining ultra-low emissions of pulping and papermaking pollution, including membrane separation in bioreactors, activated carbon adsorption, advanced oxidation, sand filtration, magnetic finishing, magnetization–enzyme-like catalytic condensation, oxidation ponds, and constructed wetlands. However, the existing ultra-low emission technologies still suffer from many disadvantages, such as high costs, difficulty in maintenance, low mass transfer efficiency, difficult regeneration, and operation instability. Therefore, future investigations will focus on deep treatment technologies that are highly efficient, cost-effective, and stable, with the aim of achieving clean and green production pulping and papermaking.

1.2 Interpretations for three key engineering research fronts

1.2.1 Microinterface behavior of combined pollution process

The types of pollutants present in the environment and their interaction with each other affects their migration, transformation, and bioavailability. Because the effects of a compound are complex, it is impossible to accurately predict its environmental risks and regulate its concentrations. Hence, pollution remediation is difficult, costly, and ineffective, threatening the safety of agricultural products and human health. Past research focused on the compound effects of pollutants in terms of their toxicity, especially that resulting due to synergism or antagonism between heavy metals, and combined pollution caused by them in soil–water–gas–biological/microorganism systems and microinterface. However, the precise behavior of pollutants remains unclear, making it difficult to accurately predict the physical, chemical, and biological processes these pollutants are involved in and the associated environmental risks. Therefore, exploration of the microinterface behavior of combined pollution is urgently required to provide theoretical support for bioavailability regulation, pollution control, and remediation.

In recent years, studies on the microinterface behavior of combined pollution processes have been conducted resulting in a series of innovative works on the characteristics, migration, transformation, in situ characterization technology, and bioavailability of pollutants on the water–soil–gas–biological microinterface. As shown in Table 1.2.1, among the 57 core papers in the past five years, China ranked first with 21 core papers, accounting for 36.84%, followed by the United States and South Korea with 18 and 5 core papers, respectively. Among the core papers in this front, 67% pertained to organic pollutants. Most of the studies were on the catalytic transformation behavior of pollutants in the nanomaterial–water interface, followed by the microinterface behavior in minerals. Only one study focused on pollutants with regard to plant/biological microinterface behavior and transformation in the ecosystem.

In terms of citations per paper (Table 1.2.1), India was the highest (136.75), followed by South Korea, Germany, and Canada. The citations per paper of core papers from China was low (56.76), indicating a lack of innovation and influence. With regard to relevance (Figure 1.2.1), many countries have carried out comprehensive and extensive collaborative research; a strong correlation was found between China and the United States. Papers from developed countries such as the United Stated and Japan mainly focused on the catalytic degradation of pollutants, membrane treatment, interaction between pollutants, and colloids. In contrast, papers from China have focused on promoting the transformation mechanism of nanomaterials on pollutants and in situ characterization techniques. There are few basic studies in the field of microinterface behavior of combined pollution processes from China; this aspect merits further exploration and development.

There are six Chinese institutions among the top 10 research institutions that have publications in the field of microinterface behavior (Table 1.2.2). The number of core papers by the Chinese Academy of Sciences, North China Electric Power University, and Wuhan University of Technology were the highest, with three papers each. The Chinese Academy of Sciences focused on the migration and characterization of pollutants on microinterfaces, while the North China Electric Power University and Wuhan University of Technology mainly studied the effects of nanomaterials on the migration, transformation, and degradation of pollutants. In terms of citations per paper, Hong Kong Polytechnic University had the highest number of citations (87.00). The two core papers focused on the removal of pollutants by graphene materials and the removal mechanism of pollutants in the presence of nanocomposites. King Abdulaziz University and the Spanish National Research Council ranktd second and third, with their citations per paper being 85.50 and 73.00, respectively.

As shown in Figure 1.2.2, strong partnerships existed between universities and institutions with the greatest output of core papers. The Chinese Academy of Sciences showed more comprehensive cooperation relationship with other institutions, followed by the Hong Kong Polytechnic University, but there is still a lack of international cooperation and exchange between Chinese universities/institutes and foreign institutes. Future studies should aim at in-depth research on the microinterface behavior of the combined pollution process, which will provide theoretical support for the development of the corresponding pollution control technology.

Among the countries that cited core papers on specific topics (Table 1.2.3), China ranked first, followed by the United States and India. Among the 10 major institutions that cited core papers (Table 1.2.4), nine were from China, among which the Chinese Academy of Sciences, the University of the Chinese Academy of Sciences, and Tongji University were the top three.

1.2.2 New spatial pattern and controlling factors of marine biological nitrogen fixation

Nitrogen is a crucial element for life, especially in nutrient-poor ocean environments. The Redfield ratio of 6.6, as the standard of carbon nitrogen ratio (C/N), is used as the basis to identify the nutrients limiting marine productivity. However, Raymond (1993) and Walsh's (1996) study on the euphotic zone in the Atlantic and eastern Pacific Ocean showed that extrapolating nitrate consumption led to significant underestimation of organic carbon export. In fact, 34%–77% of the new production is attributed to marine nitrogen fixation. Since then, they have expanded the new spatial pattern of marine nitrogen fixation and improved the estimate of marine primary productivity. Furthermore, new spatial pattern of marine nitrogen fixation has also solved the problem of "leakage sink" in the carbon and nitrogen balance budget, which has puzzled scientists for years.

Marine nitrogen fixation could provide "new" nitrogen to the global ocean, supporting carbon uptake and sequestration. Thus, marine nitrogen fixation is approximately 140 Tg N/yr. However, many questions remain regarding the regulation mechanisms of marine nitrogen fixation, including spatial and temporal characteristics, species identification, genetic ability, adaptability, and the acquisition of nutrients for growth.

The only dominant nitrogen-fixing groups previously known were *Trichodesmium* spp. and *Richelia* sp. A wide range of studies, from genetic to ecosystem level, have revealed

Table 1.2.1 Countries with the greatest output of core papers on "microinterface behavior of combined pollution process"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	21	36.84%	1 192	56.76	2016.3
2	USA	18	31.58%	1 076	59.78	2015.8
3	South Korea	5	8.77%	377	75.40	2017.8
4	Saudi Arabia	5	8.77%	349	69.80	2016.0
5	India	4	7.02%	547	136.75	2015.8
6	Germany	4	7.02%	301	75.25	2015.5
7	UK	4	7.02%	258	64.50	2017.2
8	Spain	4	7.02%	230	57.50	2015.2
9	Canada	3	5.26%	211	70.33	2016.7
10	France	3	5.26%	165	55.00	2016.3

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "microinterface behavior of combined pollution process"

Table 1.2.2 Institutions with the greatest output of core papers on "microinterface behavior of combined pollution process"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	3	5.26%	215	71.67	2015.3
2	North China Electric Power University	3	5.26%	211	70.33	2016.7
3	Wuhan University of Technology	3	5.26%	148	49.33	2017.3
4	Hong Kong Polytechnic University	2	3.51%	174	87.00	2018.0
5	King Abdulaziz University	2	3.51%	171	85.50	2015.5
6	Spanish National Research Council	2	3.51%	146	73.00	2014.5
7	Shanghai Jiao Tong University	2	3.51%	143	71.50	2017.0
8	Xi'an Jiaotong University	2	3.51%	142	71.00	2015.5
9	King Abdullah University of Science and Technology	2	3.51%	137	68.50	2016.0
10	Colorado School of Mines	2	3.51%	108	54.00	2016.5

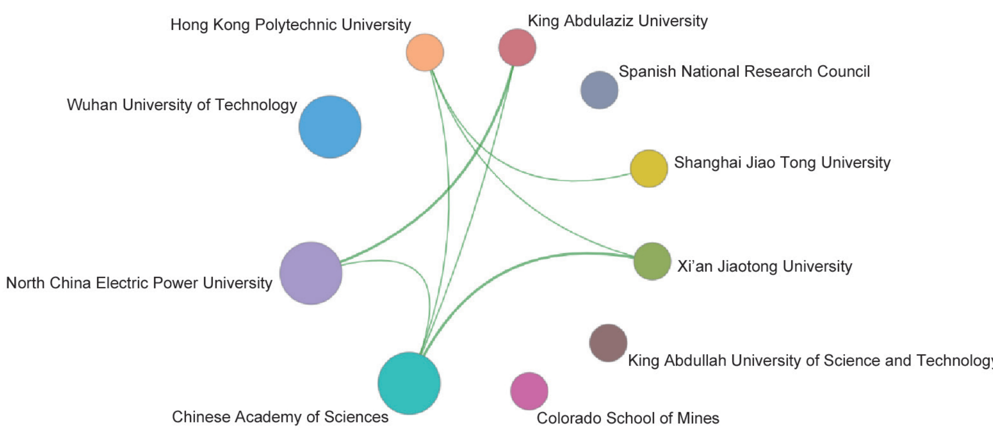

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "microinterface behavior of combined pollution process"

Table 1.2.3 Countries with the greatest output of citing papers on "microinterface behavior of combined pollution process"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	177	51.01%	2019.7
2	USA	39	11.24%	2019.7
3	India	28	8.07%	2019.4
4	South Korea	16	4.61%	2019.8
5	Australia	14	4.03%	2019.4
6	UK	14	4.03%	2019.8
7	France	13	3.75%	2019.5
8	Italy	12	3.46%	2019.8
9	Japan	12	3.46%	2019.5
10	Germany	11	3.17%	2019.5

Table 1.2.4 Institutions with the greatest output of citing papers on "microinterface behavior of combined pollution process"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	21	23.08%	2019.3
2	University of Chinese Academy of Sciences	12	13.19%	2019.0
3	Tongji University	9	9.89%	2019.7
4	South China University of Technology	8	8.79%	2020.0
5	Nankai University	7	7.69%	2019.6
6	Technological University of Malaysia	6	6.59%	2020.0
7	Zhejiang University	6	6.59%	2020.0
8	Jiangsu University	6	6.59%	2020.0
9	Hong Kong Polytechnic University	6	6.59%	2019.0
10	Harbin Institute of Technology	5	5.49%	2020.0

an increasing number of new diazotrophs, and the ability to estimate global nitrogen fixation has also improved significantly. The most striking discovery was the identification of the marine microplankton (UCYN-A, UCYN-B, UCYN-C) that, even in small size, exhibit substantial nitrogen fixation rates. These results showed that the range of biological nitrogen fixation is much wider than previously expected. Existing research has shown that biological nitrogen fixation is mainly controlled by environmental factors, such as temperature and phosphorus and iron availability. Meanwhile, global climate change and human activities also affect nitrogen fixation. For example, in the years experiencing El Niño–Southern Oscillation (ENSO) events, different spatial patterns of global marine biological nitrogen fixation are observed.

Some scholars have comprehensively studied marine nitrogen fixation and its controlling factors by establishing biogeochemical and ecological models. However, results of marine field observations are significantly different from those predicted by the models; consequently, spatial patterns of marine nitrogen fixation are characterized by discrepancies. Therefore, more systematic research is needed that involves combining field observations, laboratory analyses (e.g., molecular biology, genomics, isotopes), satellite remote sensing monitoring, and other methods. Moreover, combined with global and regional environmental changes and biogeochemical models, further studies on the spatial distribution and regulation mechanism of marine biological nitrogen fixation can be conducted. Research on the spatiotemporal expansion of biological nitrogen-fixing activity and the discovery of new diazotrophs and joint nitrogen fixation has greatly expanded our understanding of marine continental shelf ecosystems and coastal marine wetlands. The assessment of marine primary productivity and carbon and nitrogen cycle stimulate the development of marine ecological engineering, marine aquaculture, and geoengineering. In addition, research on nitrogen fixation by chemotrophs in deep-sea cold springs coupled with that on hydrothermal ecosystems can provide a new direction for the cognition of spatial-temporal patterns of marine biological nitrogen fixation.

Table 1.2.5 shows the main countries that have published the core papers on "new spatial patterns and controlling factors of marine biological nitrogen fixation." The United States ranks first in the proportion of both the number of papers published and citations, leading by a large margin. This indicates that the United States holds significant research advantage in this field. There is extensive cooperation between the major output countries (Figure 1.2.3). Table 1.2.6 shows the main institutions with the most core papers in this research front. The top 10 institutions are predominantly concentrated in the United States. According to the cooperation network of the major institutions (Figure 1.2.4), extensive collaboration can be observed.

China ranks third in terms of the citations per paper of its core papers (Table 1.2.7). The Chinese Academy of Sciences and Xiamen University ranked third and ninth, respectively, in the rankings of institutions with the greatest output of citing papers (Table 1.2.8).

1.2.3 Precise dietary regulation technology based on intestinal flora intervention

The human intestine contains trillions of microbial communities. The intestine is the site of digestion and nutrient absorption and is also an important immune organ. The intestinal flora and human have a symbiotic relationship. The intestinal flora and its metabolites directly affect the health of the host, and play a potential role in protecting the hosts from intestinal or immune system diseases, obesity, and diabetes. The composition and function of the intestinal flora are determined by the genetic background and external factors; among the latter, diet is one of the most critical factors. Diet affects the composition of the intestinal flora and its metabolites through alterations in the type of nutrients and nutrient balance, and regulates the stability of the microorganism's microecology, thus affecting human health.

The human gut microbiota varies greatly among individuals, emphasizing the need for a planned optimal diet. The temporal differences in the intestinal flora of the human body and its universality in different regions have been identified to better understand the biological impacts of specific intervention strategies for the gut microbiota. At the same time, aspects such as the influence of food on the intestinal microbiota and the specific microbiota interacting with it have been comprehensively explored to discuss the relationship between human intestinal microbiota and dietary patterns, structure, and disease occurrence and development.

With the development of the social economy, people are currently regulating the intestinal flora and its metabolic spectrum through their diet. The interaction network diagram

Table 1.2.5 Countries with the greatest output of core papers on “new spatial pattern and controlling factors of marine biological nitrogen fixation”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	17	65.38%	946	55.65	2015.3
2	Germany	6	23.08%	269	44.83	2016.0
3	Netherlands	4	15.38%	249	62.25	2016.5
4	UK	4	15.38%	220	55.00	2016.5
5	Japan	4	15.38%	180	45.00	2015.0
6	South Africa	2	7.69%	166	83.00	2016.0
7	Switzerland	2	7.69%	145	72.50	2014.0
8	Canada	2	7.69%	109	54.50	2017.0
9	Italy	2	7.69%	109	54.50	2017.0
10	India	2	7.69%	99	49.50	2015.5

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “new spatial pattern and controlling factors of marine biological nitrogen fixation”

Table 1.2.6 Institutions with the greatest output of core papers on “new spatial pattern and controlling factors of marine biological nitrogen fixation”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	University of California, Santa Cruz	4	15.38%	188	47.00	2014.8
2	University of Tokyo	4	15.38%	180	45.00	2015.0
3	University of Southern California	3	11.54%	154	51.33	2015.0
4	University of California, Irvine	3	11.54%	132	44.00	2017.0
5	University of Washington	2	7.69%	157	78.50	2014.5
6	Woods Hole Oceanographic Institution	2	7.69%	119	59.50	2014.5
7	University of Hawaii at Manoa	2	7.69%	118	59.00	2017.5
8	University of Liverpool	2	7.69%	111	55.50	2017.0
9	Utrecht University	2	7.69%	109	54.50	2017.0
10	University of California, Los Angeles	2	7.69%	99	49.50	2015.5

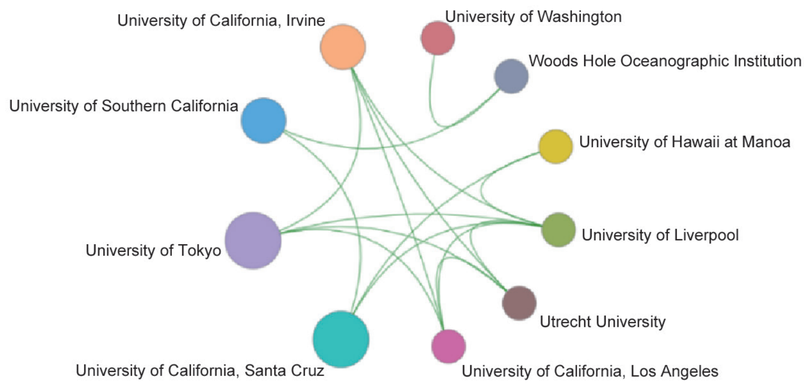

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “new spatiatial pattern and controlling factors of marine biological nitrogen fixation”

Table 1.2.7 Countries with the greatest output of citing papers on “new spatial pattern and controlling factors of marine biological nitrogen fixation”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	473	32.51%	2017.8
2	Germany	174	11.96%	2017.6
3	China	148	10.17%	2018.1
4	UK	147	10.10%	2017.8
5	France	129	8.87%	2017.8
6	Australia	109	7.49%	2018.1
7	Canada	72	4.95%	2018.1
8	Japan	71	4.88%	2018.0
9	Spain	47	3.23%	2017.8
10	India	45	3.09%	2018.0

of different ingredients in food and intestinal flora has been constructed, which is the key and basic work for achieving predefined nutritional goals, revealing the structure–function relationship of microbiota, and promoting research and development of microbiota-directed foods. This network has broad prospects in the development of safe, reliable, nutritious, healthy, and beneficial precision diet control technology that people can afford.

Table 1.2.9 shows the main output countries with core papers in “precise dietary regulation technology based on intestinal flora intervention”. The United States ranks first in both the number of core papers and the citations per paper, indicating that it has great research advantages in this respect. The collaboration among the major output countries (Figure 1.2.5) has been extensive. Table 1.2.10 shows the main output institutions with core papers in this engineering research front. Wageningen University ranks first in terms of number and percentage of core papers. According to the main inter-agency cooperation network (Figure 1.2.6), Washington University has conducted research and development independently, while other institutions have cooperative relationships.

The main countries with the greatest output of citing papers on this research front are shown in Table 1.2.11. While China ranks second in both the number and percentage of citing papers. The main institutions with the greatest number of citing papers are listed in Table 1.2.12. Compared with other institutions, Harvard University has a significantly higher number and percentage of citing papers. The Chinese Academy of Sciences ranks third among the institutions with the greatest output of citing papers.

Table 1.2.8 Institutions with the greatest output of citing papers on "new spatial pattern and controlling factors of marine biological nitrogen fixation"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	University of California, Santa Cruz	50	12.92%	2017.0
2	University of Washington	46	11.89%	2017.7
3	Chinese Academy of Sciences	41	10.59%	2017.6
4	University of Southern California	35	9.04%	2017.7
5	University of Bremen	32	8.27%	2017.9
6	Woods Hole Oceanographic Institution	32	8.27%	2017.3
7	Max Planck Inst Marine Microbiol	31	8.01%	2017.7
8	Princeton University	31	8.01%	2017.9
9	Xiamen University	30	7.75%	2018.1
10	University Toulon & Var	30	7.75%	2017.6

Table 1.2.9 Countries with the greatest output of core papers on "precise dietary regulation technology based on intestinal flora intervention"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	25	31.25%	4 180	167.20	2015.4
2	UK	18	22.50%	3 328	184.89	2014.7
3	Italy	15	18.75%	2 123	141.53	2015.4
4	Netherlands	13	16.25%	2 334	179.54	2014.2
5	Belgium	9	11.25%	1 477	164.11	2014.8
6	France	8	10.00%	1 877	234.62	2014.8
7	Sweden	6	7.50%	1 669	278.17	2015.0
8	Denmark	6	7.50%	1 317	219.50	2014.5
9	Germany	6	7.50%	1 013	168.83	2015.5
10	China	6	7.50%	747	124.50	2016.0

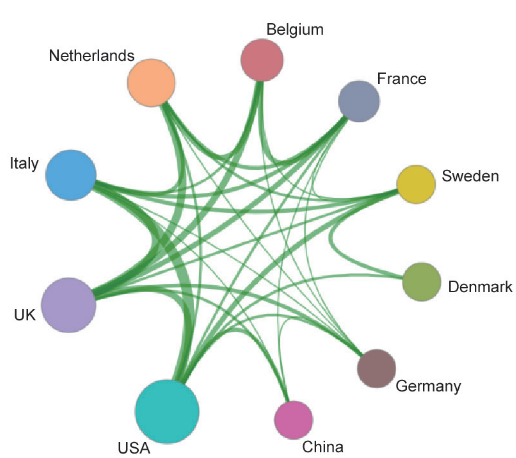

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "precise dietary regulation technology based on intestinal flora intervention"

Table 1.2.10 Institutions with the greatest output of core papers on "precise dietary regulation technology based on intestinal flora intervention"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Wageningen University	8	10.00%	1 193	149.12	2014.0
2	French National Institute for Agricultural Research	7	8.75%	1 781	254.43	2014.6
3	University of Copenhagen	6	7.50%	1 317	219.50	2014.5
4	Catholic University of Louvain	6	7.50%	1 189	198.17	2014.8
5	University of Bologna	6	7.50%	860	143.33	2014.7
6	University of Gothenburg	4	5.00%	1 528	382.00	2015.0
7	Washington University	4	5.00%	713	178.25	2015.5
8	University of Reading	4	5.00%	661	165.25	2013.8
9	University of Helsinki	4	5.00%	555	138.75	2014.2
10	University of Aberdeen	3	3.75%	759	253.00	2013.7

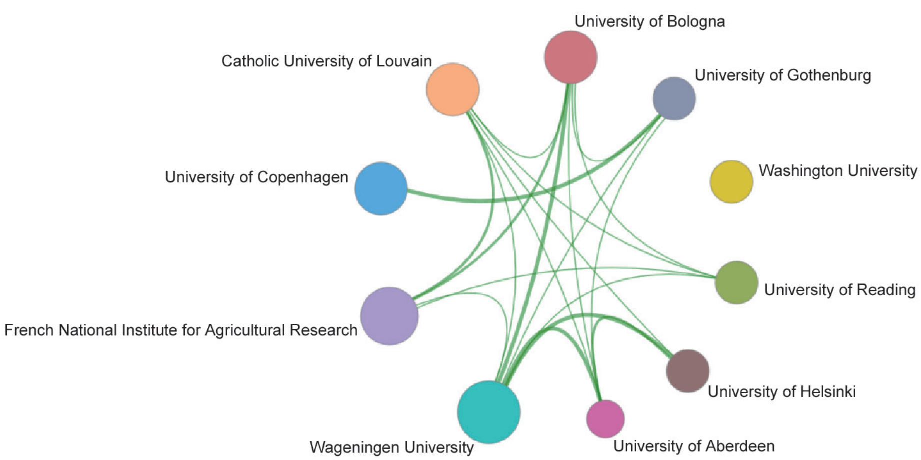

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "precise dietary regulation technology based on intestinal flora intervention"

Table 1.2.11 Countries with the greatest output of citing papers on "precise dietary regulation technology based on intestinal flora intervention"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	2 566	28.14%	2017.8
2	China	1 710	18.75%	2018.4
3	UK	762	8.36%	2017.6
4	Italy	752	8.25%	2017.7
5	Spain	575	6.31%	2017.8
6	Germany	549	6.02%	2017.8
7	France	514	5.64%	2017.5
8	Canada	487	5.34%	2017.5
9	Netherlands	471	5.17%	2017.5
10	Australia	422	4.63%	2017.9

Table 1.2.12 Institutions with the greatest output of citing papers on "precise dietary regulation technology based on intestinal flora intervention"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Harvard University	227	16.31%	2017.8
2	University of Copenhagen	175	12.57%	2017.8
3	Chinese Academy of Sciences	149	10.70%	2018.3
4	University College Cork	127	9.12%	2018.0
5	Kings College London	116	8.33%	2017.4
6	Wageningen University	106	7.61%	2016.9
7	University of Bologna	104	7.47%	2017.5
8	University of Gothenburg	100	7.18%	2017.2
9	Shanghai Jiao Tong University	100	7.18%	2017.9
10	University of Illinois	95	6.82%	2017.9

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. 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 2014 and 2019 related to these individual topics is summarized in Table 2.1.2.

(1) Synergistic remediation technologies for soil–water pollution

An intimate exchange of substances occurs between the soil and groundwater. It is imperative to control and remediate pollution from soil to groundwater to support sustainable development. Pollution of surface water, soil, and groundwater occurs around industries or refineries such as petroleum, chemical engineering, and smelting. The development of synergistic remediation technologies for soil–water pollution is important to ensure the safety of soil and groundwater. Among the main patents of this development frontier, *in situ* and *ex situ* remediation technologies account for 67.3% and 32.7%, respectively. The *in situ* remediation technologies include specialized devices for injecting and mixing remediation reagents; combined remediation employing phytoextraction, plant-earthworms, or plant-microbes; electrokinetic remediation combined with permeable reactive barriers; adsorption using activated carbon or biochar; and bioventing. The patents for devices used for injecting and mixing remediation reagents, which involve specific technologies such as high-pressure injection, oscillation, and sprinkling, dominate the developed *in situ* remediation technologies. Most of the developed *ex situ* remediation technologies are combinations of multiple techniques. Among these, the dominant patents are for the devices used for excavation, transportation, sorting, pulverization, mixing, agitation of soil, soil rinsing/filtration along with those used for the treatment of the used eluent, thermodesorption along with the adsorption/condensation of the vapor, chemical oxidation and advanced oxidation, and biological filters. The main target pollutants of *in situ* and *ex situ* synergistic remediation treatments include petroleum hydrocarbons, halohydrocarbons, and heavy metals.

Chinese patents account for over 99% in this field, demonstrating that China has paid sufficient attention to the development of synergistic remediation technologies for soil–water pollution. However, most of the developed patents focus on combined devices or systems for simultaneous remediation of soil and water with individual technologies. Practical technologies for highly synergistic remediation of soil and water are still in great demand. A promising field of research in the future is the development of highly efficient technologies for synergistic soil–water remediation based on partitioning, transport, and transformation of different pollutants between soil and water.

Table 2.1.1 Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Synergistic remediation technologies for soil–water pollution	357	635	1.78	2017.1
2	Microbial agents for wastewater treatment	711	845	1.19	2017.2
3	Collaborative treatment of multi-media pollution	1 000	3 293	3.29	2016.5
4	Airborne pathogen detector system and method	1 000	29 308	29.31	2013.6
5	Natural disaster prevention, early warning, and restoration decision-making project	1 000	13 830	13.83	2016.0
6	Nanocomposite marine antifouling coatings	214	384	1.79	2017.2
7	Offshore wave power generation technology	250	648	2.59	2016.4
8	Food intelligent manufacturing technology	624	4 506	7.22	2016.0
9	Carbon-fiber-based electronic devices	1 000	12 138	12.14	2015.8
10	Ultra-low emission technology for pulping and papermaking pollution	1 000	3 263	3.26	2017.2

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	2014	2015	2016	2017	2018	2019
1	Synergistic remediation technologies for soil–water pollution	23	29	34	124	63	76
2	Microbial agents for wastewater treatment	45	55	89	123	158	215
3	Collaborative treatment of multi-media pollution	79	93	127	185	190	231
4	Airborne pathogen detector system and method	93	97	97	93	86	103
5	Natural disaster prevention, early warning, and restoration decision-making project	102	96	150	171	173	162
6	Nanocomposite marine antifouling coatings	3	9	30	56	76	34
7	Offshore wave power generation technology	41	26	21	36	39	63
8	Food intelligent manufacturing technology	42	68	60	108	138	109
9	Carbon-fiber-based electronic devices	75	80	73	176	104	266
10	Ultra-low emission technology for pulping and papermaking pollution	14	42	146	250	254	247

(2) Microbial agents used for wastewater treatment

With the rapid development of modern industrialization, a large amount of emerging and refractory contaminants have been discharged into the environment. However, the elimination of these pollutants by conventional biochemical processes is very difficult. Microbial agents refer to the microbial communities in liquid or powder form designed to enhance the performance of wastewater treatment systems. Microbial agents, comprised of naturally existing bacteria or artificial ones with specific metabolic functions, can be produced through microbiota cultivation. By adding specific microbial agents into the wastewater treatment system, the rapid degradation of target contaminants can be achieved. These agents have obvious advantages of being user-friendly, cost-effective, widely applicable, and do not cause secondary pollution. Furthermore, they are compatible with the existing water treatment facilities. In recent years, some progress has been observed in the development of single-component microbial agents, and such agents have been widely used to treat wastewater from domestic sewage, eutrophic water bodies, livestock farms, landfill leachate, and industrial sources. Theoretically, composite microbial agents should perform better than single-component microbial agents and should have a higher application potential as they are composed of various functional microbiota. However, maintaining the stability of such agents challenging because of the complex interactions among the different microorganisms and their metabolites. Therefore, to improve the efficacy of wastewater treatment, it is essential to explore the interaction mechanisms of microbial communities, optimize the selection of bacteria, and enhance the stability of composite microbial agent populations. Product serialization and standardization should also be emphasized to increase the applicability and cost-efficiency of such agents.

(3) Collaborative treatment of multi-media pollution

The composite effect and collaborative control of environmental pollution by different media are at the forefront of scientific and technological problems. The core problem of regional environmental quality improvement is the coordinated control of multi-media (i.e., air–water–soil) composite pollution. There is a complex nonlinear relationship between source emissions, environmental concentrations of pollutants, and effects of regional composite pollution. The exposure level to multi-media compound pollutants is generally high, with complex health effects. Nitrogen and phosphorus deposition in the atmosphere aggravate eutrophication of water bodies, and mercury deposition from coal combustion poses health risks to entire ecosystems. During sewage and sludge treatment, several pollutants, such as odor gas, biological aerosols, and greenhouse gases, are released, adversely impacting the air environment. Excessive quantities of nitrogen fertilizers in soil, caused by improper application methods, enter the atmosphere in the form of ammonia and nitrogen oxides, which not only produces odor but also increases the greenhouse effect. Chemical fertilizer application and livestock breeding are important sources of ammonia emissions, which, along with $PM_{2.5}$ induce haze formation. In addition, agricultural non-point source pollution is an important source of lake eutrophication. Therefore, promotion of theoretical innovation, breakthrough in non-progressive technology, and facilitation of engineering technology implementation of multi-media pollution collaborative treatment of air, surface water, soil, and groundwater, are important. Progress can be achieved by focusing on key problems, developing monitoring and simulation technologies for large-scale environmental processes, improving clean production and risk control technologies involved in the entire process, and establishing comprehensive environmental treatment technologies and system solutions at a regional scale. A multi-media pollution control theory and technology system, with an intelligent supervision system, to achieve a new pattern of multi-media environmental security, should also be undertaken.

(4) Airborne pathogen detector system and method

In recent decades, humans have been facing threats by airborne diseases. Airborne pathogens are microorganisms that can invade susceptible hosts and cause disease; these mainly include viruses (e.g., COVID-19, H1N1 influenza, SARS) and bacteria (e.g., *Mycobacterium tuberculosis*, *Streptococcus pneumoniae*). Currently, the detection of pathogens relies on clinical observations and accurate detection of samples obtained from the patients. These processes are time-consuming and the detection range is limited, which hampers the requirement for rapid disease control and prevention.

Detecting pathogens directly from the air is an ideal method for the prevention and control of airborne diseases. However, the concentration of respirable pathogens in the air can be low, requiring sensitive detectors. In addition, the interference caused by saliva and dust particles, which are scattered and heterogeneous, poses a challenge to the accurate detection of pathogens. Another major obstacle to airborne pathogen detection is processing and automation. The detection process includes air sampling and detection by a sensor, which is usually a time-consuming manual process, making it difficult to obtain real-time feedback.

To achieve rapid prevention and control of airborne diseases, it is necessary to explore integrated, highly sensitive, low-cost detector systems and methods that can be used widely for rapid and accurate detection of in the air. The realization of this goal requires the urgent development and integration of multiple detection methods as well as automated detection, processing, and data transmission systems.

(5) Natural disaster prevention, early warning, and restoration decision-making project

The total number of global natural disasters has increased significantly over the past two decades, especially the “shocking” increase of climate-related disasters. Specifically, a total of 7348 natural disasters have been recorded globally between 2000 and 2019, leading to 1.23 million deaths, with almost 4 billion people being affected, and up to 3 trillion USD endured as economic losses.

China is one of the countries that experiences the most serious natural disasters; they are in frequent occurrence, have wide distribution, and result in massive losses to life and property. The frequency and intensity of extreme weather and climate events (e.g., El Niño, drought, floods, thunderstorms, hail, storms, high-temperature weather, sandstorms) caused by climate change have increased significantly in the 20th century, which directly endangers the development of China's national economy. With the rapid growth of China's economy, the absolute economic value of losses, caused by weather and climate disasters, for example, the large-scale floods in 2020, which severely affected numerous lives, has also increased.

Therefore, the development of natural disaster prevention, early warning, and post-disaster recovery decision-making projects is particularly important in disaster prevention and mitigation. We should adhere to the basic principle of "prevention first"; place "disaster monitoring," "forecasting," and "early warning" in a prominent position, and provide early warning information to society, including vulnerable communities. To address these, we should rely on science and technology and strengthen scientific research and technological development, adopt and promote advanced monitoring technologies and facilities, and develop emergency response plans.

(6) Nanocomposite marine antifouling coatings

Marine biological fouling has caused great harm to the coastal regions and transportation and fisheries industries. According to statistics, the annual economic loss caused by biological fouling in the United States amounts to 700 million USD, while losses in the United Kingdom amount to 50 million pounds per year. In recent years, nanocomposite marine antifouling materials have attracted the attention of researchers in several countries as new antifouling coatings that have the potential to replace organic tin antifouling coatings. Nanocomposite marine antifouling materials are modified coatings characterized by high hydrophobicity, low surface energy, and low polarity.

The current research directions of marine antifouling coatings include the development 1) that contain nanometer components that are resistant to contamination, 2) wherein nanometer components are photocatalytically sterilized and the coatings act as shields against ultra violet, 3) that contain nanometer components that prevent biological attachment, and 4) that comprise of special acting nanomaterials (such as self-polishing function, hydrophobic function).

Solving the problem of the stable dispersion and compatibility of nanomaterials in antifouling coatings is important in addition to developing marine antifouling coatings and nanocomposite marine antifouling coatings worldwide.

(7) Offshore wave power generation technology

Wave power generation technology uses wave energy devices to convert wave energy into mechanical energy and finally into electrical energy. The technology is progressing toward offshore wave energy development with a higher production capacity than the shore-based power generation devices.

Offshore wave energy converters are mainly hydraulic and of direct-drive type. A direct-drive wave energy converter device can generate electricity directly, and the energy conversion process does not need a gearbox. It has the advantages of high reliability and low maintenance cost. Hence, it has development prospects in offshore high-power grid-connected applications. At present, the main technical directions of offshore wave power generation technology include the structural design of direct-driven wave energy converter, power capture and control technology, and power fluctuation treatment technology.

A linear generator is the core energy conversion device of a direct-driven wave energy converter system. Improving the reliability and energy conversion efficiency of the generator, simplifying the structure of the composite linear generator, and reducing the device volume are important development directions for direct-drive wave energy converter technology. The development of high-performance linear generators suitable for low-speed and high-thrust wave power generation is key in promoting direct-drive wave energy converter systems. In addition, superconducting materials have great potential for applications in wave power generation.

(8) Food intelligent manufacturing technology

The food industry is an important traditional livelihood industry and acts as a pillar industry for the national economy. With the rapid development of information technology, big data, cloud computing, Internet of Things, and other emerging technologies are being increasingly applied to the food industry, and research and development encompassing the entire industrial chain development model of the food industry, the process of production-to-sales is undergoing profound changes. In recent years, widespread application of intelligent manufacturing in the food industry has provided a direction for promoting the transformation and upgrade of our food industry. Intelligent manufacturing has achieved remarkable results in ensuring product quality and safety. Regarding food safety, smart factories use the Internet of Things and other monitoring technologies to strengthen information management services, improve the controllability of the production process, and reduce manual intervention in the production line. At the same time, the smart factories can collect and analyze data independently, realize coordination and cooperation between humans and machines, and ensure the safe production of food. Furthermore, product optimization is also promoted via the use of intelligent manufacturing technology. Digital indicators can be developed in intelligent workshops by collecting, analyzing, and continuously optimizing the key indicators of each production process according to the state of the intermediate materials and the taste experience of the final product; the production process is controllable, product has stability, and product quality is greatly improved. Finally, the intelligent production system improves production efficiency. The system adopts an integrated design concept, optimizes the complex processing methodology, compresses production links, and automates production using information technology, scheduling algorithms, automatic identification, and other technologies, with high speed and precision.

(9) Carbon-fiber-based electronic devices

Carbon-fiber-based electronic devices are a series of devices constructed with fiber membranes, yarns, and fabrics that use using carbon-based fibers (that have high flexibility and integrity) as the basic unit. The diameter of the carbon-based fibers ranges from a few hundred nanometers to tens of micrometers; this property can be made use of in customizing the structure of the device from micro to macro. Currently, the main technical directions pertaining to the carbon-fiber-based electronic devices include the development of flexible fiber-based energy storage devices, flexible fiber-based sensors, and flexible smart wearable textiles, among others. More specifically, devices such as carbon-fiber-based solar cells, carbon-fiber-based supercapacitors, flexible fuel cells, carbon-fiber-based piezoelectric sensors, and carbon-fiber-based friction generators, are being progressively developed. Owing to the efficient ion and electron transport properties and outstanding flexibility of carbon-fiber-based textiles, the carbon-fiber-based electronic devices are being developed to improve performance, lightness, thinness, flexibility, integration, and resistance to wear.

(10) Ultra-low emission technology for pulping and papermaking pollution

The pulping and papermaking industry is an important basic raw material industry. With the rapid development of this industry, the environmental pollution caused by pulping and papermaking has become increasingly serious. Therefore, developing ultra-low emission technologies for pollution control from pulping and papermaking is the key to simultaneously meet social demands and the need for green and sustainable development.

The ultra-low emission technology refers to the utilization of deep treatment systems to achieve ultra-low emission of pollutants and meet the emission standards. The currently existing ultra-low emission technologies include advanced oxidation, membrane separation, membrane bioreactor activated carbon adsorption and its comprehensive application, sand filtration, magnetic finishing, magnetization–enzyme-like catalytic condensation, oxidation ponds, constructed wetlands, and other technologies. However, the current ultra-low emission technologies of pulping and papermaking pollution still lack practicability and economy. Consequently, it is an important research focus for the pulping and papermaking industry to develop mature, stable, and cost-effective ultra-low emission technologies.

2.2 Interpretations for three key engineering development fronts

2.2.1 Airborne pathogen detector system and method

In recent decades, humans have been facing the threats of various airborne diseases, such as COVID-19, H1N1, and SARS. Airborne pathogens are microorganisms, mainly viruses and bacteria, that can invade susceptible hosts and cause diseases. These pathogens spread by droplets, droplet nuclei, and dust. At present, pathogen detection relies on clinical observation and accurate detection samples obtained from the patients. These processes are time-consuming and the detection range is limited, which hinders the need for rapid disease control and prevention.Detecting pathogens directly from the air is an ideal method for the prevention and control of airborne diseases. However, the concentration of respirable pathogens in the air can be low, requiring sensitive detectors. In addition, the interference caused by saliva and dust particles poses a challenge to the accurate detection of pathogens. The size of these aerosol particles varies with the manner in which they are discharged; speaking: (33.5 ± 5) μm, breathing: (127.3 ± 20) μm, coughing: 1–40 μm, sneezing: 2–16 μm.

Another major obstacle to airborne pathogen detection is processing and automation. The detection process mainly includes air sampling and sensor detection. Several studies exist on these two aspects individually; however, few studies have focused on the integration of both processes. The loading work from sampling to detection is usually manual, making it difficult to realize the function of continuous sampling, automation, and real-time feedback.

To achieve rapid prevention and control of airborne diseases, it is necessary to explore integrated, highly sensitive, low-cost detector systems and methods that can be widely applied for rapidly and accurately detecting pathogens in the air. Real-time polymerase chain reaction, nucleic acid, mass spectrometry, colloidal gold, laser particle counting, loop-mediated isothermal amplification, enzyme-linked immunosorbent assay, and real-time quartz crystal microbalance technology are among the most efficient detection methods. In addition, it is also necessary to design an integrated, automated detection process and an intelligent data transmission system to achieve continuous and real-time airborne pathogen detection.

From a global perspective, the United States ranks first in terms of the number of patent publications and citations of "airborne pathogen detector systems and methods", as shown in Table 2.2.1. China's core patent disclosures are listed at the second place, accounting for 7.20%, while in terms of citations, it ranks sixth (with 2.01%). The number of patent publications of the United Kingdom, Germany, Canada, and other countries is less than that of China, but the citations per patent far exceeds that of China. This indicates that although the number of studies and innovations for airborne pathogen detection in China is increasing, their influence is still insufficient. The cooperation network diagram (Figure 2.2.1) shows extensive international collaboration among countries. In addition to the closest cooperation with the United States, Chinese scholars also cooperate with Swiss and British institutions.

Table 2.2.2 shows the main institutions producing core patents in this engineering research front. Among them, Bizmodeline from South Korea has 28 core patent disclosures, ranking first among all institutions and, while the average citations per patent is only 0.04. The institution with the highest average citations per patent for publishing core patents is AbbVie Inc. from the United States, which accounts for 1.70% of publications, with the citations per patent reaching 5.78%. The citations per patent of Parion Sciences, with the same number of patent publications as Abbvie, is only 0.68%. The core patents published by Abbott Laboratories also have a significant influence, with the average number of citations reaching 104.13. The institution with the most citations is Dana-Farber Cancer Institute; although its number of published patents only accounts for 1.10%, the average number of citations is 138.64. The cooperation network of major international institutions in Figure 2.2.2 shows the institutions with the most frequent cooperation relationship are AbbVie Inc. and Abbott Laboratories. In addition, Dana-Farber Cancer Institute cooperates with Harvard University and Novartis AG. In the future, China should further enhance its cooperation with other international institutions. Besides the United States, China ought to cooperate with countries with greater core patent influence, such as the United Kingdom, Germany, India, and Switzerland. The principle of "quantity first" in scholar's performance assessment should be revised, and relevant assessments of the influence and innovation should be supplemented to encourage scientific research institutions to pay more attention to the quality of the research, and to promote the sustainable development of the relevant disciplines.

2.2.2 Natural disaster prevention, early warning, and restoration decision-making project

In recent decades, the frequency and intensity of extreme weather and climate events (e.g., El Niño, drought, floods, thunderstorms, hail, storms, high-temperature weather, sandstorms) caused by climate change have increased significantly, which has caused serious effects and great losses to society, the economy, and people's lives. According to statistics, between 1991 and 2000, the yearly average number of people affected by meteorological and hydrological disasters worldwide was 211 million, which is seven times the number of people affected by wars and conflicts. Asia is the continent most frequently hit by natural disasters.

Table 2.2.1 Countries with the greatest output of core patents on "airborne pathogen detector system and method"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	620	62.00%	23 736	80.99%	38.28
2	China	72	7.20%	589	2.01%	8.18
3	South Korea	56	5.60%	155	0.53%	2.77
4	UK	48	4.80%	1 758	6.00%	36.63
5	Germany	47	4.70%	2 508	8.56%	53.36
6	Canada	40	4.00%	783	2.67%	19.58
7	Switzerland	32	3.20%	856	2.92%	26.75
8	Japan	31	3.10%	506	1.73%	16.32
9	Australia	19	1.90%	198	0.68%	10.42
10	India	16	1.60%	541	1.85%	33.81

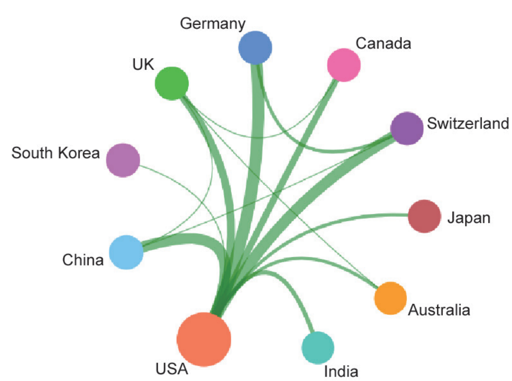

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "airborne pathogen detector system and method"

Table 2.2.2 Institutions with the greatest output of core patents on "airborne pathogen detector system and method"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Bizmodeline Co., Ltd.	28	2.80%	1	0.00%	0.04
2	AbbVie Inc.	17	1.70%	1 695	5.78%	99.71
3	Parion Sciences	17	1.70%	200	0.68%	11.76
4	Abbott Laboratories	16	1.60%	1 666	5.68%	104.13
5	Bristol-Myers Squibb Company	14	1.40%	1 376	4.69%	98.29
6	Dana-Farber Cancer Institute	11	1.10%	1 525	5.20%	138.64
7	ICU Medical, Inc.	10	1.00%	336	1.15%	33.60
8	Harvard University	8	0.80%	913	3.12%	114.13
9	Novartis AG	8	0.80%	425	1.45%	53.13
10	3M Innovative Properties Company	8	0.80%	311	1.06%	38.88

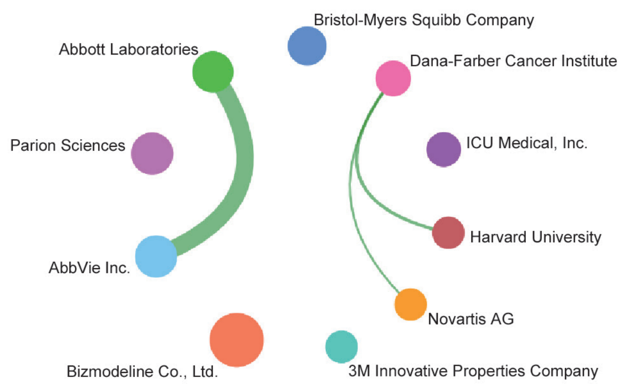

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “airborne pathogen detector system and method”

The economic losses caused by global climate change and related extreme weather events have increased by 10 times in the past 40 years. Approximately 34 million hectares (more than 500 million acres) of China’s farmland are affected by various weather and climate disasters every year. About 600 million people have suffered major disasters such as drought, rainstorms, floods, and tropical storms. The annual mean economic losses caused by weather and climate disasters account for approximately 3%–6% of the GDP. Secondary disasters caused by changes in weather and climate result in more serious economic losses.

Many effective measures have been taken by people to prevent natural disasters and reduce their impacts. We should adhere to the basic principle of “prevention first” and prioritize monitoring, forecasting, and early warning measures as well as provide effective early warning information to the society, including vulnerable communities. Meteorological disasters are public emergencies that can be predicted accurately long in advance. Strengthening the short-term forecasts, developing early warning signals, and releasing meteorological warning information are important for improving the level of disaster prevention and mitigation. We should rely on science and technology and strengthen scientific research and technological development, adopt and promote advanced monitoring technologies and facilities, and develop emergency response plans to support post-disaster recovery decision-making.

The main countries with the greatest output of core patents on this development front are shown in Table 2.2.3. China ranked first in the number of core patent disclosures, South Korea second, and the United States third. However, the average number of citations of China is only 1.78. This indicates that although China has many core patents in this field, these lack technical innovation and influence; hence, further improvements are required in this field. The collaboration network on “natural disaster prevention, early warning, and recovery decision project” (Figure 2.2.3) shows that the United States has collaboration with Colombia and Switzerland, while China has little collaboration with other countries.

The main institutions with the greatest output of core patents are listed in Table 2.2.4. The top two institutions with the hightest citations of their patents are Chengdu University of Technology (11) and State Farm Mutual Automobile Insurance (7), which are located in China and the United States, respectively. Figure 2.2.4 presents the collaboration network among these institutions. Collaboration in this development front is very weak, and only Chengdu University of Technology, Jiangxi Meteorological Observatory, and Emergent Geohazards Center of Jiangxi Province have collaboration with each other.

2.2.3 Carbon-fiber-based electronic devices

The demand for flexibility has promoted the development of carbon-fiber-based electronic devices. carbon-fiber-based materials can adapt to different working environments and usage requirements because of their excellent flexibility, outstanding conductivity and strength. The new generation of portable electronic equipment, human detectors,

Table 2.2.3 Countries with the greatest output of core patents on “natural disaster prevention, early warning, and restoration decision-making project”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	218	60.56%	387	47.43%	1.78
2	South Korea	85	23.61%	73	8.95%	0.86
3	USA	20	5.56%	299	36.64%	14.95
4	Japan	20	5.56%	40	4.90%	2.00
5	Colombia	16	4.44%	7	0.86%	0.44
6	Switzerland	1	0.28%	24	2.94%	24.00
7	Belgium	1	0.28%	10	1.23%	10.00
8	Sweden	1	0.28%	2	0.25%	2.00
9	Canada	1	0.28%	1	0.12%	1.00
10	Germany	1	0.28%	0	0.00%	0.00

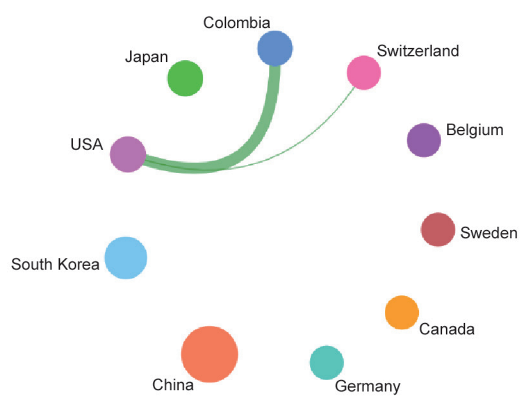

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “natural disaster prevention, early warning, and restoration decision-making project”

Table 2.2.4 Institutions with the greatest output of core patents on “natural disaster prevention, early warning, and restoration decision-making project”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Chengdu University of Technology	China	7	1.94%	11	1.35%	1.57
2	State Farm Mutual Automobile Insurance	USA	7	1.94%	7	0.86%	1.00
3	Heilongjiang Zhenmei Radio Communication Equipment Co., Ltd.	China	6	1.67%	6	0.74%	1.00
4	HOCHIKI	Japan	5	1.39%	0	0.00%	0.00
5	State Grid Corporation of China	China	4	1.11%	7	0.86%	1.75
6	Chengdu Wanjiang Gangli Technology Company	China	4	1.11%	5	0.61%	1.25
7	Electronics and Telecommunications Research Institute	South Korea	4	1.11%	1	0.12%	0.25
8	Jiangxi Meteorological Observatory	China	4	1.11%	0	0.00%	0.00
9	Emergent Geohazards Center of Jiangxi Province	China	4	1.11%	0	0.00%	0.00
10	Institute of Mountain Hazards and Environment, Chinese Academy of Sciences	China	3	0.83%	3	0.37%	1.00

and environmental sensors can make full use of these characteristics to make fully flexible devices, which will play an important role in future wearable electronic equipment and smart clothing.

In terms of major countries with the greatest output of core patents on this front (Table 2.2.5), the main patents have been produced in China, Japan, and the United States. Among them, the number of core patents published by China accounts for 32.30%, and the citations per patent is 1.42. The total number of core patents published by the United States accounts for 15.60%, and the citations per patent is 44.56. Japan, Canada, France, the United States, and the Netherlands have cooperated relatively closely in this field, while China has shown an independent research and development capability (Figure 2.2.5). In terms of output institutions, LG Chemical Ltd., Toray Industries, Inc., and Saudi Basic Industry Corporation produced the top three core patents. The top three companies in terms of citations per patent are Hydro-Quebec, Saudi Basic Industry Corporation, and Toray Industries, Inc. (Table 2.2.6). Major institutions prefer independent research and development, and only Hydro-Quebec, Arkema France, and Showa Denko K.K. have conducted collaborative research and development (Figure 2.2.6).

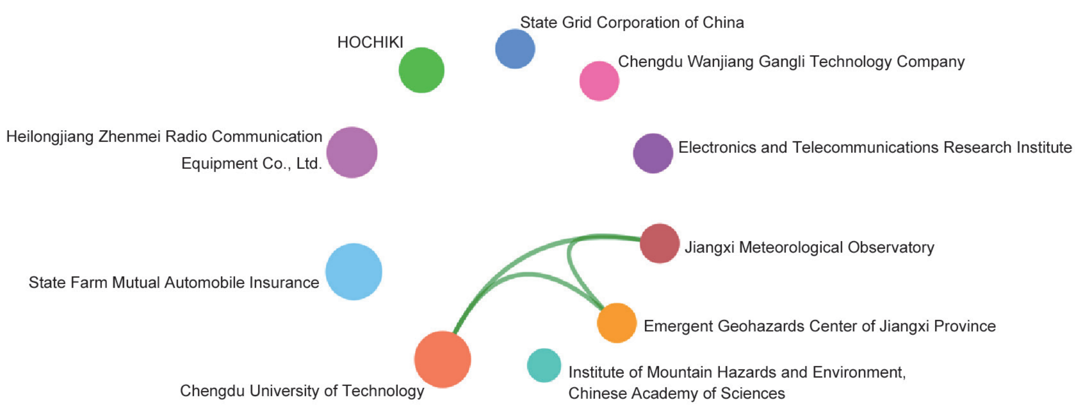

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “natural disaster prevention, early warning, and restoration decision-making project”

Table 2.2.5 Countries with the greatest output of core patents on “carbon-fiber-based electronic devices”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	323	32.30%	459	3.78%	1.42
2	Japan	261	26.10%	2 368	19.51%	9.07
3	USA	156	15.60%	6 952	57.27%	44.56
4	South Korea	99	9.90%	696	5.73%	7.03
5	Germany	41	4.10%	336	2.77%	8.20
6	France	30	3.00%	223	1.84%	7.43
7	Canada	24	2.40%	309	2.55%	12.88
8	Netherlands	22	2.20%	237	1.95%	10.77
9	Switzerland	16	1.60%	303	2.50%	18.94
10	UK	16	1.60%	267	2.20%	16.69

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "carbon-fiber-based electronic devices"

Table 2.2.6 Institutions with the greatest output of core patents on "carbon-fiber-based electronic devices"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	LG Chemical Ltd.	36	3.60%	250	2.06%	6.94
2	Toray Industries, Inc.	32	3.20%	556	4.58%	17.38
3	Saudi Basic Industry Corporation	19	1.90%	408	3.36%	21.47
4	Teijin Limited	15	1.50%	151	1.24%	10.07
5	Hydro-Quebec	12	1.20%	270	2.22%	22.50
6	Mitsubishi Chemical Corporation	11	1.10%	80	0.66%	7.27
7	Arkema France	10	1.00%	156	1.29%	15.60
8	Showa Denko K.K.	10	1.00%	101	0.83%	10.10
9	Shin-Etsu Chemical Co., Ltd.	10	1.00%	83	0.68%	8.30
10	Asahi Kasei Corporation	10	1.00%	46	0.38%	4.60

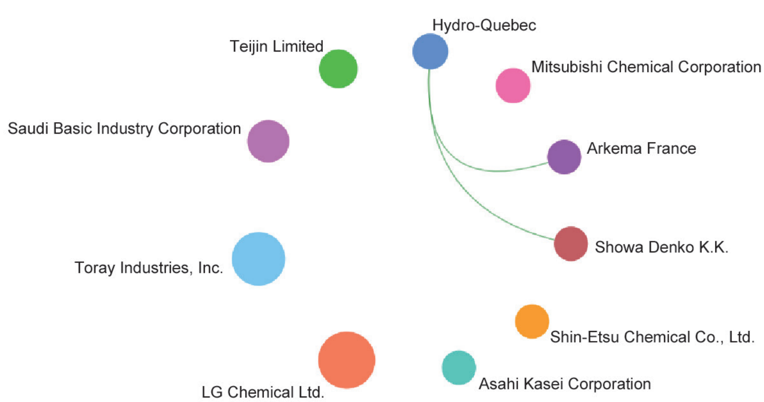

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "carbon-fiber-based electronic devices"

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VII. Agriculture

1 Engineering research fronts

1.1 Trends in top 11 engineering research fronts

The top 11 engineering research fronts in the agriculture field can be classified into two groups: 1) in-depth research on established research fronts including "origin, evolution, and genetic variation of animal viruses," "precision animal and plant breeding by design," "mining of crop functional genome structure," "efficient use of agricultural resources and circular economy," "soil biodiversity and ecosystem functions," "interaction of important animal viruses with hosts," "interaction mechanisms between pathogen and crop," "microbial driving mechanism of carbon cycling in forest soil," and "molecular basis and regulatory mechanism of sex and development in aquaculture animals," and 2) emerging research fronts including "intelligent sensing of agricultural life information and environmental information" and "object recognition and localization of agricultural robots." The number of core papers for these research fronts ranges from 8 to 109 with an average of 50, and citations per paper range from 7 to 87 with an average of 43. Most core papers were published in 2015 and 2016 whereas the core papers of "efficient use of agricultural resources and circular economy" and "soil biodiversity and ecosystem functions" were mostly published in recent three years and showed an increasing trend (Tables 1.1.1 and 1.1.2).

(1) Origin, evolution, and genetic variation of animal viruses

The tracing process of animal viruses is the process of finding the most primitive natural survival hosts, intermediate reservoir hosts/intermediate transition hosts, and terminal infection hosts. Through the study of the origin of animal viruses, the source host, vector host, cross-species transition reservoir host, and terminal host of the virus can be understood. It is of great biological significance for cutting off the source of infection, avoiding long-term circulation and spread of viruses in different hosts, and preventing and controlling infectious diseases from the source. The core scientific problem of virus traceability is to find pathogens that fulfill the Koch's postulates, analyze the genomic characteristics of the virus and the biological phenotype of virus-infected source host, vector host, and terminal host. Evolution and genetic variance are a kind of natural selection for viruses to antagonize, escape, and avoid the complex immune system of the host to maintain the replication life cycle and adapt to a new host, and is an

Table 1.1.1 Top 11 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Origin, evolution, and genetic variation of animal viruses	58	4 480	77.24	2015.4
2	Intelligent sensing of agricultural life information and environmental information	89	3 370	37.87	2015.9
3	Object recognition and localization by agricultural robots	77	2 879	37.39	2016.7
4	Precision animal and plant breeding by design	109	8 871	81.39	2015.4
5	Mining of crop functional genome structure	39	655	16.79	2016.5
6	Efficient use of agricultural resources and circular economy	8	57	7.13	2018.1
7	Soil biodiversity and ecosystem functions	55	2 189	39.80	2017.4
8	Interaction of important animal viruses with hosts	61	740	12.13	2016.5
9	Interaction mechanisms between pathogen and crop	31	1 934	62.39	2016.8
10	Microbial driving mechanism of carbon cycling in forest soil	12	1 042	86.83	2015.3
11	Molecular basis and regulatory mechanism of sex and development in aquaculture animals	10	180	18.00	2016.3

Table 1.1.2 Annual number of core papers published for the top 11 engineering research fronts in agriculture

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Origin, evolution, and genetic variation of animal viruses	15	20	10	9	4	0
2	Intelligent sensing of agricultural life information and environmental information	16	23	21	15	8	6
3	Object recognition and localization by agricultural robots	0	10	23	26	14	4
4	Precision animal and plant breeding by design	23	37	31	16	2	0
5	Mining of crop functional genome structure	10	2	7	5	9	6
6	Efficient use of agricultural resources and circular economy	0	0	0	1	5	2
7	Soil biodiversity and ecosystem functions	3	4	9	9	13	15
8	Interaction of important animal viruses with hosts	11	8	15	6	8	13
9	Interaction mechanisms between pathogen and crop	3	5	6	6	3	7
10	Microbial driving mechanism of carbon cycling in forest soil	2	6	3	1	0	0
11	Molecular basis and regulatory mechanism of sex and development in aquaculture animals	1	4	1	1	1	2

extremely complex life phenomenon. What are the driving forces of virus evolution and genetic variance? What are the ways? What is the transmission mechanism and method of the virus breaking through the species barrier? How does the host influence the genetic variation and evolution of the virus? How does the living environment of viruses and hosts affect the evolution of the virus? These questions remain unanswered. Analyzing the evolution and genetic variation mechanisms of viruses will help in understanding how viruses respond to the complex immune system of their host to maintain life and overcome interspecies barriers to achieve cross-species transmission, also this will help in understanding the regularity of intermittent recurrence virus or infectious disease after vaccine immunized animals, and thus has great epidemiological significance.

(2) Intelligent sensing of agricultural life information and environmental information

Intelligent sensing of agricultural life and environmental parameters refers to the *in-situ*, fast, and real-time measurement of plant and animal life status, the environmental conditions in plant growth, and the environmental factors in animal houses. There are two main research directions: The first direction is research on novel sensing mechanisms of plant and animal life parameters. A major trend in recent years is the novel sensing methods based on aptamer sensor, immunosensor, machine vision, and hyperspectral imaging. Using these methods, the behaviors, genders, hormones, and metabolites of plants or animals can be measured, as well as the various biological and chemical parameters of plants, such as crop biochemical components, crop diseases, and pests. High-throughput plant phenotyping has also been studied based on these sensing techniques. The second direction is research on sensing mechanisms of plant and animal environmental parameters. With the emergence of new physical sensing methods and the fast development of the performance of sensing devices, such as the better monochromaticity, power and cover bands of lasers, an emerging approach in recent years is the development of new agricultural environmental sensors. These sensors include *in-situ* sensors for soil factors, e.g., soil nitrogen, heavy metals, and microorganism. As for the sensors for animal environment, a major development is the E-nose for harmful gases measurement in livestock, which based on various principles, e.g., metallic oxide sensors, infrared absorption sensors, and mass spectrometry.

It is predicted that the techniques of intelligent sensing of agricultural life and environmental parameters will quickly develop with advances in basic science. For the sensing mechanisms, the measuring ranges, precision, and sensitivity will improve with the promoting of photoelectricity, chemistry, and nano-sciences. For the sensing parameters, the key focus in next few years will be the microcosmic and other important parameters that cannot be measured *in-situ* by current methods.

(3) Object recognition and localization by agricultural robots

Object recognition and localization by agricultural robots solve the problem of distinguishing the object from environment and calculating the distance of the object. It includes information collection and processing methods. The object recognition by agricultural robots focuses on distinguishing the object from environment, particularly developing optimization methods to improving the accuracy of object recognition for agricultural robots in complex environments, for example, crop, weed, pest, and crop disease recognition algorithms based on multi-feature and image fusion; insect and disease detection algorithms based on hyperspectral imaging. Increasing numbers of optical components are used in the object positioning and sensing of agricultural robots, such as using binocular, depth camera, and other equipment to obtain the three dimensional information about the object. The research foci mainly include: optimizing the calculation method to get the shape and position parameters of the object, and designing optimization algorithms that prevent the robotic arm from touching the object.

To achieve stable and accurate identification and location of objects in a complex and unstructured environment, the trend of agricultural robots in object recognition and positioning technology is to develop low-cost information collection equipment and optimize algorithms for recognizing and positioning the objects of interest.

(4) Precision animal and plant breeding by design

Precision animal and plant breeding by design has become the strategic core of animal and plant germplasm resources innovation, international agricultural science and technology competition, and seed industry competition. The concept of “breeding by design” was proposed in 2003. The main technical links include gene location, selection of excellent trait alleles, and aggregation of excellent genes from different individuals to achieve the goal of design breeding. With the development of multi-omics technologies, big data platforms, gene-editing, and other emerging approaches, it has brought opportunities for the analysis of genetic regulatory network of complex biological traits, built the scientific foundation for the innovation of animal and plant directional breeding by molecular design, and has provided accurate solutions for creating new types of high-production, high-quality, disease-resistant animals and plants. The main technical goals include: 1) exploring the key functional genes, quantitative trait locus (QTL), and regulatory modules that control breeding traits, and clarifying the relationships between genotype, phenotype, and environment; 2) analyzing and designing genotypes with specific breeding objectives, such as high reproduction, high quality, and disease resistance, using big data bioinformatics platform and technology; and 3) analyzing the approaches needed to achieve the target genotypes and to formulate breeding programs to breed excellent new genotypes.

(5) Mining of crop functional genome structure

The important agronomic traits of crops are underscored by related genes. The functions of a gene are not only affected by its own structure, its expression is also affected by its genome context, including the degree of the chromatin openness, the extent of epigenetic modification, and the spatial structure of the locus the gene resides. These factors not only affect the expression level of the gene, but also affect its splicing that may result in new functions. As the main component of the genome, transposable elements (TEs) can affect the structure and function of genes by inserting into various parts of a gene. TEs are closely related to the epigenetic modification, the status of chromatin openness, and remote interactions, strongly impacting the structural variation and expression dynamics of a gene. Polyploids are organisms with more than two sets of genomes. Most angiosperms (approximately 70%) have polyploidy in their history and approximately 40% of the cultivated species are polyploids including wheat, cotton, and rapeseed. Compared with diploids, polyploids are advantageous in yield and adaptability, or so called polyploid vigor.

Crop germplasms stored abundant genomic variations is present. These genetic variations, together with those in mutant libraries, transcriptomes, epigenomes, phenomes and metabolomes, form platforms of technology, information, and genetic materials for mining crop functional genes. Combined with linkage analyses and association analyses, candidate genes for high yield, high efficiency, high quality, disease resistance, and stress resistance have been obtained and experimentally verified by mutants, transgenic technology or gene editing techniques. Therefore, the molecular mechanism of target genes, the number and function of alleles, their breeding values and the path for efficient utilization are interpreted. Eventually, breakthrough progresses will be made in revealing the molecular mechanism of polyploid heterosis and its development and utilization.

(6) Efficient use of agricultural resources and circular economy

Efficient use of agricultural resources refers to the actions and methods to achieve the purpose of resource conservation and producing more agricultural products with less consumption of resources. The agricultural resources include water, soil, fertilizers, and the inputs applied in agricultural production, and also the environment. Techniques and methods can be utilized to improve the use efficiency of agricultural resources in aspects of land use and farming systems design, including germplasm screening, water-saving technologies, fertilizer management, recycling use of agricultural wastes, integrated management of feed and livestock, and crop production. Circular economy is the sustainable development model characterized by resource conservation and recycling for achieving a harmonious situation between ecological environment and economy development. The core idea of circular economy is to establish a feedback loop process of "resource input–product production–resource regeneration" through the entire agricultural production and economic value chain. It can be achieved by strengthening the recycling and promoting the rational and sustainable use of materials and energy, thereby leading to the minimum negative impacts of economic activities on the natural environment. The efficient use of agricultural resources and circular economy are considered from the perspective of the entire chain, including saving resource inputs, improving resource use efficiency, and recycling of waste. The efficient use of agricultural resources and recycling is a way to maximize the economic and ecological benefits, and an important pathway for achieving the sustainable agricultural development and the global sustainable development goals.

(7) Soil biodiversity and ecosystem functions

Soil biodiversity refers to the variability and diversity between soil animals, microorganisms, and plants in the belowground ecosystem, as well as the diversification of interactions between organisms and the environment. It includes species, genetic, structural and functional diversity. Ecosystem function is a concrete manifestation of the value of soil biodiversity. Soil biodiversity is critical for biogeochemical cycles, such as litter degradation and nutrient conversion. It also determines other ecosystem functions like soil development, soil erosion control, soil pollution remediation, agricultural pest control, climate regulation, and maintenance of primary productivity. For human society, soil biodiversity can also provide a variety of ecosystem services such as food supply, water purification, medicine, and industrial raw materials. The maintenance of soil biodiversity is the basic guarantee for the continuous improvement of soil health and productivity, and is the basis for the survival and sustainable development of human society. Currently, affected by human activities, climate change and other factors, the protection of soil biodiversity and the cultivation of healthy soil have been highly valued by governments and relevant international organizations. Conducting comprehensive and in-depth basic research on soil biodiversity protection, establishing a soil biodiversity detection network and ecosystem function evaluation system, and formulating scientific and reasonable soil biodiversity protection strategies are of great significance to ensuring human well-being and sustainable social development.

(8) Interaction of important animal viruses with hosts

Infection and immunity are the results from interaction of pathogens with hosts. Pathogens survive via infection of hosts and the hosts need to maintain a healthy status by clearing the invading pathogens. Some animal pathogens acquire capability of evading immune response of host during long time evolution, escaping from host immunity, causing persistent infections or epidemics in animals, posing an enormous threat to food safety, and leading to severe economic losses. Particularly, recent occurrence and epidemics of viral diseases in animals have adversely affected the development of animal husbandry, causing considerable economic losses, such as African swine fever, highly-pathogenic porcine reproductive and respiratory syndrome, porcine vial diarrhea, pseudorabies, avian influenza, infectious bursal disease, infectious respiratory disease, foot-and-mouth disease, and peste des petitis ruminants, all of which caused huge economic losses. As administration of standard vaccines cannot offer effective protection of animals, development of novel effective and protective vaccines requires complete understandings of the viral pathogenesis, which cannot be achieved without elucidating the mechanism of virus–host interaction. Thus, research on the interaction of important animal viruses with hosts to address these issues will always be a key focus and area needing of innovation. Viruses invade cells via binding to the specific receptors on the cell surface, and then interact with the host cells at protein and nucleic acid levels. At a protein level, viruses express some viral proteins to inhibit antiviral immune signaling of host, creating suitable conditions for their replication. However, the host senses the invaders by recognizing pathogenic features (pathogen-associated molecular pattern, PAMPs) via pathogen recognition receptors to initiate innate immune response and suppress viral replication. At a nucleic acid level, some DNA viruses directly encode microRNA (miRNA) while RNA viruses may smartly regulate miRNA expression of host, inhibiting antiviral immune signaling of host, while the host, upon recognizing PAMPs, directly target viral genomes or negative immune regulators via expressing specific miRNAs to inhibit viral replication. A successful development of novel effective vaccine for animals by reverse genetics or gene-editing techniques requires greater understanding of viral pathogenesis obtained by investigation of virus–host interactions, which will lay a foundation in the future prevention and control of animal infectious diseases of concern.

(9) Interaction mechanism between pathogen and crop

The mechanistic study of pathogen and crop interactions provides insight into sustainable crop disease management. A series of conceptual breakthroughs in the plant–pathogen interaction, as well as novel technologies to modulate crop resistance, have been made over the last decade. Based on the genomes of crops such as rice and wheat, as well as the genomes from aggressive phytopathogens, a number of genes with important theoretical and application values were cloned, such as resistance genes from crops and virulence genes from pathogens. The functional mechanisms of a few essential resistance genes were revealed. Particularly, the structure of the first plant resistosome provided novel insights into the operation of resistance genes. The key mechanisms of plant resistance led to generation of an approach to balance the crop immunity, productivity, and quality. Crops possessing elite resistant gene alleles were created through the clustered regularly interspaced short palindromic repeats (CRISPR)-based gene-editing techniques. Mechanistic study of molecules such as metabolites, effector proteins, and small RNAs enable new concepts of pathogenesis. Meanwhile, scientists have also identified the underlying mechanisms of how pathogens adapt to resistant crops and trigger epidemics in the field. In addition, the newly discovered molecules with crop immune priming function or with antimicrobial activity inform the development of new strategies on rational crop disease management.

(10) Microbial driving mechanism of carbon cycling in forest soil

About 70% of the forest carbon is stored in soil. The input of forest soil carbon mainly includes decomposition of plant litter, root exudates and turnover, soil microbes and animals, and the output mainly includes leaching and organic matter decomposition. In the face of global climate change, it is necessary to better understand the regulation and driving mechanism of specific functional microbial community to maintain the stability of soil carbon sequestration in forest ecosystems. Soil microbes regulate and affect the accumulation of soil organic carbon through active microbial communities (dissimilation metabolism) and microbial death residues (assimilation metabolism). Rhizosphere microbial community has higher carbon sequestration efficiency than wider microbial community in the soil. Ectomycorrhiza and hyphae reduce the activity of saprophytic decomposers and the production of enzyme through their competitive advantages with nitrogen and thus reduce soil respiration and increases soil carbon storage. Arbuscular mycorrhizal fungi do not only form soil aggregates through the action of hyphae to prevent the decomposition of organic matter, but also exude carbohydrates substances that are readily used by decomposers to promote saprophytic microbes to approach the rhizosphere soil and accelerate the decomposition of organic matter. With the application of soil microbial high-throughput sequencing and biogeochemical structure analysis of soil organic carbon at the molecular level, the microbial functional genes and their encoded proteins that regulate the decomposition of different carbon components in soil organic matter have been continuously discovered. However, forest ecosystem is particularly rich in soil microbial diversity, and the processes of environmental change affecting soil microbial and soil carbon cycle are extremely complex. Therefore, it is still necessary to integrate multiple disciplines concepts and methods in the future to further clarify the microbial regulation mechanism in the forest soil carbon cycle.

(11) Molecular basis and regulatory mechanism of sex and development in aquaculture animals

Sex determination and development have always been a research focus in life sciences. Compared with mammals, the sex determination mechanisms of aquaculture species are more complex and diverse. For example, there are sex determination systems such as XX/XY, ZZ/ZW, XO/XX. Characteristic hermaphroditism or sex reversal can be observed in some aquaculture species, which makes them unique material for the study of sex determination mechanisms in animals. Meanwhile, these studies also provide potential solutions to several pressing problems in aquaculture. Natural sex reversal traits are common for ricefield eels and groupers. Conversion from genetic females to physiological males of *Nile tilapia* is induced by high temperature. For aquaculture of semi-smooth tongue sole, brown flounder, and loaches, females are preferred due to their higher growth rate than males. In view of the key scientific issues during aquatic germplasm creation, such as the molecular mechanisms and regulatory networks for sex determination and gonadal development, it has been proposed to study the molecular mechanisms of sex determination and differentiation of finfish, shellfish, soft-shelled turtle, crab, sea cucumber and others; to explore the key genes and regulatory elements for sex determination, while clarifying functions and regulatory networks of related molecules; to research the associations between sex development and important production traits; to analyze the patterns and mechanisms of sex conversion responses to the environmental factors; to screen sex-specific molecular markers; and to study the reproductive characteristics of new germplasm with economic value and to clarify their regulatory mechanisms.

Using aquaculture animals with sexually dimorphic phenotypes, including finfish, shellfish, soft-shelled turtle, crab, and sea cucumber, the mechanism and evolution process of sex determination, gonadal development and environmental interaction for aquaculture animals will be investigated. Based on genomics, transcriptomics, and epigenetics analysis, research on sex determination and development of various aquatic animals will be conducted to identify the factors associated with sex differentiation or development and their expression patterns, as well as the epigenetic modification characteristics. Future research interests will include genomic analysis of aquaculture animals and identification of sex-linked genetic markers, regulatory mechanisms of sex determination and development, sex reversal and environmental factor interaction mechanisms, the effect mechanism of genome ploidy on sex and fertility, and the association mechanisms of sex development and production traits.

1.2 Interpretations for three key engineering research fronts

1.2.1 Origin, evolution, and genetic variation of animal viruses

Since 2000, humans have experienced many major infectious diseases: 2002–2004, Severe Acute Respiratory Syndrome (SARS); 2009, H1N1 Influenza A; 2009–2010, meningitis in West Africa; 2013–2016, Ebola in West Africa; 2012 to present, Middle East Respiratory Syndrome, and the COVID-19 that emerged in 2019. Recent viral diseases of economic animals have included reemergences of old viruses and continuously appearing of novel viruses.

Tracing the source of animal viruses and analyzing the origin, evolution, and genetic variation of animal viruses is important for the development of effective ways to prevent and control the spread of infectious diseases, and it has attracted considerable attention in epidemiology for many years. In the research on virus traceability, established methods include detailed epidemiological and comprehensive distribution investigations of viruses in animals and the environment. However, new methods benefit from the application of bioinformatics techniques, which makes it possible to determine the genetic relationship between different viruses through gene homology comparison and the topological results of the evolutionary tree. Accurate tracing of animal-derived viruses and understanding the mechanisms in genetic variation of viruses can intercept the source of infection in time, effectively monitoring, preventing and controling the occurrence of infectious diseases. In fact, the virus traceability work is difficult with the research process being complicated and uncertain. For example, COVID-19, which appeared at the end of 2019, has rapidly spread globally since its appearance. Scientists around the world are actively exploring the origin of SARS-CoV-2, but the source is still unresolved. Studies have shown that the virus may appear in the population earlier than expected, but it was not detected due to limitations in monitoring, and it was interspersed among other pneumonia cases. During the zoonotic transmission phase, the virus gradually acquired key mutation sites, making it fully adapted to humans. Retrospective blood tests or subgenome studies for respiratory infections may help to determine if this interpretation is correct. The exploration of the source of the SARS virus of 2003 has made substantial progress, bats are generally considered as the natural hosts, while palm civets were thought to be the intermediate hosts before the virus entered the population, but further research is needed.

In the established methods of tracing the source of a virus, the epidemiological investigation generally starts from the contact history of the first patient, known as patient zero, but sometimes it is difficult to determine the identity of patient zero, such as the tracing of patients with HIV; the investigation of the distribution of viruses in animals and the environment is the most direct and important method in the tracing process. This method has been successfully applied to research on simian immunodeficiency viruses. Compared with established methods, bioinformatics technology combines genome sequence with computational epidemiology and uses molecular clock theory to estimate the evolution time of viruses to infer the relative distance between viruses. For example, the genome comparison results of the SARS-CoV-2 and the bat-coronavirus carried by bats show that the SARS-CoV-2 completes the evolutionary transmission from bats to humans and requires at least one intermediate host as a transmission vector. Every part plays an important role in the process of virus tracing. Due to the various uncontrollable factors, the epidemiological monitoring of animal viruses should increase to effectively prevent and control the emergence and spread of new infectious diseases in the context of One Health.

The survival of the fittest in Darwinian evolution theory also applies to the survival of viruses, which means that the virus can only survive through continuous mutation and evolution. Viruses can mutate through a variety of mechanisms, and their genome can rearrange, which allows newly replicated viruses to show different characteristics from previous generations. In addition, the bases on the genetic material of the virus will mutate randomly, and this genetic drift phenomenon can also cause mutations in the virus. Studies have shown that RNA viruses are more prone to genetic mutations because, compared with DNA viruses, RNA viruses are more prone to errors in the replication process and have lower stability, such as the cross-host transmission of avian influenza viruses. The H3N2 subtype of canine influenza virus (H3N2 CIVs) appeared in dogs in Asia around 2005 and originated from avian hosts. H3N2 CIV can be divided into seven major clades and some mutation sites provided evidence for adaptive evolution. The main lineages of viruses have similar predicted genomic evolution rates, but compared to other in avian reservoir viruses, H3N2 CIV consistently shows proportionally more nonsynonymous substitutions at each site, which indicates that there has been a large-scale change in selection pressures. According to the evolution rate and amino acid site mutation analysis, it was found that the avian influenza has evolved relatively quickly after entering a mammalian host (dogs), and is more adapted to the transmission between mammalian hosts.

Given that viruses, especially RNA viruses, are prone to mutation and their evolution rate is relatively high, mastering the genetic evolution mechanisms of viruses has become a key factor in controlling virus transmission. In order to solve related problems, the genome sequence and related information are combined with bioinformatics and statistical methods that rely on high-performance computers to better analyze the genetic variation and transmission mechanisms of viruses through big data. In the study of virus traceability, evolution, and mechanisms of genetics mutation, the use of epidemiological knowledge combined with statistical science and computer algorithms has become an emerging discipline that can better serve in prevention and control strategies for viral epidemics.

Considering the distribution of papers by country, it can be seen that the main contributors of core papers on the “origin, evolution, and genetic variation of animal viruses” were the United States (62.07%), the United Kingdom (29.31%), and France (20.09%) (Table 1.2.1). The citations per paper in this field ranged from 51 to 109 across the top 10 countries, and the citations per paper for the Netherlands and India exceeded 100. The distribution of papers by research institution shows that the number of core papers were the highest for the University of Oxford and the US Centers for Disease Control and Prevention (Table 1.2.2). The collaboration networks among the major countries were common, with the United Kingdom, the United States, and France sharing the closest collaborative relationship (Figure 1.2.1). From the network diagram of collaborations among the major contributing institutions (Figure 1.2.2), it can be seen that collaborative relationships existed among all institutions. The main contributors of core paper citations were the United States, China, and the United Kingdom (Table 1.2.3), the number of citing papers in the United States accounts for more than one third, United Kingdom and China both account for more than 10%, and the average citation year of core papers was also relatively recent, which is indicative of the strong developmental momentum of research in this field. From the list of the major core paper citation-contributing institutions (Table 1.2.4), it can be seen that the US Centers for Disease Control and Prevention and the Institute Pasteur were far ahead of all other institutions, and the Chinese Academy of Sciences ranked sixth.

Table 1.2.1 Countries with the greatest output of core papers on “origin, evolution, and genetic variation of animal viruses”

No.	Country	Core papers	Percentage of ore papers	Citations	Citations per paper	Mean year
1	USA	36	62.07%	3 292	91.44	2015.5
2	UK	17	29.31%	1 648	96.94	2015.2
3	France	12	20.69%	609	50.75	2015.3
4	Australia	10	17.24%	873	87.30	2015.4
5	China	8	13.79%	743	92.88	2016.0
6	Belgium	6	10.34%	547	91.17	2015.2
7	Germany	6	10.34%	449	74.83	2015.5
8	Netherlands	5	8.62%	540	108.00	2014.4
9	Spain	4	6.90%	205	51.25	2015.8
10	India	3	5.17%	327	109.00	2014.3

Table 1.2.2 Institutions with the greatest output of core papers on “origin, evolution, and genetic variation of animal viruses”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	University of Oxford	7	12.07%	861	123.00	2015.3
2	US Centers for Disease Control and Prevention	7	12.07%	823	117.57	2016.0
3	Fred Hutchinson Cancer Research Center	6	10.34%	1 007	167.83	2015.8
4	National Institutes of Health	6	10.34%	639	106.50	2015.2
5	University of Sydney	6	10.34%	468	78.00	2016.0
6	Institute Pasteur	6	10.34%	318	53.00	2015.8
7	U.S. National Library of Medicine	5	8.62%	287	57.40	2016.6
8	University of Edinburgh	4	6.90%	790	197.50	2015.8
9	Harvard University	4	6.90%	495	123.75	2016.2
10	University of Melbourne	4	6.90%	451	112.75	2015.3

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “origin, evolution, and genetic variation of animal viruses”

1.2.2 Precision animal and plant breeding by design

Precision animal and plant breeding by design has become the strategic core of animal and plant germplasm resources innovation, international agricultural science and technology competition, and seed industry competition. In 2018, the United States released the *Science Breakthroughs to Advance Food and Agricultural Research by 2030*, which listed genomics and biological precision breeding as one of the major directions of agricultural development in the future. The precision breeding comes from the concept of “breeding by design” proposed by Peleman and Van Der Voot in 2003. It is mainly aimed at plant breeding. The technical links include gene mapping, screening of excellent alleles, and clustering of excellent genes from individuals, so as to achieve the goal of

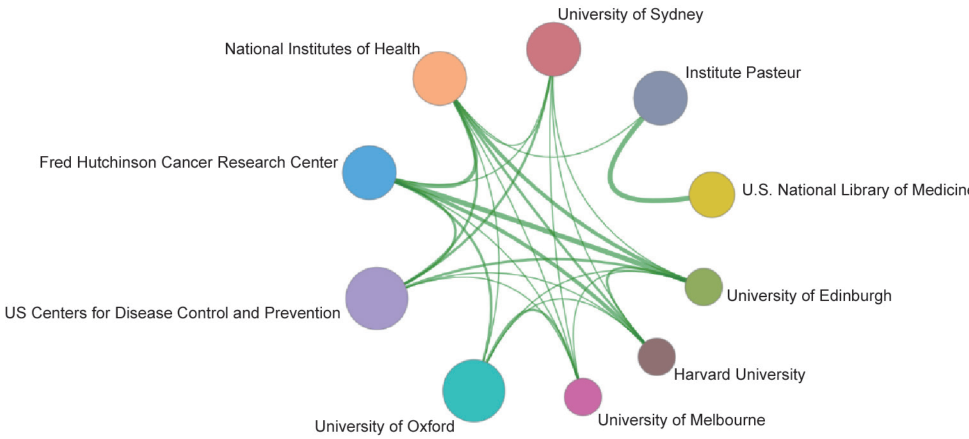

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "origin, evolution, and genetic variation of animal viruses"

Table 1.2.3 Countries with the greatest output of citing papers on "origin, evolution, and genetic variation of animal viruses"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	1 724	36.29%	2017.8
2	China	613	12.90%	2018.5
3	UK	513	10.80%	2017.8
4	France	374	7.87%	2017.6
5	Germany	319	6.71%	2017.9
6	Australia	279	5.87%	2017.9
7	Canada	213	4.48%	2018.0
8	Brazil	197	4.15%	2018.2
9	Spain	181	3.81%	2017.9
10	Italy	181	3.81%	2018.3

Table1.2.4 Institutions with the greatest output of citing papers on "origin, evolution, and genetic variation of animal viruses"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	US Centers for Disease Control and Prevention	170	14.66%	2018.0
2	Institute Pasteur	134	11.55%	2017.6
3	University of Oxford	121	10.43%	2018.0
4	Harvard University	115	9.91%	2017.9
5	University of Sydney	108	9.31%	2017.6
6	Chinese Academy of Sciences	104	8.97%	2018.3
7	National Institute of Allergy and Infectious Diseases	99	8.53%	2017.7
8	National Institutes of Health	82	7.07%	2017.2
9	The University of Texas Medical Branch	79	6.81%	2017.2
10	University of Cambridge	77	6.64%	2017.6

design breeding. At present, precision breeding by molecular design has been extended to the field of animal breeding. Around the world, in-depth research has been conducted in plants, mammals, and aquatic animals, and remarkable results have been achieved. The continuous innovation of agricultural precision breeding technology is changing the established agricultural production mode toward a more modern agriculture.

Over recent years, with the rapid development of multi-omics technologies for genomes, epigenomes, transcriptomes, proteomes, and metabolomes, the analysis of functional genes, QTLs, and regulatory modules related to important traits of animals and plants has been deepened, and the interaction mechanisms of genes, phenotypes, and environment have been increasingly clarified, which has laid a theoretical foundation for precision animal and plant breeding by design. The rapid development of bioinformatics, whole genome selection, and gene editing provides technical support for precise design of animal and plant traits. Based on the omics databases, bioinformatics technology and computer-aided means have been used to simulate the breeding process, design breeding materials according to the breeding objectives, and breed new lines. Whole genome selection technology is based on the high-throughput genotype analysis and prediction model, which aggregates excellent genotypes at the whole genome level and improves important traits of animals and plants. Gene-editing technology can precisely modify a target gene in a genome, such as deletion, substitution, and insertion, break the species boundary, and realize gene directional transfer across species. In particular, the development of CRISPR-Cas9 system significantly improves the efficiency and accuracy of gene editing, which has become one of the important means of precision breeding. The combined application of multiomics genetic information, whole genome selection, and gene-editing technology makes animal and plant breeding more efficient, accurate, and controllable, thus realizing the leap from crossbreeding to precision breeding, and solving major production problems that cannot be solved by established methods.

As standard cross-breeding is difficult to combine multiple superior genes into one line, its selection efficiency is low and the time period involved is long. Precision animal and plant breeding by design focuses on the important demand of directional breeding of new genotypes of animals and plants with high yield, high quality, and disease resistance. Taking plants and aquatic and farm animals as examples, the regulation network of genes for important economic traits was clarified, a new generation of precise design and breeding technology system of animals and plants was established, and new lines and breeding materials with important values were created. In 2018, the global planting area of genetically modified crops has reached 191.7 million hectares and 70 countries and regions have approved the planting or import of genetically modified crops and products. The popularization and application of transgenic crops significantly increased the yield of crops, reduced the amount of pesticides, and produced huge economic and social benefits. The industrialization process of gene-edited products, such as drought tolerant corn, herbicide resistant and phosphorus efficient maize, low temperature storage potato, and high-oleic-acid soybean, has been accelerated. The whole genome sequencing of wheat and rice has been completed. On the basis of clear function of major agronomic traits genes, a range of new cultivars with high yield, high quality, and disease resistance were bred through cutting and polymerization of favorable genes. The physiology of animals are more complex than plants. At present, the research is mainly based on molecular marker technology for gene polymerization, gene infiltration, and breeding of new lines by using gene-editing technology. High-yield and disease-resistant livestock, such as CD163 gene-edited pig, hornless cow with polled gene replacement, and double-muscular livestock with MSTN knockout, have been obtained. In 2015, AquaBounty Company in the United States bred a fast-growing salmon, which was approved for production and sale. This event accelerates the commercialization of gene-edited animals. The continuous innovation of agricultural biological precision design breeding technology is rapidly changing the established production mode.

The top three countries in the research on precision animal and plant breeding by design are the United States, China, and the United Kingdom. The top three countries with the highest citations per paper are Germany, Japan, and France (Table 1.2.5). Among the top 10 countries, the United States had cooperation with Mexico, Kenya, the United Kingdom, China, France, Germany, India, and Austrilia while Japan had no cooperation with other countries (Figure 1.2.3). Cornell University, Agricultural Research Service, United States Department of Agriculture (USDA ARS), and the International

Maize and Wheat Improvement Center (CIMMYT) are the top three institutions in the number of core papers published (Table 1.2.6). A paper entitled, "Genomic selection and association mapping in rice (*Oryza sativa*): effect of trait genetic architecture, training population composition, marker number and statistical model on accuracy of rice genomic selection in elite, tropical trice breeding lines" published by Jennifer Spindel and colleagues of Cornell University and many other institutions is the most cited paper (205 citations). This paper evaluated the effect of genome selection in rice inbred line breeding. Among the top 10 institutions, Cornell University, USDA ARS, CIMMYT, and Kansas State University have had more cooperation (Figure 1.2.4). The top three countries with the greatest number of citing papers are the United States, China, and India (Table 1.2.7). The main output institutions of citing papers are USDA ARS, Chinese Academy of Agricultural Sciences, and Chinese Academy of Sciences (Table 1.2.8).

1.2.3 Soil biodiversity and ecosystem functions

Healthy soil is rich in biodiversity, including bacteria, fungi, actinomycetes, nematodes, vertebrates, earthworms, mites, and insects. These soil organisms are important in promoting plant growth, enhancing soil fertility, promoting the decomposition of organic matters, suppressing pests, parasites, and pathogens, and maintaining the stability of the soil ecosystem. At present, human activities have put increasing pressure on biodiversity and ecosystem services. Deforestation, intensive farming, and excessive use of fertilizers and pesticides have greatly exacerbated the decrease in number and species of soil organisms. Subsequently, ecosystem stability is becoming more fragile, which will endanger the sustainability of soil productivity and the function of soil ecosystem. Faced with the loss of biodiversity, the United Nations officially launched the "Millennium Ecosystem Assessment" project

Table 1.2.5 Countries with the greatest output of core papers on "precision animal and plant breeding by design"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	48	44.04%	4 004	83.42	2015.8
2	China	28	25.69%	2 120	75.71	2015.8
3	UK	14	12.84%	1 155	82.50	2014.8
4	Mexico	13	11.93%	1 090	83.85	2015.3
5	Germany	10	9.17%	922	92.20	2015.2
6	France	9	8.26%	775	86.11	2015.4
7	India	8	7.34%	641	80.12	2016.3
8	Kenya	7	6.42%	435	62.14	2015.8
9	Australia	6	5.50%	389	64.83	2014.8
10	Japan	5	4.59%	452	90.40	2014.4

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "precision animal and plant breeding by design"

Table 1.2.6 Institutions with the greatest output of core papers on "precision animal and plant breeding by design"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Cornell University	12	11.01%	1018	84.83	2014.8
2	USDA ARS	12	11.01%	953	79.42	2015.2
3	CIMMYT	11	10.09%	908	82.55	2015.2
4	Kansas State University	8	7.34%	549	68.62	2015.0
5	Chinese Academy of Agricultural Sciences	7	6.42%	660	94.29	2016.1
6	University of Minnesota	7	6.42%	345	49.29	2014.7
7	DuPont Pioneer	5	4.59%	740	148.00	2015.2
8	University of Arizona	5	4.59%	604	120.80	2015.4
9	Chinese Academy of Sciences	5	4.59%	578	115.60	2016.2
10	The Sainsbury Laboratory	5	4.59%	485	97.00	2015.0

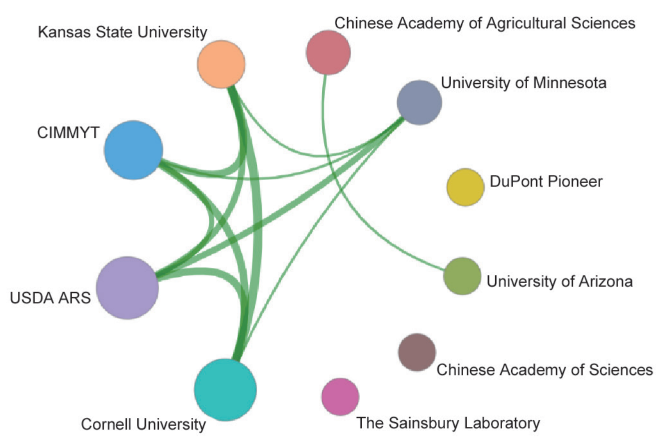

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "precision animal and plant breeding by design"

Table 1.2.7 Countries with the greatest output of citing papers on "precision animal and plant breeding by design"

No.	Country	Citing papers	Percentage of citing papers	Mean Year
1	USA	1 640	29.39%	2017.8
2	China	1 413	25.32%	2018.0
3	India	400	7.17%	2018.0
4	Germany	384	6.88%	2017.8
5	UK	333	5.97%	2017.8
6	Australia	323	5.79%	2017.7
7	Brazil	252	4.52%	2018.2
8	France	247	4.43%	2017.6
9	Japan	223	4.00%	2017.9
10	Mexico	190	3.40%	2017.8

Table 1.2.8 Institutions with the greatest output of citing papers on “precision animal and plant breeding by design”

No.	Institution	Citing papers	Percentage of citing papers	Mean Year
1	USDA ARS	262	16.18%	2017.8
2	Chinese Academy of Agricultural Sciences	253	15.63%	2018.1
3	Chinese Academy of Sciences	194	11.98%	2017.8
4	CIMMYT	137	8.46%	2017.6
5	Cornell University	133	8.21%	2017.6
6	Huazhong Agricultural University	131	8.09%	2018.0
7	University of Florida	120	7.41%	2018.1
8	Iowa State University	101	6.24%	2017.5
9	China Agricultural University	98	6.05%	2018.2
10	University of Minnesota	97	5.99%	2017.6

in 2001, scientifically assessing the status and trends of global ecosystems and the services they provide and proposing various restoration, protection or improvement countermeasures for the sustainable development and use of ecosystems. In 2012, under the leadership of the United Nations Environment Programme, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services was formally established, which is another intergovernmental environmental assessment plan after the United Nations Intergovernmental Panel on Climate Change. Soil contains a quarter of global biodiversity; therefore, the protection of soil biodiversity is essential to soil health, soil productivity, and food security.

The research on the relationship between soil biodiversity and ecosystem functions has developed rapidly over the past 40 years, and has become an important cross-disciplinary research area in ecology, agronomy, microbiology, environmental science, humanities, and economics. From the beginning, attention was given to the impact of species loss on the structure and function of the ecosystem, and gradually developed to the use of experiments or theoretical models to study the contribution sizes and mechanisms of biodiversity for primary production, biogeochemical cycles, environmental purification, climate regulation, pest control, and economic value. At present, researchers of soil biodiversity and ecosystem services and functions have basically formed a consensus in five aspects: 1) Biodiversity can improve ecosystem productivity and resource utilization efficiency. 2) Biodiversity improves ecological stability, and the longer the time, the more significant the effect. 3) The impact of biodiversity on a single process or function in the ecosystem is nonlinear and saturated. 4) The impact of species losses between different trophic levels on ecosystem functions is greater than the species losses within the trophic level. 5) The functional traits of organisms have an important impact on the performance of ecosystem functions.

Based on a large number of published studies, four research fronts have emerged. 1) Soil biodiversity and ecosystem functions under the global changes background. In addition to biodiversity itself, changes in climate and environmental conditions such as drought, warming, and soil acidification may affect the functioning of ecosystems. Therefore, analyzing the impact and contribution of soil biodiversity, climate and environmental factors on ecosystem functions, and how global changes affect soil biodiversity and ecosystem functions, is a major challenge facing the future global sustainable development. 2) Temporal and spatial scale characteristics of soil biodiversity and ecosystem service functions. Current researches mostly focus on small areas and short time scales, and there are few studies on larger landscape scales and variability over time scales. Therefore, clarifying the temporal and spatial scale characteristics of soil biodiversity and ecosystem services is of great significance for landscape-level protection and sustainable use. 3) Soil biodiversity and ecosystem multifunctionality. Maintaining multiple ecological functions requires the participation of more species than one ecological function. Therefore, soil biodiversity and the realization of multifunctionality in ecosystems has become a research hotspot in recent years. 4) Relationships between ecological benefits of soil biodiversity and species evolution.

With the development of molecular analysis technology, studies have shown that the greater the phylogenetic distance between species, the more conducive to the performance of ecosystem functions, which may be related to the increase in functional traits caused by genetic diversity between species.

The countries where core papers are published were mainly from the United States, China, and Spain. The number of citations was highest in Switzerland and the Netherlands (Table 1.2.9). In terms of the distribution of research institutions, Rey Juan Carlos University (Spain), the Chinese Academy of Sciences, and the University of Colorado Boulder (USA) were ranked at the top with core paper publications, while the number of citations was highest for papers published by the University of Zurich and the Agroscope (Table 1.2.10). A highly cited paper entitled "Soil biodiversity and soil community composition determine ecosystem multifunctionality" published in the journal *PNAS* in 2014 was cited 544 times. This work was collaboratively completed by scientists from the Agroscope and the University of Zurich, focusing on the effects of soil biodiversity and soil community composition on ecosystem multifunctionality. It showed that the reduction of soil biodiversity and the simplification of community composition would impair multiple ecosystem functions, including plant diversity, decomposition, nutrient retention, and nutrient cycling, indicating that changes in soil communities and the loss of soil biodiversity would threaten ecosystem multifunctionality and sustainability.

In terms of cooperation network among countries, the United States, Australia, Spain, and China have relatively close collaborative relationships (Figure 1.2.5). From the network diagram of collaborations among the major contributing institutions (Figure 1.2.6), every institution has a certain

Table 1.2.9 Countries with the greatest output of core papers on "soil biodiversity and ecosystem functions"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	24	43.64%	450	18.75	2017.5
2	China	18	32.73%	241	13.39	2018.2
3	Spain	17	30.91%	368	21.65	2017.4
4	Australia	14	25.45%	276	19.71	2017.4
5	Germany	11	20.00%	260	23.64	2017.3
6	Switzerland	10	18.18%	1 506	150.60	2016.4
7	Netherlands	5	9.09%	1 359	271.80	2016.4
8	France	5	9.09%	618	123.60	2017.0
9	Sweden	5	9.09%	173	34.60	2017.0
10	UK	5	9.09%	142	28.40	2016.8

Table 1.2.10 Institutions with the greatest output of core papers on "soil biodiversity and ecosystem functions"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Rey Juan Carlos University	15	27.27%	302	20.13	2017.5
2	Chinese Academy of Sciences	10	18.18%	176	17.60	2018.0
3	University of Colorado Boulder	8	14.55%	95	11.88	2018.4
4	Western Sydney University	7	12.73%	79	11.29	2018.0
5	Northern Arizona University	6	10.91%	162	27.00	2016.0
6	University of Minnesota	6	10.91%	114	19.00	2017.5
7	University of Zurich	5	9.09%	1 349	269.80	2016.4
8	Agroscope	5	9.09%	1 106	221.20	2017.2
9	Swedish University of Agricultural Sciences	5	9.09%	173	34.60	2017.6
10	Chinese Academy of Forestry	5	9.09%	152	30.40	2017.0

collaborative relationship with other institutions. The main contributors of core paper citations were China and the United States, and the average citing year was 2018, showing strong developmental momentum of research in this field. (Table 1.2.11). From the list of the major core paper citation-contributing institutions (Table 1.2.12), the Chinese Academy of Sciences was far ahead and the average citing year was 2018.

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "soil biodiversity and ecosystem functions"

2 Engineering development fronts

2.1 Trends in top 9 engineering development fronts

Based on global patent applications and authorization documents related to agriculture during 2014–2019, the top 9 engineering development fronts were identified (Table 2.1.1). These engineering development fronts can be roughly divided into three categories: (1) development fronts related to agricultural production equipment, including "intelligent equipment for unmanned farm," "the principles and techniques of advanced agricultural sensors," and "intelligent

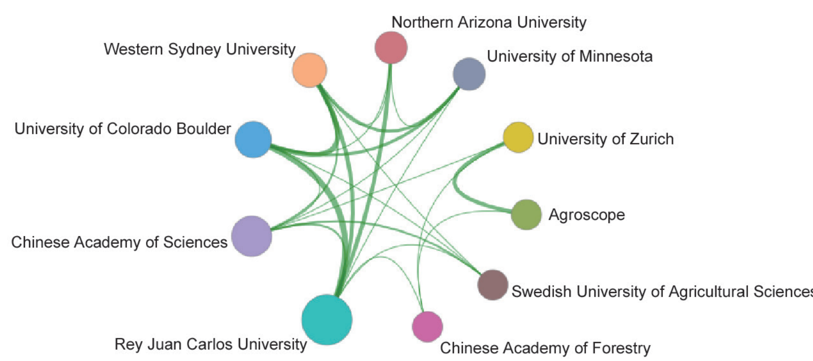

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "soil biodiversity and ecosystem functions"

Table 1.2.11 Countries with the greatest output of citing papers on "soil biodiversity and ecosystem functions"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	520	19.62%	2018.6
2	USA	475	17.92%	2018.0
3	Germany	279	10.52%	2018.0
4	UK	207	7.81%	2018.1
5	France	201	7.58%	2017.9
6	Spain	195	7.36%	2017.9
7	Switzerland	186	7.02%	2017.7
8	Australia	177	6.68%	2018.0
9	Netherlands	169	6.38%	2017.8
10	Canada	130	4.90%	2018.4

Table 1.2.12 Institutions with the greatest output of citing papers on “soil biodiversity and ecosystem functions”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	203	25.47%	2018.5
2	University of Chinese Academy of Sciences	84	10.54%	2018.6
3	University of Zurich	73	9.16%	2017.4
4	Swedish University of Agricultural Sciences	71	8.91%	2018.1
5	German Centre for Integrative Biodiversity Research (iDiv)	61	7.65%	2018.2
6	Rey Juan Carlos University	59	7.40%	2017.8
7	China State Shipbuilding Corporation Limited	55	6.90%	2017.6
8	Leipzig University	50	6.27%	2018.2
9	Agroscope	48	6.02%	2017.3
10	Utrecht University	47	5.90%	2016.9

identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection unmanned aerial rehicles (UAVs);” (2) development fronts related to environmental governance, including “resource utilization of agricultural and rural organic wastes” and “remediation of soil polluted by organic compounds;” and (3) development fronts related to the promotion of agricultural production and food safety, including “development of efficient and safe animal vaccines and diagnostic reagents,” “artificial-intelligence-assisted breeding,” “construction of economic forest high yield plant-type,” and “research and application of formulated aqua-feeds.”

Table 2.1.1 gives an overview of the core patents in these 9 engineering development fronts from 2014 to 2019. “Intelligent equipment for unmanned farm,” “remediation of soil polluted by organic compounds,” and “construction of economic forest high yield plant-type” are the three development fronts with the most core patents, each of which are more than 100. The citations per paper of “intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs” is the highest (9.3) and much higher than others. The two development fronts “resource utilization of agricultural and rural organic wastes” and “artificial-intelligence-assisted breeding,” with latest mean year of core patents, have had a large number of applications and rapid technological updates in recent years.

Table 2.1.2 shows the publishing trends of core patents in these 9 engineering development fronts from 2014 to 2019. It can be seen that, the number of core patents published for the three development fronts, “intelligent equipment for unmanned farm,” “resource utilization of agricultural and rural organic wastes,” and “artificial-intelligence-assisted breeding,” have shown a significant increase since 2017, and the growth momentum is strong.

(1) Intelligent equipment for unmanned farm

Unmanned farms are one of the possible production methods and realizations of smart agriculture. The unmanned farm is characterized by following points: 1) system covers the whole production chain, including tillage, planting, management, and harvest; 2) operating machinery can autonomously transfer between fields and garages; 3) operating machinery has the function of obstacle avoidance and emergency-triggered stop; 4) real-time monitor on the whole producing process; and 5) decision-making and precision operations are all intelligence-based and unmanned. Unmanned farms depend on the support of biotechnology, intelligent equipment, and information technology. Biotechnology provides unmanned farm with crop cultivars and cultivation modes suitable for mechanized operations. Intelligent equipment is used for intelligent perception, navigation, operation, and management. Information technology offers support on information acquisition, transmission, and processing, as well as navigation, automatic operation, and remote maintenance of agricultural machinery.

The cutting-edge technologies of intelligent equipment for unmanned farm mainly include intelligent perception, intelligent navigation, intelligent operation, intelligent

Table 2.1.1 Top 9 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Intelligent equipment for unmanned farm	206	990	4.81	2017.2
2	Development of efficient and safe animal vaccines and diagnostic reagents	80	67	0.84	2016.8
3	The principles and techniques of advanced agricultural sensors	49	50	1.02	2017.4
4	Resource utilization of agricultural and rural organic wastes	90	45	0.50	2018.3
5	Remediation of soil polluted by organic compounds	116	421	3.63	2017.4
6	Artificial-intelligence-assisted breeding	56	15	0.27	2018.4
7	Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs	45	419	9.31	2017.5
8	Construction of economic forest high yield plant-type	142	402	2.83	2016.9
9	Research and application of formulated aqua-feeds	65	88	1.35	2016.3

Table 2.1.2 Annual number of core patents published for the top 9 engineering development fronts in agricultural field

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Intelligent equipment for unmanned farm	11	16	34	48	47	50
2	Development of efficient and safe animal vaccines and diagnostic reagents	15	8	11	12	10	24
3	The principles and techniques of advanced agricultural sensors	6	4	3	6	14	16
4	Resource utilization of agricultural and rural organic wastes	2	0	0	14	28	46
5	Remediation of soil polluted by organic compounds	12	18	5	13	9	59
6	Artificial-intelligence-assisted breeding	0	0	3	9	17	15
7	Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs	6	2	2	7	11	17
8	Construction of economic forest high yield plant-type	13	20	23	27	30	29
9	Research and application of formulated aqua-feeds	16	5	5	12	8	15

management, and system integration. Intelligent perception consists of agricultural sensors, environmental information perception, animal and plant information perception, and intelligent data processing. Intelligent navigation requires technology of high-resolution map construction, route planning, precision positioning in complex environment, path following control, and multi-equipment collaborative operation. Intelligent operations include precision seeding, variable fertilization, variable pesticide application, and variable irrigation. Intelligent management includes status monitoring, remote operation, maintenance, and management of intelligent equipment.

(2) Development of efficient and safe animal vaccines and diagnostic reagents

Animal vaccines are used for preventing animal infectious disease and are typically prepared by artificially attenuating, inactivating or genetically engineering the pathogenic microorganisms (e.g., viruses and bacteria) and their metabolites. Standard inactivated vaccines have the limitations of high cost and incomplete immune effect and attenuated vaccine strains have the risk of virulence returning. Therefore, development of efficient and safe genetic engineering animal vaccines, such as DNA vaccine, gene-deleted vaccine, live vector vaccine, virus-like particle vaccine, and synthetic peptide vaccine, are the main direction of future research. New genetic engineering animal vaccines that have been licensed in China include avian influenza DNA vaccine, foot-and-mouth disease synthetic peptide vaccine, and gene-deleted vaccine against pseudorabies.

Effective diagnostic reagents are the key prerequisite for accurate diagnosis, prevention, and control of animal epidemics. The development of diagnostic reagents mainly include: research on pretreatment technology for testing samples; antigen or antibody detection technology based on immune response (such as monoclonal antibody, enzyme-linked immunosorbent assay, immune colloidal gold test stripe, immunofluorescence technology, and nano-antibody technology); molecular biological detection based on nucleic acids (such as polymerase chain reaction (PCR), quantitative PCR, loop-mediated isothermal amplification, fluorescent labeling aptamer technology, and whole genome sequencing); and simple, rapid, sensitive, accurate, high-throughput, and online detection are the development directions of diagnostic reagents.

(3) The principles and techniques of advanced agricultural sensors

Sensing principles and techniques are the basic supports of agricultural sensors. Agricultural sensors are the devices to measure and monitor the agricultural environmental parameters, life status, and the working status of agricultural machinery. Agricultural sensors consist of sensing materials, processing chips, and core algorithms, and are supported by specific physical mechanisms.

There are two main research directions. The first direction is the researches on novel sensing mechanisms and original sensing methods of agricultural sensors. In recent years, new physical, chemical, and biological sensing methods are increasingly applied in agriculture. Various sensors of different principles have been developed. This has the potential to realize the *in-situ* measurement of soil nitrogen, soil heavy metals, and water quality; non-destructive detection of crop nutrient, crop ions, and crop metabolic components; and online monitoring of animal estrus and the biochemical indicators of animal lactation. The second direction is the highly integrated design of agricultural sensors. A major focus for agricultural sensor development in recent years is the integration of sensor chips through the application of microelectromechanical systems (MEMS). Some countries, research institutes and companies have been involved in producing agricultural sensor chips, e.g., MEMS-chip-based sensors for agricultural environment parameters, and micro/nanosensors for animal rumen. Maintenance-free, reliable, low-power-consumption, and low-cost sensors can be developed through chip design and their fabrication.

One major trend of agricultural sensor techniques is the fast development of new sensing mechanisms. This will enable more agricultural parameters that can currently only be tested in laboratory to be measured online and *in-situ*. Another trend is the development of industrialization of agricultural sensors. A chain that covers sensor chip design, producing, standard test, and pilot plant test is essential for the development of an agricultural sensor industry.

(4) Resource utilization of agricultural and rural organic wastes

This development front belongs to the discipline of resource ecology science and is the frontier of established in-depth development. Agricultural and rural organic wastes are the sum of organic wastes generated by agricultural production and rural life. They mainly include agricultural byproducts, such as livestock excreta, straw, rice husk, peel (dregs), leftovers, and household kitchen wastes. There are many types and large quantities of organic wastes, which are scattered and complex. Their utilization is therefore difficult, and they pose great potential environmental risks, which seriously restricts the aesthetics of rural communities and the sustainable development of agriculture. The common ways of using these byproducts are returning them to soil directly, anaerobic fermentation, aerobic composting, incineration for power generation, and biomass carbonization. However, technical problems hinder developments, for example, the immature key technologies, low returns from resource utilization, and incomplete harmless treatment. In view of the potential damage of organic wastes to the rural ecological environment and the green development of agriculture, their resource utilization is currently a frontier technical issue that needs to be focused on.

(5) Remediation of soil polluted by organic compounds

Soil contaminated with organic substances is an important global problem, causing adverse impacts on agricultural production and food safety. The organic contaminants of organochlorine pesticides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and phthalic acid esters are predominant in the agricultural soils of China. These organic contaminants are toxic and resistant to environmental degradation and even have potential carcinogenicity, posing significant risks to ecological function of soils and human health. Therefore, studies on remediation of soil polluted by organic compounds as well as the development of soil remediation techniques are very important to the soil protection in both developed and developing countries. Soil remediation refers to the process of restoring the functions of polluted soil through different techniques, including physical, chemical, and biological treatments as well as the integrated remediation techniques. Physical soil remediation treatment is a method that removes the organic pollutants in soil through physical processes, such as thermal soil remediation. Chemical soil remediation treatments, such as chemical oxidation and catalytic degradation methods, add chemicals to polluted soils to stabilize the pollutants and convert them to less toxic or nontoxic compounds. Biological soil remediation treatment is a method that decomposes the organic contaminants using animals, plants, and microorganisms. By combining the advantages of physical, chemical, and biological soil remediation treatments, the integrated remediation techniques are becoming highly promising treatments for soil remediation with low cost and high efficiency.

(6) Artificial-intelligence-assisted breeding

In recent years, artificial intelligence (AI) has been increasingly applied in breeding, making an even more accurate and effective industry. Faced by new opportunities and challenges, AI is supporting the advent of a new round of green revolution, in four aspects. 1) AI-assisted precision crossbreeding. Crossbreeding is the process of enrichment of beneficial alleles and purging of deleterious alleles by continuous crossing and selection. AI facilitates efficient mining of beneficial alleles, as well as pinpointing deleterious alleles, thereby guiding precision crossbreeding. 2) AI-guided genome editing. Genome editing is emerging as a pivotal tool in future breeding. However, genome editing itself does not tell us where to edit and how to edit to achieve favorable agronomic traits. AI, however, provides targets for genome editing by designing artificial beneficial alleles. 3) AI-based synthetic biology. Generative models in AI have been used to design novel genomic elements, proteins, genes, and even regulatory networks that do not exist in nature, providing blue prints for intelligent design of plants and animals. 4) AI-empowered phenomics. With the widespread application of sensors, drones, and robots, AI has been used to extract phenotypic data from multiscale and multidimensional image data, supporting the construction of breeding models and decision-making in breeding programs. In combination, by revolutionizing breeding, AI has become an area where competition around the globe is significant.

(7) Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs

The system for intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs consists of a remote sensing system, a geographic information system, a precise navigation system, and a variable spraying system. The plant protection UAVs are equipped with various kinds of sensors to acquire farmland image and identify the information of crop diseases, pests, and weeds by processing, mining, and modeling the data. The remote sensing image of farmland can be acquired by digital, hyperspectral, multi-spectral, infrared thermal or laser radar camera. Classic statistical analysis, pattern recognition, and machine learning are three methods to analyze the remote sensing images. At present, the variable spraying system of plant protection UAVs is not well developed. The pulse width modulation (PWM) and change of liquid pump speed are two methods in the experimental stage for variable spray application. For precise targeted application according to the prescription map, the flight control system of UAVs needs to adjust the flight path in real time based on meteorological information such as wind speed and wind direction to ensure the spray of a precise dosage of agrochemicals in the proper area.

(8) Construction of economic forest high yield plant-type

Plant type is one of the important factors influencing the yield of an economic forest. The output of economic forests is mainly transformed from photosynthetic products. The architecture of the tree determines the distribution of the captured carbon, water, and nutrients in each part of the tree, which in turn affects the yield and quality. High-yielding plant types in the economic forests refers to tree architectures with suitable height, and the main trunks, main branches, and branch groups have certain quantitative relationship and a clear master–slave relationship. It also has a balanced ratio of nutrient branches and fruiting branches, reasonable density and distribution of branches and leaves, good ventilation and light conditions for the tree and the largest effective photosynthetic area of the canopy. A fundamental way to increase yield is to improve the photosynthetic performance of plants. The high-yielding plant type increases production mainly by increasing the photosynthetic area, i.e., trees with higher photosynthesis. The construction of high-yielding plant types of economic forests is achieved through selective breeding and plant type cultivating. The selective breeding of ideal plant types regulates and constructs high-yielding plant types for economic forests from the genetic level, while plant type cultivation adopts tree management measures such as shaping and pruning. Breeding new high-yielding plant types with a high utilization-rate of light energy is one research focus for high-yielding plant type construction. Using the apparent motions of the sun and spherical triangle related theories, studying the optimal tree parameters and mathematical models to construct the high-yielding plant types of economic forests is another research focus.

(9) Research and application of formulated aqua-feeds

In established aquaculture, direct feeding with feed ingredients such as grains and trash fish was common. This feeding strategy not only results in waste of feed ingredients but also causes pressure on the rearing environment. Spread of pathogens from trash fish to aquatic animals is also a severe problem. Formulated feeds are pellets which are made with modern machines based on comprehensive knowledge of nutrient requirements of specific aquatic animals. Formulated feeds are easier to transport and store compared to their ingredients. Based on category of processing technology, the formulated feeds mainly include extruded, pelleted, and powder feeds. Production of high-quality formulated feeds relies on deep, comprehensive, and detailed understanding of nutrient requirements of aquatic animals, including the discrepancy in nutrient requirement among different developmental stages, different rearing conditions, and different production systems. The one-sided emphasis of farmers on growth rate of aquatic animals inhibits the wide application of formulated feeds in aquaculture activities. Relevant regulations by government are needed to accelerate the application of formulated feeds. Compared to on-growing stage, formulated feed for larvae and broodstock has been less studied. Cooperative research between nutritional requirement study and processing technology are needed in this area.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent equipment for unmanned farm

Unmanned farms are one of the production systems and realizations for smart agriculture. Unmanned farms are characterized by the following: 1) The system covers the whole production chain of crops, including tillage, planting, field management (water, fertilizer and pesticide), and harvest. 2) Operating machinery can autonomously transfer between fields and garages; namely, the machinery can automatically travel from the garage to the field, and automatically returns after completing the given operations. 3) Operating machinery has the function of obstacle avoidance and emergency-triggered stop; in other words, the machinery can automatically avoid obstacles or stop itself when encountering abnormal conditions. 4) Real-time monitoring on the whole producing process; in detail, real-time monitoring of growth and disease, pests, and weeds during crop production. 5) Decision-making and precision operations are all intelligence-based and unmanned; to be specific, the system can make timely decisions based on the growth of crops and the conditions of diseases, pests, and weeds and automatically perform precision operations, including precision irrigation, precision fertilization, and precision pesticide application.

Unmanned farms depend on the support of biotechnology, intelligent equipment, and information technology. Biotechnology provides unmanned farms with crop cultivars and cultivation modes suitable for mechanized operations. Intelligent equipment is used for intelligent perception, navigation, operation, and management. Information technology offers support on information acquisition, transmission, and processing, as well as navigation, automatic operation, and remote maintenance of agricultural machinery.

Intelligent equipment refers to production equipment with the functions of perception, analysis, reasoning, decision-making, and control. It is the deep integration of advanced manufacturing technology, information technology, and intelligent technology.

Intelligent equipment for unmanned farms is a collective term for intelligent equipment and robots used in the entire process of agricultural production. It adopts new-generation technologies such as the Internet of Things (IoT), fifth generation mobile networks (5G), big data, cloud computing, and AI to form an intelligent system. Through remote intelligent management and control, it realizes full automatic or autonomous control of facilities, intelligent agricultural machinery equipment and agricultural robots, and completes all farm production operations. Sensors, IoT and 5G technologies realize the perception and transmission of farm agricultural production information and interconnect with intelligent equipment; big data and cloud computing technology complete agricultural information storage, analysis, and processing; AI, intelligent equipment, and robotics technology complete intelligent learning, intelligence decision-making, and autonomous and precise operation of equipment and robots.

The cutting-edge technologies of intelligent equipment for unmanned farm mainly include intelligent perception, intelligent navigation, intelligent operation, intelligent management, and system integration. 1) Intelligent perception consists of agricultural sensors, environmental information perception, animal and plant information perception, and intelligent data processing. 2) Intelligent navigation requires technology of high-resolution map construction, route planning, precision positioning in complex environment, path following control, and multi-equipment collaborative operation. 3) Intelligent operations contain precision seeding, variable fertilization, variable pesticide application, and variable irrigation. 4) Intelligent management includes status monitoring, remote operation, maintenance and management of intelligent equipment. 5) System integration includes X-by-wire control technology, chassis communication technology, and agricultural implement communication technology.

In addition, phenotypes of animals and plants, growth optimization and regulation models, and integration of intelligent equipment with advanced planting and agronomy will be important areas for research and development. Through application of unmanned fields, unmanned greenhouses, unmanned orchards, unmanned pastures and unmanned fishing grounds, providing a whole-process unmanned production mode, and intelligent equipment solutions for the cropping, animal production, and aquaculture will attract new attentions as well.

The major patent output countries, output institutions, inter-country cooperation networks, and inter-institution cooperation networks are shown in Tables 2.2.1 and 2.2.2 and Figures 2.2.1 and 2.2.2, respectively. The top two countries for core patent disclosure are China and the United States, while Colombia and South Korea tied in third place (Table 2.2.1). Among them, China is in leading position in terms of the number of patents. The top five patents mainly focus on agricultural machinery intelligent perception, intelligent control, and intelligent navigation, which are the key research directions of intelligent equipment for unmanned farm. There are few cooperation networks between countries, only a small amount of cooperation between Colombia and the United States (Figure 2.2.1).

The top three institutions with the highest number of core patents are Autonomous Solutions Inc., CNH Industrial America LLC, and RowBot Systems LLC (Table 2.2.2), which are all from the United States. However, there is only rare cooperation among these institutions (Figure 2.2.2).

2.2.2 Artificial-intelligence-assisted breeding

AI has brought innovation to a large number of fields, and

Table 2.2.1 Countries with the greatest output of core patents on “intelligent equipment for unmanned farm”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	102	49.51%	218	22.02%	2.14
2	USA	67	32.52%	668	67.47%	9.97
3	Colombia	8	3.88%	76	7.68%	9.50
4	South Korea	8	3.88%	3	0.30%	0.38
5	Russia	6	2.91%	8	0.81%	1.33
6	Japan	5	2.43%	39	3.94%	7.80
7	Netherlands	4	1.94%	17	1.72%	4.25
8	Germany	4	1.94%	10	1.01%	2.50
9	Switzerland	3	1.46%	6	0.61%	2.00
10	Israel	2	0.97%	20	2.02%	10.00

Table 2.2.2 Institutions with the greatest output of core patents on “intelligent equipment for unmanned farm”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Autonomous Solutions Inc.	USA	14	6.80%	39	3.94%	2.79
2	CNH Industrial America LLC	USA	11	5.34%	23	2.32%	2.09
3	RowBot Systems LLC	USA	8	3.88%	86	8.69%	10.75
4	Wuxi Kalman Navigation Technology Co., Ltd.	China	6	2.91%	14	1.41%	2.33
5	Deere and Company	USA	5	2.43%	39	3.94%	7.80
6	AGCO International GmbH	Switzerland	5	2.43%	9	0.91%	1.80
7	Jiangsu University	China	5	2.43%	5	0.51%	1.00
8	AgJunction LLC	USA	4	1.94%	95	9.60%	23.75
9	State Farm Mutual Automobile Insurance Company	USA	4	1.94%	37	3.74%	9.25
10	Kinze Manufacturing Inc.	USA	4	1.94%	34	3.43%	8.50

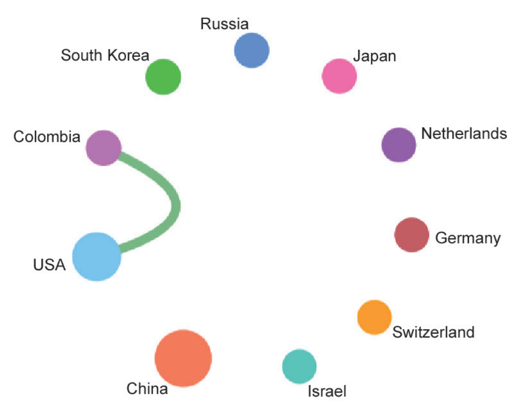

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “intelligent equipment for unmanned farm”

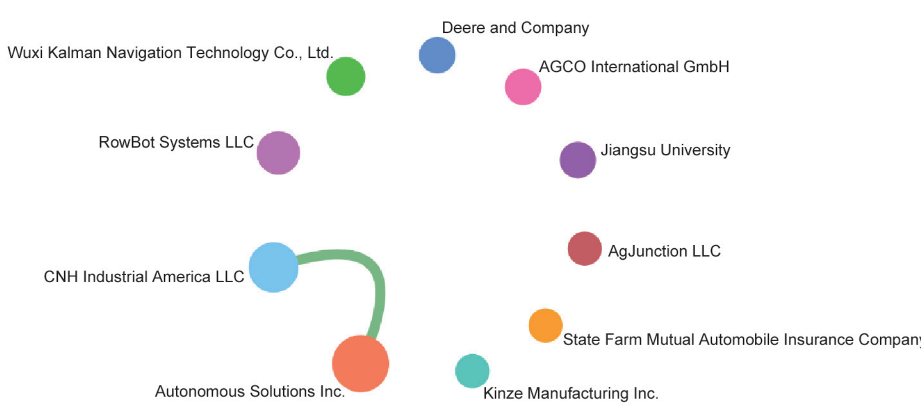

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “intelligent equipment for unmanned farm”

has become an area filled with intense competition. AI refers to theories and methods to extend human intelligence. A key branch of AI is machine learning, which uses computers, rather than human intelligence, to find solutions to problems. In machine learning, the technique that develops fastest is deep learning, which is based on deep neural networks. Currently, AI, especially deep learning, has been applied to animal and plant breeding, in four aspects.

First, identification of functional variants for precision crossbreeding. Numerous genomic variants are present in animal and plant natural populations. However, only a small fraction of them, referred to as functional variants, impact phenotypes. In crossbreeding, favorable alleles are enriched (meanwhile, deleterious alleles are depleted) by crossing and selection, thereby achieving genetic improvement of plants and animals. However, an important question is how to prioritize functional variants impacting phenotypes from huge amounts of genomic variants. Since functional variants impacting terminal traits (such as mRNA and protein abundance, or biochemical activities of proteins) by impacting molecular phenotypes at various levels (such as human disease traits, livestock and poultry quality), deep learning models can be trained to predict molecular phenotypes from genomic sequences, and then use these models to scan genomic variants to identify function variants precisely. Deep learning shows advantages in four aspects: 1) It does not rely on natural populations and therefore reduces the cost compared to association analysis. 2) It prevents the harmful impacts from low minor allele frequencies. 3) It has the ability to identify causal variants among highly linked loci. 4) It facilitates transfer learning between different loci, populations or even species. Deep learning has been widely used to predict functional variants in human diseases, and its utilization in plant and animal breeding has also been developing .

Second, design superior alleles for genome editing. Standard crossbreeding depends on functional variants that occur naturally. However, natural alleles occur at a low frequency and their effects are random. Moreover, favorable alleles are also linked with deleterious alleles. An important question is how can the limitations of natural variants be overcome to rationally design superior alleles for breeding. With the advent of the CRISPR/Cas9 system, it is possible to rationally design functional variants based on breeding goals and then incorporate designed variants into plant and animal genomes by genome editing. However, where to edit and how to edit the genome in order to improve the terminal traits needs to be determined. This will be the key problem in genome editing-based breeding. Deep learning models that predict molecular phenotypes based on biological sequences can solve this problem efficiently as it can efficiently provide guidance to genome editing.

Third, designing novel functional genomic elements for synthetic biology. Currently, generative models in deep learning has been widely applied in synthetic biology. This technique can learn from large amount of biological sequences, thereby gaining the ability to design genomic elements with specific biological functions, such as proteins and cis-elements with desirable biochemical activities. Trait improvement of plants and animals can be achieved by incorporation of such new elements into plant or animal genomes by genome editing. Synthetic biology guided by AI will bring about new ideas and technological innovations to genetic improvement of plants and animals.

Fourth, extraction of phenotypic data from images. Recent years witnessed great advances in high-throughput phenotyping systems. Drones and robots equipped with sensors generate huge amount of image data. Using machine learning, especially deep learning techniques, to extract phenotypic data (such as photosynthetic rate and canopy temperature) is becoming a routine in phenomes.

There have been 56 core patents in this field. The top countries in terms of core patent disclosure volume in this field are China (47) and South Korea (5). The citations per patent in China is 0.32 (Table 2.2.3). Patent output institutions are relatively scattered. Anhui Dongchang Agricultural Technology Co., Ltd. produced two patents and each of the other institutions had one patent. The patent of Xiangchuang Technology Beijing Co., Ltd. was cited most with four times (Table 2.2.4). The majority of patents in this development front come from China and there is no cooperation between countries. Among the top 10 output institutions (Table 2.2.4). There are enterprises and universities but no cooperation exists between these institutions.

2.2.3 Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs

Agricultural production is becoming more precise and economical. In the future, agricultural production will be

Table 2.2.3 Countries with the greatest output of core patents in the engineering development front of "artificial-intelligence-assisted breeding"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	47	83.93%	15	100%	0.32
2	South Korea	5	8.93%	0	0%	0.00
3	Australia	1	1.79%	0	0%	0.00
4	Germany	1	1.79%	0	0%	0.00
5	India	1	1.79%	0	0%	0.00
6	Japan	1	1.79%	0	0%	0.00

Table 2.2.4 Institutions with the greatest output of core patents in the engineering development front of "artificial-intelligence-assisted breeding"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Anhui Dongchang Agricultrual Technology Co., Ltd.	China	2	3.57%	0	0.00%	0
2	Xiangchuang Technology Beijing Co., Ltd.	China	1	1.79%	4	26.67%	4
3	Yunnan Agricultural University	China	1	1.79%	3	20.00%	3
4	Beijing Aojinda Agricultural Technology Development Co.	China	1	1.79%	1	6.67%	1
5	Cangnan Boya Technology Co., Ltd.	China	1	1.79%	1	6.67%	1
6	Qinghai University	China	1	1.79%	1	6.67%	1
7	Anhui Rays Agricultural Science and Technology Co., Ltd.	China	1	1.79%	0	0.00%	0
8	Asami Agricultural Combination Legal Person	Japan	1	1.79%	0	0.00%	0
9	Beijing Zhongnong Zhiyuan E-Commerce Co.	China	1	1.79%	0	0.00%	0
10	Bigstone House	South Korea	1	1.79%	0	0.00%	0

highly regionalized, integrated, mechanized, and intelligent. Intelligent plant protection machinery and precise application of pesticides has become the main trend for plant protection. Plant protection UAVs acquire the real-time geography information, plant condition, and diseases and pests information from crop canopy. According to meteorological, historical and other information, farmland is divided into several operation areas to make prescription maps for accurately forecasting and monitoring of pests and diseases. With the prescription maps, the precise targeted spraying system can be applied on a precise grid. The research on plant protection UAVs mainly include three parts.

First, farmland image acquisition by remote sensing. The crop information acquisition sensors include digital camera, multispectral camera, hyperspectral camera, thermal imager, and laser radar. Digital cameras can capture red, green, and blue visible light at low cost but low resolution. Multispectral cameras have a spectral resolution of 0.1 mm and can be modified to adapt the characteristic spectrum of diseases and pests, which basically meets the requirements of plant, disease, and pest identification. Commercial products of multispectral cameras have been introduced to agriculture. A hyperspectral sensor measures several to hundreds of bands in visible light and near-infrared region, with a resolution of nanometer level. With rich spectral information and high resolution, it can accurately distinguish the spectral of different crops in the field. Although hyperspectral sensors have many advantages for crop disease and pest monitoring, they are currently only used for research due to high cost. Laser radar is a novel remote sensing technology which can acquire 3D high-precision data. At present, the main application of laser radars in agriculture is to monitor plant height, biomass, and leaf area index. In the future, they could be combined with spectral imaging as a part of multisource remote sensing and analyze pests and diseases of crop comprehensively to improve the accuracy of crop pest and disease identification.

Second, remote sensing image interpreting. Image interpretation refers to the processing, mining, and modeling of remote sensing images in order to identify crops, diseases, pests, and weeds. Interpretation methods include classical statistical analysis and an interpreting method based on pattern recognition and machine learning. The latter method requires fewer samples and lower requirements for device performances and makes the model easier to understand. Deep learning and machine learning are new research directions with two significant features, feature learning, and deep structure, which can improve the classification accuracy of remote sensing images. At present, intelligent identification of crops, pests, and diseases is only at the feasibility stage for specific crops, fields, and diseases. In the future, it needs to be combined with agriculture, plant protection, and pathology to realize large-scale application.

Third, precise variable pesticide application. To realize precision pesticide application to a certain area based on the prescription map, the plant protection UAV needs the support of a variable pesticide application system and precise pesticide application technologies. At present, the variable pesticide application systems are Only experimental. There are two methods for variable application: One is PWM technology for hydraulic atomizing nozzles and the other is to change the speed of liquid pumps and nozzle flow for centrifugal atomizing nozzles. Precision pesticide application technology can make the real-time adjustment of flight trajectory according to wind speed, wind direction, flight altitude, flight speed, droplet size, crop characteristics and other factors to ensure that pesticide droplets can be accurately applied to the designated area.

Plant protection UAV is an emerging approach for plant protection, so the deposition and drift mechanism of drops is not well understood and it will be one of the key areas for research on precision pesticide application technology of plant protection UAVs in the future.

There are 45 core patents related to this development front. The major contribution countries are China (37 patents), the United States (7 patents), and South Korea (1 patent) (Table 2.2.5). The institutions with more patents are all from China, e.g., Guangzhou XAIRCRAFT Technology Co., Ltd., Wuxi Tongchun New Energy Science and Technology, and Zhongkai University of Agriculture and Engineering, while Working Drones Inc. and Elwha LLC from the United States each discloses one patent (Table 2.2.6). The patent of Working Drones Inc. for the navigation and control of drones using mobile terminals has 242 citations, which is the most influential patent for this development front and is one of the most important areas for drone research. Plant protection UAVs are mainly used in China and some applications in Japan and South Korea, but fewer applications in other countries. China is the largest patent output country and fewer patents of plant protection UAVs were published by other countries, so there is no cooperation between countries in this development front. In China, the competition of plant protection UAV market is intense, so there is more competition than cooperation among institutions. In addition, the development of plant protection UAVs involves commercial secrets, so no cooperation among institutions was as expected.

Table 2.2.5 Countries with the greatest output of core patents on “intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	37	82.22%	165	39.38%	4.46
2	USA	7	15.56%	254	60.62%	36.29
3	South Korea	1	2.22%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of core patents on "intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Guangzhou XAIRCRAFT Technology Co., Ltd.	China	5	11.11%	51	12.17%	10.20
2	Wuxi Tongchun New Energy Science and Technology	China	4	8.89%	34	8.11%	8.50
3	Zhongkai University of Agriculture and Engineering	China	3	6.67%	5	1.19%	1.67
4	Beijing Research Center for Information Technology in Agriculture	China	2	4.44%	29	6.92%	14.50
5	Shenzhen Autel Intelligent Technology Co., Ltd.	China	2	4.44%	10	2.39%	5.00
6	Chengdu Youlide New Energy Co., Ltd.	China	2	4.44%	0	0.00%	0.00
7	South China Agricultural University	China	2	4.44%	0	0.00%	0.00
8	Working Drones Inc.	USA	1	2.22%	206	49.16%	206.00
9	Elwha LLC	USA	1	2.22%	25	5.97%	25.00
10	Beijing Expert Aviation-Technology Co., Ltd.	China	1	2.22%	13	3.10%	13.00

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VIII. Medicine and Health

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the fields of medicine and health include public health and preventive medicine, basic medicine, clinical medicine, medical informatics and biomedical engineering, and traditional Chinese medicine (TCM) (Table 1.1.1). These 10 fronts also include "improving public health and epidemic prevention systems and emergency mechanisms," "global research on COVID-19 and emerging highly pathogenic viruses," "gut microbiota imbalances and diseases," "stem cell therapies and clinical translation," "medical robots and intelligent medicine," "brain-inspired intelligence research," "construction of the human single-cell atlas," "the collection and use of real-world evidence to support drug research and clinical application," "new target discovery and translation of active compounds in TCM," and "pathogenesis, precision diagnosis, and treatment strategy of hereditary tumors in the Chinese population."

The publication dataset of the top two fronts contains data from January 2014 to August 2020 as they are closely related to the COVID-19 epidemic. The publication dataset of the remaining seven fronts contains data from January 2014 to December 2019. All core papers detailing with these topics are listed in Table 1.1.2.

(1) Improving public health and epidemic prevention systems and emergency mechanisms

Public health and epidemic prevention systems and emergency mechanisms primarily refer to the institutions, personnel, and management operating mechanisms for the prevention and control of traditional and emerging infectious diseases, and also to the mechanisms in place to allow for a joint response in the event of a public health emergency by facilitating the deployment of medical and health resources. A modern, scientific, and complete public health and epidemic prevention system is important for any countries, and the establishment of such a system is an essential practice in the modern governance system and in the evaluation of governance capabilities. With the global outbreak of COVID-19, the need to improve the research

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	Improving public health and epidemic prevention systems and emergency mechanisms	240	2 558	10.66	2017.2
2	Global research on COVID-19 and emerging highly pathogenic viruses	2 707	195 743	72.31	2016.8
3	Gut microbiota imbalances and diseases	197	29 028	147.35	2015.9
4	Stem cell therapies and clinical translation	531	46 376	87.34	2015.3
5	Medical robots and intelligent medicine	3 272	218 591	66.81	2015.7
6	Brain-inspired intelligence research	509	43 834	86.12	2015.7
7	Construction of the human single-cell atlas	118	17 262	146.29	2016.4
8	The collection and use of real-world evidence to support drug research and clinical application	105	3 828	36.46	2016.6
9	New target discovery and translation of active compounds in traditional Chinese medicine	91	3 986	43.80	2015.6
10	Pathogenesis, precision diagnosis, and treatment strategy of hereditary tumors in the Chinese population	594	6 893	11.60	2016.6

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	2019	2020
1	Improving public health and epidemic prevention systems and emergency mechanisms	21	18	48	49	41	23	40
2	Global research on COVID-19 and emerging highly pathogenic viruses	486	408	454	387	311	95	566
3	Gut microbiota imbalances and diseases	32	47	57	41	19	1	–
4	Stem cell therapies and clinical translation	195	115	113	80	24	4	–
5	Medical robots and intelligent medicine	882	827	596	526	342	99	–
6	Brain-inspired intelligence research	130	119	101	95	55	9	–
7	Construction of the human single-cell atlas	11	21	30	27	22	7	–
8	The collection and use of real-world evidence to support drug research and clinical application	7	14	32	25	20	7	–
9	New target discovery and translation of active compounds in traditional Chinese medicine	22	24	20	15	10	0	–
10	Pathogenesis, precision diagnosis, and treatment strategy of hereditary tumors in the Chinese population	99	91	95	107	83	119	–

of public health and epidemic prevention systems and emergency response mechanisms has increased dramatically, and effective research ideas have become increasingly clear. Infectious diseases are still the main issues threatening human health, which disturb the order of production and life, thereby bringing harm to society and economy. Therefore, international community must recognize the importance of the prevention and control of infectious diseases, thereby to protect the health and safety of individuals and promote economic construction and social harmony. Additionally, public health security has become an important part of national security, and the status of disease prevention and control system as the core component of the public health system has been further clarified. Disease prevention and control services are part of the public health service functions provided by the government and require strong guarantees from public finances and institutional mechanisms.

(2) Global research on COVID-19 and emerging highly pathogenic viruses

The COVID-19 outbreak has triggered a global crisis, and the pandemic threat posed by other potentially highly pathogenic viruses should not be overlooked. Through the collaboration of the scientists in the whole world, major progress has been made in the basic knowledge and application research of the severe acute respiratory sydrome coronavirus 2 (SARS-CoV-2), which has profoundly deepened our understanding of the virus and the diseases due to it. Particularly, Chinese scientists have identified SARS-CoV-2 as the pathogen in a short time, and shared the full genome sequence with the world. The structures of this novel coronavirus and its key coding proteins have been resolved rapidly. Reliable cell and animal models were established for further research and development of vaccines and pharmaceuticals. Several vaccines and therapeutic drugs are undergoing the phase III clinical trial. The domestic contagion was effectively controlled in a short time. All of these achievements have embodied the strength of Chinese science and technology. The critical scientific issues of the global research on novel coronavirus and emerging highly pathogenic viruses include the origin, evolution and the molecular mechanism of interspecies transmission to and among humans of the novel coronavirus, the mechanisms of the viral life cycle and severe viral infection. The global research on novel coronavirus and emerging highly pathogenic viruses focus on the structures and functions and their mechanisms of the genome and encoding proteins of novel coronavirus, clinical progress and outcome, the mechanism of infection and immune protection, the screening and evolution of new vaccines and anti-virus pharmaceuticals. Generally, in the future, the research will rely on a more integrated application of single-cell sequencing, system biology, reverse genetics, big data, and artificial intelligence (AI) for the further investigation of the infection, pathogenesis, and transmission of novel viruses. More next-generation vaccines and drugs based on rational design will come to clinical trials in the near future.

(3) Gut microbiota imbalances and diseases

The gut microbiota is essentially an "important organ," as it plays an indispensable role in human health and disease. The human gastrointestinal tract contains trillions of bacteria, fungi, and viruses. Among them, there are more than 1000 species of bacteria alone, and this is equivalent to approximately 10-fold the number of human cells. The number of genes encoded by these bacteria is 50–100 times that of the human host, and these encoded genes are equivalent to the "second genome" of humans and contain important genetic information. Gut microbes and their living environment constitute the gut microbiota, and this microbiota is an important maintainer of host digestion and absorption, immune response, and material and energy metabolism. The gut microbiota constantly undergoes alterations with age, and these changes are closely related to aging and longevity. Research examining gut microbiota imbalances and diseases has enhanced the traditional understanding of major diseases such as infection, liver disease, tumors, and metabolic diseases in medicine, and the findings from these research projects have facilitated revolutionary changes in the prevention, diagnosis, and treatment of various diseases. Research examining gut microbiota and diseases has attracted a great deal of attention from governments, scientific and technological circles, enterprises, and the public. Developed countries regard it as an important field in their national science and technology strategic planning.

(4) Stem cell therapies and clinical translation

Stem-cell therapies are therapies that involve the use of stem cells or their derived substances. Stem cells are unspecialized cells that possess the abilities of self-renewal and differentiation into any cell within an organism. These cells exist in embryos, fetal/perinatal tissues, and adult tissues. Based on this, stem cells are classified into the following: embryonic stem cells, perinatal stem cells, and adult stem cells. Stem cells are also named according to their function, such as hematopoietic stem cells (HSCs), neural stem cells, and mesenchymal stromal/stem cells (MSCs). The development of different gene manipulation technologies has allowed researchers to produce novel stem cells such as induced pluripotent stem cells (iPSCs) and gene-edited stem cells. Typically, stem cells exert their therapeutic activities through either cell replacement and/or paracrine regulation. Therapies using stem-cell–derived substances such as exosomes are considered as cell-free stem cell therapies. Thus, stem cell therapies include stem cell replacement therapy and stem-cell-based tissue function and structure improvement therapy.

The key issues related to the clinical translation of stem cells include the best choice of stem cells for a given clinical indication; the large-scale, cost-effective, and reproducible production of high-quality stem cells or their derivatives; the analysis of the mechanism and biological effects of stem cells; the development of gene-edited stem cells; stem-cells-based gene therapy and combination therapy of stem cells; and large-sample and multicenter clinical trials and follow up of their long-term effects.

HSCs transplantation is the typical stem cell replacement therapy that has been used for over half a century and that plays an important role in the treatment of several blood diseases, autoimmune diseases, and genetic diseases. In recent decades, HSCs, due to their ability to differentiate into vascular endothelial cells, have been used to effectively treat critical limb ischemia and other vascular diseases. Therapies using autologous stem cells, iPSC-derived tissue stem cells, Human Leukocyte Antigen type-matched allogenic HSCs, and gene-edited HSCs are all cell replacement therapies. MSCs possess high immunomodulatory and pro-angiogenic activities in addition to multipotent differentiation ability, and therefore MSCs have been used in the treatment of a variety of diseases, including tissue regeneration, autoimmune diseases, vascular diseases, and inflammatory diseases. Heterotopic transplantation of autologous MSCs can be considered as a replacement therapy. In contrast, allogenic MSCs obtained from several different tissues have also been reported to be effective in the treatment of a variety of diseases and do not exhibit clearly visible immune rejection. The combination of the replacement therapy and the functional improvement of different stem cells can result in a synergetic effect. For example, co-transplantation of HSCs and MSCs has been shown to promote the engraftment of HSCs and to decrease the development of graft-versus-host disease.

(5) Medical robots and intelligent medicine

AI is a technical science, which can be used to simulate and extend the theory, methods, and applications of human intelligence. Intelligent medicine is the science of assisting or replacing humans in the field of medical behavior through AI technology. The application of AI in biomedicine can increase the accuracy and safety within a number of biomedical fields, including health screening and early warning, disease diagnosis and treatment, rehabilitation training and evaluation, medical services and management, drug screening and evaluation, and gene sequencing and characterization. Medical robots are an important branch of intelligent medicine.

The research status of medical robots and intelligent medicine can be summarized primarily according to six aspects. 1) Health screening and warning primarily involves disease screening, chronic disease management, and wearable health monitoring devices. Alzheimer's disease classification, hypertension management, diabetes identification (diabetes classification and screening for diabetic retinopathy and other complications) can be performed using deep neural networks and fuzzy control methods to achieve early warning and effective management of chronic diseases. 2) Disease diagnosis and treatment primarily involves automatic lesion recognition, intelligent treatment decision-making, scientific evaluation of curative effects, robotic-assisted surgery, and remote surgery. Quantitative disease diagnosis and prognosis are organically combined by in-depth learning methods. 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, and it can reduce the misdiagnosis rate and labor cost. 3) Rehabilitation training and evaluation primarily involves cognitive impairment rehabilitation, disability and rehabilitation, robotic care, intelligent prosthesis, and orthosis (including assistive exoskeleton devices). Virtual reality and intelligent robotics combined with AI technology can be applied to the rehabilitation of disabled people. Intelligent rehabilitation devices have been rapidly developed in recent years, and these devices include artificial limbs, rehabilitation training robots, exoskeleton auxiliary devices and orthoses, escort robots, intelligent bed chairs, virtual reality rehabilitation systems, and electronic artificial larynx. Medical robots are also used extensively in clinics. 4) Medical services and management primarily involve electronic medical record management, intelligent automatic drug delivery, and the medical Internet of Things services. 5) Drug screening and evaluation primarily involves drug target identification, drug screening, drug efficacy tests, drug safety evaluation, and adverse reaction data management. AI technology has been widely used in drug target identification, drug screening, drug safety assessment, drug efficacy tests, and data collection, and this technology has also been used in the pharmacological evaluation of TCM and possesses potential for many broad applications. 6) Gene sequencing and characterization primarily involves gene screening, genome sequencing, gene editing, and individualized precise medical treatment. This technology integrates the features of patient pathological sampling with extracted genome sequencing data, and involves using gene screening, genome sequencing, and gene editing to achieve disease prediction and detection. Clinical guidelines and evidence-based medicine can be combined to achieve personalized treatment.

The overall developmental trends include the advancement of the application of AI in biomedicine from pathological diagnosis to clinical treatment and the integration of AI, robotics, 5G communications, and other frontier technologies to alter the concept 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 artificial intelligence and TCM is attracting increasing attention. 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.

(6) Brain-inspired intelligence research

From brain-inspired intelligence research, we can learn from the mechanisms by which the brain processes information. By simulating the dynamic evolution of brain neural systems and advanced cognitive functions, research teams can establish calculations and theoretical models with biological and mathematical foundations, develop a new generation of brain-inspired intelligence algorithms, achieve an intelligent system with the capacity to learn from self-experience, and apply the system to specific fields. Through brain–computer interaction, the algorithm will dynamically blend with individuals and groups of humans to build a brain–computer hybrid information processing terminal, and this will allow researchers to finally establish a new computing structure and intelligent form to achieve intelligence augmentation and the application of group intelligence.

The key scientific issues include neuroscience theory, mathematical theory and methods, computer system architecture, and chip implementation. Specifically, these issues involve: 1) dynamic behavior analysis and data assimilation method of neuron biophysical impulse dynamics and axon-synaptic network mathematical models based on the knowledge of neuromorphology, neurophysiology, and multi-scale brain imaging data, 2) the non-Von Neumann computer architecture with communication as the core of computing–storage–communication integration and the high-speed adaptive routing communication system, and 3) new theories and novel methods in mathematical fields such as functional analysis, algebra, geometry, and computational mathematics for a multi-mode and multi-channel integrated intelligent system aiming at perception that is capable of judgment, decision-making, and control through the integration of memory, emotion, language, and rewards and punishments.

The European Union, the United States, and Japan conduct competitive research in this field through universities, research institutions, and companies based on state mandates. Supported by the “Human Brain Project,” a research team at the University of Manchester has constructed a model known as Spinnaker using the Acorn RISC machine. The largest Spinnaker machine is capable of simulating one billion simple neurons. The US company IBM and the US Air Force have developed a chip named TrueNorth. This chip mimics the function of the human brain and can achieve the neuromorphic computation of 64 million neurons and 16 billion synapses. The American company Neuralink has developed practical brain–computer interface equipment and implanted brain surgery equipment.

Universities and research institutions in China, including Tsinghua University, Peking University, Zhejiang University, and Fudan University, initiated their brain-inspired intelligence research at a slightly later date compared to that of the international groups. The current study mainly focuses on visual/auditory chips and spiking neural network dynamics. However, we do possess state-of-the-art laboratory facilities for brain research and large-scale population sample data.

(7) Construction of the human single-cell atlas

Single-cell analysis primarily refers to the use of a digital matrix to systematically describe, classify, and integrate the gene expression characteristics of every single cell. The construction of the human single-cell atlas was based on single cell analysis in the human body. The present human cell atlas primarily relies on the transcriptome data of a single cell, and it still requires a series of -omics data, i.e., genome, proteome, and metabolome, to ensure data integration, visualization, and sharing. It is generally established that there are 30 trillion cells within the human body, and that the gene expression profile of these cells changes throughout the life cycle, thus contributing to the diversity of cell types and cell states and generating cell heterogeneity. Under normal circumstances, different types of cells work in concert in an orderly manner to perform the functions of tissues and organs. However, when stimulated by endogenous or exogenous environmental factors, more heterogeneous changes occur in the cells, ultimately leading to the emergence of pathological conditions and various diseases. Therefore, the information contained within the single cell atlas can more importantly be used to construct the single-cell atlas of diseases, particularly major diseases that seriously endanger human health.

Since 2016, researchers have completed the construction of human single-cell atlases of various organs and tissues, including the nervous system and immune system. In 2020, a team from Zhejiang University in China constructed a human cell atlas covering cells in both embryonic and adult stages from eight major systems to provide a foundation for the comprehensive identification and definition of normal and diseased cell types. Current and future research will establish a human cell atlas that integrates data from clinical observation, experimental research, and computational biology. Furthermore, it will be a space–time specific cell atlas that is associated with development and disease. Therefore, during the process of disease occurrence and development, the human single-cell atlas will provide a powerful means by which to identify novel disease biomarkers and to explore the network characteristics of molecular regulation of different cell types, cell states, and cellular interactions that are closely related to clinical therapeutics. The Human Tumor Atlas Network, a part of the National Cancer Institute Cancer Moonshot Initiative that was launched in 2016, aims to chart tumor transitions across space and time at a single-cell resolution. The construction of a complete human cell atlas will help us comprehensively decipher the dynamic process of prenatal and postnatal development, maturation, aging, and disease transitions, particularly those involved in health and disease. In the near future, the construction of human single-cell atlas will allow researcher the opportunity to integrate information from multidisciplinary research, thus making it possible to investigate the entire process of life and disease thoroughly, variably, and three-dimensionally. It will reveal the individual and common pathogenesis of major human diseases to provide a foundation for clinically accurate diagnosis, personalized treatment, and targeted therapy. Finally, the human single-cell atlas exhibits the potential to be a prominent player in medicine in the era of great human health.

(8) The collection and use of real-world evidence to support drug research and clinical application

Real-world evidence refers to collected health care information outside of traditional clinical trials. Health care information can be derived from various sources, including, but not limited to, electronic health records, claims and billing data, product and disease registries, data gathered through personal devices, and data from observational studies. In December 2018, the US Food and Drug Administration (FDA) released a framework outlining how the FDA will evaluate real-world evidence intended to support the approval of a new indication for an approved drug or biologic or to help support or satisfy post-approval study requirements for drugs. In China, the National Medical Products Administration has also begun to explore this field. On January, 2020, it issued its first set of guidelines titled "Guiding Principles for the Development and Evaluation of Drugs Supported by Real-World Evidence (Trial)" that clarifies some basic definitions of real-world evidence such as research and data and clearly proposes the application of real-world evidence to support drug regulatory decisions to cover multiple links such as pre-market clinical research and development and post-market re-evaluation. Furthermore, "Guiding Principles for Real-World Data Used to Generate Real-World Evidence (Draft for Solicitation of Comments)" and "Technical Guidelines for the Development and Evaluation of Drugs for Children Supported by Real-World Research (Trial)" were successively issued in August 2020.

The value of real-world evidence is its potential for complementing the information gained from a traditional clinical trial. Although randomized, double-blind, clinical trials are regarded as the gold standard to evaluate the treatment efficacy and safety, they are known to possess limitations. real-world evidence, if of high quality, is expected to 1) provide evidence of the effectiveness and safety for the registration and marketing of new drugs, 2) provide evidence for modification of indications or safety information of approved drugs, 3) provide evidence for post-marketing study requirements or re-evaluation of drugs, and 4) guide the design and implementation of clinical trials.

Scientifically, internal and external validity is the ultimate goal of medical research. Randomized and controlled clinical trials (RCTs) exhibit the highest internal validity; however, they may be limited in external validity due to stringent inclusion and exclusion criteria. Conversely, real-world data are derived from multiple sources and diverse populations, thus extending their reach to broader populations. It is underscored that the process from real-world data to real-world evidence must be derived from sound research design and implementation, vigorous data cleaning and statistical analysis, and careful consideration and control of biases and confounding factors, as these are of particular concern for observational studies. Therefore, RCTs and real-world studies should be regarded as complementary. Observational real-world research alone cannot be used to draw definite conclusions; however, the results of these studies can complement RCTs and provide important insights for the design and implementation of subsequent RCTs. Technically, real-world data can be massive and messy. Based on this, it will be necessary to apply advanced and secure information technology to collect and store information and to apply advanced statistical methods, including machine learning, to integrate and analyze multi-dimensional and complex data.

Some legislative challenges are related to the policies and implementation of real-world evidence. In China, these challenges include 1) data acquisition and sharing, including administrative and geographical restrictions as well as many practical problems such as information security, usage rights, and ethics, 2) data quality, including the standards, integrity, accuracy, authenticity, and traceability of the data that must be integrated as a requirement and standard, 3) data management and analysis methods where for different types of data, continuous methodological innovation will be required, and 4) expertise, where scientists with expertise in this field and high-quality training programs will be critically needed.

(9) New target discovery and translation of active compounds in traditional Chinese medicine

The discovery of new active compounds in TCM involves using certain physical, chemical, and biological means to produce the desired biological phenotypes of drug-treated cells or animal models for exploration of new targets and target functions under the guidance of TCM. Meanwhile, research findings of new targets can be translated into clinical disease diagnosis, prevention and treatment, prognosis evaluation, and new drug development.

The key scientific issues include the existence of TCM as a complex system with the integrated regulation function of "multi-component, multi-pathway, and multi-target." These issues include the determination of active compounds in TCM and the selection of model target cells, the effective discovery and validation of new targets using interdisciplinary techniques, the relationship between new targets and disease models, and new target-based drug-forming and clinical application of active compounds. The aim of new target discovery is to identify active compounds in TCM that possess certain pharmacological activities. The correlation between new targets and disease phenotypes is the focus of this study. Further clinical translation of the new target for the treatment of diseases and the discovery of active compounds for these targets are the key points for drug development.

Recently, active compounds in TCM have been demonstrated to play important roles in the prevention and treatment of many diseases, including chronic and viral diseases, as they exhibit unique advantages. Research focused on the discovery of new targets based on the active compounds in TCM has been lagging; however, the identification of label-free drug targets by Mass Spectroscope-Cellular Thermal Shift Assay has rapidly developed and has attracted increasing attention. Additionally, the active compounds in TCM provide rich and valuable resources for modern drug research and development. The successful translation of these active compounds in TCM into innovative clinical drugs with clear targets and the classical advantages of TCM have become hot topics in modern Chinese medicine research.

(10) Pathogenesis, precision diagnosis, and treatment strategy of hereditary tumors in the Chinese population

Hereditary tumors represent a type of genetic disease caused by germline mutations of specific genes, and these tumors account for approximately 5%–10% of the tumors in humans. Many types of hereditary tumors exist, and complicated classification methods are currently available. The pathogenesis of hereditary tumors is still unclear. The "two-hit theory," "chromosomal imbalance hypothesis," and "single and multi-gene hypothesis" are generally recognized in academic circles. With the widespread use of next-generation sequencing technology, precise genetic detection provides a direction for the diagnosis of hereditary tumors and the development of new drugs and also provides more opportunities for individualized treatment.

The major scientific issues include using molecular biological methods to explore the genetic mechanisms underlying tumorigenesis and development. Moreover, these issues also include identifying unknown genetic susceptibility genes and clarifying the value of variants of uncertain significance. Multidisciplinary collaboration for comprehensive data analysis promotes the development of precise molecular pathology, thus allowing for the construction of a complete clinical and genetic information database. Additionally, it is also used explore a comprehensive map of hereditary tumor families, analyze the correlation between genotype and phenotype, screen existing hereditary tumors for key variant genes, determine new applications for old drugs, and develop new molecular targeted drugs. Approximately 50% or more of patients or families who meet the clinical diagnosis do not exhibit a clear molecular pathogenesis. Large-scale genome-wide association studies are required to determine new susceptible loci. Compared to common hereditary tumors, the etiology of rare hereditary tumors is more complex, and the research is relatively lagging. It is essential to identify commonly mutated genes in patients and to reveal the mechanism underlying the pathogenesis of these rare hereditary tumors. The standard use of gene testing technology combined with genetic counseling in genetic risk assessment, early screening, molecular diagnosis, risk management, long-term follow-up, and other cancer cycle management strategies is particularly significant in the advancement of research on hereditary tumors.

In the Chinese population, mutation identification and accurate treatment of hereditary tumors have commenced; however, there are still some limitations that include a lack of core guidelines and an inadequate consensus for genetic consultation, a limited understanding of pathogenesis, and a delayed advancement of corresponding molecular targeted drugs. Presently, based on genome research and systematic genetic screening in China and abroad, several pathway changes driven by key gene abnormalities have been detected, and rationally designed treatment strategies for tumors with gene mutations, including inducing ferroptosis, promoting oxidative stress, and metabolic changes have been implemented. A favorable response of certain hereditary tumors to immunotherapy is also a major direction of treatment. With the in-depth study of molecular biological characteristis of hereditary tumors, these treatment strategies are constantly being improved. In the future, it will be necessary to consider the application of experimental treatment strategies into clinical practice, particularly the possible precise gene-editing technology that may become available in the future to prevent the onset of hereditary tumors.

1.2 Interpretation for three key engineering research fronts

1.2.1 Improving public health and epidemic prevention systems and emergency mechanisms

Public health involves organizing the community to improve environmental sanitation conditions, prevent and control the spread of diseases, develop good hygiene and a civilized way of life, and provide medical services to prevent diseases and promote the health of the people. Public health requires collective, cooperative, and organized actions as well as sustainable policies to improve the health of the entire population and reduce health inequality. Public health and epidemic prevention systems and emergency mechanisms primarily refer to the institutions, personnel, and management operating mechanisms in place for the prevention and control of traditional and emerging infectious diseases and to the mechanism for joint response in the event of a public health emergency by allowing for the deployment of medical and health resources. The disease control system is an important component of the public health service system, and is also the main provider of national public health services and health protection for the people. The scope of this system includes environmental health, control of infectious and non-communicable diseases, individual health education, organization of early diagnosis and treatment of diseases, and development of social systems to ensure that all individuals enjoy a healthy status of living and achieve healthy production and longevity throughout their entire lives.

A modern public health and epidemic prevention system should include prevention-oriented ideology, a clear management system of powers and responsibilities, a unified and efficient emergency command and dispatching work mechanism, a strong legal protection system, a well-trained expert team system, a meticulous complete disease monitoring system, an accurate laboratory testing technology system, a rapid response and guarantee system, a scientific and advanced information system, and a practical public health service system.

In response to COVID-19, China has undertaken powerful measures and demonstrated excellent leadership, response ability, organization and mobilization ability, and implementation ability. However, this prevention and control exercise also exposes the deficiencies of the infectious disease prevention and control system and the health emergency mechanism in China. These deficiencies include an outdated concept and model of epidemic early warning, insufficient coordination of medical treatment, disease prevention and control, and medical security, an insufficient application of modern technology in professional institutions of public health, and an unclear legal status for health technology departments.

The key scientific issues for improving the public health epidemic prevention system and emergency response mechanism include 1) improving domestic and international public health-related laws and regulations in China, enhancing the feasibility and scientific nature of the legalization of epidemic prevention and control, actively participating in global prevention and control actions and health emergencies, and promoting the improvement of the leadership and resource coordination capabilities of the World Health Organization (WHO); 2) improving the public health management system that combines general situations and emergencies, establishing a scientifically standardized approach to prevent and control the spread of infectious disease, and establishing a unified emergency command and dispatch system, and improving a unified public health guarantee system; 3) establishing a multi-point trigger mechanism and a multi-channel surveillance mechanism and early warning mechanism for infectious diseases, establishing an online platform for multidisciplinary data sharing, improving the ability of infectious disease surveillance and early warning, and scientific nature and efficiency of decision-making about public health emergencies; 4) realizing the modernization of infectious disease prevention and control and health emergency technology and combining traditional theoretical knowledge with information technology, AI, big data, and other technologies. The research hotspots include 1) reformation of the medical treatment system for major epidemics, 2) grass-root infectious disease prevention and control capacity building, 3) measures and policies regarding public health emergencies and epidemic prevention and control policies, 4) comparison of the prevention and control measures for infectious diseases in various countries, and 5) construction of a national public health safety system.

When focusing on core papers, the top 10 countries in this research front of "improving public health and epidemic prevention systems and emergency mechanisms" are from North America, Europe, Asia, and Africa. Among them, the United States, the United Kingdom, and China are the top three (Table 1.2.1), where the United States accounts for 57.50%, and China and the United Kingdom eaeh account for greater than 10% of the published papers. The number of papers contributed by Chinese authors is second only to that of the United Kingdom, and the average citation frequency is 14.71, indicating that there is still room for improvement. From the cooperation network of core paper-generating countries, the top 10 countries with respect to the number of core papers have cooperative relations (Figure 1.2.1). Among the top 10 institutions with greatest output of core papers on "improving public health and epidemic prevention systems and emergency mechanisms", three were from the United States, three were from the United Kingdom, two were from Africa, one was the WHO, and one was from China. Among the institutions, the top three institutions are US Centers for

Table 1.2.1 Countries with the greatest output of core papers on "improving public health and epidemic prevention systems and emergency mechanisms"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper
1	USA	138	57.50%	1 674	12.13
2	UK	29	12.08%	644	22.21
3	China	28	11.67%	412	14.71
4	Australia	16	6.67%	294	18.38
5	Switzerland	16	6.67%	398	24.88
6	France	13	5.42%	302	23.23
7	Netherlands	10	4.17%	238	23.80
8	Germany	9	3.75%	152	16.89
9	Sierra Leone	9	3.75%	107	11.89
10	Italy	7	2.92%	118	16.86

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "improving public health and epidemic prevention systems and emergency mechanisms"

Disease Control and Prevention, Harvard University, and WHO; and Fudan University ranks 10th based on the number of papers published (Table 1.2.2). The cooperation network chart for the top 10 core paper producers indicates that cooperation exists among these institutions (Figure 1.2.2).

1.2.2 Global research on COVID-19 and emerging highly pathogenic viruses

The SARS-CoV-2 is currently the seventh known coronavirus that is pathogenic to humans. A large number of other coronaviruses also exist in nature. To cope with the threat of the COVID-19 pandemic, we aimed to systematically study the viral proliferation and infection, and mechanism underlying the pathogenesis of COVID-19, to explore the features of transmission, epidemiology, and outbreak, to elucidate the origin, evolution, and mutation, and to develop vaccines and medicines to allow for the safe and efficient treatment of this disease and ultimately provide scientific support for the prevention and control of the pandemic. Through the collaboration of scientists throughout the world, major progress has been made with respect to the basic knowledge and application research of SARS-CoV-2, and the knowledge gained from these studies has profoundly deepened our understanding of the virus and the diseases caused by it. In particular, Chinese scientists identified SARS-CoV-2 as the pathogen underlying this disease very rapidly, and they determined the full genome sequence of this virus and shared it with the world. Chinese scientists have demonstrated that SARS-CoV-2 can be transmitted via human to human

Table 1.2.2 Institutions with the greatest output of core papers on “improving public health and epidemic prevention systems and emergency mechanisms”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper
1	US Centers for Disease Control and Prevention	65	27.08%	718	11.05
2	Harvard University	18	7.50%	512	28.44
3	WHO	18	7.50%	447	24.83
4	Johns Hopkins University	9	3.75%	37	4.11
5	University of Oxford	8	3.33%	292	36.50
6	London School of Hygiene & Tropical Medicine	6	2.50%	236	39.33
7	Ministry of Health & Sanitation-Government of Sierra Leone	5	2.08%	73	14.60
8	Aix-Marseille University	4	1.67%	178	44.50
9	Ministry of Health, Republic of Liberia	4	1.67%	51	12.75
10	Fudan University	4	1.67%	18	4.50

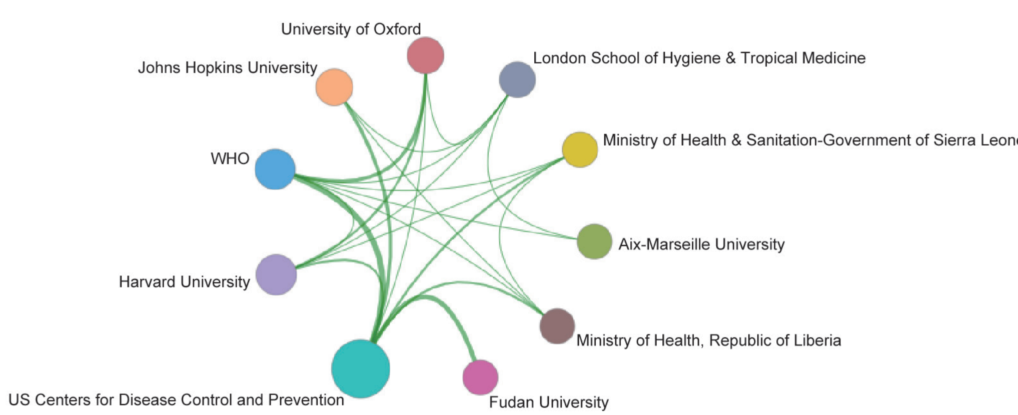

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “improving public health and epidemic prevention systems and emergency mechanisms”

transmission. The structures of the SARS-CoV-2 and their key coding proteins have been resolved rapidly. Reliable cell and animal models have been established for further research and development of vaccines and pharmaceuticals. Several vaccines and therapeutic drugs are undergoing phase III clinical trials. The domestic contagion was effectively controlled in a very short period of time. All of these achievements have embodied the strength of Chinese science and technology.

The critical scientific issues regarding global research on the SARS-CoV-2 and emerging highly pathogenic viruses include a lack of clarity regarding the molecular mechanism underlying interspecies transmission of the SARS-CoV-2 in humans, poor knowledge regarding the distribution, evolution, and recombination/mutation of coronaviruses derived from different animals in the natural ecological system, and a lack of clarity regarding the key stages in the viral life cycle, including replication, translation, assembly, and release. The structures and functions of the viral genome and the encoded proteins of the SARS-CoV-2 and other emerging highly pathogenic viruses remain to be determined through the use of structural biology, bioinformatics, and molecular biology technologies. Additionally, mechanisms by which the immune system is activated after viral infection and the pathogenesis of acute lung injury and multi-organ failure remain to be investigated. Specific diagnostic markers, risk factors for severe disease, and correlates for immune protection remain to be determined. Novel findings from basic researchers and clinical discoveries are required for more effective clinical guidance.

Global research on SARS-CoV-2 and emerging highly pathogenic viruses focuses on 1) the origin, evolution, and genetic mutation of coronaviruses derived from animals; 2) the structures, and function of the genome and encoded proteins of SARS-CoV-2; 3) the clinical manifestations, diagnosis, and management of diseases caused by the SARS-CoV-2; 4) the mechanism of immune protection and pathological damage; 5) the transmission pattern and the intervention strategies applied; 6) the mechanism of immune protection and the development of vaccines; and 7) the screening and evolution of anti-virus pharmaceuticals. In general, future research will rely on a more integrated application of single-cell sequencing, systems biology, reverse genetics, big data, and AI for further investigation of the infection, pathogenesis, and transmission of SARS-CoV-2. A greater number of next-generation vaccines and drugs based on rational design will enter clinical trials in the near future. More precise protection and control and also the management concept will be verified in practice.

When focusing on core papers, the top five countries in the research front involving "global research on COVID-19 and emerging highly pathogenic viruses" are the United States, China, the United Kingdom, Germany, and France (Table 1.2.3). In terms of the citation frequency for each article, the research content of this front is the focus of attention, and the citation frequency of core papers is very high. Cooperation network of the core paper-producing countries revealed that the top 10 countries in the number of core papers possess close cooperative relations (Figure 1.2.3). The top 10 institutions publishing the highest number of core papers were the US Centers for Disease Control and Prevention (USA), the Chinese Academy of Sciences (China), Harvard University (USA), the University of Hong Kong (China), the National Institute of Allergy and Infectious Disease (USA), the University of Texas Medical Branch (USA), the University of Oxford (UK), Huazhong University of Science and Technology (China), the University of North Carolina (USA), and Fudan University (China) (Table 1.2.4). The collaboration network of the top 10 core paper-producing institutions reveals that a number of institutions have developed mutual collaborations (Figure 1.2.4). The above analysis reveals that China is on the same line with international peers in the research frontiers of the global study on SARS-CoV-2 and potential highly pathogenic viruses, and advances in pathogen identification and animal models. Nevertheless, the research team in China remains limited, and comprehensive international collaboration should be encouraged.

1.2.3 Gut microbiota imbalances and diseases

Research examining gut microbiota imbalances and diseases has enhanced the traditional understanding of major diseases such as infections, liver disease, tumors, and metabolic diseases in medicine, and the findings from these research projects have facilitated revolutionary changes in the prevention, diagnosis, and treatment of various diseases. The occurrence and development of diseases are both primarily related to immunity and metabolism. The gut is one of the largest immune and metabolic organs. Gut microbes and their products can directly or indirectly affect the occurrence, development, and prognosis of disease through

Table 1.2.3 Countries with the greatest output of core papers on "global research on COVID-19 and emerging highly pathogenic viruses"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper
1	USA	1 309	48.36%	92 353	70.55
2	China	650	24.01%	64 924	99.88
3	UK	348	12.86%	31 554	90.67
4	Germany	249	9.20%	22021	88.44
5	France	217	8.02%	22 860	105.35
6	Canada	161	5.95%	16 315	101.34
7	Italy	154	5.69%	14 037	91.15
8	Brazil	148	5.47%	17 307	116.94
9	Switzerland	137	5.06%	15 805	115.36
10	Netherlands	122	4.51%	12 971	106.32

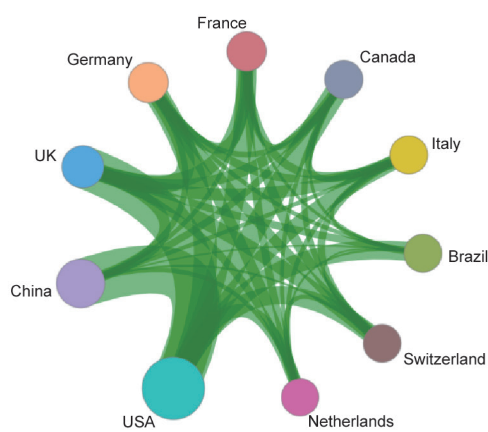

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "global research on COVID-19 and emerging highly pathogenic viruses"

Table 1.2.4 Institutions with the greatest output of core papers on "global research on COVID-19 and emerging highly pathogenic viruses"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper
1	US Centers for Disease Control and Prevention	233	8.61%	28 131	120.73
2	Chinese Academy of Sciences	127	4.69%	24 128	189.98
3	Harvard University	100	3.69%	12 249	122.49
4	The University of Hong Kong	92	3.40%	11 535	125.38
5	National Institute of Allergy and Infectious Disease	88	3.25%	6 931	78.76
6	University of Texas Medical Branch	88	3.25%	5 448	61.91
7	University of Oxford	75	2.77%	10 257	136.76
8	Huazhong University of Science and Technology	71	2.62%	13 079	184.21
9	University of North Carolina	70	2.59%	10 201	145.73
10	Fudan University	64	2.36%	8 696	135.88

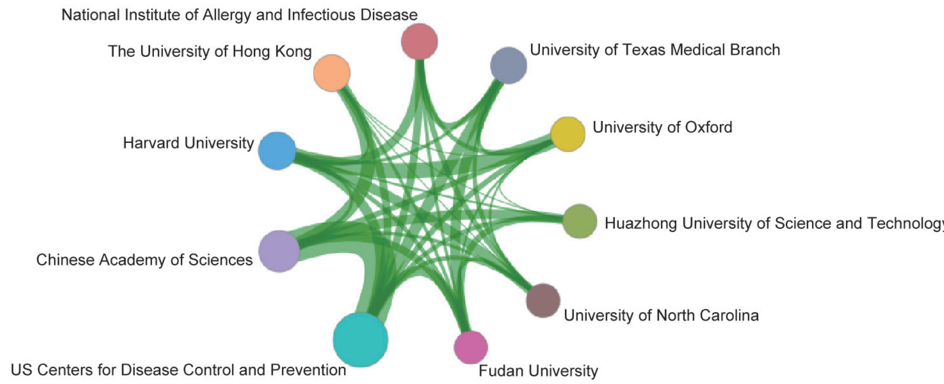

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "global research on COVID-19 and emerging highly pathogenic viruses"

the gut. Under the influence of the external environment, the microbiota balance between normal microbes and/or between normal microbiota and their host changes from a physiological combination to a pathological combination. In recent years, studies have found that gut microbiota imbalances play an important role in the occurrence and development of infection, tumors, cardiovascular disease, liver disease, obesity, diabetes, inflammatory bowel disease, autoimmune disease, and nervous system diseases, which led to new breakthroughs in the pathogenesis of major diseases. At the same time, new diagnostic methods based on changes in gut microbiota have provided new directions for the rapid and accurate diagnosis of conditions such as unexplained infections and difficult and complicated diseases. Additionally, gut microbiota regulation can be used as a strategy to prevent and treat many difficult-to-treat diseases, including *Clostridium difficile* infection and inflammatory bowel disease. Furthermore, research focused on gut microbiota imbalances and disease has provided new targets and new approaches for drug application. The efficacy and treatment successes or failures of many oral and injection drugs are closely related to the composition and function of the gut microbiota. Moreover, research examining gut microbiota and disease has opened up a new field interpreting the mechanism of action of TCM in China.

Research examining gut microbiota and diseases has attracted a great deal of attention from governments, scientific and technological circles, enterprises, and the public. Developed countries regard it as an important field to be developed under national science and technology strategic planning. Since the establishment of the "Human Microbiome Project" and "Metagenomics of the Human Intestinal Tract Consortium" in 2008, as well as the establishment of the National Microbiome Initiative in the United States in 2016, many countries throughout the world have established dozens of large-scale "microbiome" programs with billions of dollars invested in gut microbiota and their role in health and diseases. Many key deployments have been made in the fields of gut microbiota imbalances and major diseases, microbiota and biosafety, and the clinical application of microbiota. It is hoped that through basic research in these fields, major scientific issues associated with gut microbiota can be solved and that the development of the entire related medicine, machinery, and information industry will be promoted.

Currently, the key scientific issues in studying gut microbiota imbalances and diseases include integrating the theoretical basis (i.e., life science, modern medicine, and information science) and technical means from the perspective of the interaction mechanism between gut microbiota and human body; revealing the causal relationship and mechanism between the occurrence and development of diseases and gut microbiota imbalance; and accurately mining early warning, prediction, diagnosis and treatment target of diseases based on gut microbiota. Additionally, we should systematically research and develop new drugs and technologies to correct the imbalances in gut microbiota to prevent the occurrence and development of diseases.

The overall development trend extends from research examining the changes in gut microbiota structure and function in the process of disease occurrence and development and its correlation with diseases to research on the causal mechanism of gut microbiota changes and disease occurrence and development in combination with the development of related drugs and therapies. Research hotspots include 1) the role of gut microbiota imbalances in the occurrence and development of diseases and their association with diseases; 2) mechanism underlying gut microbiota imbalance and disease occurrence and development; 3) disease diagnosis and treatment target mining based on gut microbiota imbalance; 4) immunological mechanism and clinical application of the influences of gut microbiota on disease treatment effects; 5) the effect of gut microbiota on the metabolism and efficacy of oral drugs and the underlying mechanism; and 6) new drugs, strategies, and methods to correct the imbalance in gut microbiota.

Among the top 10 countries producing core papers focused on "gut microbiota imbalances and diseases," the United States is clearly in the leading position and accounts for 50.25% of these papers. China and France ranked second and third with respect to the number of core papers, accounting for 16.75% and 13.20%, respectively. The citation frequency of the core papers in this research front was 117.67–209.33 (Table 1.2.5), and the citation frequency of Chinese core papers was 138.00, indicating that the influence of the research work of Chinese scholars in this front still has room for improvement. The cooperation network of core paper-producing countries reveals that the top 10 countries generating the most number of core papers have cooperative relations within a certain range (Figure 1.2.5). Among the top 10 institutions that published core papers focused on "gut microbiota imbalance and disease," the top three institutions were Harvard University, French National Institute for Agricultural Research, and the University of California San Diego. The Chinese Academy of Sciences and Shanghai Jiao Tong University ranked 7th and 9th in this list (Table 1.2.6). The cooperation network of the top 10 core paper producing institutions reveals a cooperation among these institutions (Figure 1.2.6). The above analysis revealed that China is at par with foreign countries in the engineering research front of "gut microbiota imbalances and diseases."

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

This section of the review describes the top 10 engineering development fronts in the field of medicine and health, including the fields of basic medicine, clinical medicine, pharmacy, medical informatics and biomedical engineering, public health, and preventive medicine. The three emerging fronts are "human organoids-on-a-chip technology", "5G+ health care", and "human microbiome diagnostic prevention and intervention". Traditional research has focused on the "development of vaccines and drugs for major infectious diseases", "development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases", "small molecule discovery in cancer immunotherapy", "research and development of new antibiotics, artificial intelligence-based clinical decision support systems", "off-target effects and their

Table 1.2.5 Countries with the greatest output of core papers on "gut microbiota imbalances and diseases"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper
1	USA	99	50.25%	16 866	170.36
2	China	33	16.75%	4 554	138.00
3	France	26	13.20%	4 468	171.85
4	Canada	15	7.61%	3 140	209.33
5	Spain	15	7.61%	2 217	147.80
6	Belgium	14	7.11%	2 217	158.36
7	Sweden	12	6.09%	2 260	188.33
8	Japan	12	6.09%	1 412	117.67
9	Germany	11	5.58%	2 046	186.00
10	Denmark	10	5.08%	2 326	232.60

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "gut microbiota imbalances and diseases"

Table 1.2.6 Institutions with the greatest output of core papers on "gut microbiota imbalances and diseases"

No	Institution	Core papers	Percentage of core papers	Citations	Citations per paper
1	Harvard University	16	8.12%	3 035	189.69
2	French National Institute for Agricultural Research	11	5.58%	2 713	246.64
3	University of California San Diego	9	4.57%	1 881	209.00
4	University of Copenhagen	8	4.06%	2 118	264.75
5	Emory University	8	4.06%	1 831	228.88
6	Broad Institute	8	4.06%	1 812	226.50
7	Chinese Academy of Sciences	7	3.55%	1 362	194.57
8	Baylor College of Medicine	7	3.55%	951	135.86
9	Shanghai Jiao Tong University	7	3.55%	724	103.43
10	French National Institute of Health and Medical Research	6	3.05%	1 545	257.50

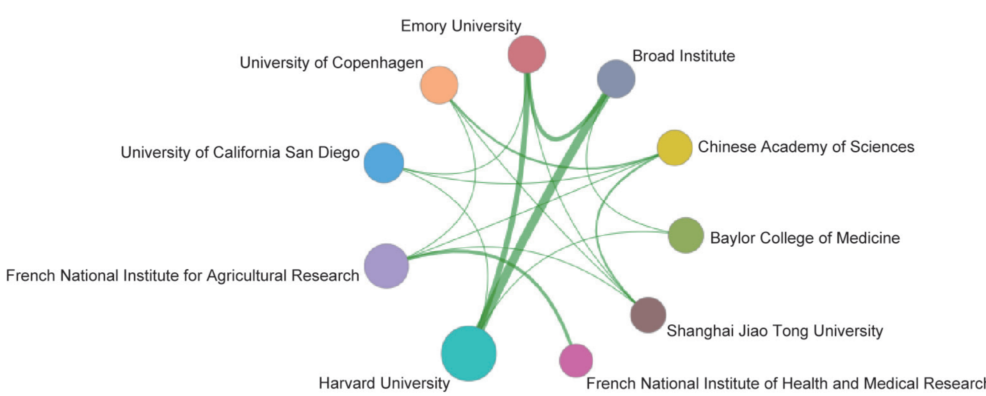

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "gut microbiota imbalances and diseases"

countermeasures", and "chimeric antigen receptor-modified T (CAR-T) treatment technology for solid tumors" (Table 2.1.1). All patents related to these 10 fronts published between 2014 and 2019 have been listed in Table 2.1.2.

(1) Development of vaccines and drugs for major infectious diseases

A major infectious disease outbreak can occur in a short time period and can affect a wide range of individuals and ultimately cause a large number of infections and/or deaths. Such an outbreak of emerging acute infectious diseases or diseases of unknown origin that poses a major threat to human health, seriously affects social stability and requires emergency management. The incidence of major infectious diseases is far more common than that of diseases that occur perennially.

As the COVID-19 epidemic continues to spread in 2020, there is an urgent need for drugs and vaccines for controlling and treating SARS-CoV-2 infections in a global scale. As "globalization" allows more infectious diseases to spread more rapidly, further and more detail-oriented development of vaccines and drugs targeting major infectious disease has become a necessity. Some key technical challenges in the development of vaccines and drugs for major infectious diseases include the ability to quickly detect and clarify unknown pathogens, a means by which to search for a safe and effective vaccine type for a certain disease, methods to overcome the problem of genetic variation of pathogens,

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	Development of vaccines and drugs for major infectious diseases	2 537	30 145	11.88	2014.6
2	Development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases	842	7 777	9.24	2015.6
3	Human organoids-on-a-chip technology	108	463	4.29	2017.1
4	Research and development of new antibiotics	600	3 093	5.16	2015.2
5	Small molecule discovery in cancer immunotherapy	1 918	31 621	16.49	2014.7
6	5G+ health care	326	5 256	16.12	2015.9
7	Artificial intelligence-based clinical decision support systems	6 416	26 796	4.18	2017.6
8	Off-target effects and their countermeasures	196	2 947	15.04	2017.4
9	CAR-T treatment technology for solid tumors	1 764	16 923	9.59	2017.0
10	Human microbiome diagnostic prevention and intervention	2 754	31 741	11.53	2014.6

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	2014	2015	2016	2017	2018	2019
1	Development of vaccines and drugs for major infectious diseases	160	187	291	353	384	352
2	Development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases	40	60	103	163	156	150
3	Human organoids-on-a-chip technology	6	9	10	19	29	28
4	Research and development of new antibiotics	74	54	66	66	101	100
5	Small molecule discovery in cancer immunotherapy	167	205	236	226	280	274
6	5G+ health care	21	22	38	45	60	80
7	Artificial intelligence-based clinical decision support system	185	248	398	771	1524	2924
8	Off-target effects and their countermeasures	11	14	15	35	54	62
9	CAR-T treatment technology for solid tumors	57	83	203	344	393	549
10	Human microbiome diagnostic prevention and intervention	215	236	274	370	393	419

means of coping with or avoiding pathogen drug resistance, and techniques to achieve high efficiency in monitoring and management of suspected infectious disease spread.

(2) Development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases

Major emerging and re-emerging emergency infectious diseases refer to infectious diseases caused by new species or new pathogenic microorganisms and also to reoccurring ancient infectious diseases that seriously affect the social stability and pose a major threat to human health. The development of diagnostic reagents and equipment for major emerging and re-emerging infectious diseases is of great significance in the field of disease prevention and control, as it can affect health, economic development, and social stability. Due to economic integration and globalization, human habitat urbanization, large-scale application of living utilities, and the popularity of modern transportation, especially railways and flights, infectious diseases now occur more frequently and spread more rapidly. To respond to major emerging and re-emerging infectious disease emergencies in a timely and effective manner, the global demand for diagnostic reagents and equipment is continuously growing.

Presently, the development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases depends on solving the following key technical problems: collecting pathogen strains from different regions—local and non-local—to enrich the pathogen source library and gene information databases; providing a prerequisite for the rapid identification and genetic variation monitoring of the pathogens responsible for causing emerging and re-emerging emergency infectious diseases; developing key technical components of equipment to improve the testing speed, through-put, and sensitivity of equipment; promoting the function integration, miniaturization, and portability of equipment in order to fulfill the different practical requirements associated with centralized detection and individual detection in different scenarios; and performing innovative research on the key components of diagnostic reagents and the principles of testing methods to improve testing sensitivity and specificity.

(3) Human organoids-on-a-chip technology

Human organoids-on-a-chip represents a three-dimensional culture technology based on microfluidic chip platforms to induce pluripotent cells to differentiate into cell clusters and tissues *in vitro*. This technology aims to form spatial structures similar to the tissue sources on the chip by simulating and controlling biological behaviors of the cell clusters and to further reproduce crucial functions to achieve values in drug screening and evaluation, genetic disease modeling, cell therapy, and various biomedical applications. Although research focused on organoids-on-a-chip is still in its initial stages, it has been highly valued due to the vast potential and development prospects of these platforms. Current topics of interest focus on the following aspects: 1) intelligent biomaterials; 2) interaction between substrates and cultured cell clusters; 3) co-culture systems; 4) organoid real-time monitoring; 5) internal micro-environmental regulation; 6) connection and cooperation of multiple organoids-on-chips; 7) drug screening, toxicity classification, and model establishment.

(4) Research and development of new antibiotics

Antibiotics are chemical substances naturally produced by a living organism, typically microbes, which are resistant to pathogens or other substances. Antibiotics control the growth and division of competing microorganisms or cause death by interfering with critical biological processes, such as synthesis of nucleic acids, proteins, and cell walls, or with membrane integrity and permeability. However, antimicrobial resistance (AMR) occurs when pathogenic bacteria develop the ability to escape from the selective pressure exerted by antibiotics that are designed to inhibit their growth or kill them.

Due to the rapid emergence of AMR, there is a growing need to discover new antibacterial agents to address the shortages within the clinical arsenal. However, our technologies and the ability to discover antibiotics from environmental microbes remain inadequate. Additionally, antibiotic complementary and alternative therapies such as antibiotic adjuvants, anti-virulence strategies, phage therapy, and methods to regulate human microbial flora are still in the early stages of proof-of-concept. Due to the shortage of available targets and chemical spaces, there are numerous problems in the discovery, design, synthesis, and optimization of new antibacterial agents, particularly those with novel modes of action. The clinical application of antibacterial agents has enabled numerous complicated medical methods to become successfully realized and to even become routine. However, the increasing problems raised by AMR bring global challenges to curing infections. The development of new antibacterial agents could help to overcome multidrug-resistant bacteria-induced problems such as a lack of effective anti-infectious drugs, increased mortality, and high medical expenses.

The contradiction with the increasing multi-drug resistant strains is that the enthusiasm for developing new antibacterial drugs is extremely low. One major reason is that generic antibiotics are still effective for treating many infections, and this results in low profits. Additionally, the uncoordinated costs of investment and return have caused many big pharma companies to leave this field. Repairing the AMR and antibacterial pipelines is a comprehensive problem that requires joint support from multiple directions that include novel methods for antibiotic discovery, appropriate clinical usage of antibiotics, drug development and regulation, and increasing financial support and business. In the era of bacterial resistance, the ideas regarding anti-infection agents would switch from broad-spectrum to narrow-spectrum agents based on thorough comprehension of the bacteria and pathogenesis and on the interaction with the host. Additionally, the international community should extensively investigate any strategies that can serve complementary to antibiotics, combination therapy, and rapid and accurate diagnosis of bacterial infections. These transformations will greatly broaden the target diversity of antibacterial agents, open new avenues to extend the clinical life of antibiotics, and eventually overcome the rapid emergence of AMR.

(5) Small molecule discovery in cancer immunotherapy

Small-molecule drugs in tumor immunotherapy target the innate immune system or the tumor immune microenvironment and act on natural/adaptive immune cell molecules or pathways to relieve tumor immunosuppression and restore the anti-tumor immunity within the body. Immunotherapy based on small molecules can offer compensation for the limited bio-distribution of macromolecules, improve antitumor efficacy, and reduce systemic immune toxicity, which will be the primary research and development direction of future immunotherapy. Small-molecule drugs targeting immunotherapy can be administered in an “on/off” manner over time to achieve precise control of efficacy and toxicity. In contrast to the high specificity of monoclonal antibodies, small-molecule drugs non-specifically bind to cells and molecules with low oral bioavailability and uneven distribution to affect the pharmaceutical properties of the compound. Small-molecule drugs can easily enter cells, target different immune cells, and induce various immune effects. Thus, small changes in molecular structure may lead to tremendous variations in efficacy and toxicity. There is an urgent need to simulate the interaction between diverse molecular structure and the activation or inhibition targets in immune cells. Additionally, the efficacy and toxicity of these drugs must be clearly delineated as indicated in the “immunological small molecule drug structure-effect diagram.” Compared to immunotherapy based on biological antibodies, oral small molecules can more easily enter the tumor microenvironment and can simultaneously act on intracellular and external targets to enhance the anti-tumor efficacy. Screening for small-molecule drugs that cross certain physiological barriers, such as the blood-brain barrier, can benefit more cancer patients. Additionally, small-molecule immunotherapy can also provide the best pharmacokinetic and pharmacodynamic parameters, thus effectively avoiding immune-related adverse events caused by the systemic immunogenicity of monoclonal antibodies. Small molecule drugs used alone or in combination with monoclonal antibodies can solve the problem of low clinical response and drug resistance. Accordingly, small-molecule immunotherapy is expected to play a comprehensive role in mediating anti-tumor immunity. Following the development of monoclonal antibody immunotherapies, significant progress has been achieved in small-molecule immunotherapy in recent years. Tremendous breakthroughs have been achieved in small molecule immunotherapy and have allowed for the targeting of PD-1/PD-L1, IDO, STING, TLR, A2A, and other newly discovered co-suppression and co-stimulation targets. Moreover, small molecule drugs targeting PD-1/PD-L1, IDO-1, and STING have successively entered clinical trials. As no small-molecule immunological drugs have been approved to date, future research will continue to focus on discovering new small molecules with particular chemical types and higher potency in an attempt to identify biomarkers that can accurately classify patients.

Given their low production and development costs, small-molecule drugs are expected to benefit cancer patients to a greater extent. Small molecule immunotherapy can be combined with biological agents or traditional cancer therapies such as immune checkpoint inhibitors, targeted therapy, or chemotherapy to enhance the anti-tumor efficacy and to provide inherent advantages over biological immunotherapy that include a wider range of molecular targets and lower rates of immune-related adverse events. By exploring the molecular mechanism of small-molecule immunotherapy and optimizing the strategies and timing of small-molecule drug combination therapy to maximize its effect, we can achieve effective transformation from basic discovery to clinical application and open a new chapter in tumor immune precision therapy.

(6) 5G+ health care

Emerging 5G+ healthcare is based on the high speed, low latency, low power consumption, and large capacity of 5G technology (i.e., the fifth-generation mobile communication technology), and it allows for full use of the advantages of medical technology in large hospitals as it allows them to focus on providing digital, mobile, and remote health and medical services in pre-diagnosis and during and after diagnosis. This emerging 5G+ health care uses Internet terminals, such as smartphones, tablets, Virtual reality/augmented reality, wearables, and multimedia communication devices; and intelligent medical equipment, such as surgical robots, medical imaging equipment, and *in vitro* diagnostic equipment that is linked to the 5G medical private network composed of networks, such as wireless access networks, bearer networks, and core networks. The real-time, dynamic, and continuous monitoring of vital sign data, such as blood pressure, blood glucose, and heart rate; and remote transmission and access of image data can all be realized Examination reports, electronic medical records, and ultra-high-definition long-distance communications, such as video calls and real-time information feedback are performed smoothly to allow for real-time and high-quality interaction between doctors and patients and among the doctors themselves. The application of 5G+ health care is becoming increasingly extensive, and 5G+ health care is gradually taking shape and maturing. The first example is medical monitoring and nursing applications based on the wireless monitoring of medical equipment data, including mobile infusion, mobile care, and patient positioning. The second example is medical diagnosis and guidance applications based on video and image interaction, such as mobile rounds, remote diagnosis, remote consultation, and mobile-first aid. The third example is remote control applications based on video and force feedback, such as remote robotic ultrasound inspection, robotic endoscopy, and remote robotic surgery. 5G+ health care is an important part of future health care. Countries with a strong information infrastructure are racing to increase investments in 5G+ health care standards, technology, and applications. The sustainable development of 5G+ health care is inseparable from the construction of the 5G private medical network, the iteration of smart mobile terminals, and the innovation of smart medical equipment. It will be promoted through further integration with big data, the Internet of Things, robotics, artificial intelligence, and other new technologies. The healthcare industry continues to develop and evolve towards wireless, intelligent, and fully connected service to provide patients with high-quality, efficient, and convenient healthcare services, ultimately improving the health of the population.

(7) Artificial Intelligence-based clinical decision support system

Artificial intelligence-based clinical decision support system (AI-CDSS) refers to an information system that assists healthcare providers with comprehensive analysis and judgment decisions by applying the artificial intelligence technology along with their comprehensive clinical knowledge and the subjective and objective conditions of patients. AI-CDSS aims to enhance the accuracy, individualization, and efficiency of clinical decision-making and actions by reinforcing the medical intervention ability, thus improving healthcare quality and capability. AI-CDSS primarily extracts the potential connections and knowledge from structurally diverse medical big data, such as pictures, videos, and texts, through the use of technologies, such as natural language processing, knowledge engineering, computer vision, machine learning, and others to integrate with biomedical technologies to further construct the clinical diagnosis and deduction logic, classifications, and prediction models. The developed system or model is integrated into the clinical information system and embedded into the diagnosis or treatment process to provide enhanced decision support abilities in medical practice. AI-CDSS can be applied throughout the diagnosis process, including during the analysis and processing of disease information, the prediction of disease risks, the intelligent diagnosis support of disease, the guidance of medication use, the assistance with the treatment, the prevention and prognosis of disease for patients, and other tasks. Currently, it is the most widely used tool in specialization-oriented intelligent diagnosis support in rheumatoid arthritis, cancer, lung disease, heart disease, diabetic retinopathy, hepatitis, Alzheimer’s disease, liver disease, dengue fever, and Parkinson's disease. In 2016, the global market value of the clinical decision support system was 79 million USD, and it is estimated to increase to 1.76 billion USD by 2023. AI-CDSS is not only the core developmental direction of CDSS, but it also represents the key position of artificial intelligence applications in healthcare. In the context of global ageing and insufficient medical resources, AI-CDSS is regarded as an important approach to supplement medical resources and to improve service quality and efficiency, and has already become an essential component of the medical industry worldwide. To construct reliable and sustainable AI-CDSS, standardized expression of complicated medical knowledge, integration of multi-source knowledge, and semantic normalization of data are the foundations that must be developed. Additionally, to improve the interpretability and transportability of the system, the development of multi-modal data and multi-disciplinary clinical decision support abilities are important directions for AI-CDSS. With the increased involvement of AI in clinical diagnosis, the pattern of human–computer interaction for enhanced clinical decision making, and the ethical principles and regulatory mechanism adhered to, and the practicing requirements of AI-CDSS will be crucial to accelerate the development of the industry.

(8) Off-target effects and their countermeasures

The off-target effects of novel gene editing technology refer to non-targeted site editing when using the CRISPR/Cas system. These non-target site editing events can be divided into sgRNA-dependent and -independent events. Previously, a variety of off-target detection methods have been developed that include off-target prediction software (e.g., CRISPR Design Tool, E-CRISP, and Cas-OFFinder), high-throughput genome-wide translocation sequencing, break labeling *in situ* and sequencing (BLESS), and genome-wide unbiased identification of DSBs enabled by sequencing (i.e., GUIDE-seq). However, the sensitivity and accuracy of these technologies cannot meet the needs of the growing field of gene editing. Currently, CRISPR/Cas possesses multiple functions, such as DNA double-strand breaks, DNA single-strand breaks, DNA targeting, RNA cutting, single-base editing, and prime editing, thus providing broad prospects for disease treatment. However, off-target effects have become a bottleneck for the clinical application of this technology. It is hoped that the safety evaluation of existing gene technologies and the development of new high-fidelity gene editing tools would make this technology suitable in a variety of situations. The problem of off-target effects seriously hinders the industrialization of gene editing technology. There is no medicine for diseases caused by gene mutations. The market for gene therapies that allow for correcting or compensating for mutated genes through gene editing is vast. The research and development pipelines of pharmaceutical giants cover several gene therapies, and original innovative drug R&D companies based on gene editing technology are rapidly emerging around the world. Currently, multiple CRISPR/Cas drugs are undergoing phase I/II clinical trials. Undoubtedly, there is a worldwide R&D competition. In the future, several gene therapies may enter the market one after another, and clinicians may be seeking a balance between the therapeutic effects and safety risks. In the long term, safety will be the goal pursued by this type of medicine, and in turn, achievement of this goal will promote the clinical application of gene editing technology. This reminds us that while promoting the development of new technologies, we should pay attention to reducing the off-target effects, establishing off-target effects quality control standards, and developing and optimizing a new generation of gene editing technologies to further promote the applications of gene editing technology.

(9) CAR-T treatment technology for solid tumors

CAR-T cell-based immunotherapy is an innovative approach to tumor treatment that has been demonstrated to potentially exhibit major histocompatibility complex-independent anti-tumor effects. These cells could directly recognize tumor cells by virtue of genetic modifications resulting in the expression of a chimeric antigen receptor (CAR), and they were activated to exhibit durable persistence *in vivo* through the action of a T cell activation endodomain with co-stimulatory signaling molecules. The screening of solid tumor target antigens, optimizing CAR affinity, hinge length, and flexibility and selection of stimulating molecules in the intracellular region can directly increase the homing, proliferation, and anti-tumor effects of CAR-T cells in patients with solid tumors, thus ensuring the long-term survival and anti-tumor ability of CAR-T cells *in vivo*. Additionally, specific issues related to the production of CAR-T cells, such as blood collection and transportation, preparation of viral vectors, and *in vitro* culture of autologous cells, are crucial for the treatment of tumors. The pharmaceutical evaluation of CAR-T cells should focus on the principle of "identification and control of drug safety and risks, taking into account the specificity of cell products." After two decades of preclinical research and clinical trials, the safety and feasibility of CAR-T cell-based immunotherapy have both been confirmed, and unprecedented clinical results have been obtained for hematological malignancies such as B-cell lymphoma and leukemia. Additionally, CAR-T cell-based immunotherapy has been demonstrated to be safe and effective in the treatment of solid tumors, including non-small cell lung cancer, biliary tract cancer, pancreatic cancer, and liver cancer, suggesting a new treatment regimen for patients with solid tumors. On the basis of the broad application prospect of the CAR-T cell-based immunotherapy in tumor treatment, countries worldwide have attached great importance to research on CAR-T cells. A series of technology start-ups have been founded in recent years, and they have gradually achieved breakthroughs in improving the safety and efficacy of CAR-T cells with respect to the treatment of solid tumors. Based on this, the market for the technologies reached a certain scale and exhibited continuous high-speed growth. Selecting solid tumor target antigens such as neoantigens, choosing the appropriate conditioning regimens to disrupt the tumor microenvironment, improving homing ability and the ability to resist the tumor microenvironment for CAR T cells, and improving the clinical safety and efficacy are all vital for the treatment of solid tumors using CAR-T cells. Research and development in the field of CAR-T cell products is exhibiting an increasing trend, and this includes clinical trials on CAR-T cells that recognize different targets and improvements and optimization of these cells on the basis of these results. The continuous improvement of CAR-T cells will make them a powerful tool in the treatment of solid tumors, and it will significantly benefit the field in the future.

(10) Human microbiome diagnostic prevention and intervention

Human microbiome diagnostic prevention and intervention detects the second genome, i.e., the microbiome of humans to reflect the health status of various ecological niches and uses this information for the early detection of chronic diseases, the diagnosis of infectious diseases, and selection of biological interventions and treatments related to microorganisms in an effort to prevent the occurrence of diseases or to improve the health status. Through the use of amplicon sequencing, metagenomic or transcriptome sequencing, nucleic acid extraction, sequencing library construction, data analysis, and function prediction, human microbiome diagnosis prevention and intervention techniques can accurately analyze the human microbial flora spectrum to provide its function and expression, mine the key biomarker and species, outline the bacteria–host (people) relationship within the environment (ecological) complex, and provide accurate microbiota information for individual and population health and disease status. With the development of sequencing technology, human microbiome diagnostic prevention and intervention technology has been gradually applied in clinical practice at the scientific research level, including microbiome detection during early diagnostic screening of diseases, developing biotherapeutic drugs and agents targeting individual microbiomes, and improving individual health by the transplantation of intestinal flora. Additionally, metagenomics next-generation sequencing is widely used during diagnosis and treatment to assist in the precise treatment of clinically unidentified infectious diseases, such as central nervous system infections, respiratory tract infections, and blood flow infections. Advancements in the field of the human microbiome have broad prospects in the field of chronic disease prevention and control, personalized and precise diagnosis and treatment, and health management of microbial drugs and preparations, and these advancements are the strategic frontier of a new round of scientific and technological revolution. In recent years, a series of technology start-ups that include third-party medical detection, gene sequencing, molecular diagnosis, and microbial agents have gradually achieved technological breakthroughs in biological marker gene detection, microbiome diagnosis, and disease-specific target screening to launch new products based on the diagnosis of human microbiome prevention and intervention technology application products. This market formed at a certain scale, and the market scale has continuously experienced high-speed growth. The update of sequencing technology, the large-scale application of individual microbiome detection in popularization, the biological big data analysis ability, and the analysis of the association between the whole microbiome and the human genome will be the key for promoting human microbiome diagnosis prevention and intervention technology. The deep integration of human microbiome diagnosis with prevention and intervention technology and life and medicine, computer science, microbiology, and big data analysis will result in the development of new ideas for the diagnosis and management of chronic diseases, and this will also make microbiome technology a bridge between human health and microflora. The research achievements with respect to microflora, including early screening of non-invasive colorectal cancer, individualized chronic disease and health management, probiotic intervention, and fecal bacteria transplantation, have been applied in the context of human health. In the context of the nternet era and with the progress in sequencing technology, the improvement in user education and acceptance, and the transformation of 2B (to business) to 2C (to consumer) business, the industrialization of human microorganisms will bring great benefits in the future to the medical field and the lives of people in general.

2.2 Interpretations for three key engineering development fronts

2.2.1 Development of vaccines and drugs for major infectious diseases

Since the Spanish influenza pandemic was recorded in 1918, severe acute respiratory syndrome (SARS), Ebola, hemorrhagic fever, Middle East respiratory syndrome (MERS), COVID-19, and other epidemics have emerged. The fight between human beings and infectious diseases has become increasingly fierce. By the 1940s, antibiotics were discovered to treat bacterial infections, and with the development of antibiotics, new drugs, vaccines, new diagnosis, and treatment technologies, an increasing number of infectious diseases could be prevented and treated. The development of vaccines has enhanced protection, especially in infants and young children, and has reduced their mortality. Similarly, vaccines have exerted an important protective effect on adults and have prevented the outbreak of pandemic diseases such as cholera and yellow fever. It has become clear that the quick development of vaccines and drugs for infectious diseases is a powerful weapon for human beings to fight against major infectious diseases.

Since 1970, more than 1500 new pathogens have been identified, and 70% of which have been shown to originate from animals, including the Ebola virus and the human immunodeficiency virus (HIV). As the COVID-19 epidemic continues to spread in 2020, the global need for drugs and vaccines to control and treat SARS-CoV-2 infections has never been more urgent. Some key technical challenges in the development of vaccines and drugs for major infectious diseases include means by which to rapidly detect and clarify unknown pathogens, methods to search for a safe and effective vaccine type for a certain disease, approaches to overcome the problem of genetic variation of pathogens, means by which to avoid and cope with pathogen drug resistance, and ways in which to achieve high efficiency in the monitoring and management of suspected infectious disease spread.

Currently, major international research has focused on a number of topics that include: (1) the completion of recognition of infectious disease monitoring systems, such as big data monitoring, rapid laboratory detection, gene sequencing, and others; and (2) the development of vaccines, which includes (i) establishment of a vaccine R&D and production platform for emerging infectious diseases that will allow researchers to produce a medicinal vaccine with a determined structure, antigenicity, purity, stability, and sterile need, (ii) development of multiple downstream and production processes to allow researchers to identify and save pathogens antigen protein structure characterizations, (iii) determining adjuvants and types of production, separation, and purification for vaccines, and (iv) establishing quality standards for vaccine evaluation and clinical research to allow researchers to perform relevant preclinical tests and clinical trials. The types of vaccines include inactivated vaccines, recombinant protein vaccines, virus vector vaccines, nucleic acid vaccines, and live attenuated vaccines. The research has also focused on 1) development of diagnostic tools such as nucleic acid diagnosis (e.g., polymerase chain reaction (PCR) targeted sequencing, portable rapid diagnostic sequencing, whole genome sequencing, RNA/cDNA sequencing, and epigenetic sequencing that can be used to analyze the genetic resistance of pathogens), imaging diagnosis, and direct observation of pathogens; and 2) development of therapeutic drugs, including blood products, immunotherapy, and drug therapy development.

By the end of 2018, a total of 77 preventive vaccines for 41 diseases were approved globally, and these covered approximately two-thirds of major infectious diseases. However, at the same time “vaccine hesitation” is likely to lead to a resurgence and increase in infectious diseases. Currently, there are still approximately 20 diseases such as malaria, hepatitis C, HIV, dengue fever, and MERS without effective vaccines. It is acknowledged that a 1 USD investment in vaccine research and development will result in savings between 2 USD and 27 USD in healthcare costs. The global vaccine market is expected to reach 44.8 billion USD in 2024, ultimately ranking 4th in all therapeutic areas.

Novel coronavirus infection caused large-scale infection and outbreak in the world. In the face of infectious diseases, China quickly responded and quickly established a research and development and production technology platform for such new infectious diseases. Achievements in epidemic prevention and control of coronavirus enabled China to reduce the social burden and avoid more economic losses to a certain extent. A large Chinese population brings huge demand for vaccines, and the development of effective vaccines will also reduce the burden of public health expenditure. In recent years, with the improvement of ability of individuals to pay and the enhancement of their awareness in preventing infectious diseases, the demand for vaccinations has been continuously increasing. The size of the Chinese vaccine market has increased from approximately 19.9 billion CNY in 2013 to 31.1 billion CNY in 2019, and the vaccine market is expected to develop rapidly.

The top five countries that published the most core patents are the United States, China, France, Japan, and the United Kingdom (Table 2.2.1). From the cooperation network among the major countries producing core patents (Figure 2.2.1), it can be observed that the United States closely cooperates with Switzerland, China, and Canada.

The top three institutions for core patent output were the U.S. Department of Health and Human Services, Novartis AG, and the University of Texas (Table 2.2.2). It can be observed from the cooperation network among the major institutions (Figure 2.2.2) that there is a partnership between the French National Centre for Scientific Research and the French National Institute of Health and Medical Research, and there is also a relationship between the U.S. Department of Health and Human Services and the University of California.

2.2.2 Development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases

Major emerging and re-emerging emergency infectious diseases refer to infectious diseases caused by new species or new pathogenic microorganisms and to those caused by reoccurring of ancient infectious diseases that seriously affect social stability and pose a major threat to human health. Laboratory testing for infectious diseases has passed through different stages that include the initial empirical diagnosis based on clinical symptoms, pathogen culture, serological testing, and modern comprehensive testing that is focused on the products of pathogens and host responses such as the combination of pathogen nucleic acid, antigen, and antibody tests. The development of laboratory technology provides indispensable technical means for epidemic monitoring, early diagnosis, and efficacy evaluation of infected patients.

Currently, the development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases depends upon solving key technical

Table 2.2.1 Countries with the greatest output of patents on “development of vaccines and drugs for major infectious diseases”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	1 333	52.54%	20 022	66.42%	15.02
2	China	392	15.45%	1 183	3.92%	3.02
3	France	106	4.18%	895	2.97%	8.44
4	Japan	97	3.82%	877	2.91%	9.04
5	UK	96	3.78%	1 351	4.48%	14.07
6	Germany	91	3.59%	2 953	9.80%	32.45
7	South Korea	84	3.31%	98	0.33%	1.17
8	Switzerland	83	3.27%	1 370	4.54%	16.51
9	Canada	76	3%	1 160	3.85%	15.26
10	Netherlands	40	1.58%	658	2.18%	16.45

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “development of vaccines and drugs for major infectious diseases”

Table 2.2.2 Institutions with the greatest output of patents on “development of vaccines and drugs for major infectious diseases”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	U.S. Department of Health and Human Services	67	2.64%	736	2.44%	10.99
2	Novartis AG	39	1.54%	1 085	3.60%	27.82
3	University of Texas	37	1.46%	426	1.41%	11.51
4	French National Centre for Scientific Research	36	1.42%	235	0.78%	6.53
5	Gilead Sciences, Inc.	34	1.34%	976	3.24%	28.71
6	French National Institute of Health and Medical Research	33	1.30%	157	0.52%	4.76
7	Academy of Military Medical Sciences PLA	33	1.30%	41	0.14%	1.24
8	University of California	29	1.14%	769	2.55%	26.52
9	Harvard University	25	0.99%	627	2.08%	25.08
10	University of North Carolina	24	0.95%	148	0.49%	6.17

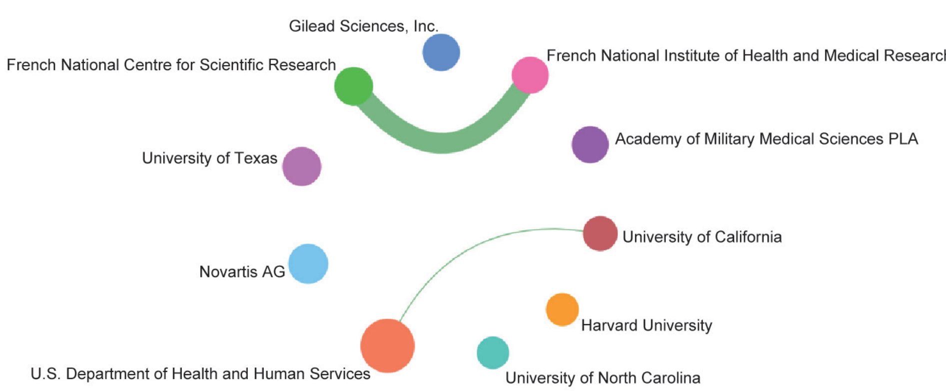

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “development of vaccines and drugs for major infectious diseases”

problems that include: 1) collecting pathogen strains from different regions to enrich the pathogen source library and gene information database to provide a prerequisite for the rapid identification and genetic variation monitoring of the pathogens that have caused emerging and re-emerging emergency infectious diseases; 2) developing key technical components of equipment to improve the testing speed, through-put, and sensitivity of equipment and to promote the functional integration, miniaturization, and portability of equipment to fulfill the different practical application needs of centralized detection and individual detection in different scenarios, and 3) performing innovative research on the key materials of diagnostic reagents and the principles of testing methods to improve the testing sensitivity and specificity. The global demand for diagnostic reagents and equipment is growing continuously. The global market size for infectious disease *in vitro* diagnostic (IVD) reagents and equipment was valued 16.3 billion USD in 2019 with a compound annual growth rate of approximately 7.4% from 2020 to 2027, and it is expected to reach 23.17 billion USD in 2027. This is closely related to favorable government initiatives and to an increase in research and development funds.

The current hotspots in the clinical application of diagnostic reagents and equipment for infectious diseases including: 1) Real-time PCR, a classic pathogen nucleic acid testing technology, has been developed to further improve the speed, sensitivity, throughput, and automation under the premise of ensuring the accuracy of the results. 2) Isothermal nucleic acid amplification technology was also able to achieve rapid amplification of target nucleic acids at constant temperature by incorporating the use of new nucleases. Currently, isothermal amplification technologies primarily include loop-mediated isothermal amplification, recombinase polymerase amplification, nucleic acid dependent amplification detection, and transcription-mediated amplification. 3) Hybridization and mass spectrometry analysis are additional technologies that must be discussed. Molecular nucleic acid hybridization is a technique used to analyze nucleic acids qualitatively and quantitatively based on nucleic acid denaturation and renaturation. Such technology attaches target DNA fragments to a solid matrix such as a membrane, glass, latex particles, or nanoparticles, and it can then be used for multiple pathogens testing according to hybridization and fluorescent labeling. 4) High-throughput sequencing is primarily used in the diagnosis of infections that are acute, complicated, and in the identification of difficult-to-cultivate or new pathogens. Additionally, it also plays an important role in tracing the source of infectious diseases and in epidemic monitoring and control. 5) Immunologic tests primarily include antigen testing against pathogens and host humoral and cellular immune response tests. Antigen testing employs specific antibodies to detect antigens of a pathogen to determine the existence of an infection caused by a specific pathogen. Antibodies conversing from negative to positive or a significant increase in antibody titer can be used to make laboratory diagnoses for pathogens as well as to evaluate the severity and population prevalence of the pathogenic infection during the outbreak of infectious diseases.

China is a large country with a large population. Due to the economic integration and globalization, the changes in living habits, etc., China has experienced outbreaks of several emerging and re-emerging emergency infectious diseases since the SARS outbreak in 2003. In the course of fighting against the COVID-19 epidemic, with the active support of the government and the sufficient investment of scientific research funds, increasing IVD reagent and device manufacturers and scientific research institutions have joined into the research and development of diagnostic reagents and equipment. They have developed dozens of nucleic acid and antibody testing reagents, as well as rapid PCR amplification devices, microfluidic nucleic acid microarray platforms, portable molecular nucleic acid detection workstations, and other new equipment. Such diagnostic reagents and equipment played a critical role in pathogen identification, laboratory diagnosis, efficacy assessment, early warning, and monitoring of the epidemic.

As shown in Table 2.2.3, the United States, China, South Korea, Japan, and Germany are ranked as the top five countries in terms of the number of active patents. The patents output by Chinese researchers account for 28.74% of the global total, ranking second only to the United States. As shown in the collaboration network of the top 10 patent-producing countries (Figure 2.2.3), the United States has close collaborations with Germany, Switzerland, Canada, and China in this field.

The top three institutions in terms of patent output in this front are the U.S. Department of Health and Human Services, the Academy of Military Medical Sciences PLA (China), and Curetis GmbH (Germany) (Table 2.2.4). Additionally, the collaboration network of the top 10 patent-producing institutions shows cooperation between Curetis GmbH and Ares Genetics GmbH (Germany) and between the French National Centre for Scientific Research and the Institut Pasteur (Figure 2.2.4).

2.2.3 Human organoids-on-a-chip technology

Human organoids-on-a-chip technology has been highly valued and regarded as a catalyst for the development of translational medicine due to its feasibility with respect to multi-organ integration and high bio-functional simulation. The fact that organoids-on-a-chip can serve as substitutes for animal models has tremendous strategic significance, and this technology has therefore been important for the development of new drug evaluation systems.

Several vital scientific issues underlying human organoids-on-a-chip primarily include the structural design of chips, the expansion of the cell or tissue sources, appropriate substitutes for the extracellular matrix, the development of cell substrates, the exploration of the co-culture system, the combination of multi-organoids and their bio-functions, the regulation and control of the inner microenvironment, and

Table 2.2.3 Countries with the greatest output of core patents on “development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases”

No.	Country	Published Patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	320	38.00%	5 706	73.37%	17.83
2	China	242	28.74%	560	7.20%	2.31
3	South Korea	68	8.08%	32	0.41%	0.47
4	Japan	41	4.87%	157	2.02%	3.83
5	Germany	37	4.39%	525	6.75%	14.19
6	Switzerland	20	2.38%	269	3.46%	13.45
7	France	20	2.38%	153	1.97%	7.65
8	UK	18	2.14%	172	2.21%	9.56
9	Canada	16	1.90%	256	3.29%	16.00
10	India	13	1.54%	48	0.62%	3.69

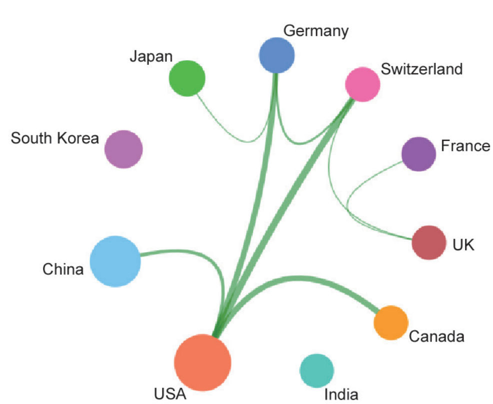

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases”

Table 2.2.4 Institutions with the greatest output of core patents on "development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases"

No.	Institution	Published Patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	U.S. Department of Health and Human Services	19	2.26%	142	1.83%	7.47
2	Academy of Military Medical Sciences PLA	14	1.66%	13	0.17%	0.93
3	Curetis GmbH	14	1.66%	12	0.15%	0.86
4	University of Texas	12	1.43%	111	1.43%	9.25
5	Ares Genetics GmbH	9	1.07%	12	0.15%	1.33
6	Harvard College	8	0.95%	504	6.48%	63.00
7	Institut Pasteur	8	0.95%	88	1.13%	11.00
8	French National Centre for Scientific Research	8	0.95%	45	0.58%	5.63
9	Coyote Bioscience Company	8	0.95%	3	0.04%	0.38
10	Korea Center for Disease Control and Prevention	8	0.95%	1	0.01%	0.13

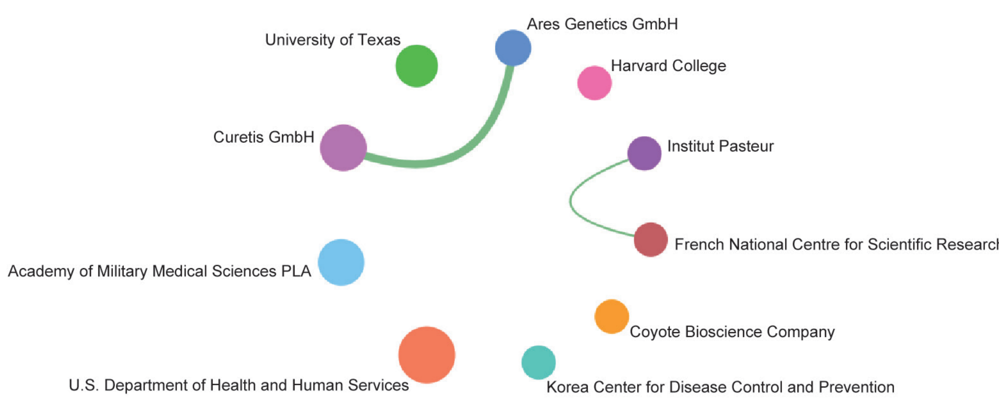

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "development of diagnostic reagents and equipment for major emerging and re-emerging emergency infectious diseases"

the integration of the detection and sensing units. The current hot topics have focused on the following seven aspects.

(1) Intelligent biomaterials. Studies are focused on the development of controllable functionalized biomaterials, such as patterned surfaces for cellular orientation induction, selective-permeable membranes for liquid ion exchange, biomimetic vessels, and 3D bio-scaffolds to improve the bio-functions by adjusting the composition of materials, the structure of substrates, and other parameters.

(2) Interaction between substrates and cultured cell clusters. The research aims to determine the impact of material properties, such as rigidity and viscoelasticity on cell adhesion, migration, and proliferation, as well as the impact of material structural properties, such as microstructures, nanopatterns, and dynamic variations on cell growth, migration, and stem cell differentiation. The further stages aim to develop the most suitable biomaterials that match each organoid for regenerating organ capabilities and to construct organ-chips that include heart-on-chips, liver-on-chips, lung-on-chips, kidney-on-chips, bladder-on-chips, intestine-on-chips, pancreas islet-on-chips, amnion cavity-on-chips, and skin-on-chips.

(3) Construction of cell co-culture systems. Multi-structured organoids-on-a-chip, such as chips with multi-layer structures, tube-shape networks, loop structures, or multi-regions, are

required to develop cell co-culture systems. Studies on the interaction of each type of cells and tissues are combined with microfluidic chips for simulating *in vivo* tissue structure and fluid circulation. By controlling signal interactions between cells and between cells and scaffolds, these devices could achieve organ functions and cooperation *in vitro*. The research aims to construct organ co-culture systems combining heart, liver, lung, and kidney, and vessel-related co-culture systems with cancer cells, vascular endothelial cells, and fibroblasts.

(4) Organoid real-time monitoring. The research aims to develop biomaterials with signal transformation capability to act as integrated sensing and imaging units in organoids-on-chips. The further stages aim to detect and analyze real-time cell state inside chips based on electric or optical signals of sensing elements, which are corresponding signal-transforming units of electric, electrochemical and optical materials designed for different physiological characteristics of various organ cells. Utilizing multi-structure chips, the driving systems and auxiliary devices are connected onto the chips to attain liquid cycling inside the chip and allow for dynamic cell monitoring.

(5) Internal micro-environmental regulation. This involves the use of organoids-on-chips with oxygen concentration controllability to simulate the oxygen environment in different organs *in vivo*. The differences in morphology and function of cells from the placenta, lung, heart, and other organs could be observed and studied under different oxygen conditions. Integrating functional biomaterials, sensors, and imaging units within the microfluidic chips can allow for the real-time monitoring of the biomarkers and metabolites of cells during each biochemical stage, and this technology will allow researchers to determine the dynamic distribution of pH, oxyhemoglobin saturation, and other factors inside the chip.

(6) Connection and cooperation of multiple organoids-on-chips. This requires the formulation of strategies for culturing different cells with different growth conditions on the same microfluidic chip. The research aims to construct microfluidic chips with multi-cavity or multi-layer structures, design microchannels to simulate circulatory system and explore integration ways of different organoids-on-chips. This will allow researchers to investigate the functional integration of multi-organoids-on-chips, the interaction among different cells, simulate the signal conduction in organoids, and integrate and cooperate organ functions within a single chip.

(7) Drug screening, toxicity classification, and mold establishement. This would require combining analysis techniques and real-time monitoring techniques for organ feature extraction to investigate cellular bio-information and resistance law under drug condition and further construct drug evaluation system based on human organoids-on-chips. Based on the typical cellular physiological reactions to the presence of compounds, this approach would enable toxicity screening and poison classification via electrochemical, optical, bioinformatics, and other analytical methods. Utilizing cells with differentiation potential, this technology could be used to simulate organ formation, growth, and maturity, and thus construct original organoid developmental models. The pathological organ model and drug evaluation model could be developed by developing channel networks and fluid circulation, and further investigating the reaction and interaction between organoid cells and additives such as nanoparticles, surfactants, and pharmaceuticals in circulating fluid chips.

Although research focused on organoids-on-a-chip is still in its initial stages, it has been highly valued due to its vast potential and development prospects. In respect to the status, western research institutes and biotechnology companies are promoting the development of related technologies, and they have already dominated some essential technological patents. As a trend of constructing new drug evaluation systems, organoids-on-a-chip possesses great strategic significance for supporting national innovative drug research and translational medical development. Over the recent years, the share of international patents for human organoids-on-a-chip from China has been gradually rising, which reflects the progress in related research. Whereas, it still exist challenges to meet the requirements, such as human physiological chip-systems construction, multi-organ functional association and synergy, chips standardization and sensing-detection integration.

Core patents have been applied for human organoids-on-a-chip. The United States, China, Germany, the Netherlands, and Japan are ranked as the top five countries with the most patents (Table 2.2.5). As shown in the cooperation network of patent-producing countries (Figure 2.2.5), China, the United States, and Singapore cooperate most closely.

The top three institutions with the most inventors of the core patents in force are Harvard University, the Graduate School at Shenzhen of Tsinghua University, and Emulate Inc. (Table 2.2.6). Additionally, the collaboration network among international institutions reveals cooperation between Harvard University and Vanderbilt University and among TissUse GmbH, Tesyus Inc., and University of Berlin (Figure 2.2.6).

Table 2.2.5 Countries with the greatest output of core patents on "human organoids-on-a-chip technology"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	42	38.89%	343	74.08%	8.17
2	China	40	37.04%	35	7.56%	0.88
3	Germany	6	5.56%	75	16.20%	12.50
4	Netherlands	6	5.56%	4	0.86%	0.67
5	Japan	5	4.63%	5	1.08%	1.00
6	South Korea	4	3.70%	0	0.00%	0.00
7	UK	2	1.85%	0	0.00%	0.00
8	Singapore	2	1.85%	0	0.00%	0.00
9	Russia	1	0.93%	1	0.22%	1.00
10	Switzerland	1	0.93%	0	0.00%	0.00

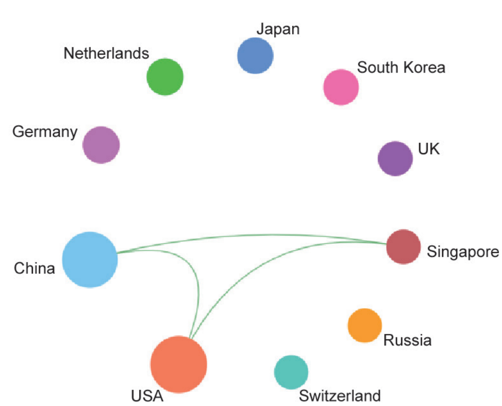

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "human organoids-on-a-chip technology"

Table 2.2.6 Institutions with the greatest output of core patents on "human organoids-on-a-chip technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citation per patent
1	Harvard University	15	13.89%	279	60.26%	18.60
2	Graduate School at Shenzhen, Tsinghua University	5	4.63%	20	4.32%	4.00
3	Emulate Inc.	5	4.63%	17	3.67%	3.40
4	TissUse GmbH	4	3.70%	73	15.77%	18.25
5	Massachusetts Institute of Technology	4	3.70%	0	0.00%	0.00
6	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	3	2.78%	2	0.43%	0.67
7	BGI Shenzhen	3	2.78%	0	0.00%	0.00
8	Vanderbilt University	2	1.85%	110	23.76%	55.00
9	Tesyus Inc.	2	1.85%	58	12.53%	29.00
10	University of Berlin	2	1.85%	9	1.94%	4.50

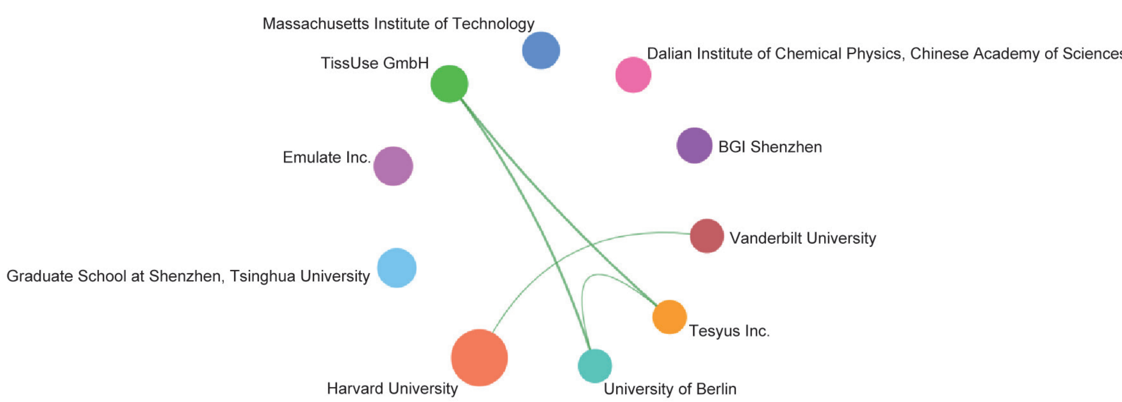

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "human organoids-on-a-chip technology"

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IX. Engineering Management

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

In the field of engineering management, this year's top 10 global engineering research fronts are "medical material supply and allocation under magnitude outburst public health incident," "supply chain resilience," "social responsibility for major projects," "urban flood risk management under extreme rainfall conditions in the future," "cooperative driving control and management," "project management based on blockchain," "industrial intelligence based on big data," "cascading failure simulation of urban lifeline system and toughness coupling analysis technology," "electric vehicle charging infrastructure layout and optimization," and "simulation optimization under artificial intelligence background". The core papers are shown in Tables 1.1.1 and 1.1.2. Among them, "medical material supply and allocation under magnitude outburst public health incident," "supply chain resilience," and "social responsibility for major projects" will be interpreted with emphasis, and the current development status and future trends will be interpreted in detail later.

(1) Medical material supply and allocation under magnitude outburst public health incident

Medical materials refer to the general term of materials provided by the society to the health department and the public in order to provide medical services under certain social and economic conditions. The key medical materials in dealing with magnitude outburst public health incidents include: 1) medical protective materials, such as masks and protective clothing; 2) medical drugs; 3) medical treatment equipment, such as respirators. The supply and allocation of medical materials refers to the reserve, procurement, donation, and shift and expanded production of medical materials in a planned way, accurately matching supply and demand, and distributing medical materials fairly and efficiently based on scientific demand forecast of medical materials. In response to magnitude outburst public health incidents such as SARS, Ebola virus, and COVID-19 pandemic, the demand for medical materials has surged, and it is time-sensitive and irreplaceable, which brings great challenges to the supply and allocation of medical materials. In response

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	Medical material supply and allocation under magnitude outburst public health incident	10	133	13.30	2016.6
2	Supply chain resilience	33	963	29.18	2017.6
3	Social responsibility for major projects	34	643	18.91	2017.4
4	Urban flood risk management under extreme rainfall conditions in the future	10	1 146	114.60	2016.7
5	Cooperative driving control and management	44	1 265	28.75	2016.9
6	Project management based on blockchain	27	2 835	105.00	2018.1
7	Industrial intelligence based on big data	52	5 322	102.34	2017.6
8	Cascading failure simulation of urban lifeline system and toughness coupling analysis technology	17	120	7.06	2016.6
9	Electric vehicle charging infrastructure layout and optimization	51	3 089	60.56	2017.1
10	Simulation optimization under artificial intelligence background	17	195	11.47	2017.5

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

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Medical material supply and allocation under magnitude outburst public health incident	1	0	5	2	0	2
2	Supply chain resilience	2	0	4	6	11	10
3	Social responsibility for major projects	0	3	4	11	9	7
4	Urban flood risk management under extreme rainfall conditions in the future	1	0	2	5	2	0
5	Cooperative driving control and management	4	2	9	13	10	6
6	Project management based on blockchain	0	0	3	3	9	12
7	Industrial intelligence based on big data	0	0	7	16	21	8
8	Cascading failure simulation of urban lifeline system and toughness coupling analysis technology	3	1	6	0	4	3
9	Electric vehicle charging infrastructure layout and optimization	5	4	9	6	15	12
10	Simulation optimization under artificial intelligence background	1	1	1	3	7	4

to the COVID-19 epidemic, many countries have experienced "shortage of medical materials." Therefore, the United Nations initiated an initiative to guarantee the supply of medical materials, the European Commission decided to build a shared strategic inventory of medical equipment, and the United States launched the *Defense Production Act* (DPA). Medical material support directly affects the overall situation of dealing with magnitude outburst public health incident. Key scientific issues, such as accurate prediction of medical material demand, supply mode according to local conditions, matching between supply and demand, and fair and efficient distribution mechanism, are the international frontier topics and hotspots of emergency management, psychology and industrial engineering.

(2) Supply chain resilience

In the current political, economic, and natural environment, the supply chain is facing more and more sudden risks, such as terrorism, economic blockade, earthquakes, and hurricanes. These risks can easily lead to the interruption of the supply chain and affect the continuous operation of projects or enterprises. Different from traditional supply chain risks, it is difficult for us to predict the occurrence probability and impact of unexpected risks in advance through statistical data. Many unexpected risks are even "unknowns," so the traditional risk management framework of "risk identification—risk evaluation—risk response—risk monitoring" is difficult to adapt to sudden risks. In this context, a resilient supply chain has become an important tool to deal with sudden risks, which makes the research on supply chain resilience increasingly important. Supply chain resilience emphasizes the ability to return to its original state or a more ideal state after being disturbed by sudden risks. In the existing research on supply chain resilience, key scientific issues, for example how to effectively measure and evaluate supply chain resilience, and how to improve supply chain resilience, are the research hotspots of civil engineering and industrial engineering. At the same time, the endogenous decision-making problem of supply chain resilience, the choice of strategies for improving supply chain resilience, and the research on supply chain resilience in specific situations (such as infrastructure operation or aerospace and other specific engineering situations) are possible research directions in the future.

(3) Social responsibility for major projects

Major infrastructure projects (referred to as major projects) are large-scale public projects that have an important impact on national politics, economy, society, scientific and technological development, environmental protection, public health, national security, etc. They have huge investment scale, long implementation period, complex uncertain factors, numerous stakeholders, and far-reaching impact on the ecological environment. With the openness of major projects, diversification of subjects, and the complexity of projects caused by the application of new technologies, the social responsibility management of major projects is facing unprecedented challenges, mainly including the lack of social responsibility of participating subjects, weak awareness of ecological and environmental protection in project construction, and imperfect health and safety system of construction workers. Social responsibility for major projects refers to the social responsibility undertaken by various stakeholders for the impact of their decisions and activities on society and environment in different stages of the whole life cycle of projects, such as planning, design, construction, and operation. At present, the academic circles have made fruitful explorations, but there is still a lack of systematic research. The strategic management system with the sustainability of major projects as the goal and social responsibility as the important support has not yet been established, which is difficult to provide theoretical support and practical guidance for the management practice of major projects. Especially facing the new trend of internationalization of major projects, under the background of political, economic, regulatory, and cultural differences, the conflicts of demands of different stakeholders will also lead to a series of brand-new topics in the research on the management theory and governance system of social responsibility for major projects. It can be seen that the key scientific issues such as the theory, method and modernization of governance system, and governance capacity of social responsibility for major projects will become research hotspots in this field.

(4) Urban flood risk management under extreme rainfall conditions in the future

Urban flood refers to the phenomenon that urban areas are flooded and waterlogged due to heavy rain, torrential rain, or continuous rainfall, and its risk is generally measured by the probability of urban flood and its consequences, such as casualties, infrastructure damage, and environmental damage. Climate change leads to the increase of global temperature and extreme precipitation. Urban expansion increases the impervious area of the region, significantly changes the urban water cycle process, and leads to the increase of surface runoff coefficient and frequent urban floods. Meanwhile, cities are densely populated areas with concentrated productivity and wealth, which can easily cause heavy casualties and property losses. In addition, since the city is a complex open system, flood disasters will have a chain reaction within and between systems, which is more likely to induce secondary and derivative disasters and form a disaster chain, thus further expanding the potential risks of urban flood disasters. Facing the extreme rainfall trend in the future, many countries put forward the urban flood prevention and control system and risk management system according to local conditions, so as to alleviate the negative impact of urban floods on people's life safety, property, social order, and economy. How to assess urban flood risk under extreme rainfall conditions in the future and improve urban flood prevention and control ability has become a key scientific problem to be solved urgently at home and abroad. With the development of big data and artificial intelligence technology, the integration paradigm of "data-driven" and "model-driven" provides a new idea and technical basis for revealing the mechanism of urban flood disaster, developing the real-time monitoring and early warning and forecasting technology of urban flood based on multi-source data fusion, researching and developing the whole scene simulation platform of urban flood risk, and constructing the coordinated comprehensive prevention and control system of flood control project scheduling and social disaster reduction.

(5) Cooperative driving control and management

Cooperative driving refers to coordinating the trajectory and motion control of multiple vehicles with the support of internet of vehicles and automatic driving technology, so as to make the vehicles run more smoothly and quickly, improve traffic safety and efficiency, and reduce travel time, energy consumption, and pollution. Compared with the traditional traffic control strategies, such as traffic congestion vehicle guidance, traffic congestion pricing, and traffic signal control, cooperative driving deals with the problems of overall traffic management and local vehicle control together, and is thus considered as the fundamental solution to the ground traffic problem. In recent years, new advances in artificial intelligence, big data, and intelligent network connection have provided feasible technical support and research means for in-depth study of cooperative driving. These technologies have greatly changed the means, content, and scope of information acquisition and interaction among traffic participants, vehicles, and road infrastructure, which will promote the whole-process collaborative planning and comprehensive collaborative control of traffic, and then lead to deep changes in traffic safety guarantee, road intelligent management, and efficient travel services, making traffic safer and travel smoother. At present, the key issues of cooperative driving research are collection and fusion of dynamic traffic information in full time and space, collaborative safety and active control of vehicles, cooperative driving under mixed driving of people and vehicles, integration and collaboration of intelligent traffic management and services under panoramic traffic information environment, etc. Studying cooperative driving can greatly improve the perception and decision-making ability of unmanned vehicles, and at the same time, it will provide application scenarios for high-tech such as 5G communication and cloud computing, and provide theoretical basis and decision support for further upgrading and development of transportation systems.

(6) Project management based on blockchain

All kinds of projects, including infrastructure construction, aerospace, water conservancy and water transport, and energy development, have jointly promoted China's economic and social development and played an important role in enhancing China's comprehensive strength and improving people's livelihood. Engineering projects usually have the characteristics of large amount of investment, long project cycle, and many participants. The complex cooperation relationship and low level of mutual trust in the project will easily lead to the inconsistency of objectives among participants, weaken productivity, even breed crimes, and hinder the realization of project management objectives. Building trust relationship has become the key to improve project performance and achieve management objectives. Blockchain technology has the characteristics of information tamper-proof, traceability, openness and transparency, automatic execution, etc. It has the potential to change the interaction mode within the organization of engineering projects, and provides the possibility to create a cooperative environment of mutual trust. It has become an important content of strategic information infrastructure in many countries.

Blockchain technology helps to clarify the responsibilities and rights of all participants in the project, reduce the fluke mind and speculative behavior, and promote deep cooperation. The integration of intelligent contract can realize the automation of various businesses including project supply chain collaboration, project data protection, project digital asset transfer, project insurance, project payment, and project human resources and performance appraisal, thus simplifying management logic and reducing management costs. At present, the research on blockchain in the field of engineering management is booming, but it is still in its infancy, lacking empirical exploration, and its potential in engineering bidding, engineering design, engineering implementation, engineering operation and maintenance, engineering supply chain and other aspects is worth studying. In addition, the exploration and verification of the integration of blockchain technology with communication network infrastructure such as 5G, Internet of Things, and Industrial Internet, new technology infrastructure such as artificial intelligence and cloud computing, and computing power infrastructure such as data center and intelligent computing center will help the project management shift to high standard, high efficiency, and high quality paradigm.

(7) Industrial intelligence based on big data

Industrial intelligence is to bring together industry technology, control technology and information technology, so that the process of dynamic operation, management, and service of production has the intelligent ability of perception, memory, learning, self-adaptation, and self-decision similar to human beings. Data is not only the storage form of information in industrial process, but also the carrier of decision and control orders. In recent years, with the improvement of information technology, big data processing technologies, such as data collection, data storage, data analysis and data visualization, have been continuously improved. Therefore, industrial big data can be better collected, sorted, and analyzed, and can better serve industrial management decision-making, operation optimization, and process control. Industrial intelligence based on big data means to realize the intelligent ability of self-perception, self-learning, self-adaptation, and self-decision of industrial process by means of big data processing based on industrial process data such as data parsing, blockchain, and cloud platform. Its main contents include industrial process intelligent perception under the Internet of Things environment, industrial big data storage and management based on cloud platform, industrial big data statistics and analysis, and whole process collaborative optimization and control. In the past decade, the blueprint for industrial intelligence development including Germany's "Industry 4.0" has been widely valued by governments and industries in various countries. With the continuous improvement of big data technology, how to realize the continuous improvement of industrial intelligence level by combining the production environment of different industries, the customization requirements of technological processes, and the stable and efficient means of big data storage and analysis will become the frontier research focus of academia and industry.

(8) Cascading failure simulation of urban lifeline system and toughness coupling analysis technology

Lifeline engineering system refers to the basic engineering system that maintains modern city functions and regional economy, including transportation, water supply, power supply, gas supply, and communication systems. Compared with a single building or bridge structure, lifeline engineering as a system has the characteristics of extensive spatial distribution, complex structural composition, and complex coupling between systems. In recent ten years, the global urbanization process has led to the rapid expansion of city scale, and the complexity and coupling relationship of urban lifeline system have been significantly enhanced, which makes the resilience quantitative model of lifeline system, especially the simulation model of cascading failure and coupling recovery between lifeline systems under different disaster conditions and its efficient algorithm, become a hot issue in current research. On this basis, the resilience quantitative model of urban built environment including lifeline system has been derived, and its practical exploration in different fields such as urban design, planning, reconstruction, and disaster management has been carried out. One of the visible research frontiers in this field in the future is intelligent orientation, that is, by means of advanced technologies in computer communication fields such as artificial intelligence, big data, and 5G network, an efficient and accurate analysis method and intelligent management mode of urban lifeline system toughness are developed. In addition, because the city itself is an ecosystem with highly complex characteristics, it is an inevitable trend to cross-integrate lifeline resilience research with urban social, economic, and environmental disciplines, and it is expected to further promote the development of multi-dimensional (physical, environmental, social, economic, organizational, etc.), multi-scale (streets, districts, cities, urban agglomerations, etc.), and multi-stage (before, during, and after disasters) comprehensive resilience simulation technology, so that the influence of comprehensive quantification, analysis, and management of disasters on the urban built environment, human settlements, social function, regional economy, and even globalization becomes possible.

(9) Electric vehicle charging infrastructure layout and optimization

Charging infrastructure refers to all kinds of charging and replacing facilities that supply electric energy for electric vehicles, including power infrastructure as well as control and communication infrastructure. According to the characteristics of service objects, it can be divided into charging infrastructure in public service field, user's residence and unit charging infrastructure, urban public charging network, and intercity fast charging network. With the rapid development of electric vehicle industry, the planning and construction of charging facilities have entered a large-scale and networked era. How to scientifically and systematically optimize the layout of charging infrastructure is particularly important. A perfect charging infrastructure system is an important guarantee for the popularization of electric vehicles, the rational allocation of power resources, and the reduction of greenhouse gas emissions. Technical characteristics of electric vehicles, behavior characteristics of service objects, different business models, and electricity price, and load of power grid will directly affect the layout and optimization decision of charging infrastructure. In addition, emerging technologies, including wireless power transmission, connected mobility, autonomous driving, sharing mode and energy internet, will bring technical changes to future electric vehicle applications. Electric vehicles, can be used not only as transportation tools, but also as a node of power loads (G2V), distributed energy storage (V2G) of power grids, energy storage (V2B) of buildings, and network communication. Optimization issues such as location and scale layout of charging infrastructure, timing of investment and construction, charging and discharging scheduling of electric vehicles, integration of charging facilities and smart grid, and construction of intelligent charging service platform are the international frontier research hotspots of urban planning, traffic engineering, management science, and electrical engineering.

(10) Simulation optimization under artificial intelligence background

Artificial intelligence is a technical science that studies how to simulate and extend human intelligence through computers, including key technologies such as machine learning and system simulation. In recent years, machine learning technology has been widely used in society, such as driverless cars and product recommendation of shopping software. System simulation describes the operation, evolution, and development process of the system through simulation model, which is one of the key technologies of artificial intelligence. Under the background of Industry 4.0, more and more intelligent systems have applied machine learning technology, which puts forward higher requirements for system simulation. In developing the corresponding simulation model, it is necessary not only to integrate the machine learning module, but also to spend more energy to calibrate and optimize the complex simulation model. On one hand, researchers can not only apply simulation data to neural network training, but also directly apply simulation models to deep reinforcement learning, thus improving the accuracy of machine learning technology; on the other hand, machine learning and intelligent sampling methods can speed up the calibration and optimization of simulation models. Under the background of the rise of digital twins, how to improve the simulation efficiency of high-fidelity simulation model by using machine learning method has become an international research hotspot. The main research directions include studying the simulation optimization theory and method aiming at improving the quality of machine learning algorithms, exploring how to improve the accuracy and operational efficiency of the simulation model by machine learning, and realizing the real-time optimization decision of digital twin model by using offline simulation, real-time simulation, and machine learning methods.

1.2 Interpretations for three key engineering research fronts

1.2.1 Medical material supply and allocation under magnitude outburst public health incident

In economics, “supply” refers to the products and quantities that producers will and can supply at a given price within a specific time. “Allocation” refers to allocating an appropriate amount of materials to the appropriate demanders according to the demand information. In 1979, Professor Ilhan and Professor Pierskalla of Turkey first studied the blood supply and allocation between major hospitals. Subsequently, they studied the disaster types that the medical materials were supplied and allocated to, including earthquakes, hurricanes, and SARS, aiming to meet the demand for medical materials. The supply and allocation of medical materials are the core and key to improve the level and ability to deal with magnitude outburst public health incident, and they are also the premises to further improve the national emergency management system and realize the modernization of the national governance system and governance capacity.

The following part is a more in-depth analysis of the demand forecast, supply mode, supply-demand matching, and allocation mode of medical materials; and the development trend of medical materials supply and allocation is prospected.

(1) Demand forecast of medical materials

Demand forecast of medical materials refers to the forecasting of the demand of certain medical materials by collecting and analyzing relevant data and selecting appropriate forecasting methods in order to identify the quantity of materials needed by medical institutions and the public in providing or receiving medical and health services. Accurate demand forecast of medical material is the basis of good medical material supply and allocation. Generally, the demand forecast of medical materials aims at identifying the demand of inpatient or outpatient service. Moving average and linear regression methods are usually used to forecast the daily demand of medical resources such as beds, medical staff, and blood in medical institutions, and the demand fluctuation is often small. However, for the epidemic situation of major infectious diseases, the demand for medical supplies such as protective equipment and first aid equipment is determined by the severity of the epidemic situation, and the demand will fluctuate with the development of the epidemic situation. Under the background of COVID-19 epidemic, the demand forecast of medical material considering the evolution of epidemic situation is the mainstream of research. Scholars have put forward various forecasting indexes and corresponding forecasting methods. The research hotspots of medical material demand forecast mainly include the demand forecast of medical material considering the coupling relationship between medical material supply and epidemic evolution, and based on the correlation of epidemic transmission among regions.

(2) Supply mode of medical materials

Under the magnitude outburst public health incident, the government-led diversified supply mode of medical materials has achieved remarkable results in the prevention and control of COVID-19 epidemic in China, including four major supply modes of reserve, social donation, market procurement, and shift and expanded production. Shift and expanded production of medical materials means that the government encourages and guides social enterprises to switch to and expand the production of medical materials through mobilization mechanism, and uniformly allocates the materials to meet the needs of medical institutions and the public for medical materials. Shift and expanded production is the guarantee of medical material supply in the prevention and control of COVID-19 epidemic in China, which was also adopted by other countries like the United States and Canada. For example, Ford, General Motors, and Tesla in the United States switched to the production of respirators, Canadian beer giant Labatt switched to produce disinfectant, and Canada Goose switched to produce protective clothing urgently needed by front-line medical staff. In order to support the shift and expanded production of medical materials, the corresponding countries have given a series of policies, such as providing venues and financial support, reducing taxes or providing subsidies. In the case of dynamic evolution of epidemic situation, the capacity design of shift and expanded production of medical materials should be dynamically optimized in multiple stages. In the supply mode of medical materials, the research hotspots of capacity design mainly include mobilization mechanism of shift and expanded production of medical materials, evolutionary game model between medical institutions and the public, enterprises for shift and expanded production and government, and dynamic optimization mechanism of medical material price control, tax incentives, and financial subsidies under the evolution of epidemic situation.

(3) Supply and demand matching of medical materials

For the supply of medical materials donated by the society, the key is to effectively match the information of supply and demand of medical materials and solve the problem of information asymmetry between supply and demand sides. Social donation is a voluntary donation made by the people or units in order to rescue disasters, relieve poverty, help the disabled and other difficult social groups and individuals, support scientific, educational, cultural, and health undertakings, and environmental protection, and build social public facilities. Internet platform has become the main carrier of matching supply and demand of social donated medical materials. Under the Internet platform, the core of matching the supply and demand of social donated medical materials is to realize the identification and automatic matching of supply and demand information by using information processing technology. Social media, as the medium of post-disaster supply and demand information release, is the source of post-disaster supply and demand information data. Many scholars consider material types and geographical factors, and use relevant information processing methods to study the effective matching of social donation materials information and demand information on social media. The research hotspots of medical material supply and demand matching mainly include the design of medical material supply and demand matching index under the Internet platform, the establishment of dynamic interactive model of medical material supply and demand matching under uncertain conditions, and the development of data processing technology for obtaining and matching medical material supply and demand information.

(4) Allocation mode of medical materials

The allocation mode of medical materials refers to the allocation strategy and scheme of medical materials. In the response to magnitude outburst public health incidents, the allocation of medical resources is often coupled with the ability of medical treatment and the evolution of events. On one hand, the allocation of medical materials will affect the ability of receiving and treating and the efficiency of treatment, and then affect the evolution of the whole epidemic situation; on the other hand, the evolution of the epidemic situation will in turn affect the strategies and schemes for the distribution of scarce materials. Current research discusses the coupling relationship between medical materials and the spread and evolution of infectious diseases from different angles. In the process of dealing with large-scale infectious diseases, graded treatment is the key measure to avoid the spread of diseases and to facilitate the rational allocation of scarce materials. Current research mainly focuses on the grading criteria for individual patients and the principle of providing them with scarce medical resources, mainly considering the principle of fairness and the goal of minimizing casualty rate. From the level of scientific research and medical practice, the medical community has explored the guiding principle of grading patients according to the use of some specific key medical equipment from a more detailed level, so as to improve the survival rate when a large-scale epidemic occurs. The research hotspots of medical material allocation mode mainly include the mutual influence law between medical material allocation and epidemic evolution, and the dynamic allocation mechanism of medical materials under the graded treatment mode.

(5) Development status and future development trend

The United States Naval Medical Research Unit has studied the algorithms for effectively predicting the types, quantities, and configurations of medical materials, and developed the Estimating Supplies Program to improve the supply and management level of medical materials. In response to the COVID-19 outbreak, the World Health Organization has set up a working group to implement the United Nations initiative to ensure the supply of medical materials, and plans to establish a global material supply platform to accept applications for material supply from countries in need, purchase materials centrally, and distribute materials according to the urgency of demand. In 2020, the National Natural Science Foundation of China launched the special project "Response, Governance, and Impact of Public Health Events such as COVID-19 pandemic," in which the mode of medical resources supply and allocation under magnitude outburst public health incidents is the key funding direction. Based on the current research status, the future development trends mainly include modeling and verification of the coupling law between medical material supply, allocation, and epidemic evolution, combination optimization among different medical material supply modes under the dynamic evolution of epidemic situation, and optimization of medical material allocation under the Internet environment.

Two countries with the most core papers in the engineering research front of "medical material supply and allocation under magnitude outburst public health incident" are China and the United States (Table 1.2.1). China mainly focuses on impact assessment of public health events and the risk management of the allocation of emergency materials, while the United States focuses on the distribution of the last kilometer of emergency supplies. The number of documents in Germany, Brazil, India, and the United Kingdom is equal, studying the allocation of emergency and non-emergency medical service resources, the emergency supply of medical personnel, the matching of supply and demand of medical resources based on multimedia information mining, and demand prediction and analysis of medical resources, respectively. There is no cooperative relationship between these countries.

Beijing Normal University ranks first in the number of core papers, which mainly studies the risk prediction of contamination in material transportation. Other institutions have the same number of core papers (Table 1.2.2). According to the cooperation network diagram of core paper producing institutions (Figure 1.2.1), among the top 10 institutions in the number of core papers publishment, University of Sao Paulo, Universidade Federal Fluminense, Brazilian Ministry of Health, and Inter-Union Department of Statistics and Socio-Economic Studies (DIEESE) have more cooperation.

According to Table 1.2.3, China ranks first in citing core paper. According to Table 1.2.4, the top institutions are North China Electric Power University, Chinese Academy of Science, Wright State University, and Beijing Normal University .

1.2.2 Supply chain resilience

The concept of "supply chain resilience" was first proposed by Professor Rice and Professor Caniato in 2003, but its definition was first proposed by Professor Christopher and Professor Peck in 2004, who defined supply chain resilience as "the ability of the supply chain to return to its original state or a more ideal state after being disturbed." As scholars realize that resilient supply chain is an important tool to deal with sudden risks, the research on supply chain resilience has gradually increased. The following part mainly analyzes the theoretical research perspective, research methods, hot research issues, measurement and evaluation, and improvement of supply chain resilience.

(1) The theoretical research perspective of supply chain resilience

In the study of supply chain resilience, scholars have adopted more than 20 kinds of theories, including macro theory, meso theory, and micro theory. Among these theories, the most commonly used theories are resource-based view, dynamic capability theory, relationship theory, and system theory/complex adaptive system theory, among which resource-based view is the most basic and core theory. The resource-based view of the firm regards enterprise as a collection of a series of resources. The ability and competitive advantage of enterprises originate from the valuable, scarce, unrepeatable, and irreplaceable resources owned by enterprises. Under the complex and changeable environmental disturbance, enterprises need to continuously integrate, construct, and reconfigure internal and external resources, so as to enhance the supply chain resilience. However, because the resource-

Table 1.2.1 Countries with the greatest output of core papers on “medical material supply and allocation under magnitude outburst public health incident”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	3	30%	56	18.67	2016.0
2	USA	3	30%	37	12.33	2015.7
3	Germany	1	10%	20	20.00	2017.0
4	Brazil	1	10%	14	14.00	2016.0
5	India	1	10%	4	4.00	2019.0
6	UK	1	10%	2	2.00	2019.0

Table 1.2.2 Institutions with the greatest output of core papers on “medical material supply and allocation under magnitude outburst public health incident”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Beijing Normal University	2	20%	50	25	2016
2	Wright State University	1	10%	29	29	2014
3	Charite	1	10%	20	20	2017
4	DIEESE	1	10%	14	14	2016
5	Brazilian Ministry of Health	1	10%	14	14	2016
6	Universidade Federal Fluminense	1	10%	14	14	2016
7	University of Sao Paulo	1	10%	14	14	2016
8	Xi’an Jiaotong University	1	10%	6	6	2016
9	U.S. Department of Health and Human Services	1	10%	4	4	2016
10	Emory University Hospital	1	10%	4	4	2016

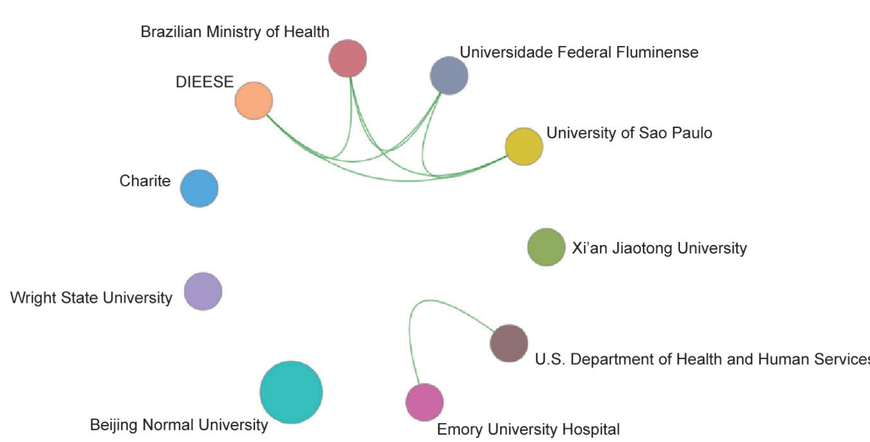

Figure 1.2.1 Collaboration network among major institutions in the engineering research front of “medical material supply and allocation under magnitude outburst public health incident”

based view is static in nature, ignoring the influence of market dynamics, scholars have adopted dynamic capability theory and relationship theory to expand the resource-based view under the dynamic environment. In addition, some scholars believe that the supply chain is a complex system, and that resilience is an inherent feature of the system, so they adopted

Table 1.2.3 Countries with the greatest output of citing papers on "research on medical material supply and allocation under magnitude outburst public health incident"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	39	27.27%	2018.3
2	USA	32	22.38%	2018.3
3	Germany	23	16.08%	2017.9
4	Brazil	16	11.19%	2018.4
5	Australia	9	6.29%	2018.7
6	Canada	6	4.20%	2019.0
7	UK	5	3.50%	2018.8
8	Iran	4	2.80%	2018.5
9	Belgium	3	2.10%	2017.0
10	India	3	2.10%	2018.7

Table 1.2.4 Institutions with the greatest output of citing papers on "research on medical material supply and allocation under magnitude outburst public health incident"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	North China Electric Power University	7	14.58%	2018.3
2	Chinese Academy of Sciences	6	12.50%	2017.8
3	Wright State University	5	10.42%	2016.8
4	Beijing Normal University	5	10.42%	2017.8
5	Tianjin University	4	8.33%	2017.8
6	University of Tehran	4	8.33%	2018.5
7	Wuhan University	4	8.33%	2019.5
8	Charite- Medical University of Berlin	4	8.33%	2018.5
9	China Institute of Water Resources and Hydropower Research	3	6.25%	2019.0
10	Pan American Health Organization	3	6.25%	2018.7

system theory/complex adaptive system theory to study the supply chain resilience.

(2) Research methods of supply chain resilience

The research methods of supply chain resilience can be divided into qualitative research methods and quantitative research methods. Among them, qualitative research methods are mainly case studies, while quantitative research methods mainly include optimization, decision analysis, network modeling, and simulation. Optimization is the most frequently used quantitative research method, including multi-objective linear programming, stochastic programming, and objective programming. The main methods used in decision analysis are multi-objective decision analysis, analytic hierarchy process, and network analysis. The methods of network modeling include Bayesian network, graphic modeling, and clustering supply chain network model. The simulation methods include agent-based simulation and discrete event simulation.

(3) Hot research issues of supply chain resilience

When the supply chain resilience was put forward in the early days, scholars paid more attention to the definition and connotation of supply chain resilience. With the deepening of research, scholars focus on the measurement and evaluation of supply chain resilience, and the improvement of supply chain resilience.

(4) Measurement and evaluation of supply chain resilience

Although scholars have different definitions of supply chain resilience, they have a strong consensus on the connotation and essence of supply chain resilience, that is, they think that supply chain resilience refers to the ability to return to the original state or a more ideal state after being disturbed, but scholars use different methods to measure and evaluate the supply chain resilience. At present, the existing methods for measuring and evaluating supply chain resilience can be divided into four categories. 1) Measuring the resilience with core elements. The supply chain resilience is decomposed into several core elements, and these core elements are scored by questionnaire. The most common core elements include flexibility, redundancy, and agility. 2) Using direct quantitative indicators to measure the resilience. The quantitative indicators used in this kind of method include the time required for the supply chain to return to its original or more ideal state after being disturbed, the degree of recovery, and the degree of loss of supply chain performance during the recovery period. 3) Measuring the resilience with specific quantitative indicators of supply chain performance evaluation. Scholars use one or more supply chain performance evaluation indicators, such as customer service level and order satisfaction rate, and evaluate the resilience through simulation and other methods. 4) Using topological index to measure the resilience. This kind of indicators mainly measure resilience from the perspective of complex networks, and commonly used indicators include density, complexity, node criticality, and average path length.

(5) Improvement of supply chain resilience

The main purpose of studying supply chain resilience is to improve the supply chain resilience and establish a resilient supply chain. Therefore, scholars have given a series of strategies on how to improve the supply chain resilience. These strategies can be divided into two categories: One is the active strategy before interruption and the other is the passive strategy after interruption. The active strategy before interruption refers to the measures that can resist interruption, such as improving the flexibility of product, contract, and procurement to improve the resilience of supply chain before interruption; promoting the information sharing and cooperation of all participants in the supply chain through the integration of supply chain, so as to resist the possibility of interruption; enhancing the supply chain resilience through business diversification and financial services such as insurance in the case of strong financial strength. Passive strategy after interruption refers to the measures that can still maintain certain basic functions and quickly restore normal functions after interruption. The main promotion strategies are response strategies, such as setting up emergency response teams and responding quickly to market demands, and recovery strategies, such as making contingency plans after interruption, building the ability to absorb losses, and considering the improvement of supply chain resilience by optimizing recovery costs.

As an important tool of supply chain risk management, the supply chain resilience has been widely studied by scholars, but there are still some problems to be solved urgently.

First, the endogenous decision-making research of supply chain resilience. Enhancing supply chain resilience plays an important role in dealing with unexpected risks, but it usually comes at the expense of the overall efficiency of the supply chain, that is, a stronger supply chain usually means lower supply chain efficiency. Although scholars have done a lot of research on supply chain resilience, these researches basically assume that supply chain resilience is exogenous, so how to make decisions on the strength of supply chain resilience is the first problem to be solved in future research. Second, the research on the choice of strategies for improving the supply chain resilience. Scholars have put forward many strategies on how to improve supply chain resilience, such as increasing supply chain redundancy and enhancing information sharing among supply chain members. Different strategies or combinations of strategies have different effects on enhancing supply chain resilience. How to choose strategies to improve supply chain resilience is also a problem to be solved in future research. Third, the study of supply chain resilience in specific situations. At present, the research on supply chain resilience is usually aimed at the general supply chain, and the conclusions obtained are difficult to be directly applied to specific situations. How to study supply chain resilience by considering the unique characteristics of a specific situation is also one of the future research directions, such as the research on resilience management of overseas infrastructure construction and operational supply chain.

From the published core papers, the top three countries are Germany, France, and the United States (Table 1.2.5), The research priorities of the three countries are different. Germany and France are more inclined to the expansion and development of quantitative research methods for supply chain resilience, while the United States pays more attention to the study of strategies for improving supply chain resilience, especially the active strategy before the interruption occurs. The top three countries in citations per paper are Russia, Germany, and France (Table 1.2.5). As show in the cooperation network diagram of core paper output countries (Figure 1.2.2), Russia, France, and Germany have more cooperation. The top two institutions in the published core papers are Berlin School of Economics and Law and Russian Academy of Sciences (Table 1.2.6). As show in Cooperation network diagram of major institutions, Berlin School of Economics and Law and Russian Academy of Sciences have more cooperation (Figure 1.2.3).

According to Table 1.2.7, USA ranks first in citing core papers. According to Table 1.2.8, the top institutions are Berlin School of Economics and Law, Saint-Petersburg State University of Information Technologies, Mechanics and Optics (ITMO Universitg), and Royal Melbourne Institute of Technology University .

1.2.3 Research on social responsibility for major projects

Major projects have become the lifeline of national economic and social development, and social responsibility has become an important support for the construction and management of major projects. Social responsibility for major projects involves direct participants (government, project contractors,

Table 1.2.5 Countries with the greatest output of core papers on "supply chain resilience"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Germany	16	48.48%	597	37.31	2017.6
2	France	13	39.39%	477	36.69	2017.7
3	USA	12	36.36%	287	23.92	2017.8
4	Russia	9	27.27%	397	44.11	2017.2
5	UK	5	15.15%	97	19.40	2018.2
6	Netherlands	3	9.09%	54	18.00	2018.0
7	India	2	6.06%	39	19.50	2017.5
8	Australia	2	6.06%	35	17.50	2018.5
9	Poland	2	6.06%	33	16.50	2018.0
10	South Korea	1	3.03%	27	27.00	2016.0

Figure 1.2.2 Collaboration network among major countries in the engineering research front of "supply chain resilience"

Table 1.2.6 Institutions with the greatest output of core papers on "supply chain resilience"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Berlin School of Economics and Law	15	45.45%	563	37.53	2017.6
2	Russian Academy of Sciences	6	18.18%	293	48.83	2016.8
3	Institus Mines-Telecom Atlantique (IMT Atlantique)	4	12.12%	164	41.00	2018.0
4	French National Centre for Scientific Research (CNRS)	4	12.12%	127	31.75	2018.2
5	ITMO University	3	9.09%	111	37.00	2017.3
6	The University of Oklahoma	2	6.06%	48	24.00	2018.0
7	Erasmus University Rotterdam	2	6.06%	45	22.50	2018.0
8	Michigan State University	2	6.06%	39	19.50	2018.0
9	University of Plymouth	2	6.06%	35	17.50	2018.5
10	University of Southern Mississipi	2	6.06%	34	17.00	2019.0

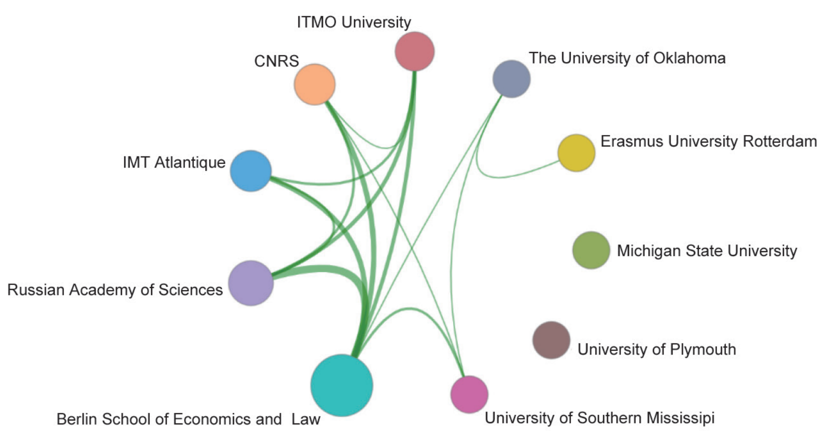

Figure 1.2.3 Collaboration network among major institutions in the engineering research front of "supply chain resilience"

Table 1.2.7 Countries with the greatest output of citing papers on "supply chain resilience"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	77	18.03%	2018.2
2	Germany	59	13.82%	2018.1
3	China	57	13.35%	2018.2
4	France	47	11.01%	2017.9
5	Russia	35	8.20%	2017.6
6	UK	35	8.20%	2018.4
7	Australia	32	7.49%	2018.2
8	India	30	7.03%	2018.5
9	Iran	28	6.56%	2018.1
10	Canada	15	3.51%	2018.4

Table 1.2.8 Institutions with the greatest output of citing papers on "supply chain resilience"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Berlin School of Economics and Law	41	31.78%	2017.9
2	ITMO University	16	12.41%	2016.5
3	Royal Melbourne Institute of Technology University	13	10.08%	2017.8
4	CNRS	11	8.53%	2018.4
5	IMT Atlantique	9	6.98%	2018.3
6	AGH University of Science and Technology	9	6.98%	2017.3
7	University of Tehran	9	6.98%	2018.0
8	University of Kent	7	5.43%	2018.3
9	Russian Academy of Sciences	7	5.43%	2017.1

suppliers, designers, employees, etc.) and other stakeholders (the public, community, non-governmental organizations, etc.), and the implementation of related activities needs to run through the whole life cycle of major projects. Social responsibility for major projects can be summarized as: all stakeholders of major projects take sustainable development as the goal during the whole life cycle of the project, and take responsibility for the impact of their decisions and activities on society and environment through transparent and ethical behaviors.

(1) Social responsibility and internationalization strategy of major projects

Internationalization of major projects has broken through the traditional construction industry, which requires the organic integration of engineering construction, equipment manufacturing, financial services, consulting services, etc. The promotion of its value chain also needs to transform from construction to construction service integration. Based on this, it is necessary for all participants to consider more dimensions of social responsibility for major projects facing internationalization, including more environmentally friendly construction schemes, more inclusive organization methods, and design schemes that are more in line with the cultural regulations of the host country. At the same time, it is necessary for relevant subjects to push forward from the whole process and all directions, such as realizing environmental sustainability through technological innovation, meeting the employment needs of local labor force through organizational innovation, and promoting local economic development through mechanism innovation. The participants shall promote the social responsibility for major projects, adhere to people-oriented, respect local culture and tradition, ensure the safety and quality of projects and the rights and interests of owners, and take the responsibility from multiple dimensions such as supply chain management and fair competition, so as to actively and effectively lay out the internationalization strategy of major projects. The research issues include the path of multi-dimensional heterogeneity of social responsibility for major projects facing internationalization to the dynamic capabilities of participants, impact of innovation of integration mode of construction services for major projects on social responsibility, social responsibility for major projects, and adaptability of internationalization strategy.

(2) Social responsibility governance system for major projects

The internationalization of major projects in the global pattern can no longer take low cost as its competitive advantage, but needs to be promoted through all-round integration of policy guidance, industry promotion, enterprise implementation, and social participation. Social responsibility for major projects has become an important symbol of major project brands. The governance of social responsibility for major projects requires full participation, not only the construction of industry guidelines, but also the active participation of enterprises and information disclosure. The governance system of social responsibility for major projects needs to be promoted from three dimensions of whole subject, omnibearing, and whole process, covering governance principles, governance logic, and governance paradigm. Related research issues include governance subjects of social responsibility for major projects and their mutual relations, principles of social responsibility governance for major projects and elements of governance capacity, evaluation index system and measurement method of social responsibility governance capacity of major projects, the function path of social responsibility governance capacity of major projects to enhance international competitiveness.

Under the background of the new era, major projects have become an important benchmark of national comprehensive competitiveness, and the urgency and importance of social responsibility governance of major projects have become increasingly prominent. Based on the current research situation and the practical needs of major project management, we can see that the future development trends mainly include the theory and method of social responsibility for major projects facing complex environment and social responsibility governance system for major projects under the international situation.

Judging from the existing research results, the top three countries in the number of core papers in the engineering research front of "social responsibility for major projects" are China, Australia, and the United Kingdom (Table 1.2.9). The top three countries in average citation are Australia, the United States, and China (Table 1.2.9). As show in the core paper output country cooperation network map (Figure 1.2.4), China and Australia have more cooperation. Chinese scholars put forward the topic of social responsibility for major projects firstly. The theoretical framework of social responsibility research for major projects and a three-dimensional dynamic model of "whole life-stakeholders-social responsibility" are established. By relying on the Hong Kong–Zhuhai–Macao Bridge, Guangxi Nanning East Railway Station, Shanghai Maglev and other major projects, the governance framework of major projects for public participation and government participation is put forward. The sustainable effects of major projects in different dimensions, such as economy, environment, and society are revealed. Australian scholars have conducted in-depth research on resource conservation and environmental protection in the social responsibility of major projects. By improving the level of technology and management, the water use efficiency of construction sites is improved, and the generation of waste is eliminated or reduced. Environmental compensation is used to reduce the impact of major projects on the environment. It is proposed to improve the design, approval, evaluation, and supervision process of environmental compensation policies, so as to improve the effectiveness of environmental compensation policies.

The top three institutions in the number of core papers are Hong Kong Polytechnic University, South China University of Technology, and Tongji Univiversity (Table 1.2.10). According to the cooperation network diagram of institutions producing core papers (Figure 1.2.5), among the top 10 institutions in the number of core papers publishment, the University of Hong Kong, South China University of Technology, and Queensland University of Technology have more cooperation. The research team members from the Hong Kong Polytechnic University mainly study the social responsibility issues of major projects from the perspective of stakeholders. They mainly analyze the complexity of stakeholders in major projects and propose to solve the problem of unclear responsibilities in major projects by constructing a framework of stakeholder cooperation, and to balance the rights and corresponding social responsibilities of stakeholders in the project. They put forward the expectation management strategy for stakeholders to pursue the goal of social, environmental, and economic sustainability, which provides support for major engineering practices. The research team members from South China University of Technology and Tongji University analyze the specific behavioral characteristics of social responsibility for major projects from the perspective of stakeholders. They study the specific social responsibility behavior, as well as the motivation and influencing factors of stakeholders' choice of social responsibility behavior, and put forward the multi-stakeholder multi-objective decision-making method during the period of public participation in major infrastructure projects. The research team members from Shanghai Jiao Tong University focus on the connotation and key elements of social responsibility of major projects, put forward a three-dimensional model of social responsibility of major projects, and construct an index system for evaluating social responsibility of major projects. They put forward the social governance model of social responsibility of major projects and analyze the industry spillover effects of social responsibility of major projects.

According to Table 1.2.11, China ranks first in citing core papers. Meanwhile, according to Table 1.2.12, the top institutions are Hong Kong Polytechnic University and Tongji University.

Table 1.2.9 Countries with the greatest output of core papers on “social responsibility for major projects”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	21	61.76%	489	23.29	2017.5
2	Australia	13	38.24%	430	33.08	2016.9
3	UK	7	20.59%	92	13.14	2017.3
4	USA	6	17.65%	173	28.83	2016.7
5	Netherlands	2	5.88%	25	12.50	2017.5
6	Poland	1	2.94%	14	14.00	2018.0
7	South Korea	1	2.94%	12	12.00	2017.0
8	Malaysia	1	2.94%	2	2.00	2018.0
9	Iran	1	2.94%	0	0.00	2019.0

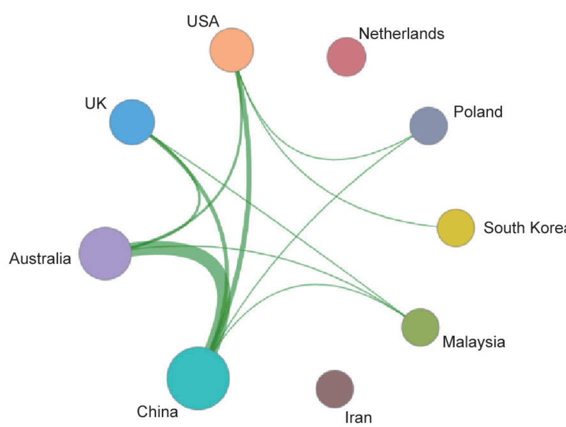

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “social responsibility for major projects”

Table 1.2.10 Institutions with the greatest output of core papers on “social responsibility for major projects”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Hong Kong Polytechnic University	6	17.65%	207	34.50	2017.5
2	South China University of Technology	5	14.71%	75	15.00	2017.8
3	Tongji University	5	14.71%	21	4.20	2018.4
4	Shanghai Jiao Tong University	4	11.76%	150	37.50	2016.8
5	The University of Hong Kong	4	11.76%	74	18.50	2017.5
6	Queensland University of Technology	4	11.76%	44	11.00	2017.8
7	Royal Melbourne Institute of Technology University	3	8.82%	194	64.67	2016.3
8	Nanjing Audit University	3	8.82%	72	24.00	2017.3
9	University of Florida	2	5.88%	104	52.00	2016.0
10	University of South Australia	2	5.88%	54	27.00	2015.5

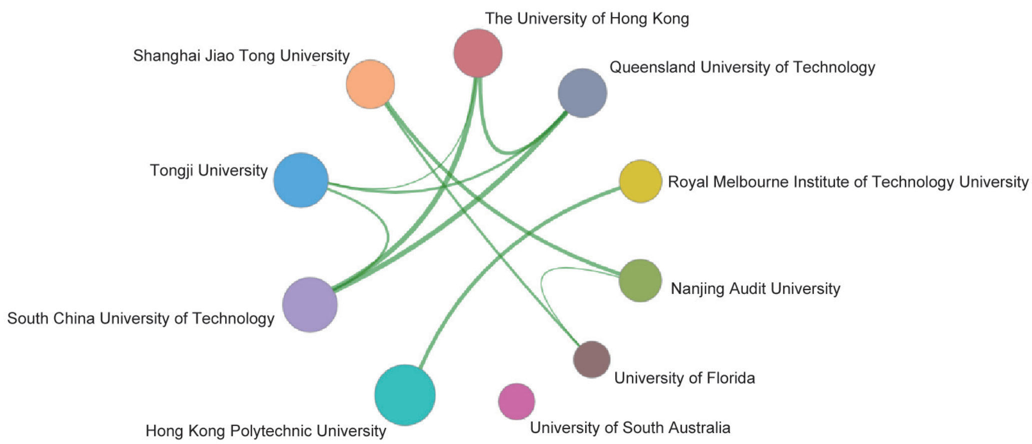

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "social responsibility for major projects"

Table 1.2.11 Countries with the greatest output of citing papers on "social responsibility for major projects"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	210	40.08%	2018.4
2	Australia	93	17.75%	2018.4
3	UK	66	12.60%	2018.5
4	USA	49	9.35%	2018.6
5	Netherlands	30	5.73%	2018.3
6	Iran	18	3.44%	2018.3
7	Malaysia	15	2.86%	2017.7
8	Spain	14	2.67%	2018.2
9	South Africa	10	1.91%	2018.8
10	Brazil	10	1.91%	2018.3

Table 1.2.12 Institutions with the greatest output of citing papers on "social responsibility for major projects"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hong Kong Polytechnic University	44	21.36%	2018.1
2	Tongji University	30	14.56%	2018.2
3	Shenzhen University	18	8.74%	2018.7
4	Harbin Institute of Technology	16	7.77%	2018.6
5	University of Groningen	16	7.77%	2018.6
6	University of Adelaide	15	7.28%	2018.3
7	Shanghai Jiao Tong University	15	7.28%	2018.4
8	Tianjin University	14	6.80%	2017.9
9	Queensland University of Technology	13	6.31%	2018.5
10	The University of Hong Kong	13	6.31%	2018.5

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

In the field of engineering management, this year's top 10 global engineering development fronts are "supply chain management system and method based on blockchain technology," "remote diagnosis and treatment system and method based on high-speed mobile network," "comprehensive emergency technology for urban safety," "epidemiological investigation technology and method based on big data," "research on simulation system and method based on digital twin," "agricultural tracking and monitoring system based on Internet of Things," "digital twin technology and method in smart city," "intelligent dispatching system for microgrid optimization," "infrastructure health monitoring system and method based on big data," and "management system and method of intelligent distribution service". The core patents are shown in Tables 2.1.1 and 2.1.2. These 10 engineering development fronts include agriculture, transportation, medicine, architecture, electronics, and many other disciplines. Among them, "supply chain management system and method based on blockchain technology," "remote diagnosis and treatment system and method based on high-speed mobile network," and "comprehensive emergency technology for urban safety" will be interpreted with emphasis, and the current development status and future trends will be interpreted in detail later.

(1) Supply chain management system and method based on blockchain technology

Blockchain technology is essentially a decentralized database, which is a new application mode combining distributed storage, point-to-point transmission, consensus mechanism, and cryptography. It can be divided into public chain, alliance chain, and private chain. Since its birth in 2008, the application of blockchain has extended to various fields of economy and society starting from digital cash, such as e-government, financial services, culture and entertainment, intelligent manufacturing, social welfare, education, and supply chain management. Supply chain is a system composed of logistics, information flow, and capital flow, in which suppliers, manufacturers, transportation enterprises, distributors, and retailers convert raw materials into final products and supply the products to consumers. Supply chain management is to design and manage seamless value-added processes between different organizations to meet the real needs of end customers. Blockchain, especially alliance chain, is naturally suitable for supply chain management and can realize large-scale cooperation among different organizations. However, in the practical application process, the supply chain is usually dynamic, and different supply chains also have interactive behaviors, while the alliance chain is relatively stable. Therefore, how to make alliance chain dynamically adaptable

Table 2.1.1 Top 10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Supply chain management system and method based on blockchain technology	15	43	2.87	2018.7
2	Remote diagnosis and treatment system and method based on high-speed mobile network	43	1 865	43.37	2016.8
3	Comprehensive emergency technology for urban safety	57	263	4.61	2018.4
4	Epidemiological investigation technology and method based on big data	31	892	28.77	2017.0
5	Research on simulation system and method based on digital twin	13	2	0.15	2018.9
6	Agricultural tracking and monitoring system based on Internet of Things	25	132	5.28	2016.7
7	Digital twin technology and method in smart city	28	7	0.25	2018.6
8	Intelligent dispatching system for microgrid optimization	21	46	2.19	2018.1
9	Infrastructure health monitoring system and method based on big data	14	33	2.36	2017.5
10	Management system and method of intelligent distribution service	15	81	5.40	2016.0

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

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Supply chain management system and method based on blockchain technology	0	0	0	0	4	11
2	Remote diagnosis and treatment system and method based on high-speed mobile network	3	9	7	10	4	10
3	Comprehensive emergency technology for urban safety	0	2	5	4	17	29
4	Epidemiological investigation technology and method based on big data	3	3	5	6	9	5
5	Research on simulation system and method based on digital twin	0	0	0	0	2	11
6	Agricultural tracking and monitoring system based on Internet of Things	2	5	6	3	4	5
7	Digital twin technology and method in smart city	0	0	0	3	6	19
8	Intelligent dispatching system for microgrid optimization	0	0	1	3	10	7
9	Infrastructure health monitoring system and method based on big data	1	1	1	1	7	3
10	Management system and method of intelligent distribution service	4	3	1	3	4	0

and how to realize the interaction between different chains are important problems to be solved, and cross-chain technology needs to be studied in depth. In addition, the blockchain itself can only ensure that the data will not be tampered after being uploaded, but cannot guarantee the authenticity of the uploaded data. The combination with the Internet of Things, big data, and artificial intelligence technology is expected to solve this problem. Furthermore, there is a common problem of blockchain that restricts the alliance chain's application in supply chain management, that is, "impossible trinity" of decentralization, security, and scalability, which needs to be weighed according to different scenarios. Therefore, it is an important research direction in the future to further develop cross-chain technology, combine emerging technologies such as Internet of Things, big data, and artificial intelligence, and optimize the fields of privacy protection, security, efficient authentication, cross-chain, and scalability.

(2) Remote diagnosis and treatment system and method based on high-speed mobile network

The remote diagnosis and treatment system based on high-speed mobile network is based on high-speed mobile network communication technology, and assists cross-regional medical care with low delay and high reliability through intelligent terminal medical equipment and integrated information collection terminal. At present, with the maturity of the remote communication technology of high-speed mobile network, a new solution is provided for the medical staff to implement more complex diagnosis and treatment behaviors, and the remote diagnosis and treatment technology has further shown broad application prospects in the fields of navigation and aviation security, disaster emergency rescue, and public health safety. In addition, with the application of artificial intelligence technologies such as Internet of Things and deep learning in related fields, the ability of remote diagnosis and treatment system to acquire and process information has been further improved, and the interactive service system and method around remote diagnosis and treatment have become a research hotspot in academic circles. However, in the engineering application management, the inconsistent data specifications and unfixed remote interactive environment caused by the difference of medical equipment terminals restrict the application of remote diagnosis and treatment system based on high-speed mobile network. Artificial intelligence technology based on edge computing and cloud–edge fusion provides support for high-speed processing and standardization of terminal information. Therefore, in the future, it is the main development trend of modern remote diagnosis and treatment system to develop a terminal service system of medical service that integrates and expands multi-source information flow, so that interactive information can be conveyed efficiently and accurately, and to improve the quality of remote medical service by combining edge computing technology with human–computer interaction technology.

(3) Comprehensive emergency technology for urban safety

The comprehensive emergency technology for urban safety is based on the information technology and realizes the functions such as information fusion, data collection, forecasting and early warning, situation assessment, and emergency decision-making through the establishment of urban safety emergency management system platform, so as to assist urban operation and emergency management. From the business perspective of urban safety, the comprehensive emergency response includes four aspects of prevention and emergency preparation, monitoring and early warning, emergency response and rescue, and post-event recovery and reconstruction. At present, the rapid development of emerging information technologies, such as Internet of Things, big data, cloud computing, and spatial geographic information technology, provides new technical support for the emergency management system, which makes comprehensive emergency technology show a broader application prospect. How to deeply integrate and apply the emerging information technology with business domains such as comprehensive emergency response and urban safe operation has become a new academic research hotspot. However, in practical engineering management applications, urban security involves multi-source and heterogeneous cross-level data information such as water, electricity, gas, heat, transportation, environment, and meteorology. Behind the appearance of excess information, there is the deficiency of theoretical models and the lack of effective information. Especially in emergency situations, the research and judgment of incomplete cross-domain information restrict the development of comprehensive emergency technology. Artificial intelligence technologies such as knowledge map, deep learning, and intelligent simulation can perceive data more accurately and efficiently and make decisions more intelligently. Therefore, in the future, how to combine safety engineering knowledge with artificial intelligence technology and mine multi-source heterogeneous big data to accurately identify and evaluate urban safety risks, and how to scientifically predict and comprehensively judge different disaster scenarios/decision-making stages and intelligently generate decision-making suggestions will be the two development trends of future research.

(4) Epidemiological investigation technology and method based on big data

Big data refers to the collection of complex data that exceeds the processing capacity of traditional data systems, goes beyond the scope of classical statistical analysis, and is difficult to perform single machine analysis with mainstream software tools and technologies. Through modern computer technology and innovative statistical methods, data can be purposefully acquired, managed, and analyzed, and valuable patterns and knowledge hidden in it can be revealed. Health care big data is a product of the integration of medicine and big data in the development process. Its main sources are health administration data, demographic and disease monitoring data, real-world health-related records (electronic medical records, medical images, physical examination data, etc.), scientific research data (biomarkers, clinical trials or cohort study multi-omics data), registration data (such as equipment registration, process registration, disease registration data), data from mobile medical devices, and data reported by patients. The establishment and development of big data collection and preprocessing, storage and management, computing mode and system, analysis and mining and visual analysis make health care big data widely used in public health such as disease diagnosis and treatment, residents' health management, etiology exploration, disease prediction and early warning model construction, disease prevention and control decision-making, etc. The development of health care big data will provide rich resources and a broad platform for scientific research such as epidemiological research of infectious diseases, etiology research of chronic diseases, co-morbid research of the elderly, and practical research, and provide an opportunity for epidemiology to refine research problems in richer and more complex data and open up new research directions. At the same time, to better transform the rich information in big data into knowledge and tools in time, it is necessary to construct new epidemiological research methods and develop big data analysis technology and statistical software for big data mining and analysis. The development of epidemiological investigation technology and method based on big data will help the construction of "digital public health".

(5) Research on simulation system and method based on digital twin

Digital twin is to establish a virtual model completely mapped with physical entities in a digital way, map the attributes, structure, state, performance, function, and behavior of physical entities to the virtual world, and simulate the behavior of physical entities in the real environment with the help of data, so as to observe, recognize, understand, control, and transform the physical world. Simulation is to simulate and reproduce the real dynamic system by using the model and evaluate and improve the system performance by performing various experiments on the simulation model. As an indispensable technology in product development and manufacturing, simulation has been widely used in various fields of industry. With the rapid development of digital twin and the increasing research on its theory and technology, simulation research and application based on digital twin, driven by data and model, has become a new hot research direction, including design simulation based on digital twin, production system simulation based on digital twin, and operation and maintenance simulation based on digital twin. However, massive multi-source heterogeneous data processing, accurate modeling and solution of complex models, real-time virtual–real interaction, and closed-loop control of digital twins bring new challenges to the simulation based on digital twins. Therefore, how to realize the construction, assembly, reconstruction, and consistency verification of multi-dimensional and multi-time scale dynamic models, how to analyze and fuse multi-source heterogeneous twin data in real time and efficiently, how to reduce the order and solve the simulation model in a unified way, how to reveal the coupling mechanism between twin data and model and realize the real-time simulation driven by model and data fusion are the main technical directions for realizing the simulation based on digital twin. In the future, through the creation of digital twins, the increasingly rich data will be combined with powerful model simulation, so as to help enterprises improve quality, increase efficiency, and save costs in product design, manufacturing, health management, remote diagnosis, intelligent maintenance, and shared services, which will be the main development trend of future research.

(6) Agricultural tracking and monitoring system based on Internet of Things

The agricultural tracking and monitoring system based on the Internet of Things is supported by the Internet of Things, which tracks and monitors all links in the agricultural product supply chain in real time, such as planting, picking, processing, and logistics of crops, and realizes real-time data collection, transmission, storage, and processing of data at all links, which is convenient for automatic, scientific, and efficient control of all links, and finally realizes refined and intelligent management of agriculture and quality control of agricultural products, thus promoting the development of smart agriculture. At present, the agricultural tracking and monitoring system based on the Internet of Things has shown a broad application prospect, which can be applied to crop pest identification and early warning, crop growth environment monitoring, agricultural product traceability and so on. With the application of cutting-edge technologies such as cloud computing, deep learning, and blockchain in agriculture, and the continuous advancement of Precision Agriculture and Agriculture 4.0, the research of agricultural tracking and monitoring system based on Internet of Things will usher in a rapid development stage. However, the agricultural tracking and monitoring system is faced with many complex problems, such as environmental factors like a wide variety of crops, temperature, light, soil nutrients, and air humidity affecting the growth of crops, frequent crop diseases and changeable symptoms, which make the data collected by the system have the characteristics of multi-source heterogeneity, high uncertainty, dynamic, and high matrix sparsity. Therefore, how to effectively process and analyze these data and apply them to intelligent agricultural management is a difficult point that needs to be overcome urgently. The combination of artificial intelligence technology such as deep learning, cloud computing technology, blockchain, 5G, intelligent unmanned aerial vehicle, and Internet of Things technology can complete the safe storage, analysis, and calculation of massive data, so as to monitor the operation of each link in the agricultural product supply chain more accurately, efficiently, and intelligently, thus creating a traceable, safe, and credible agricultural product supply chain. Therefore, in the future, how to combine artificial intelligence, cloud computing, blockchain, and Internet of Things and propose data analysis and processing methods with agricultural characteristics to improve the intelligence, automation, and scientific level of agricultural tracking and monitoring system based on Internet of Things, and how to provide expert-level agricultural management suggestions according to the continuous improvement of agricultural practice level and to improve the continuous penetration and application of cutting-edge technologies in practice will be the two major development trends of future research.

(7) Digital twin technology and method in smart city

With the urban governance and operation becoming more refined and precise in the digital age, the urban data resources urgently need to be transformed into urban digital assets in the era of connotative urbanization, and the concept of digital twins in the industrial field has been applied to the field of smart cities. Digital twins are virtual copies of material products or assets, which are updated in real time or periodically to make them as consistent as possible with their counterparts in the real world. Digital twin city means that all the components, elements, and activities of the city are copied into virtual cities, and the virtual cities interact with real cities in real time or at high frequency. In the future, cities themselves will gradually become the products of superposition of entities and virtual spaces of different scales and real-time dynamic communication among different groups. This is not only the integration of geographic information system, building information model and Internet of Things , but also the innovative integration of emerging technologies such as low-Earth-orbit satellite network, 5G, cloud computing, edge computing, real-time integration and call of multi-source heterogeneous data. According to domestic and foreign patents and articles, digital twin city technology has preliminary exploratory applications in urban emergency safety, community governance, smart education and medical care, smart tourism, and smart transportation. However, digital twin cities have changed the development path of traditional smart cities, focusing more on new digital spaces such as urban planning, construction, and operation and their communication modes. Driven by digital spaces, they promote the reconfiguration of land, capital, and talents in physical spaces, which in turn, constructs richer digital spaces and forms new urbanization of digital twins. The research difficulty lies in how digital twin cities provide a more interactive mode of human–computer interaction, more real-time super-large-scale computing, and a more self-learning iterative urban mechanism.

(8) Intelligent dispatching system for microgrid optimization

Microgrid refers to a small-scale power generation and consumption autonomous system that organically integrates distributed power sources, loads, energy storage devices, and monitoring and protection devices. The microgrid can achieve power balance, meet load demand, and ensure safe, stable, and economic operation of microgrid by optimizing dispatching and fully coordinating controllable units such as distributed generation, energy storage devices, and flexible loads. With the development of microgrid technology, its structure and function have undergone new changes, gradually expanding from single power structure to multi-energy forms including gas, heat, and electricity, and continuously merging with transportation systems such as electric vehicles and charging piles, information communication systems such as 5G base stations, etc., and evolving into integrated energy systems. At the same time, there will be a microgrid group composed of multiple microgrids in the same area, and the dynamic interaction process between microgrids and between microgrids and power systems is more complicated, so the optimal dispatch of microgrids is facing severe challenges. In recent years, artificial intelligence technology and 5G technology have made new energy power generation and load forecasting, system state perception, and optimal dispatching and decision-making more accurate and efficient. At the same time, the centralized collection and dispatching mechanism that the optimal dispatching system relies on gradually changes to the distributed point-to-point interactive negotiation mechanism, which greatly enhances the flexibility and scalability of the dispatching system. Therefore, it will be an important development trend in future research and development to fully consider the complementary characteristics of multi-energy coupling in microgrid (group), as well as the dynamic interaction and compatible operation with large power grid, and to build an optimized intelligent dispatching system by combining advanced artificial intelligence technology, 5G technology, and distributed dispatching architecture.

(9) Infrastructure health monitoring system and method based on big data

A large number of sensing devices are installed in the infrastructure health monitoring system to obtain environmental load and structural response information in real time. By analyzing massive monitoring data, possible structural damage can be identified and structural safety status can be recognized. The development of advanced intelligent sensing technology promotes the formation of infrastructure health monitoring big data, and makes infrastructure health monitoring system and method based on big data gradually become research hotspots, which will bring revolutionary changes to traditional health monitoring technology. Big data method is still in the exploratory stage in the field of infrastructure health monitoring, and its main technical directions include the research and development of intelligent monitoring equipment, analysis methods and efficient analysis, and calculation means of multi-source heterogeneous massive data. Tools like intelligent monitoring equipment and smart phones have broad application prospects in infrastructure health monitoring, which will provide more valuable information for infrastructure health monitoring; automatic and intelligent monitoring means produce a large amount of unstructured data, which requires in-depth study of effective data fusion methods, to comprehensively utilize the unstructured data and structured data, and maximize the value of massive multi-source heterogeneous data; health monitoring data contains a lot of noise and error information, and automatic data preprocessing is a problem to be solved in advance for health monitoring big data analysis; as an important task of infrastructure health monitoring, the key problem of damage identification based on big data is to extract characteristic indicators sensitive to structural damage but insensitive to changes in environment and operating load, and effectively judge the damage state of the structure after infrastructure cracking and extreme load; in the future, the monitoring of infrastructure health status will focus on groups, which will face the problem of insufficient analytical computing power or low computational efficiency, and it will become an inevitable trend to develop an efficient cloud computing platform. Therefore, the combination of big data analysis method with artificial intelligence, Internet of Things, and supercomputer technology is the development trend of infrastructure health monitoring in the future, which will provide a more reliable and effective guarantee for the safe operation of infrastructure.

(10) Management system and method of intelligent distribution service

Distribution service management system usually includes transportation management system and warehouse management system, which mainly systematizes and informationizes the traditional manual and document operation processes and presents them in the form of computer software system. At present, there are many software suppliers of distribution service management systems in the market, and this kind of system has been applied by enterprises in many fields, such as automobile manufacturing, food and medicine, retail fast-moving and electric commerce. In essence, the distribution service management system only enables the operation process of enterprises to be efficiently managed, and the data can be accurately shared, but it cannot provide excellent decision-making schemes for enterprises in operation, and most of the decisions in enterprises still rely on the human brain at present. Intelligent distribution service management system refers to the distribution service management system embedded with intelligent decision algorithm engine. Based on the current situation of business processes, input data and owned resources of enterprises, it can use operational optimization algorithm to generate the optimal decision scheme through complex calculations for direct use by enterprises or as decision support. Operational optimization algorithms mainly include branch-and-price algorithm, dynamic programming algorithm, heuristic algorithm based on column generation, tabu search algorithm, variable neighborhood search algorithm, and large neighborhood search algorithm. These algorithms are the mainstream methods to solve practical problems of enterprises, which are very efficient and have been widely used. In recent years, many scholars have tried to apply artificial intelligence algorithms based on neural networks, such as reinforcement learning and deep learning to solve the optimization problem in the field of distribution services, which has become a hot spot in current academic research. However, the related methods and theoretical achievements are still not rich, and the effect of related algorithms is still not as good as that of traditional operational optimization algorithms. It is the future research trend to combine artificial intelligence algorithm based on neural network with traditional operational optimization algorithm and use their respective advantages to solve the optimization problem in the field of distribution service.

2.2 Interpretations for three key engineering development fronts

2.2.1 Supply chain management system and method based on blockchain technology

Supply chain is composed of many participants, and there is a lot of interaction and cooperation. Information is discretely stored in each link and system, which lacks transparency. The unsmooth information transmission makes it difficult for each participant to accurately understand the real-time status and existing problems of related matters, which affects the collaborative efficiency of supply chain. When there is a dispute between the subjects, it takes time and effort to give evidence and pursue responsibility. In the future, the market scope of enterprises is becoming larger and larger, and the logistics links are characterized by multi-regions and long time span, which requires intelligent and efficient anti-counterfeiting traceability. In addition, many small-and medium-sized enterprises in the supply chain are difficult and expensive to finance, which often affects their effective operation and then affects the performance of the whole supply chain. Supply chain finance is one of the methods to solve this problem, which has been consistently sought after by the industry when it was put forward, but it has been limited by the problem of risk control cost for a long time and cannot play its ideal role.

Blockchain has the advantages of non-tamperable data, traceability, cost reduction, trust building, etc., which can solve the above pain problems in traditional supply chain management to a great extent. Non-tamperable data: Blockchain uses asymmetric encryption and hash algorithm to ensure that data recording and transmission are true, non-tamperable, and non-repudiation. Traceability: the main body interaction of supply chain information is realized through embedded identification technology and pervasive algorithm, and a unique and continuous "chain" is constructed in public "blocks" according to time series, thus ensuring the uniqueness and traceability of supply chain transaction information. Cost reduction: Blockchain technology supported by timestamp, password protection, node protection, and other technologies can ensure the security and accessibility of supply chain data, which makes blockchain naturally meet the cost control needs of supply chain. Trust building: Blockchain is known as "trust machine." In the blockchain system, the consensus mechanism solves and guarantees the consistency and correctness of each uploaded information data on all chain nodes, ensures that the data blocks can be directly written and recorded in the blockchain without relying on the approval of the centralized organization, and then enters the whole traceability system to complete the operation.

Meanwhile, it should be pointed out that there are some shortcomings in the application of blockchain in supply chain. For example, the privacy protection technology system for the concealment of trading behavior and smart contracts is still incomplete; there may be security loopholes and backdoor influence in the implementation of intelligent contract code, which may lead to business fraud and other risks; information interaction and value transfer between different blockchains need to be solved urgently; with the increase of the number of nodes, the communication cost will increase sharply, which will affect its scalability and system availability in terms of the number of users and transactions.

From the perspective of patent analysis, supply chain management systems and methods based on blockchain mainly include two categories, that is, supply chain traceability methods and systems based on blockchain and supply chain financial management methods and systems based on blockchain.

(1) Supply chain traceability method and system based on blockchain

It comprises the following steps: composing a predetermined number of monomer products into a product logistics unit, equipping the product logistics unit with a satellite positioning chip, acquiring position information, and generating a current hash value. The private key of batch products is stored in the blockchain and the blockchain is associated with the current product batch. By recording logistics traceability information, we can ensure the integrity of logistics information records, prevent the loss of logistics traceability information, and facilitate the query of logistics traceability information.

(2) Supply chain financial management method and system based on blockchain

It mainly includes supply chain financial platform and risk assessment platform. The supply chain financial platform includes supply service platform of upstream raw material, brand service platform, processor service platform, and downstream store service platform. The risk assessment service platform includes an industry big data assessment module and a financial transaction service platform, wherein the industry big data assessment platform is connected with a risk early warning module and the financial transaction service platform is connected with a transaction asset service module. The supply chain financial service platform based on blockchain is helpful to understand financial services in detail, so as to make financial investment and reduce investment risks.

It can be seen that the blockchain mainly solves the trust and security problems of transactions. Based on this problem, this paper puts forward some innovations such as distributed ledger, asymmetric encryption and authorization technology, consensus mechanism, and intelligent contract. Blockchain's decentralization, openness, autonomy, non-tamperable information, and anonymity provide good support for supply chain management.

In terms of the number of published patents, the top two countries are China and the United States (Table 2.2.1). The citations per patent is 14.27 and 22, respectively (Table 2.2.1). At present, China focused on two fields, blockchain-based supply chain tracking and traceability methods and blockchain-based supply chain financial anti-counterfeiting tracking methods, the first method mainly use radio frequency identification, near field communication, and QR codes to generate product tags and complete the transaction process; the second method realizes the agreement between the buyer and the seller through smart contracts, logistics supervision and financial evaluation, to reduce cumbersome procedures and improve processing speed. The United States focused on blockchain-based supply chain traceability methods to manage the transportation of goods from the origin to the destination, and uses smart contracts to speed up transactions and ensure compliance with operating procedures.

The top one institution in the number of patents is University of Electronic Science and Technology of China (Table 2.2.2), which focused on supply chain financial management methods based on sovereign blockchain technology and blockchain-based freight logistics management methods. The supply chain financial management method based on sovereign block chain technology mainly uses sovereign block chain technology to build a block chain application platform suitable for China's supply chain finance, that can improve the security and traceability of supply chain financial applications, reduce transaction costs, and realize the supervision of the entire process of supply chain finance; the blockchain-based freight logistics management method combines sub-blockchains to establish a blockchain platform to realize the trustworthy data sharing of the entire freight logistics process, and the problem of difficulty obtaining data of freight logistics in the later stage is to be solved.

2.2.2 Remote diagnosis and treatment system and method based on high-speed mobile network

The remote diagnosis and treatment system is derived from English "telemedicine", which is the product of the rapid development of telecommunication technology in the 20th century. Early remote diagnosis and treatment was completed by telephone and short-range radio, which mainly served the exchange of medical information and assisted the areas with asymmetric medical resources to complete diagnosis and treatment activities. With the innovation of modern communication technology, its connotation is constantly enriched. Modern telemedicine service system includes resource providers, service demanders, and interactive communication devices, which has gradually evolved

Table 2.2.1 Countries with the greatest output of core patents on "supply chain management system and method based on blockchain technology"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	11	84.62%	157	78.11%	14.27
2	USA	2	15.38%	44	21.89%	22.00

Table 2.2.2 Institutions with the greatest output of core patents on "supply chain management system and method based on blockchain technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	University of Electronic Science and Technology of China	3	23.08%	35	17.41%	11.67
2	Wuxi Jingtum Network Technology Co., Ltd.	2	15.38%	21	10.45%	10.50
3	Qianhai Yunlian Technology Shenzhen Co.	2	15.38%	15	7.46%	7.50
4	Hangzhou Yunxiang Network Technology Co.	2	15.38%	60	29.85%	30.00
5	Zhonglian Technology Co., Ltd.	1	7.69%	8	3.98%	8.00
6	Guangdong University of Technology	1	7.69%	18	8.96%	18.00
7	Skuchain Inc.	1	7.69%	37	18.41%	37.00

from the early single information exchange service to the information system technology facing multi-party real-time interaction in complex scenes such as emergency rescue, health care, and emergency treatment. The construction of modern remote diagnosis and treatment system is the result of multidisciplinary integration, including modern communication, Internet of Things, intelligent medical equipment, edge computing, and distributed artificial intelligence, which makes remote diagnosis and treatment system no longer limited to the exchange of information, but can dig deeper into the value of information itself and interaction process. While ensuring the timeliness of data transmission, it can further improve the presentation of effective information in the interactive process, and assist medical staff to improve the service level of remote diagnosis and treatment according to the interactive information.

In engineering application management, the inconsistent data specifications and unfixed remote interactive environment caused by the differences of medical equipment terminals restrict the application of remote medical service system based on high-speed mobile network. Therefore, the development and integration of expansive medical service terminal equipment and remote medical service based on the combination of edge computing technology and human–computer interaction technology are the main trends to improve the efficiency of remote medical service in the future. From the patent analysis, the remote diagnosis and treatment system and method based on high-speed mobile network mainly include medical Internet of Things, computer aided diagnose, medical robots, diagnosis and treatment information retrieval, and telemedicine edge computing technology.

(1) Medical Internet of Things

Medical Internet of Things is a product of the integration and development of modern intelligent Internet of Things and high-speed communication technology. It is an information management system that connects terminal facilities such as medical patients and pharmaceutical equipment and supports real-time interaction of diagnosis and treatment information. In the field of engineering management, medical Internet of Things can complete the functions of automatic information identification, key information location, automatic data collection, traceability tracking, comprehensive information management, regional information sharing and so on under the medical interconnection environment. However, at present, due to the inconsistent information collection standards of IoT devices, the degree of human–machine interconnection is not high. The medical Internet of Things technology based on artificial intelligence can effectively standardize the data information in the terminal equipment, so that the medical Internet of Things technology can effectively serve modern medical management.

(2) Computer aided diagnosis

Computer aided diagnosis (CAD) is a system that helps doctors interpret diagnosis and treatment data. CAD mainly deals with a large amount of information generated by imaging technology in X-ray, MRI, and ultrasonic diagnosis in the early stage, thus reducing the time of reading films for medical staff in imaging departments. At present, in the field of engineering practice, CAD has been widely used in specialized departments. Although it can assist medical care to complete diagnosis and treatment in some links, it is limited by the multi-source and multi-modal types of diagnosis and treatment data, and CAD technology needs manual intervention to complete diagnosis and treatment. With the development of artificial intelligence technology based on human–machine collaboration, it is expected to realize intelligent auxiliary diagnosis and treatment system based on human–machine coupling in the future.

(3) Medical robots

Medical robot is a kind of robot that assists or replaces medical staff to complete diagnosis and treatment services by constructing precise electrical devices. It contains many kinds. For example, the surgical manipulator used in surgery in ocean navigation or remote areas can complete more accurate and less invasive surgery; the monitoring robot in COVID-19 epidemic can complete the collection of personal sign information without cross infection; and the remote control robot used in remote surgery can assist doctors to complete complex surgical operations across regions. At present, in the field of engineering practice, medical robots are closely integrated with use scenarios, but their environmental adaptability is weak. Developing medical robots suitable for human–machine coupling environment is the mainstream development direction in the future.

(4) Diagnosis and treatment information retrieval

Diagnosis and treatment information retrieval refers to the process of inquiring and displaying information in the diagnosis and treatment system. Traditional diagnosis and treatment information retrieval is completed by the information system built in medical institutions, which requires low data retrieval efficiency. In the process of remote diagnosis and treatment, in order to complete high-quality remote diagnosis and treatment activities, the diagnosis and treatment information retrieval technology should be used to quickly locate multi-modal related information including electronic medical records, pathological images, and diagnosis and treatment videos. In engineering management, classical information retrieval techniques include vector space model and probability model based on structured data. However, due to the modal diversity of remote diagnosis and treatment system data, the existing retrieval methods are generally inefficient. With the development of semantic understanding technology based on deep learning, realizing high-level semantic understanding and association retrieval of multimodal medical data is a main direction of medical information retrieval in the future.

(5) Telemedicine edge computing

Telemedicine edge computing refers to providing the nearest intelligent diagnosis and treatment service by integrating the computing resources stored, transmitted, and managed on the side of resource request or data sources in the process of completing the intelligent remote diagnosis and treatment service. For example, the mobile reading terminals in mobile medical treatment can assist doctors to automatically analyze and display diagnosis and treatment information; distributed shared storage used in remote consultation can support real-time access and storage of multi-party data in remote diagnosis and treatment. With the application of high-speed communication technologies such as 5G, modern edge computing can complete more complex multi-modal diagnosis and treatment data analysis and medical resource request allocation, and can partially delegate the original computing resources deployed in the cloud-to-edge medical terminals, thus completing data analysis and preprocessing at edge terminals, reducing the communication load pressure during remote diagnosis and treatment, and reducing the risk of medical information leakage. At the same time, with the development of distributed artificial intelligence technology, edge computing will play an important role in the future remote diagnosis and treatment system.

In terms of the number of patents published, the top two countries in the number of patents are the United States and South Korea (Table 2.2.3), which mainly include remote consultation systems with interactive ability and long-term real-time nursing monitoring systems with active early warning capability. The sensing information is rich, and some of them use CAD technology based on edge computing, but China is still in the catch-up stage. The top three countries in citations per patent are the United Kingdom, the United State, and the Netherlands (Table 2.2.3). Their core contents are related to abnormal information early warning of patients with chronic diseases such as diabetes, as well as remote health monitoring in special environments such as ocean voyage. From the patent output cooperative network diagram (Figure 2.2.1), a cooperative relationship has been formed between the United States and the Netherlands in the key areas of remote video transmission in the mobile network. The top two institutions in the number of patents are: MI Express Care Licensing Company and Koninklijke Philips Electronics NV (Table 2.2.4), but they are limited to the field of long-term health monitoring and are mainly based on multiple types of sensors. From the cooperation network diagram of patent output institutions (Figure 2.2.2), the scale of regional cooperation has been initially formed, but there is no cross-regional cooperation network, in which Koninklijke Philips Electronics NV and Ishihara Corporation (U.S.A.), OBS Medical Ltd. and E-SAN Limited in the United Kingdom have cooperation in the field of chronic disease monitoring, and the core technology involves primary semantic diagnosis and treatment information retrieval. Enterprises in our country are in the synchronous catch-up stage in the field of chronic disease monitoring and remote diagnosis and treatment, but thanks to the development of high-speed mobile communication networks in China, the remote diagnosis and treatment technology in special fields such as telemedicine consultation and telemedicine robots in China has certain first-mover advantages.

2.2.3 Comprehensive emergency technology for urban safety

Urban buildings are dense, the infrastructure network is complex, and the subsystems are closely coupled in structure and function, which will show high vulnerability under the hazards of emergencies. In 1989, the concept of “safe city” was formally put forward in the first academic conference on

Table 2.2.3 Countries with the greatest output of core patents on “remote diagnosis and treatment system and method based on high-speed mobile network”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	31	51.67%	1581	75.14%	51.00
2	South Korea	10	16.67%	34	1.62%	3.40
3	China	8	13.33%	26	1.24%	3.25
4	Germany	2	3.33%	26	1.24%	13.00
5	Japan	2	3.33%	3	0.14%	1.50
6	UK	1	1.67%	364	17.30%	364.00
7	Netherlands	1	1.67%	34	1.62%	34.00
8	Canada	1	1.67%	28	1.33%	28.00
9	Finland	1	1.67%	25	1.19%	25.00
10	Denmark	1	1.67%	17	0.81%	17.00

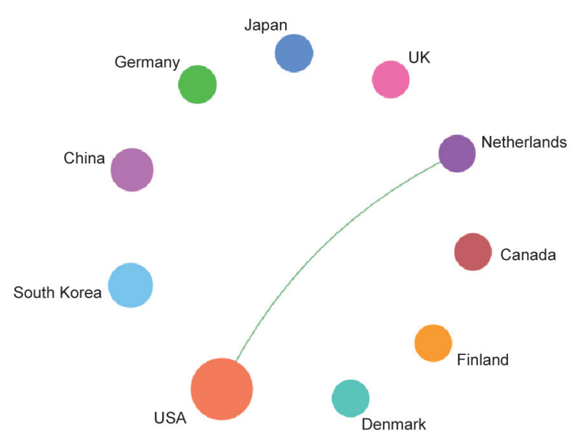

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “remote diagnosis and treatment system and method based on high-speed mobile network”

Table 2.2.4 Institutions with the greatest output of core patents on “remote diagnosis and treatment system and method based on high-speed mobile network”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	MI Express Care Licensing Company	7	11.67%	26	1.24%	3.71
2	Koninklijke Philips Electronics NV	2	3.33%	1385	65.83%	692.50
3	Ishihara Corporation (U.S.A.)	1	1.67%	1351	64.21%	1351.00
4	E-SAN Limited	1	1.67%	364	17.30%	364.00
5	OBS Medical Ltd.	1	1.67%	364	17.30%	364.00
6	Abbott Diabetes Care Inc.	1	1.67%	52	2.47%	52.00
7	KT Freetel Co., Ltd.	1	1.67%	30	1.43%	30.00
8	Telehealth Broadband, LLC	1	1.67%	28	1.33%	28.00
9	Verathon Inc.	1	1.67%	28	1.33%	28.00
10	INCREA OY	1	1.67%	25	1.19%	25.00

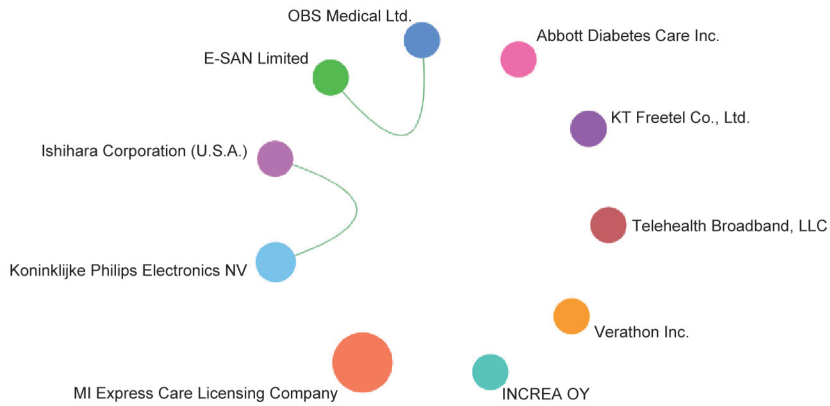

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "remote diagnosis and treatment system and method based on high-speed mobile network"

"Preventing Accidents and Losses." After the "9·11" incident in the United States in 2001, the concept of Emergency Management was put forward. In recent years, with the rapid development of urbanization, the risk factors of urban security have increased dramatically and the comprehensive emergency technology for urban safety has attracted more and more attention. Urban safety comprehensive emergency technology is an interdisciplinary subject, which covers many research fields, such as information system, safety engineering, system engineering, and decision management. The rapid development of emerging information technologies, such as Internet of Things, big data, and cloud computing, has provided new impetus for comprehensive emergency technology. Scientific issues such as emergency big data modeling, information sharing and full-process application, and emergency decision-making theories and methods supported by emerging information technologies have become emerging academic research hotspots and are considered to be one of the important directions for the future development of emergency management.

In practical engineering management applications, urban safety data types are cross-domain, cross-level, and cross-modal, and data information is often incomplete in emergency situations. How to integrate domain knowledge and models, multi-source heterogeneous and incomplete data, and emergency management business needs is an urgent problem to be solved in urban safety comprehensive emergency technology. From the patent analysis, the comprehensive emergency technologies for urban security mainly include big data fusion, urban risk monitoring and early warning, urban risk assessment, emergency intelligent decision support, and visualization of emergency map.

(1) Big data fusion

Big data fusion is to establish multi-dimensional and multi-granularity relationships among data, information, and knowledge fragments by means of models, entity links, and relationship deduction, so as to realize knowledge interaction at more levels. There are many kinds of data and information related to urban safety. From the perspective of emergency technology application, big data fusion can partially solve the problems of one-sided understanding and wrong decision-making caused by information fragmentation, but it still needs to conduct more efficient and accurate fusion management for emergency big data to support comprehensive emergency decision-making of urban safety.

(2) Urban risk monitoring and early warning

Risk monitoring and early warning uses the Internet of Things technology, and connects any article with the Internet through information sensing equipment such as radio frequency identification, infrared sensor, global positioning system, and laser scanner according to the agreed protocol, and exchanges and communicates information to realize intelligent identification, positioning, tracking, monitoring, and management of articles. The Internet of Things provides a great deal of data information for urban risk monitoring and early warning, which is different from the traditional technology. How to apply the Internet of Things technology to improve the monitoring ability of urban emergency, and how to study the analysis model based on new data to improve the accuracy of early warning are the problems that need to be focused on and solved in the future.

(3) Urban risk assessment

Risk assessment needs all kinds of disaster analysis models to predict and simulate various elements of urban operation. Disaster analysis models are gradually developing to refinement. Large-scale input of data and large-scale calculation ensure the accuracy of calculation, but also increase the calculation time. High-precision disaster simulation based on cloud computing can provide capacity support for practical risk assessment.

(4) Emergency intelligent decision support

With the development of science and technology, artificial intelligence technology is gradually applied to emergency intelligent decision. Robot, language recognition, image recognition, natural language processing, and expert system are becoming mcreasingly mature. However, the actual emergency scenarios are complex and changeable, and it is often required to make decisions quickly based on known massive information. The comprehensive application of artificial intelligence for emergency decision scenarios needs further exploration.

(5) Visualization of emergency map

One map refers to collecting, managing, analyzing, and displaying the data related to geographical distribution in space by using a geographic information system. Combining geography and cartography, remote sensing, and computer science, visualization of the emergency map has been widely used in the field of urban safety and emergency response. Multi-source data are displayed based on the same base map, which brings a lot of convenience for emergency decision-making. Meanwhile, how to realize efficient integration and fast and effective visual display of massive data in complex urban situations brings new challenges to urban safety emergency decision-making based on one map.

The top two countries in terms of the number of published patents are China and the United States (Table 2.2.5). The top two countries in terms of citations per patent are China and the United States (Table 2.2.5). The number of patents in different institutions is equal (Table 2.2.6).

The core patents in the field of urban safety comprehensive emergency technology in different countries have different research characteristics. China pays attention to the application of the Internet of Things technology, and puts forward a comprehensive evaluation system related to urban multi-dimensional security, such as the road traffic information cloud computing and cloud service realization system based on the Internet of Things, the urban natural gas intelligent leakage alarm system, and the dynamic monitoring and early warning system of the urban underground pipeline corridor based on the Internet of Things. These systems skillfully apply the advanced technologies such as the Internet of Things and big data to the urban comprehensive evaluation, monitoring, and early warning. The United States pays more attention to anti-terrorism security issues, such as non-military unmanned aerial vehicle signal detection and video feedback, accurate positioning of construction personnel, and emergency response research, while Japan pays attention to natural disasters such as earthquake and tsunami. Its research content is basically related to escape guidance and disaster monitoring, such as the escape guidance system used in earthquake, fire or tsunami, and the urban earthquake intelligent monitoring and early warning system. The research foci of different institutions are also different. For example, Zhejiang University of Technology focuses on the research of accurate positioning of urban vehicles and proposes an information center system with a data receiving and storage server of a global position system, which can monitor road traffic information on a large scale in real time. GSM Solution Inc. attaches importance to image processing and processing, and puts forward a system based on geographic information systems and Internet subsystems to process landscape images, geographic information system data, and measurement information in real time and determine the target locations. READ ENG KK pays more attention to the research of guiding personnel to escape correctly in disaster events and puts forward an indication system to determine the best evacuation area according to the disaster location information and current location information, to help people escape efficiently in disasters such as earthquakes.

Table 2.2.5 Countries with the greatest output of core patents on "comprehensive emergency technology for urban safety"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	28	57.14%	175	66.29%	6.25
2	USA	12	24.49%	63	23.86%	5.25
3	South Korea	6	12.24%	17	6.44%	2.83
4	Japan	3	6.12%	9	3.41%	3.00

Table 2.2.6 Institutions with the greatest output of core patents on "comprehensive emergency technology for urban safety"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Jiangsu Posts & Telecommunication Planning & Designing Institute Co., Ltd.	1	2.04%	50	18.94%	50
2	Redsky Technologies Inc.	1	2.04%	34	12.88%	34
3	Zhejiang University of Technology	1	2.04%	25	9.47%	25
4	Guangzhou Hanrun Information Technology Co., Ltd.	1	2.04%	25	9.47%	25
5	Hangzhou Chenqing Heye Technology Co., Ltd.	1	2.04%	12	4.55%	12
6	Korea Gas Safety Corporation	1	2.04%	8	3.03%	8
7	Shenzhen Yichuang Information Technology	1	2.04%	8	3.03%	8
8	GSM Solution Inc.	1	2.04%	6	2.27%	6
9	READ ENG KK	1	2.04%	6	2.27%	6
10	Beijing Beipai Design and Research Institute Co., Ltd.	1	2.04%	5	1.89%	5

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