Engineering Fronts

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Engineering Fronts

Contents

Foreword

The Engineering Fronts reports are important guidelines for the future development directions of engineering science and technology. The Chinese Academy of Engineering (CAE) has been conducting studies pertaining to Engineering Fronts for two years since 2017, with the aim of offering academic guidance and assistance in decision making.

In collaboration with *Clarivate Analytics*, studies in Engineering Fronts rely on nine core academic divisions and “1+9” academic journals of the CAE (i.e., Engineering and nine other specialized journals). Each year, the study issues 94 identified engineering research fronts and 96 engineering development fronts in both Chinese and English. Among them, 27 key engineering research fronts and 27 key engineering development fronts are selected for detailed interpretations.

The studies in Engineering Fronts combine quantitative and qualitative analyses. On the one hand, published journal papers (e.g., from the SCIE), conference papers, and global patents are taken into consideration to obtain the initial alternative fronts. On the other hand, experts are involved in the whole study process, including proposing candidate engineering fronts from their perspective and experience, researching the results from data-mining, and interpreting the key results.

This report consists of two parts. The first part introduces the methodology. The second part includes a total of nine reports on the engineering research fronts and engineering development fronts in nine fields corresponding to the nine core academic divisions.

Part 1 Methodology

Combining both quantitative and qualitative analyses, engineering front study applied deep integration of data analysis and expert advice to select a total of 94 engineering research fronts and 96 engineering development fronts in 2018. The number distribution of engineering fronts of nine fields corresponding to the nine academic divisions of the Chinese Academy of Engineering (CAE) is shown in Table 1.

Clarivate Analytics conducted quantitative analysis and obtained 702 candidate engineering research fronts based on the co-citation clustering method and 53 ThemeScape maps of 53 disciplines of nine fields.

In addition, experts of nine fields proposed candidate engineering fronts based on their insights before the original dataset was determined and after data mining was conducted. This was done to supplement potential gaps in the content coverage for each field in quantitative analysis. After several rounds of expert group meetings and questionnaires, approximately 10 engineering research fronts and 10 engineering development fronts were determined. Among them, three key engineering research fronts and three key engineering development fronts were selected for detailed interpretation.

1 Identification of engineering research fronts

In this report, the basic materials of engineering research fronts were extracted in the following two methods. In the first method, *Clarivate Analytics* clustered the top 10% highly cited papers of journal literatures and conference proceedings indexed in the *Web of Science Core Collection* based on the co-citation clustering method to obtain the topics. The second method was based on expert proposal. These two methods yielded 482 candidate engineering research fronts. After expert group meetings and questionnaires, approximately 10 engineering research fronts were selected from each field.

1.1 Production of topics

Clarivate Analytics matched the *Web of Science Core Collection* journal/conference proceedings to the nine CAE academic divisions, including a total of 12 882 journals and 28 626 conference proceedings. Experts manually reviewed the journal/conference proceeding mapping table for each field and finalized the list by making appropriate adjustments with their domain knowledge. Additionally, *Clarivate Analytics* reassigned publications in 67 Multidisciplinary Sciences journals such as *Nature* and *Science* to their most relevant subject area. By using the information found in the cited references of each publication, it was possible, in most cases, to algorithmically reassign them to a subject area. The final publication dataset comprised of articles, reviews, and proceeding papers that were published in matched journals and conference proceedings from the above methods. These

Table 1 Number distribution of engineering fronts of nine fields

Field	Number of engineering research fronts	Number of engineering development fronts
Mechanical & Vehicle Engineering	10	10
Information & Electronic Engineering	10	10
Chemical, Metallurgy & Materials Engineering	12	12
Energy & Mining Engineering	13	14
Civil, Hydraulic & Architecture Engineering	10	10
Environmental & Light Textile Engineering	10	10
Agriculture	10	10
Medicine & Health	9	10
Engineering Management	10	10
Total	94	96

publications were published between January 2012 and 2017, with citation counts to the end of February 2018.

In each field, *Clarivate Analytics* identified publications that were in the world's top 10% by number of citations received, considering the publication year and Journal Subject Category (JSC). Because citation rates differ for different modes of publication, conference proceeding papers and journal papers were treated separately. For each field, *Clarivate Analytics* clustered these top 10% highly cited publications based on co-citation clustering analysis. The first step of quantitative analysis was to obtain clustered topics.

The second step was to select 50 topics for each of the nine fields. To reflect the emerging feature of the fronts, the topics with the average publication year later than 2016 were paid more attention. For topics with the average publication year between 2016 and 2017, 20 clustered topics with no significant overlapping were selected by the order of indicators of the number of core publications, total citations, and the percentage of consistently cited publications. For topics with the average publication year before 2016, 30 clustered topics with no significant overlapping were selected by the order of indicators of the number of core publications, total citations, average publication year of core publications, and the percentage of consistently cited publications. Following this two-step process, 702 topics for nine fields were identified.

1.2 Expert review

Expert insights about engineering fronts are necessary supplements for bibliometric analysis.

Before data mining was conducted, experts from nine fields proposed key engineering research topics based on their expertise and then librarians for intelligence analysis of different subjects transferred the topics to search queries. This was an important component of the original dataset.

After data mining, to supplement potential gaps in the content coverage for each field, experts proposed key words, typical papers, or typical journals of specific subject to support *Clarivate Analytics* to perform custom search.

When reviewing the 702 topics of bibliometric analysis, experts proposed key engineering research topics once again, and librarians for intelligence analysis of different subjects provided data support.

The topics from bibliometric analysis and expert proposal were merged and condensed to produce a total of 482 candidate engineering research fronts.

Finally, after several rounds of expert group meetings and questionnaire, 94 engineering research fronts were selected for nine fields.

2 Identification of engineering development fronts

The basic materials of engineering development fronts were also obtained via two methods. In the first method, *Clarivate Analytics* clustered the top 5000 highly cited patent families from *Derwent Innovation* to obtain a total of 53 ThemeScape maps of nine fields. From these maps, experts obtained potential engineering development fronts. The second method was based on expert proposal. These two methods yielded 415 candidate engineering development fronts. Then, approximately 10 engineering development fronts of every field were selected after several rounds of expert group meetings and questionnaires.

2.1 Production of ThemeScape map

Clarivate Analytics established the mapping relationship between Derwent Manual Code and the specialty division criteria system of the CAE's academic divisions to determine the original patent search scope. Following the experts' manual review, the patent search strategy was constructed for 53 subjects in nine fields. Original data for patent analysis were obtained by searching on *Derwent Innovation*. These patents were published between January 2012 and 2017, with citation counts to the end of February 2018.

With comprehensive consideration to average citation of patent family and technical coverage width, we obtained the top 5000 highly cited patent families of each subject. Based on the semantic similarities of patent texts, 53 ThemeScape maps, which can visually present the distribution of engineering technologies were obtained.

With the assistance of librarians for intelligence analysis of different subjects, experts extracted technology information from ThemeScape maps to obtain candidate engineering development fronts of each subject.

2.2 Expert review

Experts played a crucial role in this study. Before data mining was conducted, experts from nine fields proposed key engineering development topics based on their expertise and then librarians for intelligence analysis of different subjects transferred the topics to the patent search queries. This was an important component of the original dataset.

After data mining, experts proposed key issues once again to supplement potential gaps in the content coverage for each field.

The results from ThemeScape map interpretation and expert proposal were used to produce 415 candidate engineering development fronts. Ninety-six engineering development fronts were obtained through expert group meetings and questionnaires.

Furthermore, from the perspective of future development prospects, 27 key engineering research fronts and 27 key engineering development fronts were selected for detailed interpretation.

3 Terminologies

Citations: The citation count is the number of times that a citation has been recorded for a given publication since it was published.

Publications/Papers: Publications/Papers include substantive peer-reviewed research journal articles, review articles, and conference proceedings.

Highly cited papers: Papers in the top 10% in terms of citation frequency are considered to be highly cited, taking into account the year of publication and Journal Subject Category (JSC).

Topics: Topics are clusters of the top 10% highly cited papers based on co-citation clustering analysis.

Core papers: Core papers are a group of highly cited papers forming a clustered topic.

Citing papers: Citing papers refer to the papers that cite core papers.

Mean publication year: The mean publication year refers to the average number of publication years of all the core papers of a topic.

Consistently cited publications: Publications in the top 10% in terms of citation velocity are considered to be consistently cited, taking into account the year of publication and JSC.

Citation velocity: Citation velocity is a measure of the rate of citation accumulation based on a certain frequency within a set period of time. The citation velocity for each paper is a measure of the rate of citation accumulation per month, i.e., from the month it is published until February 2018. Note that publications that are only cited in the same month when published will have citation velocity of 0.

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

Technical coverage width: Technical coverage width is measured by the number of Derwent Manual Codes that each patent family belongs to.

Percentage of published papers/patents: When counting the output of core papers/patents of countries/regions or institutions, if one paper/patent is of co-authors from different countries/regions or institutions, each country/region or institution will add one, so the total percentage of all countries/regions or institutions is more than 100%.

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

Part 2 Reports in Different Fields

I. Mechanical & Vehicle Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts in mechanical and vehicle engineering (hereafter called the mechanical field) include mechanical engineering, ship and marine engineering, aeronautical and astronautical science and technology, weapon science and technology, power and electrical equipment engineering and technology, and transportation engineering (Table 1.1.1). "Self-adaptive tracking of autonomous underwater vehicles," "consistency control of multi-agent systems," "self-adaptive neural network control of manipulators," "underwater autonomous navigation systems," "global navigation satellite system (GNSS) optimization," and "assessment and utilization of inshore wave energy resources" are the traditional research subjects in this field. Further, "thermal management technology of lithium-ion batteries," "cognitive wireless networks," "target recognition based on tactility," and "electro/magnetic field enhancing nanofluid convective heat transfer" are a few examples of emerging topics. A summary of the data on the annual publication of papers from 2012 to 2017 is presented in Table 1.1.2. The results indicate that "thermal management technology of lithium-ion batteries" and "electro/magnetic field enhancing nanofluid convective heat transfer" are two of the most rapidly growing topics.

(1) Self-adaptive tracking of autonomous underwater vehicles

Autonomous underwater vehicles are typical strongly coupled nonlinear systems. Therefore, such vehicles are susceptible to time-varying factors such as underwater

Table 1.1.1 Top 10 engineering research fronts in mechanical field

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Self-adaptive tracking of autonomous underwater vehicles	6	75	12.50	2014.67	0.0%	0.00
2	Consistency control of multi-agent systems	18	1 197	66.50	2014.72	11.1%	0.00
3	Self-adaptive neural network control of manipulators	3	376	125.33	2016.00	66.7%	0.00
4	Underwater autonomous navigation systems	5	106	21.20	2014.80	0.0%	0.00
5	Thermal management technology of lithium-ion batteries	13	169	13.00	2016.23	15.4%	0.00
6	Global navigation satellite system optimization	8	217	27.13	2013.63	0.0%	0.13
7	Cognitive wireless networks	22	755	34.32	2014.86	9.1%	0.00
8	Target recognition based on tactility	4	112	28.00	2016.75	50.0%	0.00
9	Assessment and utilization of inshore wave energy resources	32	925	28.91	2014.19	9.4%	0.00
10	Electro/magnetic field enhancing nanofluid convective heat transfer	19	801	42.16	2017.00	10.5%	0.00

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

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Self-adaptive tracking of autonomous underwater vehicles	0	1	1	3	1	0
2	Consistency control of multi-agent systems	1	3	4	3	6	1
3	Self-adaptive neural network control of manipulators	0	0	0	0	3	0
4	Underwater autonomous navigation systems	0	1	1	1	2	0
5	Thermal management technology of lithium-ion batteries	0	0	0	1	8	4
6	Global navigation satellite system optimization	1	4	0	3	0	0
7	Cognitive wireless networks	2	4	2	2	11	1
8	Target recognition based on tactility	0	0	0	0	1	3
9	Assessment and utilization of inshore wave energy resources	4	9	4	8	6	1
10	Electro/magnetic field enhancing nanofluid convective heat transfer	0	0	0	0	0	19

current and have stronger model and parameter uncertainty compared generally to rigid body vehicles. Currently, self-adaptive technology is generally used for nonlinear systems with linear forms of unknown parameters, to estimate these unknown parameters online. For systems with no linear form of parameters, neural network methods can be used to compensate for system uncertainties and ensure tracking error stability. According to the propeller configuration, research on the tracking of autonomous underwater vehicles is mainly divided into the two categories of under-drive and full-drive underwater vehicle tracking control. The tracking error of the former system has a strong nonlinear coupling between the different degrees of freedom of motion; scholars have primarily adopted reverse step and cascade system controls to realize the asymptotic stability of the tracking error. Considering the independent control input for every degree of freedom of the tracking control system of full-drive underwater vehicles, many scholars have relied extensively on reverse step control to produce trajectory-tracking controllers with global linear stability. The cooperative tracking and detection efficiency of autonomous underwater vehicle formation is substantially superior to that of monomer tracking detection, and according to the gradual improvement of self-adaptive monomer tracking control technology of autonomous underwater vehicles, research on self-adaptive formation cooperative control and intelligent path planning technologies is the likely trend of this research direction.

(2) Consistency control of multi-agent systems

As demonstrated by clusters of birds, fish, insects, bacteria, and cells, widespread mass movement occurs in nature. The clusters formed by interconnected and constantly moving individuals are characterized complex and highly coordinated dynamic behavior. Multi-agent systems provide a means of understanding the behavior of biological and other natural clusters and have a considerable application value in such disparate fields as industrial multi-robot group coordination, unmanned aerial vehicle (UAV) formation control, human group behavior regulation and guidance, and wireless sensor network optimization. A multi-agent system is composed of a series of interacting agents, with each agent using communication, cooperation, coordination, scheduling, management, and control methods to relay the structure of the system and function, and the behavior characteristics, thereby completing many complex tasks that cannot be performed by a single agent. A multi-agent system has autonomy, distribution, and coordination functions and exhibits self-organization, learning, and inference capabilities. Therefore, the use of multi-agent systems to solve real problems offers strong robustness and reliability. As biology, computer science, artificial intelligence, automation science, physics, and other disciplines intersect with each other and develop as interdisciplinary fields, multi-agent systems are increasingly considered a focal point in engineering control. Research on the collaboration of multi-agent systems was inspired in its early stage by the clustering phenomenon, which widely exists in nature, and was explored in the fields of mathematics, computer simulation, and system science. In recent decades, much research has been conducted on multi-agent system cooperative control theory. The primary areas of interest in multi-agent coordination control include consistency, cluster, swarm, and formation controls. Consistency control is one of the most basic challenges in multi-agent system coordination control, and its research can be promoted and applied to other cooperative control problems. Consistency control refers to the design of a consistency protocol that enables each agent to interact with local information to achieve the consistency of the target state value of all agents. Research on consistency control can be broadly separated into three key areas: the complexity of intelligent body dynamics, communication topology, and network information transmission. At present, the most important application of multi-agent systems is in the collaboration of group robots. In particular, the traditional multi-robot production line often adopts a centralized control structure in which adaptations to production are accomplished based on small task-oriented batches. In this case, dealing with many varieties is typically difficult because of the lack of agile manufacturing capacity. Given that the international manufacturing industry is moving toward a large, complex, dynamic, and open direction, the complex operation of modern manufacturing requires multi-robot cooperation. As such, a group robot system with superior compliance, consistency, and optimal performance is urgently required.

(3) Self-adaptive neural network control of manipulators

A multi-fingered dexterous manipulator is a complex nonlinear system with dynamic coupling, time-varying characteristics, and uncertain factors such as system modeling error, high frequencies, joint friction, and signal detection error. These objective realities lead to a deterioration of control system performance, thereby hindering conventional feedback technology from achieving control requirements. A neural network, which has nonlinear transformation characteristics and high parallel computation capability, can effectively identify manipulator system parameters, but cannot completely solve the uncertainty problems caused by such issues including robot manipulator modeling error and outside interference. To use neural networks for self-adaptive control of manipulator systems, other algorithms must be integrated, including sliding mode, robust, and intelligent controls. Present intelligent control algorithms based on knowledge rules and learning inference, such as fuzzy control, learning control, expert control, genetic, and particle swarm optimization algorithms have their own advantages in addressing system uncertainties. Furthermore, the integration of various control methods, enabling their learning from each other, and combining such methods organically to create new control methods have become an area of intense interest and a development trend related to the self-adaptive control of multi-fingered manipulators.

(4) Autonomous underwater navigation systems

Autonomous underwater vehicles are widely used and are the foundation of many scientific, industrial, and military underwater activities. Therefore, realizing high-precision positioning of underwater vehicles and the cooperative navigation of multiple underwater vehicles has developed into a research topic of international interest. Ultrashort baseline positioning systems, a type of underwater acoustic positioning technology with acoustic waves as the information carrier, have been widely used in recent years. The system receives a signal and calculates the underwater azimuth and distance based on the signal emitted from the underwater vehicle's sound beacon and the ultrashort baseline array on the surface of the water. Such a system provides a software scheme using an algorithm that is based on the Kalman filter, expansion card of the Kalman filter, or the dispersed extended information filter. The sensor elements, such as the inertial measurement units, fiber optic gyroscopes, and Doppler logs constitute the hardware of the system. The most important factor that affects system precision during underwater positioning and navigation is the estimation algorithm of the underwater vehicle motion, which affects not only the positioning and navigation results in the position error between the expected and execution paths, but also the geographic reference data obtained by the underwater vehicle. Therefore, the motion estimation algorithm of autonomous underwater vehicles must be precise and lightweight. In addition, the acoustic modem server, as an alternative to the ultrashort baseline array, also has considerable application potential in synchronous clock one-way-travel-time acoustic navigation based on single autonomous underwater vehicles.

(5) Thermal management technology of lithium-ion batteries

With the combined threat of energy crisis and environmental pollution, the development of electric vehicles has recently attracted much attention. Because of their numerous advantages, including high energy and power density, long cycle life, and low self-discharge ratio, lithium-ion batteries have become the best power source for electric vehicles. However, these batteries can generate considerable thermal energy and may even cause thermal runaway during the process of a high-current charge/discharge cycle. Improper utilization will greatly affect the performance, lifespan, and safety of lithium-ion batteries. Experiments and numerical simulations are generally used to analyze the thermal behavior of batteries and battery packs for ensuring superior thermal management. Given that an accurate thermal model is crucial for the numerical simulation analysis of lithium-ion batteries, the energy conservation, heat generation, and boundary conditions in these batteries must be accurately expressed and the electrochemical and equivalent circuit models must cooperate to allow the performance of auxiliary calculations. Currently, research on power battery cooling primarily focuses on air, liquid, phase changing material, boiling, and heat pipe cooling methods. Meanwhile, research on thermal management technology cannot be neglected since it provides key information as to whether lithium-ion batteries can be used normally in low-temperature and high-altitude regions. Each type of thermal management technology has advantages and disadvantages. For practical applications, all aspects, including the costs, complexity, weight, cooling capability, temperature uniformity, and parasitic power consumption must be considered for the effective thermal management of lithium-ion batteries.

(6) Global navigation satellite system optimization

GNSSs are widely used in military, navigation, mapping, exploration, transportation, and other fields. The reliability, response speed, and positioning accuracy optimization of GNSS technology are areas of international research focus. In recent years, GNSS technology has been largely used in automotive navigation, smartphones, and other consumer-grade products, thereby indicating a wide variety of application prospects. By extracting “pseudo-range” parameters from multiple navigation satellite signals, GNSS technology can achieve position estimation. However, the high density of buildings in cities blocks and interferes with satellite signals, thereby affecting the positioning accuracy and response speed of GNSS. Therefore, improving the robustness of GNSS under urban working conditions, in addition to optimizing their positioning and navigation accuracy are difficult. GNSS technology has been instrumental in improving positioning precision and response speed for urban road conditions in recent years. New technologies, such as 3D building model-assisted prediction, digital map-assisted identification, and shadow-matching algorithms, are important in the development of high-precision positioning in cities, and substantially improve the reliability of GNSS. However, this technology is still adversely affected by a series of complex working features, such as urban viaducts, bridges, and tunnels, which pose considerable challenges.

(7) Cognitive wireless networks

Cognitive wireless network is an advanced technology based on wireless networks. The key idea involves exploiting spectrum sensing, autonomous decision-making, and network reconfiguration to achieve dynamic spectrum allocation, thereby improving the efficiency of spectrum resource utilization and adapting to dynamic changes in the networks. Spectrum sensing is used to acquire free frequency bands by detecting spectrum usage information in a wireless network. Autonomous decision-making and network reconfiguration involve analysis of the available spectrum resources, adjustment of network parameters, and self-adaptive configuration based on real-time changes in user demand in addition to spectrum utilization strategies. Several new development directions have emerged in cognitive wireless networks in recent years. Firstly, the combination of cognitive wireless networks and power transfer has been used to enable networks to conduct simultaneous wireless transmission of information and electric power. Secondly, cooperative relay has been introduced into cognitive wireless networks; and the secondary users, as relays, assist the main users in the cooperative transfer of data and conduct information collaboration. Regarding the future of the Internet of Things (IoT) and intelligent transportation, dense wireless sensors and intelligent vehicles will result in an explosion of communication demand and a shortage of wireless spectrum resources. Cognitive IoT and cognitive Internet of Vehicles, which are both based on cognitive wireless networks, will be important tools in attempting to alleviate the increased burden on spectrum resources due to heavy utilization.

(8) Target recognition based on tactility

A robot can perceive the external environment or a target object using a fingertip tactile sensor. Tactile sensing can capture multiple object properties, such as texture, roughness, spatial characteristics, flexibility, and the friction of an object's surface. Thus, it has become an important sensing mode in the field of intelligent robots. Environmental perception based on tactility is crucial in operations that require delicate dexterous manipulation, such as contact-sensitive submarine welding. In actual robot operation, the manipulator usually has many fingers, and the tactile data of different fingers construct a sequence. The use of tactile sequence datasets is advantageous and considers the intrinsic relationship between multiple fingers. The development of the joint kernel sparse coding model and the kernel dictionary learning method have proven to be helpful in improving the performance of tactility-based object recognition. In addition, with the rapid development of intelligent robot technology, there is a desire to confer tactile perception capability to robots with a functionality similar to that of human skin, thereby improving the performance of intelligent bionic robots. Therefore, research on flexible tactile sensors has become a significant area of interest in tactile sensing, and the research and development of flexible multidimensional tactile sensors remain a difficult key point.

(9) Assessment and utilization of inshore wave energy resources

Inshore wave, as a type of renewable clean energy, has a high energy density and a wide distribution surface. The development and utilization of inshore waves are potentially important in resolving energy crises, environmental pollution, and climate change. Scientific research on inshore wave energy is primarily focused on two aspects. The first is evaluating wave energy reserves and the temporal–spatial distribution in the near coast, thereby providing effective guidance for the design of wave energy power stations and conversion devices. The second aspect refers to the design, development, and experiment related to wave energy conversion devices. At present, with regard to ocean wave field analysis and wave energy resource assessment in the global seas, the numerical simulation of ocean waves is the main means of acquiring wave parameters. However, its prediction precision is restricted by many factors. The capability to simulate a complex wave field is limited and there is a knowledge gap in the available field observation data. Thus, a field observation method that can generate long-term and high-range wave results is required to improve the accuracy of evaluation and to enrich extant evaluation methods. In addition, the marine environment is complex and variable, and waves have interesting inherent features such as instability, huge reserve, wide distribution, and difficult utilization. Thus, wave power devices applied to a marine environment are readily subjected to the vagaries of catastrophic marine climates. Therefore, assessment and utilization problems of inshore wave energy resources still need to be addressed in the theoretical research and device development aspects. These aspects include the comprehensiveness and improvement of the accuracy of wave energy assessment and prediction; design optimization and improvement of response speed, conversion efficiency, stability, and reliability of wave energy devices; and the reduction of manufacturing and installation costs.

(10) Electro/magnetic field enhancing nanofluid convective heat transfer

Nanofluid is a heat transfer cooling fluid formed by the addition of nanoparticles to a fluid. It has high thermal conductivity and good fluid following capability. The thermal effect of the system can be greatly improved in the process of heat convection with nanofluids. In recent years, heat convection enhanced by electro/magnetic field has gradually become an area of international research focus, based on traditional nanofluids. At present, with the aid of theory and numerical simulation methods, single-phase and multiphase flow heat transfer of nanofluids under electro/magnetic fields has been investigated in detail and is well understood. Particle size, shape, surface features, chemical properties of the particle and fluid, and the influential roles of electro/magnetic field characteristic parameters on the nanofluid convective heat transfer have been studied. However, because the force and flow status of nanoparticles in electro/magnetic fields is complex, the proposed theories and models cannot comprehensively account for the influential factors of heat convection. Therefore, advanced and accurate test methods should be implemented to experimentally study electromagnetic field enhanced nanofluid convective heat transfer such that abundant experiment data are accumulated. It is expected that this will result in an improvement of the nanofluid convective heat transfer model under electromagnetic fields. On such a basis, accurate clarification of a nanofluid convective heat transfer mechanism enhanced by electro/magnetic field is expected to improve its industrial application.

1.2 Interpretations for three key engineering research fronts

1.2.1 Self-adaptive tracking of autonomous underwater vehicles

With the wide application of autonomous underwater vehicles in marine scientific research and underwater target detection, self-adaptive tracking technology of autonomous underwater vehicles has elicited considerable attention from scholars, and several theoretical research and engineering practices have been implemented.

The tracking and controlling problem of autonomous underwater vehicles refer to the challenge of designing a controlling input for the controlled object, such that autonomous underwater vehicles can adhere to given reference tracks or paths under the inertial coordinate system from the initial status. The main issues are related to the track-and path-tracking problems; the difference between the two problems lies in whether the controlling input is related to the time when tracking reference paths. The former is clearly and strictly constrained by time. From a theoretical perspective, the track-tracking problem is more complex than the path-tracking problem.

According to the propeller configuration, research on tracking and control of autonomous underwater vehicles is divided into under-drive underwater vehicle tracking control and full-drive underwater vehicle tracking control. At present, most underwater vehicles fall into the category of under-drive underwater vehicle control, whose controlling system has an incomplete restriction. As for the specific tracking and control problems, scholars have performed research via Lyapunov's direct method, backstepping control method, cascade system controlling method, and cascade–backstepping combination method, among others. Currently, the main research trend has been to divide the current complex systems into several cascade systems following the specific tracking problem. From the stability principle of the cascade system and the self-adaptive backstepping method, the global uniform asymptotic stability of the control system and the adaptability to the parameter uncertainty are guaranteed when a relatively simple control rule is used.

Regarding the full-drive underwater vehicle tracking control problem, scholarly research via nonlinear control methods has included areas such as sliding mode control and feedback linearization, and intelligent control methods, such as fuzzy, neural network, and model predictive controls. The current research trend is to use the self-adaptive backstepping method to guarantee the overall uniform stability of tracking errors and to use the BP neural network method to solve the uncertainties of the fluid-dynamic parameters in the dynamic model of autonomous underwater vehicles.

In addition, according to the completion of tracking control research on single underwater vehicle, research on the tracking control problem of multiple underwater vehicles is the main development trend heading into the future. By using the coupled spatiotemporal sequential control strategy, the single underwater vehicle is guaranteed to be in its own expected tracking path, and the cooperative control law is introduced. Furthermore, the path parameter consistency algorithm is designed to accomplish the aim of coordinated tracking control of multiple underwater vehicles.

The countries or regions with the most core papers on self-adaptive tracking of autonomous underwater vehicles are China (3), India (1), South Korea (1), and Iran (1). The top three countries/regions with the highest average number of citations are India (19), South Korea (13), and China (11) (Table 1.2.1). Based on the sample data, major countries/regions that publish papers do not cooperate with each other (Figure 1.2.1). The institutions that published the core papers are Dalian Maritime Univ (2), IIT Delhi (1), NIT Rourkela (1), Anhui Sci & Technol Univ (1), Chosun Univ (1), and Islamic Azad Univ (1). It is seen that the top three institutions with the highest average number of citations are IIT Delhi (19), NIT Rourkela (19), and Chosun Univ (13) (Table 1.2.2). Among the institutions that published papers, IIT Delhi and NIT Rourkela cooperate with each other (Figure 1.2.2). The top three countries/regions with the most cited core papers are China (41), Iran (8), and India (4) (Table 1.2.3). The main institutions that publish the cited core papers are Harbin Engn Univ (12), Shanghai Jiao Tong Univ (10), and Dalian Maritime Univ (10) (Table 1.2.4).

Table 1.2.1 Countries or regions with the greatest output of core papers on the "self-adaptive tracking of autonomous underwater vehicles"

No.	Country/Region	Core papers	Percentage of core papers	Citation	Percentage of citations	Citations per paper
1	China	3	50.00%	33	44.00%	11.00
2	India	1	16.67%	19	25.33%	19.00
3	South Korea	1	16.67%	13	17.33%	13.00
4	Iran	1	16.67%	10	13.33%	10.00

Table 1.2.2 Institutions with the greatest output of core papers on the "self-adaptive tracking of autonomous underwater vehicles"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Dalian Maritime Univ	2	33.33%	21	28.00%	10.50
2	IIT Delhi	1	16.67%	19	25.33%	19.00
3	NIT Rourkela	1	16.67%	19	25.33%	19.00
4	Anhui Sci & Technol Univ	1	16.67%	12	16.00%	12.00
5	Chosun Univ	1	16.67%	13	17.33%	13.00
6	Islamic Azad Univ	1	16.67%	10	13.33%	10.00

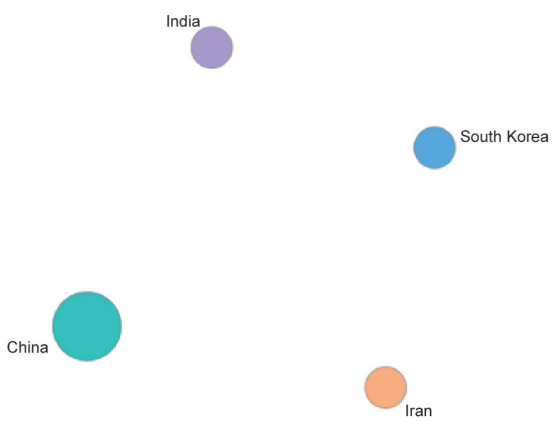

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "self-adaptive tracking of autonomous underwater vehicles"

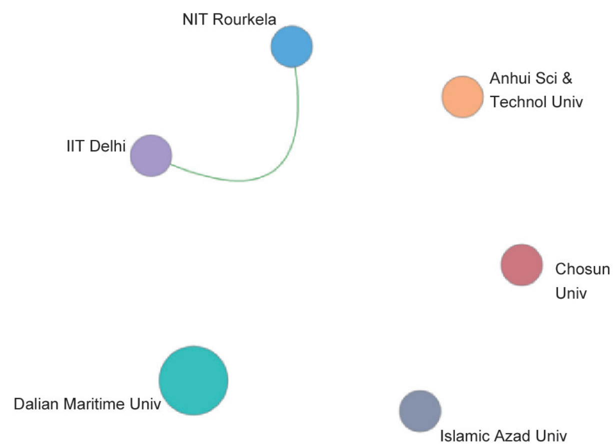

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "self-adaptive tracking of autonomous underwater vehicles"

1.2.2 Consistency control of the multi-agent systems

Consistency control of the multi-agent system refers to the design of a consistency protocol that enables each agent to interact with local information to achieve consistency of the target state value of all the agents. The research on consistency control is mainly divided into three areas, namely, the complexity of intelligent body dynamics, communication topology, and network information transmission. Multi-agent systems have been gradually applied in industrial multi-robot group coordination, UAV formation control, human group behavior regulation, and guidance, and wireless sensor network optimization in addition to theoretical research.

(1) Complexity of intelligent body dynamics

Different dynamic characteristics of intelligent bodies introduce difficulties in consistency research on multi-agent systems to

Table 1.2.3 Countries or regions with the greatest output of citing papers on “self-adaptive tracking of autonomous underwater vehicles”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	41	62.12%	2016.49
2	Iran	8	12.12%	2016.25
3	India	4	6.06%	2016.50
4	UK	3	4.55%	2015.67
5	South Korea	3	4.55%	2017.00
6	USA	2	3.03%	2017.00
7	Canada	2	3.03%	2017.00
8	Italy	1	1.52%	2015.00
9	Portugal	1	1.52%	2016.00
10	Malaysia	1	1.52%	2016.00

Table 1.2.4 Institutions with the greatest output of citing papers on the “self-adaptive tracking of autonomous underwater vehicles”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Harbin Engn Univ	12	23.53%	2016.50
2	Shanghai Jiao Tong Univ	10	19.61%	2016.70
3	Dalian Maritime Univ	10	19.61%	2017.30
4	Islamic Azad Univ	6	11.76%	2016.17
5	Minist Educ China	3	5.88%	2017.67
6	Northwestern Polytech Univ	2	3.92%	2015.50
7	Ocean Univ China	2	3.92%	2015.50
8	Dalian Univ Technol	2	3.92%	2015.50
9	Natl Inst Technol Rourkela	2	3.92%	2016.50
10	Amirkabir Univ Technol	2	3.92%	2016.50

various degrees. Isomorphic multi-agent systems are primarily investigated in research. In recent years, consistency research on heterogeneous multi-agent systems has increased with the main objective being to simultaneously output information to all intelligent bodies. Typically, consistency research usually consists of two aspects, namely, the design of a distributed isomorphic multi-agent system to achieve consistency control and the design of an output adjustment controller to achieve a reference system of output tracking design for each intelligent body. Considering the information type transmitted in the network, the two categories can be considered as two independent processes if the information referred to from the multi-agent system is transmitted in the network. If the output of intelligent body only exists in the information transmitted through the network, then the two categories are coupled and must be embarked upon simultaneously. As such, the consistency analysis will be more complex.

(2) Complexity of communication topology

Communication topology describes the interactive information relationship between intelligent bodies and can be abstracted into a figure. Therefore, algebraic graph theory knowledge is introduced to implement relevant analysis. Topology can be divided into fixed and time-varying topologies, based on whether the topology changes with time. Consistency research on multi-agent systems under fixed topology is a relatively mature field, whereas time-varying topology is still faced with numerous challenges. Based on the considerable body of research data, it is known that joint connectivity is the weakest assumption in the case of time-varying typology. For multi-agent systems with different types of dynamics, contemporary research usually adds additional assumptions to the joint connectivity topology and achieves consistency under static or dynamic collaborative control laws. Therefore, further research is needed.

(3) Complexity of network information transmission

Consistency in a multi-agent system depends on the information interaction between intelligent bodies. Interactive intelligent bodies must transmit the information associated with themselves throughout the network. Considering that information transmission is discontinuous in actual application, many sample collaborative controllers are designed to achieve consistency. To reduce the network transmission burden and to improve the network communication efficiency, a significant amount of research in recent years has focused on the consistency control problem under the event-driven strategy. One difficulty of the event-driven control is the analysis of the zeno phenomenon, especially for nonlinear multi-agent systems, because contemporary research has many limitations and requires further exploration.

The top three countries/regions with the most core papers on consistency control of multi-agent systems are China (10), the United States (8), and Italy (3). The top three countries/regions with the highest average number of citations are Australia (549), the United States (95.13), and China (82.9) (Table 1.2.5). In the top 10 countries/regions in terms of the number of publications, China has frequent cooperation with the United States, the Netherlands, and Russia (Figure 1.2.3). The top three institutions with the most core papers are the Chinese Acad Sci (6), Univ Calif Riverside (4), Catholic Univ Louvain (2), Univ Illinois (2), Huazhong Univ Sci & Technol (2), Univ Groningen (2), and Beijing Inst Control Engn (2). The top three institutions with the highest average number of citations are City Univ Hong Kong (549), RMIT Univ (549), and Southeast Univ (549) (Table 1.2.6). Among the Top 10 institutions in terms of the number of publications, Chinese Acad Sci and Univ Calif Riverside have frequent cooperation with Beijing Inst Control Engn (Figure 1.2.4). The top three countries/regions with the most cited core papers are China (597), the United States (181), and Australia (75) (Table 1.2.7). The main institutions that published the cited core papers are Chinese Acad Sci (63), Southeast Univ (51), and Univ Illinois (34) (Table 1.2.8).

1.2.3 Self-adaptive neural network control of manipulators

A manipulator is a typical nonlinear and time-varying system that has limited joint and task space. Some uncertainty factors such as system modeling error, high-frequency characteristics, joint friction, and signal detection error exist. These objective realities will lead to poor control system performance of a manipulator, thereby restricting the use of conventional feedback technology, such as robust control, the computed torque method, proportional–integral–differential (PID) control with independent joint, variable

Table 1.2.5 Countries or regions with the greatest output of core papers on the “consistency control of multi-agent systems”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	10	55.56%	829	69.26%	82.90
2	USA	8	44.44%	761	63.58%	95.13
3	Italy	3	16.67%	211	17.63%	70.33
4	Belgium	2	11.11%	76	6.35%	38.00
5	Netherlands	2	11.11%	34	2.84%	17.00
6	Russia	2	11.11%	34	2.84%	17.00
7	Australia	1	5.56%	549	45.86%	549.00
8	Sweden	1	5.56%	25	2.09%	25.00
9	France	1	5.56%	6	0.50%	6.00
10	Saudi Arabia	1	5.56%	28	2.34%	28.00

Table 1.2.6 Institutions with the greatest output of core papers on the "consistency control of multi-agent systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	6	33.33%	239	19.97%	39.83
2	Univ Calif Riverside	4	22.22%	634	52.97%	158.50
3	Catholic Univ Louvain	2	11.11%	76	6.35%	38.00
4	Univ Illinois	2	11.11%	52	4.34%	26.00
5	Huazhong Univ Sci & Technol	2	11.11%	48	4.01%	24.00
6	Univ Groningen	2	11.11%	34	2.84%	17.00
7	Beijing Inst Control Engn	2	11.11%	43	3.59%	21.50
8	City Univ Hong Kong	1	5.56%	549	45.86%	549.00
9	RMIT Univ	1	5.56%	549	45.86%	549.00
10	Southeast Univ	1	5.56%	549	45.86%	549.00

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "consistency control of multi-agent systems"

structure control, and self-adaptive control, from complying with control requirements. In recent years, researchers have used consistent approximation capability, parallel distributed processing, learning and self-adaptive capability, fault tolerance capability, and a structure that is easy to implement in hardware acquired from neural networks to conduct research on the control and identification of nonlinear systems and positive results were achieved. Such approaches are effective ways of addressing the uncertainties in solving manipulator modeling and control.

A neural network must experience abundant offline training before being implemented into a closed-loop system, thereby achieving a stable neural network control system of manipulators. Early research on neural network control

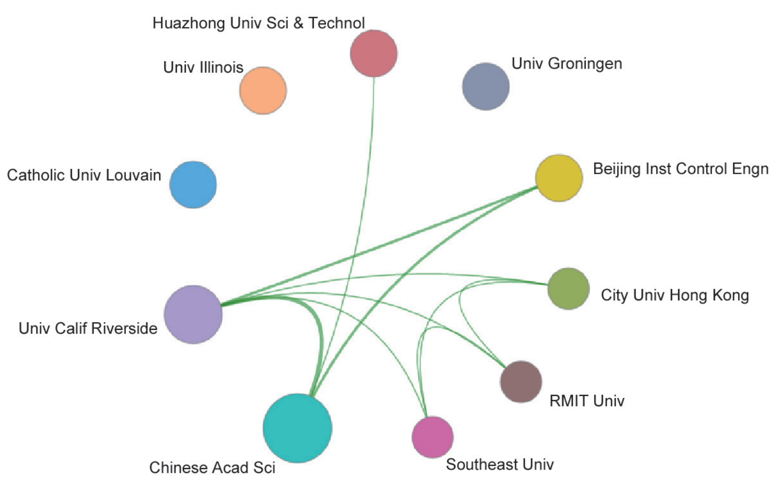

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "consistency control of multi-agent systems"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "consistency control of multi-agent systems"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	597	54.82%	2015.74
2	USA	181	16.62%	2015.74
3	Australia	75	6.89%	2015.88
4	Singapore	40	3.67%	2015.65
5	Italy	38	3.49%	2015.42
6	Netherlands	35	3.21%	2015.74
7	Sweden	35	3.21%	2015.74
8	UK	34	3.12%	2015.47
9	France	30	2.75%	2015.80
10	Russia	24	2.20%	2015.63

Table 1.2.8 Institutions with the greatest output of citing papers on the "consistency control of multi-agent systems"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	63	19.03%	2015.30
2	Southeast Univ	51	15.41%	2015.39
3	Univ Illinois	34	10.27%	2015.44
4	Nanyang Technol Univ	31	9.37%	2015.81
5	Peking Univ	28	8.46%	2015.46
6	Australian Natl Univ	27	8.16%	2016.19
7	City Univ Hong Kong	25	7.55%	2015.56
8	Shanghai Jiao Tong Univ	25	7.55%	2015.80
9	Huazhong Univ Sci & Technol	24	7.25%	2015.38
10	Univ Elect Sci & Technol China	23	6.95%	2015.30

was mainly focused on emulation and experiment analysis of specific cases and lacked the analysis of the stability, robustness, and convergence of closed-loop neural network control systems. The difficulty lies in the utilization of the nonlinear parameter network used when the function approaches neural network control system. When the selected initial neural network weight approaches the ideal weight, a multilayer neural network is used as the function to approach the neural network control, thereby guaranteeing the stability and convergence of the closed-loop system. To avoid the learning step of offline training, a neural network control method based on Lyapunov stability theory is successively initiated by researchers. The advantage is that the self-adaption of the neural network weight is gained by the Lyapunov analysis method, and offline training is not needed despite the stability of the closed-loop system being maintained.

Although the self-adaptive neural network has accomplished significant breakthroughs and progress, and movement-tracking control of a manipulator has already been applied, it cannot completely solve the uncertain problems caused by the robot manipulator modeling error and outside interference. In recent years, intelligent control algorithms based on knowledge rules and learning inference, such as fuzzy control, learning control, expert control and genetic algorithm, and particle swarm optimization-algorithm, have been widely studied. These approaches have their own advantages in addressing system uncertainties. Nevertheless, different control theories and methods have advantages and shortcomings. As such, achieving ideal control effects using a single method is difficult. Therefore, multiple control methods must be integrated, such that each method complements each other's limitations, and can be organically combined to form a new control method. Such a strategy is already well known in contemporary robot control research. Mixed methods with fuzzy neural network control, robust control of neural networks, fuzzy sliding mode variable structure control, and robust self-adaptive control as representatives examples, have already been developed and applied in the research on the control method of manipulators.

The country/region with the most core papers on self-adaptive neural network control of manipulators is China (3), with an average number of citations of 125.33 (Table 1.2.9). The institutions that published the core papers are Univ Elect Sci & Technol China (3), Univ Sci & Technol Beijing (2), and Southeast Univ (1). The top three institutions with the highest average number of citations are Southeast Univ (138), Univ Elect Sci & Technol China (125.33), and Univ Sci & Technol Beijing (119) (Table 1.2.10). Among the publication institutions, Univ Elect Sci & Technol China has frequent cooperation with Univ Sci & Technol Beijing (Figure 1.2.5). The top three countries/regions with the most cited core papers are China (216), the UK (27), and USA (17) (Table 1.2.11). The main institutions that published the cited core papers are Univ Sci & Technol Beijing (46), Univ Elect Sci & Technol China (34), and South China Univ Technol (31) (Table 1.2.12).

Table 1.2.9 Countries or regions with the greatest output of core papers on the "self-adaptive neural network control of manipulators"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	3	100.00%	376	100.00%	125.33

Table 1.2.10 Institutions with the greatest output of core papers on the "self-adaptive neural network control of manipulators"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Elect Sci & Technol China	3	100.00%	376	100.00%	125.33
2	Univ Sci & Technol Beijing	2	66.67%	238	63.30%	119.00
3	Southeast Univ	1	33.33%	138	36.70%	138.00

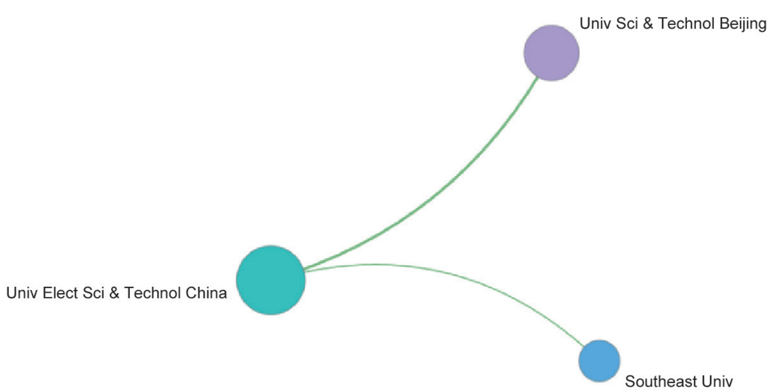

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "self-adaptive neural network control of manipulators"

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "self-adaptive neural network control of manipulators"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	216	68.14%	2016.77
2	UK	27	8.52%	2016.93
3	USA	17	5.36%	2016.76
4	Singapore	16	5.05%	2016.69
5	Canada	9	2.84%	2016.89
6	Iran	9	2.84%	2017.11
7	Japan	8	2.52%	2016.50
8	Australia	7	2.21%	2017.00
9	India	5	1.58%	2017.00
10	South Korea	3	0.95%	2016.67

Table 1.2.12 Institutions with the greatest output of citing papers on the "self-adaptive neural network control of manipulators"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Univ Sci & Technol Beijing	46	21.00%	2016.57
2	Univ Elect Sci & Technol China	34	15.53%	2016.50
3	South China Univ Technol	31	14.16%	2016.97
4	Liaoning Univ Technol	19	8.68%	2016.74
5	Chinese Acad Sci	17	7.76%	2016.76
6	Southeast Univ	15	6.85%	2016.73
7	Harbin Inst Technol	15	6.85%	2016.93
8	Natl Univ Singapore	14	6.39%	2016.71
9	Northwestern Polytech Univ	14	6.39%	2016.86
10	Swansea Univ	14	6.39%	2017.00

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The top 10 engineering research fronts studied in the field of mechanical and vehicle engineering involve mechanical engineering, ship and marine engineering, aeronautical and astronautical science and technology, weapon science and technology, power and electrical equipment engineering and technology, transportation engineering, and other disciplines (Table 2.1.1). The exploration of the traditional studies includes "microelectromechanical (MEMS) sensors," "gas turbines," "marine survey and positioning technology," "autonomous control of unmanned ground vehicles," "over-ocean communication, navigation, and positioning technology," "new generation of image display technology," and "takeoff, landing, and flying of aircraft." The emerging hotspots include "new ship propulsion systems" and "UAVs". Table 2.1.2 presents the data on the annual publication of papers from 2012 to 2017. UAV is the most significantly growing popular topic for papers published in recent years.

(1) MEMS sensors

The MEMS sensor, which is manufactured by a micromachining technology, is a new type of sensor and an important branch of MEMS devices. The MEMS sensor is a core and frontier technology that is currently being developed worldwide. In recent years, the rapid development of intelligent devices and systems has elicited the attention of a large number of research institutions toward high-performance MEMS sensors. MEMS sensors are available in a wide variety of form and can

Table 2.1.1 Top 10 engineering development fronts in mechanical field

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	MEMS sensors	227	5 716	25.18	2013.16
2	New types of ship propulsion system	152	884	5.82	2014.56
3	UAVs	460	12 880	28.00	2014.76
4	Gas turbines	265	3 870	14.60	2013.45
5	Marine survey and positioning technology	191	1 567	8.20	2013.75
6	Autonomous control of unmanned ground vehicles	70	1 591	22.73	2014.19
7	Over-ocean communication, navigation, and positioning technology	175	1 857	10.61	2013.81
8	New generation of image display technology	202	2 626	13.00	2013.68
9	Takeoff, landing, and flying of aircraft	99	955	9.65	2013.67
10	New types of engine technology	200	6 400	32.00	2013.52

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	2012	2013	2014	2015	2016	2017
1	MEMS sensors	82	81	29	21	9	5
2	New types of ship propulsion system	22	25	33	19	24	29
3	UAVs	55	63	54	102	138	48
4	Gas turbines	76	82	46	43	10	8
5	Marine survey and positioning technology	47	46	40	31	19	8
6	Autonomous control of unmanned ground vehicles	11	11	21	14	7	6
7	Over-ocean communication, navigation, and positioning technology	39	54	33	17	15	17
8	New generation of image display technology	49	50	48	32	17	6
9	Takeoff, landing, and flying of aircraft	27	19	26	15	11	1
10	New types of engine technology	67	35	53	29	4	12

be divided into several types in accordance with the measured quantity, including systems designed to measure acceleration, pressure, displacement, flow, electromagnetic field, image, temperature, gas composition, and ionic concentration. The MEMS sensor, as a key device for information acquisition, plays a significant role in promoting the miniaturization of various sensor devices, which have been widely used in aerospace, biomedicine, and consumer electronics. At present, with the introduction of new materials such as nanomaterials, biological materials, and intelligent materials, in addition to the continuous development of nanomanufacturing technology, the MEMS sensor is rapidly developing into a high-precision, high-reliability, and multi-functional integration, intelligence, and micro-power consumption. In addition, the emergence of the IOT has greatly increased the demands for wireless MEMS sensors, and the power supply of these devices has become a key point. An energy-harvesting chip is used to transform solar, wind, vibration, and thermal energies to electrical energy, thereby driving the wireless sensor module and realizing the passivity of MEMS sensors, which will become a significant development tendency.

(2) New types of ship propulsion system

At present, “prime mover–drive system–propeller” is the most widely used propulsion mode for naval and merchant ships. This mode possesses the advantages of high power and a mature design method and manufacturing process. However, several disadvantages are also revealed in the process of ship development, such as the complicated coupled vibration between the hull and propeller shaft of a large-scale marine and the insufficiency of the multi-direction and maneuverability of the underwater vehicle. In the future, the water–road–air triphibious vehicle will need a propeller that can adapt to multiple environments; the vibration and noise of the propeller shaft are universal problems that restrict the stealth capability of submarines. Under these circumstances, the development of a high-efficiency and reliable ship propulsion system has become a hotspot and difficulty. The new type of propulsion system has the characteristics of integration, simulation, high efficiency, and intelligence. Firstly, electrical energy is mostly used as the power and concentrates on the improvement of motor efficiency and power density. The induction, switch reluctance, permanent magnet, and superconducting motors have successively been demonstrated. Low-speed motor topology optimization, water environment adaptability, and high-precision control are the main research focus. The new flow passage component is the key to improving the efficiency of the new type of propulsion system, such as the co-axial contra-rotating propeller, pump spray pipe–impeller–guide vane, and inner blade of the shaftless propeller. The specific flow passage structure leading to the complicated coupled and non-steady flows lacks the relevant flow field description and design theory support. The shaft technology with a high load and long period is the key security technology of the new propulsion system. The development of new shaft materials and structure targeted to low speed, heavy load, and sediment environment are key aspects. The intelligent control technology of the new propulsion system is also the future research focus. In addition to realizing the motor speed of the propulsion system, the control of the simulation structure and vector motions also involves the operation control of the “propelling device–ship” system.

(3) UAVs

A UAV often maintains its movement in the air through the lift force generated by fixed or rotor wings. With the rapid development of this field in recent years, research interest has transitioned from designing a simple platform and application technology to the design of multiple platforms and complicated function technologies. A heterogeneous UAV group collaborative operation technology is an attractive and challenging present research direction. Such a group constitutes a complicated multi-agent model, which includes fixed and rotor wings. Meanwhile, the weight of the airplane can also vary, and the UAV in the cluster cannot be considered as a rigid body; the effects of aeroelasticity on clustering must also be reflected in the multi-agent model. To reduce the energy consumption and improve the flight efficiency and reliability, the aerodynamic interference between UAVs in the collaborative flight must be considered. As such, this leads to the establishment of the technical requirements for route optimization, autonomous navigation control, collision avoidance, and intelligent obstacle avoidance. In addition, some new developments have been generated for special occasions, such as foldable wings for transport or launch, tilt-rotor UAV technology for vertical takeoff and landing, and unmanned vehicle technology designed for logistics, which are all part of the development frontiers of UAV technology.

(4) Gas turbines

A gas turbine is often used in ships (mostly naval), vehicles (large vehicles, such as tanks and engineering vehicles), and generator units. In recent years, research on gas turbines has mainly focused on improving the combustion chamber structure and the combustion technology to increase efficiency and reduce emissions, and for combining advanced intelligent detection algorithms and sensor technology for real-time state detection and fault diagnosis. With the continuous enhancement of environmental protection requirements, high efficiency and low emissions have become important performance indicators for assessing the advanced performance of gas turbines. By optimizing and improving the cooling structure design in the combustion chamber, and by increasing the lightweight interstitial cooling and reheating circulation system with compact heat exchange efficiency, the performance of the engine can be effectively improved. However, the complicated structure system and increased components lead to a large-scale increase in the cost of the engine quality, manufacturing, and maintenance. All these technical bottlenecks hinder the increase in efficiency and reduction of emission of gas turbines. As a typical complicated mechanical system, the gas turbine has complicated structure forms, adverse working conditions, and various inevitable mechanical failures. All types of faults, such as vibration and friction wear of the failed rotating parts of the gas path of the engine, seriously affect the safety, reliability, and efficiency of a gas turbine. The status diagnosis of the complicated gas turbine system is challenging. Modeling a solution based on traditional classical mathematics theory is difficult because of the strong nonlinearity, instability, and uncertainty. Rapidly developing intelligent algorithms, such as neural network, genetic algorithm, and expert system provide new solution concepts for these types of problems. These solutions are expected to realize localization and determination efficiently through fault detection with limited parameters.

(5) Marine survey and positioning technology

The oceans are abundant with natural resources and are a substantial site for geological research. In recent years, the ocean has received increasing attention due to its huge economic potential and important strategic status. Marine surveys are important means of obtaining ocean environment, resource, energy, and equity information. With marine enterprise development, the new generation of detection technology allows for the technical reassurance of high-precision ocean detection. High-precision navigation and positioning are the bases for high-precision ocean detection. Accurate navigation positioning of mother ships and the accurate navigation positioning for underwater detection systems are necessary to achieving high-precision navigation positioning. The commonly used marine detection and positioning technologies are tow sonar, sky-wave radar, antenna array, and gyroscope. Naval vessels equipped with tow sonar can maintain a certain patrol speed while controlling the surrounding underwater environment. Sky-wave radars possess remote detection capability and can determine the surface characteristics, undersea targets, and overseas targets within a range of 800–3500 km. Antenna array can be used to detect parameters such as the salinity of ocean waters. An inertial navigation system that consists of a gyroscope can measure the 3D attitude of the current carrier in real time. Detection and positioning often cannot be performed alone due to the limitations that exist in single detection and positioning systems. Composite systems that focus on the advantages of multiple detections and positioning systems are increasing in number and are part of the future development trend.

(6) Autonomous control of unmanned ground vehicles

The development of intelligent automotive technology has simplified driving operations and improved steering security and is thus being gradually adopted. One of the most typical and popular future applications is unmanned cars. The autonomous control of unmanned cars realizes a driverless system through artificial intelligent technology, radar, mathematical calculations, monitoring device, and the navigation system. Currently, the development focus of the autonomous control of unmanned cars mainly includes high-precision positioning, GPS, environment awareness, obstacle avoidance, and automatic parking systems. The bottlenecks for the industrial production of unmanned cars are mainly related to technical problems, cost, driving behavior, laws, and regulations. The mass production of unmanned cars must experience four stages, namely, driver-assisted, semi-autonomous, highly automated, and full self-driving. Regardless of various problems of the industrial production of unmanned cars, their essence is established based on an automotive active safety technology and the gradual upgrade of the intelligent technologies. As long as the demand for these technologies is constant, the evolution of the automobile into a completely unmanned autonomous vehicle will be sustained.

(7) Over-ocean communication, navigation, and positioning technology

With the rapid development of large ships and increasing traffic density and loading capacity, maritime traffic accidents and economic losses are increasing, and shipping safety and marine ecology are gradually being threatened. Over-ocean communication, navigation, and positioning technologies play important roles in the maritime industry. They provide a strong reassurance of rapid and safe development of the maritime military transport industry, maritime tourism, coastal fishery, and other industries. As a part of over-ocean communication, over-ocean navigation and positioning technology are mainly attributed to the GPS of the United States, GLONASS of Russia, Galileo of Europe, and BeiDou Navigation Satellite System of China. The accuracy-response speed reliability of navigation positioning and the stability security of communication positioning are the main development direction of this technology. Moreover, over-ocean communication technology includes over-ocean wireless, over-ocean satellite, shore-based mobile, and integrated ocean communication systems. At present, the problems of small coverage, low transmission efficiency, poor communication reliability, and high communication cost remain. In recent years, 5G mobile communication, three-path ocean channel model, and microwave scattering technologies have significantly improved over-ocean communication efficiency, quality, and distance. The long-term development direction of this marine communication technology is predicated on building a long-distance communication rate with wide transmission range, high reliability, and low price.

(8) New generation of image display technology

Eighty percent of the information acquired by human beings comes from vision, images, and image treatment and displays, which are widely utilized in industry, medicine, aerospace, and the military. The frontier focus of the new generation of image display technology includes infrared imaging technology, true-color night vision technology, and displays for 3D imaging. Using multi-spectral, multi-system, multi-mode, polarization imaging, distributed networking, and multi-sensor data fusion, infrared imaging detection systems aim to quickly obtain and exploit multi-dimensional dynamic information of various targets to precisely identify and track them. Thus, the infrared imaging detection system enters a new stage of high-resolution, large field of view, multi-dimensional and multiple sensors working together. True-color night vision can restore the true color of a scene at night, overcoming the limitations of traditional night vision imaging, such as colorlessness, dark luminance, and weak contrast ratio. Existing studies are mainly based on image fusion and color conversion to realize true-color night vision. 3D imaging can display such object information as depth perception, layering, and spatial position. This system helps in obtaining 3D information consistent with real objects, which include 3D, holographic 3D, and integrated imaging 3D displays. 3D display technology is a frontier research direction of the international electronics industry. Rapid development of the photoelectronic industry will drive the industrialization process of 3D display technology.

(9) Takeoff, landing, and flying of aircraft

Aircraft are widely used in the fields of transportation, prospecting survey, and military reconnaissance. The current development focuses on aircraft technology include vertical takeoff and landing, and flying control. The former includes low altitude flight of the aircraft, performance at low speed, vertical takeoff and landing, and hovering function. The latter includes the autonomous control of the aircraft, which involves body design, environment perception, map, positioning, navigation, and obstacle avoidance. In recent years, the development orientation of aircraft has primarily entailed the unmanned aircraft aspect, i.e., to realize intelligent autonomous control and to improve the autonomy, adaptability, and stability of an aircraft. In addition, cooperative reconnaissance, cooperative tracking, and collision warning among multiple aircraft are realized to form a multi-machine cluster system. By focusing on the polygonality of the environment information and the diversity of tasks, flight management systems conduct trajectory planning and action deployment of aircraft. This process realizes the routine and attitude real-time control of single aircraft and cluster control of multiple aircraft. In addition, to adapting to the swift multiple-task environment, the variable configuration design of the aircraft shape, power system at high altitude long endurance, high anti-interference multi-modal control, high-speed and high-precision path tracking adaptive control, obstacle detection, and prediction and avoidance during motion are the development direction of future aircraft technology.

(10) New types of engine technology

An engine is a device that converts the heat generated through fuel combustion into mechanical energy by changing the state of the working medium, thereby powering a system and determining the economic stability and environmental protection of this system. In recent years, the engine, driven by a new type of technology, has developed toward increased efficiency and reduced oil cost and pollution. Direct injection technology optimizes the intake mixing efficiency and achieves a high-power output with high efficiency. Variable valve timing technology can provide the required high-speed power and low-speed torque. Meanwhile, supercharging technology can increase combustion efficiency, save fuel, and improve emissions in the entire rotation range. Exhaust gas recirculation technology substantially reduces mechanical and pump losses, while reducing emissions. Finally, variable pump technology can automatically change the flow rate of the coolant in the engine's cylinder (based on temperature), to meet the cooling demand of the engine under different working conditions, and reduce energy consumption. The research and development of a new engine technology to improve engine power performance, reduce fuel consumption, and reduce pollution remain the primary area of interest in the engine engineering development field. Under the demand of environmental protection and energy saving, miniaturization and weight reduction have also become main trends of engine development. In addition, the integration of sensor and big data analysis technology to monitor engine health has become a frontier technology related to improving engine reliability.

2.2 Interpretations for three key engineering development fronts

2.2.1 MEMS sensors

MEMS are micro-devices or systems that integrate micro-sensors, micro-actuators, micromechanical structures, micro-energy, signal processing and control circuits, interfaces, and communications. These systems are widely used in high-technology industries. MEMS are a key technology that relate to national technological development, economic prosperity, and defense security. The MEMS sensor is an important branch of MEMS devices. In 1962, the advent of the first silicon micro-pressure sensor pioneered the use of MEMS technology. Since 2000, various micro-sensor components have appeared in the fields of acoustics, optics, biology, and energy. MEMS sensors are varied and can be divided into physical, chemical, and biological types in accordance with their working principles. Based on the measured parameter, MEMS can be divided into different sensor types including acceleration, pressure, displacement, flow, electromagnetic field, image, temperature, gas composition, and ion concentration. MEMS sensors are also widely used in numerous disparate fields. As a key component of information acquisition, MEMS sensor technology has promoted the miniaturization of various sensing devices and have been adopted in aerospace, automotive, biomedical, and consumer electronics.

In recent years, under the multiple roles of market guidance, technology promotion, venture capital, and government intervention, MEMS sensor technology has developed rapidly. With the continuous development of new principles, materials, and technologies, new products based on MEMS sensors continue to emerge. At present, MEMS sensors are developing toward the objective of high-precision, high-reliability, multi-function integration, intelligence, miniaturization, and micro-power consumption. By using new materials such as SiC, sapphire, diamond, and SOI, various new MEMS sensors with high reliability have been developed with desirable properties which include high-temperature resistance, corrosion resistance, and radiation endurance. Nanotubes, nanowires, nanofibers, photoconductors, superconductors, and smart materials may eventually form the basis materials for the creation of the next generation of MEMS sensors. New MEMS fabrication and assembly technologies enable MEMS sensors to be small and have low power consumption, improved performance, and vibration and shock resistance. Through specialized integrated design and process, sensitive circuit components can be fabricated on the same chip to facilitate signal detection and processing, which constitutes a powerful intelligent sensor that can realize the required sensor miniaturization and integration. Sensor integration is an important requirement for the miniaturization, intelligence, and versatility of sensors. MEMS sensors have always been the hotspot and focus of research, and are the core and cutting-edge technology developed by several countries, thereby attracting the attention of research institutions, universities, and companies. The world's major countries, such as the United States, Germany, and Japan, regard MEMS sensor technology as a strategic research field. These nations have formulated development plans and have invested substantially in special research, which has shown significant leading advantages. Some universities and research institutions in China have begun to develop and study MEMS sensor technology, but they still lag behind foreign entities in terms of sensitivity, reliability, and new technology capabilities. Numerous MEMS sensor types, which require further improvement, are not yet produced in batches and are far from being practical and commercialized.

The top three countries/regions with the most public core patents in engineering development devoted to MEMS sensors are the United States (105), Germany (34), and Japan (32). The top three countries/regions with the greatest average number of citations are Canada (44.5), the Netherlands (30.33), and the United States (27.15), as shown in Table 2.2.1. Among the top 10 countries/regions with the highest number of public core patents, the United States cooperates with both France and China, as shown in Figure 2.2.1. The top three institutions with the highest number of public core patents are BOSC (17), FAID (17), and INFN (11), as presented in Table 2.2.2. Among the top 10 institutions with the highest number of public core patents, FAID, and Shortcut Semiconductor Suzhou Co., Ltd. have frequent cooperation, as shown in Figure 2.2.2. Nineteen core patents related to engineering development devoted to MEMS sensors are public in China, and the mainland institution that is often in public is Shortcut Semiconductor Suzhou Co., Ltd.

2.2.2 New types of ship propulsion system

(1) Bionic propulsion system

Bionic propulsion has significant advantages in promoting efficiency and adapting to special environments. Therefore, the development of bionic propulsion technology is a valuable component in the development of high-performance underwater vehicles. Studies on the investigation of fish-like fluctuations and bionic jet propulsion have been conducted internationally. Research on fish wave propulsion is focused on the swimming propulsion mechanism and fish bionic experimental research. The studies on fish bionic spray propulsion mode involves the analysis of the propulsion mechanism and movement mode of jellyfish, and the corresponding design driving mechanisms for propulsion devices. A multi-tail–fin coordinated propulsion method that organically combines wave and jet propulsion modes is also available. In addition, new propulsion mechanisms have been developed, such as turtle-like and duck-like propulsions, which are based on lift flapping movement. The technical difficulties of bionic propulsion systems are related to the development of a propulsion mechanism with high efficiency, high mobility, low noise, and strong environmental

Table 2.2.1 Countries or regions with the greatest output of core patents on the "MEMS sensors"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	105	46.26%	2 851	49.88%	27.15
2	Germany	34	14.98%	808	14.14%	23.76
3	Japan	32	14.10%	822	14.38%	25.69
4	China	19	8.37%	371	6.49%	19.53
5	France	6	2.64%	125	2.19%	20.83
6	South Korea	6	2.64%	94	1.64%	15.67
7	Taiwan of China	4	1.76%	82	1.43%	20.50
8	Italy	3	1.32%	51	0.89%	17.00
9	Netherlands	3	1.32%	91	1.59%	30.33
10	Canada	2	0.88%	89	1.56%	44.50

Table 2.2.2 Institutions with the greatest output of core patents on the "MEMS sensors"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	BOSC	17	7.49%	385	6.74%	22.65
2	FAID	17	7.49%	475	8.31%	27.94
3	INFN	11	4.85%	248	4.34%	22.55
4	TOKE	7	3.08%	182	3.18%	26.00
5	FRSE	6	2.64%	170	2.97%	28.33
6	HONE	6	2.64%	123	2.15%	20.50
7	ROEC	6	2.64%	141	2.47%	23.50
8	SHIH	6	2.64%	152	2.66%	25.33
9	SHOR	5	2.20%	121	2.12%	24.20
10	SMSU	5	2.20%	78	1.36%	15.60

BOSC: Robert Bosch GmbH; FAID: Fairchild Semiconductor Corporation; INFN: Infineon Technologies AG; TOKE: Kabushiki Kaisha Toshiba; FRSE: Freescale Semiconductor Inc.; HONE: Honeywell International Inc.; ROEC: Rosemount Aerospace Inc.; SHIH: Seiko Epson Corporation; SHOR: Shortcut Semiconductor Suzhou Co., Ltd.; SMSU: Samsung Electronics Co., Ltd.

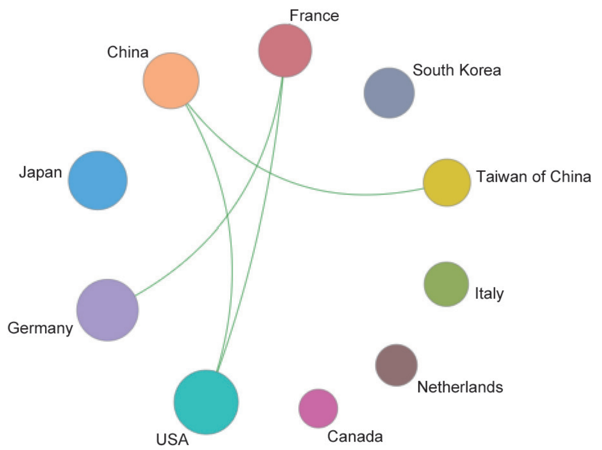

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "MEMS sensors"

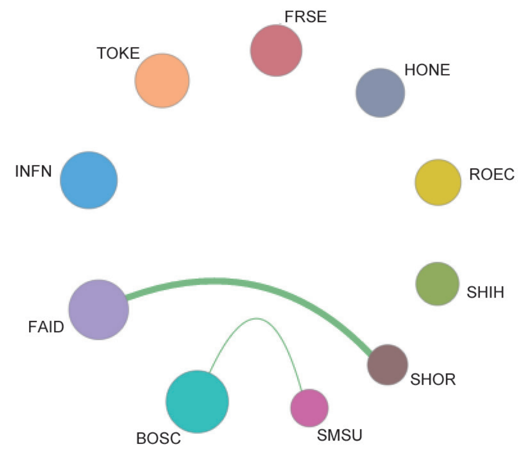

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "MEMS sensors"

adaptability, in addition to the adoption of effective and energy-saving means of driving.

(2) Robot fish

The propulsion model and body shape of bionic robot fish are concealed and feature maneuverability, speed, propulsion efficiency, and low noise. In some special occasions, such as underwater detection and tracking, seabed detection, and water quality monitoring, the model has advantages that render it distinctly superior to traditional propeller systems. Bionic robots can be divided into body and/or caudal fin propulsion (BCF) and media and/or paired fin propulsion (MPF) modes based on the body parts that mimic the propulsive movement of a fish. The BCF mode is suitable for most fish. Fish with the MPF mode have better maneuverability, higher stability, and stronger anti-interference capability compared to BCF mode, which is a key area of interest in future research of robot fish. The literature regarding robot fish focuses on the following: ① improved speed and propulsion efficiency of robot fish, ② improved flexibility and mobility of robot fish, ③ capability to float and dive rapidly, ④ intelligent control algorithm for robot fish, and ⑤ load and endurance. The design and development of the system fuses various disciplines, such as mechanics, optics, electronics, automatic control, material technology, sealing technology, and fluid mechanics.

(3) Vector propulsion system

A vector propulsion system adopts thrust vector technology to provide the required pitching force, moment, and yaw force by directly changing the thrust direction. The aim is to provide the control force instead of the ship's gymnastics rudder method, thereby demonstrating the advantages of space saving and flexible swinging. From the perspective of realizing vector propulsion function, various solutions have emerged, including multi-propeller cooperation, mechanical guide-plate vector water jet propulsion, straight-wing propulsion, and vector propeller propulsion schemes. Among them, the vector-propeller propulsion scheme has attracted the most research attention, and the gear, linkage, spherical parallel, screw-nut, and hydraulic mechanisms are currently available. Under the condition of large thrust, improving the stiffness, control precision, and seawater corrosion resistance and reducing the navigation resistance of the vector mechanism are the main research focus. To establish the ship vector thruster–fluid system dynamics model and propose a multi-objective motion–force–energy system, the multi-variable collaborative design method and reliable motion control technology are considered the future development directions.

(4) Electric propulsion system

The main feature of the ship's electric propulsion system is the use of a ship-integrated power station to provide propulsion power, auxiliary machinery, and daily power to an entire ship, and to complete the ship maneuvering system and related tasks with the highly comprehensive economy and reliability. This process can improve the effective cabin area and operability. The technical development of the marine electric propulsion system is mainly focused on the efficiency of the propulsion device, greenization of the power source, and intelligentization of the control system. Currently, the commonly used electric propellers are the pod and full-rotating propellers, with the former being more integrated than the latter and can coaxially convert electrical energy to mechanical energy. High-power pod propellers face several challenges, including large resistance of appendages, high bearing temperature, and sealing failure. Shaftless rim propulsion systems with integrated motor and propeller have high power density and low noise and have become a research hotspot of the new generation of electric propellers. The main sources of electrical energy are diesel generator sets, power batteries, shore-based power supplies, fuel cells, and solar energy. The new high-efficiency thermal power generation system also has a broad prospect of development.

(5) Deformable propulsion system of amphibious robot

The deformable propulsion system of an amphibious robot achieves high maneuverability and environmental adaptability in its underwater and terrestrial amphibious environments by integrating various conventional propulsion methods and using autonomous switching of configuration transformation and motion mode. By utilizing the modular structure to change its own configuration, this system can stimulate the underwater swimming gait and land motion of natural creatures based on the bionic principle. In accordance with the walking mechanisms of amphibious robots, the current amphibious robots can be divided into spherical, leg-type, wheel paddle, and snake-shaped. International exploratory research has been conducted on the amphibious robot propulsion mechanism and some progress has been achieved to date. However, the service performance indicators, such as speed, mobility, and terrain adaptability, are relatively poor, and the amphibious activity capability is difficult to guarantee. To develop a practical amphibious robot propulsion system, the problems of composite propulsion system modeling, design, and implementation; motion control and optimization of the amphibious composite propulsion mechanism; and the autonomous switching mechanism of water and land motion mode must be resolved.

The top three countries/regions with the most public core patents in the engineering development devoted to new propulsion systems for ships are China (109), South Korea (18), and the United States (11). The top three countries/regions with the highest average number of citations are the United States (9.36), Japan (7.88), and Germany (5.8), as presented in Table 2.2.3. Among the top countries/regions with the highest number of public core patents, the United States frequently cooperates with South Korea, as shown in Figure 2.2.3. The top three institutions with the highest number of public core patents are HYMR (17), Hangzhou Changdong Intelligent Technology (13), and CHSB (6), as presented in Table 2.2.4. The top 10 institutions with the highest number of public core patents do not cooperate with each other, as shown in Figure. 2.2.4. A total of 109 core patents related to engineering development was devoted to the new propulsion systems for ships, are public in China, and the mainland institution often in public is Hangzhou Changdong Intelligent Technology.

2.2.3 UAVs

(1) Development of flight platform technology

Present UAV multi-platforms are mainly composed of fixed wings, rotors, and multi-rotors. Their technology is relatively mature and widely used. In particular, the multi-rotor UAV accounts for 90% of the market. In recent years, vertical takeoff and landing UAVs that combine fixed wings and rotors have been developed. They are equipped with two rotors on both sides of the fixed wings. The rotors work when taking off, and the fixed wings work during flat flight, which can complete

Table 2.2.3 Countries or regions with the greatest output of core patents on the “new types of ship propulsion system”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	109	71.71%	612	69.23%	5.61
2	South Korea	18	11.84%	83	9.39%	4.61
3	USA	11	7.24%	103	11.65%	9.36
4	Japan	8	5.26%	63	7.13%	7.88
5	Germany	5	3.29%	29	3.28%	5.80
6	Taiwan of China	2	1.32%	8	0.90%	4.00

vertical takeoff and landing, and air hovering. The tilting rotors on both sides can also increase thrust during flat flight. However, the rotor has a limited lift and the take-off weight is small due to the small blade radius of the rotor. Therefore, an important research direction is the improvement of the take-off weight. Switching between the fixed-wing and rotor modes during the operation of such a UAV is also an important research direction. In addition, the UAVs used in special working environments, such as foldable configuration and nano-UAVs are also hotspots in in-depth research.

(2) Multi-UAV cluster collaboration technology

At present, most of the research on UAVs is concentrated on a single platform technology, and a group of multi-UAVs can realize functions that numerous units cannot achieve separately. The UAVs that form part of the group are not limited by the difference in configuration and take-off weight. Consequently, heterogeneous multi-UAV cluster collaboration technology has attracted considerable attention. Multi-agent collaborative control technology is common in ground robots, but its control methods are mostly based on rigid body control modeling. Moreover, its research objects are typically two-degree-of-freedom motion. In the cooperating UAV group, a single UAV cannot be considered as a rigid body. The aeroelasticity influence

Table 2.2.4 Institutions with the greatest output of core patents on the “new types of ship propulsion system”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	HYMR	17	11.18%	68	7.69%	4.00
2	HANG	13	8.55%	14	1.58%	1.08
3	CHSB	6	3.95%	49	5.54%	8.17
4	UHEG	5	3.29%	32	3.62%	6.40
5	HOND	4	2.63%	33	3.73%	8.25
6	UNWP	4	2.63%	29	3.28%	7.25
7	CAZD	3	1.97%	34	3.85%	11.33
8	CSHI	3	1.97%	22	2.49%	7.33
9	MITO	3	1.97%	20	2.26%	6.67
10	BRUH	2	1.32%	8	0.90%	4.00

HYMR: Hyundai Motor Company; HANG: Hangzhou Changdong Intelligent Technology Co., Ltd; CHSB: Hudong-Zhonghua Shipbuilding (Group) Co., Ltd.; UHEG: Harbin Engineering University; HOND: Honda Motor Co., Ltd; UNWP: Northwestern Polytechnical University; CAZD: Institute of Automation Chinese Academy of Sciences; CSHI: 719th Research Institute of China Shipbuilding Industry Corporation; MITO: Mitsubishi Heavy Industries Ltd.; BRUH: Brunswick Corporation.

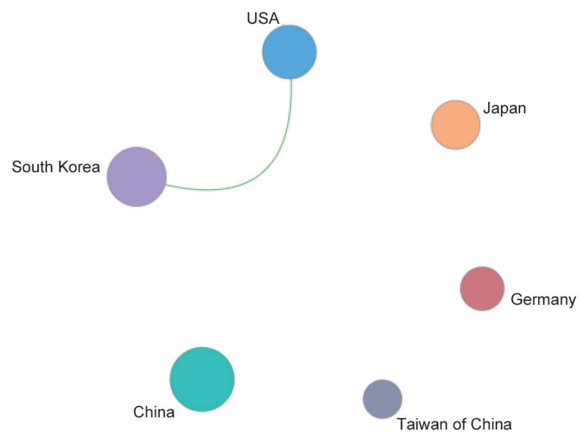

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “new types of ship propulsion system”

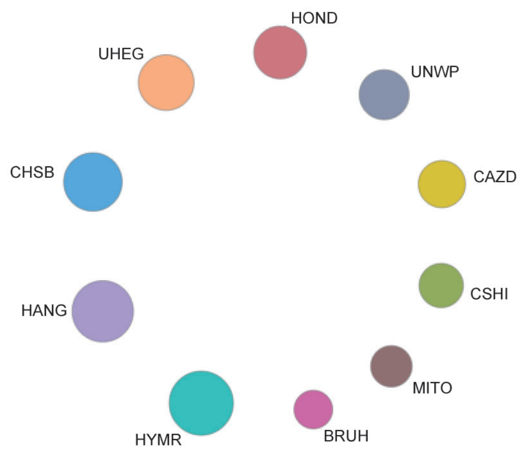

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "new types of ship propulsion system"

on the UAV group must also be reflected in the multi-agent model. The UAV group is a multi-body dynamic model that is based on six-degree-of-freedom motion. Therefore, in the investigation of multi-UAV cluster coordination technology, anti-collision, and intelligent obstacle avoidance are important research fields in addition to track optimization and autonomous flight navigation control. Furthermore, airborne micro-sensors, multi-machine coordinated flight/task management systems, and dynamic data fusion technologies based on intelligent algorithms should be investigated.

The top three countries/regions with the most public core patents in the engineering development devoted to UAVs are the United States (249), China (62), and Canada (8). The top three countries/regions with the highest average number of citations are Switzerland (50.33), Canada (40.88), and the United Kingdom (38.5), as presented in Table 2.2.5. Among the top 10 countries/regions with the highest number of public core patents, the United Kingdom frequently cooperates with Germany, as shown in Figure 2.2.5. The top three institutions with the most public core patents are DJII (34), BOEI (31), and GOOG (16), as presented in Table 2.2.6. The top 10 institutions with the most public core patents do not cooperate with each other, as shown in Figure 2.2.6. Sixty-two core patents related to the engineering development devoted to UAVs are public in China, and the mainland institution often in public is DJII.

Table 2.2.5 Countries or regions with the greatest output of core patents on the "UAVs"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	249	67.12%	6 740	68.21%	27.07
2	China	62	16.71%	1 428	14.45%	23.03
3	Canada	8	2.16%	327	3.31%	40.88
4	Germany	7	1.89%	195	1.97%	27.86
5	France	7	1.89%	163	1.65%	23.29
6	UK	6	1.62%	231	2.34%	38.50
7	South Korea	5	1.35%	62	0.63%	12.40
8	Israel	4	1.08%	144	1.46%	36.00
9	Switzerland	3	0.81%	151	1.53%	50.33
10	Italy	3	0.81%	78	0.79%	26.00

Table 2.2.6 Institutions with the greatest output of core patents on the "UAVs"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	DJII	34	9.16%	884	8.95%	26.00
2	BOEI	31	8.36%	867	8.77%	27.97
3	GOOG	16	4.31%	585	5.92%	36.56
4	AMAZ	12	3.23%	123	1.24%	10.25
5	VEZN	12	3.23%	373	3.77%	31.08
6	EADS	11	2.96%	252	2.55%	22.91
7	HONE	8	2.16%	449	4.54%	56.13
8	QCOM	8	2.16%	81	0.82%	10.13
9	UNMA	8	2.16%	138	1.40%	17.25
10	DISY	6	1.62%	240	2.43%	40.00

DJII: SZ DJI Technology Co., Ltd.; BOEI: Boeing Co.; GOOG: Google Inc.; AMAZ: Amazon Technologies Inc.; VEZN: Verizon Patent and Licensing Inc.; EADS: EADS Deutschland GmbH; HONE: Honeywell International Inc.; QCOM: Qualcomm Incorporated; UNMA: Unmanned Innovation Inc.; DISY: Disney Enterprises Inc.

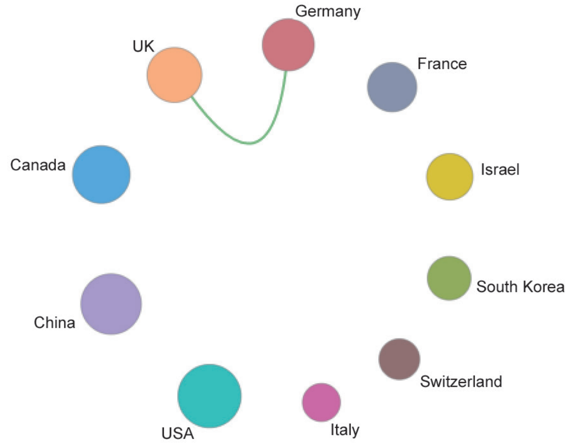

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "UAVs"

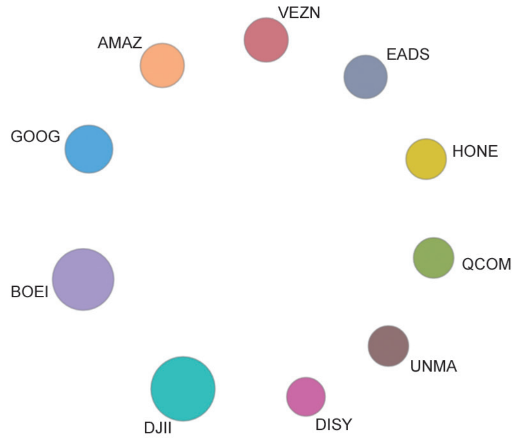

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "UAVs"

Participants of the Field Group

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Members

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II. Information & Electronic Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts reviewed by the Information and Electronic Engineering Group are summarized in Table 1.1.1, and include 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 research fronts, "radar stealth technology," "new-generation mobile communication technology," "quantum coherence measurement and decoherence control," "software robot control method," "high-resolution remote sensing scene classification and image processing technology," and "human body gesture recognition method based on deep neural network" are based on the popular topics provided by *Clarivate Analytics*. Furthermore, "interpretable deep learning," "networked collaborative sensing and control theory," "blockchain technology," and "silicon-based optical interconnect chip technology" are recommended by the experts.

The number of core papers related to each front, published from 2012–2017, is shown in Table 1.1.2. Considering the number of core papers published in recent years, "high-resolution remote sensing scene classification and image processing technology" is the most significant front.

(1) Radar stealth technology

Radar stealth technology is also known as radar low observable technology or radar target feature signal control technology. It is used for controlling the scattering direction, polarization mode, and radiation intensity and mode of the incident electromagnetic wave on the target surface by its shape, material, and comprehensive object and circuit designs, thereby reducing the probability of detection and recognition by the enemy radar system. Using radar is the

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	Percentage of consistently-cited papers	Patent-cited papers
1	Radar stealth technology	24	788	32.83	2015.42	25.0%	0.00
2	Interpretable deep learning	5	148	29.60	2015.40	–	–
3	New-generation mobile communication technology	9	386	42.89	2016.00	33.3%	0.00
4	Networked collaborative sensing and control theory	139	5 602	40.30	2013.45	–	–
5	Blockchain technology	16	213	13.31	2015.88	–	–
6	Quantum coherence measurement and decoherence control	37	1 015	27.43	2015.81	40.5%	0.00
7	Software robot control method	24	1 498	62.42	2014.67	20.8%	0.00
8	High-resolution remote sensing scene classification and image processing technology	69	2 327	33.72	2015.55	36.2%	0.00
9	Silicon-based optical interconnect chip technology	21	790	37.62	2013.52	–	–
10	Human body gesture recognition method based on deep neural network	7	229	32.71	2016.29	28.6%	0.00

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

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Radar stealth technology	0	1	3	6	13	1
2	Interpretable deep learning	0	1	1	0	1	2
3	New-generation mobile communication technology	0	0	1	2	2	4
4	Networked collaborative sensing and control theory	43	37	24	23	12	0
5	Blockchain technology	0	0	2	3	6	5
6	Quantum coherence measurement and decoherence control	0	0	0	11	22	4
7	Software robot control method	1	1	8	10	3	1
8	High-resolution remote sensing scene classification and image processing technology	1	3	7	18	26	14
9	Silicon-based optical interconnect chip technology	5	4	8	4	0	0
10	Human body gesture recognition method based on deep neural network	0	0	0	2	1	4

most efficient method of detecting targets from a long distance; thus, radar stealth technology has been the focus of stealth technology development since its inception.

Considering electromagnetic wave manipulation in technology implementation, radar stealth technology includes mainly integrated design and evaluation of shape stealth, material stealth, and stealth-integrated design and evaluation. In shape stealth, the incident direction and scattering mode of the electromagnetic wave are adjusted by the shape design to achieve the stealth effect. It aims at reflecting the incident wave to the nonthreatening directions and reducing or blocking the strong scattering source and discontinuous structure scattering of the target surface at dihedral/trihedral angles. In material stealth, the electromagnetic waves are either attenuated or their radiation is changed by applying and mounting special functional materials on the target surface or its key parts. The active stealth technology refers to real-time generation of electromagnetic field signals that are opposite to the target's scattering field, according to the incident electromagnetic wave and target states of the target surface, thereby realizing zero scattering by spatial cancellation and reducing the target's radar cross section. Stealth-integrated design and evaluation must be emphasized and focused on in the application of radar stealth technology. This is one of the primary reasons that although the principle of stealth technology is open to everyone, only a few countries have mastered it.

As the detection and anti-detection technologies continue to progress, the main directions of future radar stealth technology development are: ① very low and ultra-low observables; ② wideband and omnidirectional stealth; ③ dual/multiple station radar stealth; ④ integrated synthesis and thin stealth design; and ⑤ disturbance/attenuation field reduction.

(2) Interpretable deep learning

In recent years, deep learning methods represented by convolution depth, cyclic, and generic neural networks, and deep reinforcement learning have been applied in the fields of image classification and target detection, speech recognition and synthesis, and natural language processing; and their performance has improved dramatically. Although deep learning exhibits excellent performance in various artificial intelligence (AI) applications, its interpretability has always been its weakness. Currently, the highly discriminative ability of deep neural networks is layered by constructing multiple layers of nonlinear mapping functions. As abstraction, the black box effect is presented, and the relationship between its internal network structure and learning parameters, and its decision output is difficult to establish. Interpretable AI can break through the primary bottlenecks of deep learning, such as effective learning of small samples or weakly labeled data, human–computer interaction learning at the semantic level, and semantic debugging of neural network representation.

Currently, the study of understanding or decoupling complex neural network representation to improve its interpretability includes mainly five aspects: ① visualization of the convolutional neural network representation in an intermediate network layer; ② pairs of convolution features, mapping space, and correspondence of different semantic categories for diagnosis; ③ decoupling mixed modes of different convolutional layers; ④ establishing interpretable deep network models, such as interpreting convolution depth neural networks and capsule networks; and ⑤ semantic layer learning by human–computer interaction. Moreover, anti-machine learning detects the vulnerability of deep learning models by constructing anti-samples. Anti-machine learning builds against sample detection based on the vulnerability of deep learning models. Preliminary studies have shown that it is helpful to open the black box of a depth model by adding the confrontation sample formed by the perturbation to the meta-predictor or constructing the influential function traceability model prediction for its training data, and to a certain extent its predicted behavior or decision boundaries are interpreted.

Combining rule-based symbolic reasoning with data-driven learning processes can enhance the interpretability of intelligent learning processes. For example, inductive learning combines neural perceptrons with logical reasoning so that the learning process can directly use domain knowledge, thereby enhancing the learning process. Both attention and memory play an important role in the process of human cognitive reasoning, especially for knowledge acquisition, understanding, and reasoning of sequence data, such as text, speech, and video. Constructing deep neural reasoning mechanisms with the support of attention mechanism and memory structure to enhance the interpretability of intelligent learning and reasoning is an important research field of interpretable deep learning.

(3) New-generation mobile communication technology

To cope with the explosive growth of mobile data traffic, simultaneous access of massive devices, and emergence of various services in the future, the new-generation mobile communication technology needs to provide ms-level and end-to-end connectivity for hundreds of billions of devices, provide peak Gbit/s transmission rate, and support ultra-high mobility, traffic density, connectivity density, and other diverse application scenarios. The new generation of mobile communication technology will integrate various wireless access modes to achieve flexible network deployment, operation, and maintenance; comprehensively enhance the spectrum, energy, and cost efficiencies; and promote the sustainable development of the mobile communication industry. The new generation of communication technology involves the design, development, and production of the new generation of mobile chips and related core technologies. Furthermore, it involves the development of the entire information industry. It is directly related to industrial transformation and upgrading, and has a direct, significant, and simultaneous impact on the manufacturing industry and services. Further, development of a communication technology involves global standards, various patents, and huge network construction costs. Thus, for every country, the development of a new mobile communication technology brings great economic and social benefits.

(4) Networked collaborative sensing and control theory

A networked collaborative sensing and control system usually consists of a set of sensors and controllers, in which the sensors get information from the environment to be monitored, while the controllers try to change the environment via control signals, and the sensors and controllers are connected via communication networks. A networked collaborative sensing and control system has the functions of sensing and changing the physical world, and is applied in various areas, such as disaster relief, intelligent building, factory automation, underground safety control, and biochemical attack detection.

Compared with conventional centralized sensing and control methods, the networked distributed cooperative sensing and control methods have the following advantages. ① Decentralization of sensing and control functions improves the robustness of the system to the failure of sensing and control nodes. ② In large-scale distributed systems, achieving full network synchronization is difficult, and the nodes may work asynchronously. Conventional centralized sensing and control methods cannot deal with asynchronous information. However, in a network-based distributed structure, the asynchronous sensing and control problem can be solved via the hierarchical information processing approach. ③ The computational efficiency of a system can be greatly improved by the decentralization of sensing and control functions. Through information interaction among subsystems, computational complexity can be reduced while achieving good performance with centralized sensing and control.

In recent years, the research on the theory and method of distributed sensing and control based on information interaction has received great attention. However, many theoretical and application-related problems are still open, including distributed sensing and control based on the cooperative (such as controllers and sensors) and noncooperative modes of nodes. These include the asynchronous multi-rate distributed sensing and control of each subsystem in an asynchronous working state, extensibility of distributed cooperative sensing and control (allowing the arbitrary access and exit of any node), and the influence of network topology and vulnerability on distributed sensing and control. It is believed that breakthroughs in the future will effectively promote the development of intelligent manufacturing, networked autonomous systems, smart grids, and other fields under industrial Internet.

(5) Blockchain technology

Blockchain technology, which includes P2P technology, cryptography, and consensus algorithms, aims to provide a mechanism for information and value transfer in untrusted environments and is a cornerstone for the development of the future Internet. It has the features of unchangeable data, collective system maintenance, and information disclosure. Blockchain, as a versatile technique, accelerates distributed technology applications from digital currencies into other areas and integrates innovations from all industries. It has the following three advantages. ① The consensus algorithm ensures that the data on the blockchain is secure and difficult to tamper with. ② Each node of a blockchain has a piece of data; thus, it is heterogeneous and reliable. ③ With smart contract attributes, it can automatically perform decentralization of applications.

From a single application to multiple fields, the blockchain technology still has a long way to go. It will continue to evolve in the future, and technical processes, such as consensus algorithms, sharded services, processing methods, and organizational forms will continue to change. However, there are a few challenges as well. First, performance and scalability cannot meet requirements. The transaction throughput and storage bandwidth are far from meeting the actual requirements of applications. Currently, Bitcoin’s transaction throughput rate is seven transactions per second and that of Ethereum is 14 transactions per second. How to improve transaction throughput without affecting the overall security of the system will be worth studying. Furthermore, by compressing the block time and increasing the block size, the sharding technology can effectively improve the transaction throughput rate. Second, data privacy and access control require improvement. In the existing public blockchains, each participant can obtain a complete data backup. All data are transparent to the participants, and it is impossible for the participants to obtain only specific information. How to ensure transaction privacy without affecting the public blockchain execution efficiency is still a challenge. Currently, research in this area includes the coin-conserving, zero-knowledge proof, and ring signature mechanisms to protect a user's transaction privacy data. Third, the governance mechanism requires improvement. Public blockchain communities have explored various upgrade mechanisms, such as “hard fork” and “soft fork”; however, the remaining problems cannot be ignored. Public blockchains cannot be “closed,” and its bug fixes are extremely troublesome; thus, it can be fatal if there is a security breach.

(6) Quantum coherence measurement and decoherence control

Quantum coherence and quantum phase transition play an important role in quantum information. Although systems have always been coherent in theory in the evolution process, an actual system is not strictly closed. Thus, it will inevitably become entangled with the environment and cause decoherence. In quantum mechanics, the quantum coherence of open quantum systems is gradually lost over time due to quantum entanglement with the external environment. This effect is called “quantum decoherence.” Quantum decoherence is the consequence of quantum entanglement between quantum systems and the environment. The interference phenomenon caused by quantum coherence will disappear because of quantum decoherence. Quantum decoherence changes the quantum behavior of a system into a classical behavior, and this transition is called quantum-to-classical transition. Hans Zehe, a German physicist, first proposed this concept of quantum decoherence in 1970. Since 1980, quantum decoherence has become a popular research topic.

Quantum decoherence usually occurs very quickly; therefore, making superimposed objects in macroscopic or mesoscopic forms is difficult. To experimentally verify the quantum decoherence effect, witness the smooth boundary between quantum and classical behaviors, test and improve the theoretical model of quantum decoherence, and find out any difference from quantum mechanical evolution, we must perform the following challenging tasks: ① preparing several quantum superposition states of macroscopic or mesoscopic states that can be resolved; ② designing a set of methods to confirm quantum superposition; ③ having the duration of quantum decoherence long enough to observe it correctly; and ④ designing a set of methods to supervise quantum decoherence.

The influence of decoherence on quantum information science can be roughly divided into two parts: quantum computing and quantum communication. We know that in quantum information science, the state of quantum systems contains information. Quantum decoherence causes loss of some or all information of the system; thus, it will cause calculation errors during quantum computation. In quantum communication, the information in the transmission channel is prone to disturbance and interference, and the receiver at the end of the channel can possibly receive noise and error information; thus, it requires assistance from a debugging system, such as an encoder.

(7) Software robot control method

The research on control of soft robots is essentially to solve the inverse kinematics problems. Unlike conventional rigid-bodied robots that are driven by electric motors, soft robots generate motions using soft materials similar to natural muscles, which arm the soft robots with animal-like agility and flexibility, increase adaptability in complex working environments, and reduce hazards related to human–machine interactions. Theoretically, a soft robot has an infinite number of degrees of freedom, making it possible to produce extremely complicated motions, such as stretching, bending, and twisting. Thus, motion control in soft robots is faced with enormous challenges. Currently, soft materials employed for artificial muscles include pneumatic artificial muscles, shape memory alloys, electroactive polymers, and so on. Although these materials exhibit intriguing attributes, such as high energy density, large deformation, and low weight, they are usually highly nonlinear with strong viscoelasticity. Moreover, considering their inherent compliance, soft robots are likely to work in environments with remarkably high uncertainties. Therefore, fine adaptability and strong robustness are preferred for the control of soft robots. Generally, control of soft robots can be achieved using two types of approaches: ① model-based and ② learning-based control approaches. The former approach develops a dynamic model of the system through the first principle or data-driven methods and achieves motion control using conventional feedback control schemes. However, the drawback of this method is that it partly depends on the model; a kinetic/dynamic model of soft robots will result in a lot of uncertainties during their interactions with the environments. To overcome such limitations, the latter approach, inspired by the similarities between soft actuators and natural muscles, draws lessons from the motor control of natural muscles and compensates for the model uncertainties through on-line learning, which is processed in an artificial neural network. However, many explorations are required for the optimization of the network structure and the tuning of the parameters.

(8) High-resolution remote sensing scene classification and image processing technology

High-resolution remote sensing imagery is a large spatial data related to emergency and disaster mitigation applications, which influence national economy and livelihood of the people. Remote sensing scene classification belongs to the research category of overall image understanding. Scene classification should analyze, judge, interpret, and label image scenes. It is a mapping process for learning and discovering images and scene semantic content tags. Scenes usually contain multiple targets, and scene classification is also a key issue in image understanding. Common scene classification algorithms include scene classification of local and middle-level semantics, and that of semantic topic models. According to the hierarchy, scene classification can be divided into two main methods: low-level and middle-level feature descriptions. However, low-level feature descriptions tend to have poor generalization performance and are difficult to process during image classification outside the training set; thus, most of the current scene classification algorithms focus on scene classification based on middle-level semantic modeling.

The middle-layer feature is a type of aggregation and integration of low-level features, and its essence is to use statistical distribution to establish a relationship between features and categories. Generally, the global low-level features cannot reflect local objects. Considering local low-level feature description, multi-local feature fusion and integrated learning can improve the recognition rate of scene classification. The scene classification based on the bag-of-visual-words (BoVW) model is a widely used middle-level semantic algorithm. Considering that spatial symbiosis and context of the vocabulary will help to improve the interpretation of the semantics of the scene structure, the BoVW model does not need to analyze the specific target composition of the scene, establish visual words according to the statistical characteristics of the low-level features of the scene, and then express the image scene information by using the visual word distribution of the image. However, the number of words to be set in the BoVW model is not known. The generated objects tend to have a greater correlation with the training samples that is an important factor affecting the robustness of the algorithm.

Statistical learning theory is a relatively mature research algorithm. In multi-sensor fusion remote sensing image scene classification, the use of support vector machines based on structural risk minimization principle and random forest algorithm using bootstrap resampling has been reported. To achieve scene classification of airborne radar and multispectral images, classification is often conducted using random forests combined with a classical priori model and an unsupervised image segmentation tool, Markov random field (MRF). Recently, semantic topic models such as pLSA and LDA that originated from text classification research have achieved good experimental results in scene classification of spaceborne landslides and airborne aerial photography.

The middle-level semantic scene classification alleviates the problem of semantic gap to a certain extent; however, there are no good solutions to the change of scene scale, the difference of sensor shooting angle and time, and the change of semantic object combination.

(9) Silicon-based optical interconnect chip technology

Silicon is not only an electronic material but also a photonic material. Using silicon as the substrate, photonic devices can be fabricated using existing integrated circuit processes. Silicon-based optical interconnect chip technology uses silicon and silicon-based substrate materials as an optical media to fabricate corresponding photonic devices and optoelectronic devices (including silicon-based optical transceivers, silicon-based optical modulators, and silicon-based optical waveguides) through integrated circuit processes. Further, they use these devices to process and manipulate photons to achieve optical interconnection between systems, motherboards, chips, CPUs, and CPU cores. Inter-chip and on-chip optical interconnections, compared with electrical interconnection technology, has the fundamental advantages of ultra-high bandwidth, high speed, low power consumption, low distortion, low crosstalk, and no electromagnetic interference. The main research directions of silicon-based photonic integration for optical interconnection are as follows: ① light sources for emitting light waves as an information carrier; ② optical waveguides for transmitting optical signals; ③ modulator for generating calculation unit (the electrical signal is loaded on the optical wave carrier); ④ optical signal receivers for receiving the optical signal and converting it into an electrical signal for feedback to the computing unit; and ⑤ system integration.

Although silicon has many unique advantages as an optical interconnect material, as a single material it cannot accomplish all the functions of an optical interconnect device. For example, optical transmission and detection are a contradiction. Light transmission requires the material be transparent to photons, while light detection requires the material be opaque to light and absorb photons. Silicon is an indirect bandgap semiconductor that cannot achieve stimulated radiation easily; thus, fabricating it as a source material is difficult. Furthermore, silicon has some technical bottlenecks to overcome in optical interconnect applications. For example, the silicon-based photonic processors developed in 2015 and 2018 by the University of Berkeley and other institutes, as reported by *Nature*, used external light sources. Therefore, an important development trend is to find other materials that are compatible with silicon-based CMOS processes to compensate for the deficiencies of silicon in the optical interconnect chip technology.

(10) Human body gesture recognition method based on deep neural network

Human motion recognition based on smart phones and wearable devices, such as wristbands and watches, has become a mainstream recognition method. Traditional machine learning methods, such as support vector machines, Bayesian networks, time- and frequency-domain analysis, and other machine learning methods, require extraction of features based on professional human motion domain knowledge. Neural network-based methods are still few, and neural networks and deep learning still require artificial extraction features. Feature extraction is a key step in machine learning and deep learning. Similarly, for human motion recognition, feature extraction of sensor data is extremely important.

Human motion recognition is an important research topic, especially in the popularity of smartphones and smart wearable devices nowadays. For human motion recognition, machine-learning methods include mainly traditional support vector machine, decision tree, KNN, naive Bayes, neural network, and deep learning. Model-dependent training data sources include a single acceleration sensor, or a combination of gyroscopes, magnetic fields, and even sound information. The position of the sensor in motion recognition is divided mainly into a fixed position (a plurality of sensors are generally fixed positions) and a nonfixed position. Feature extraction is conducted mainly in the time domain, and in fewer cases, in the frequency domain.

1.2 Interpretations for three key engineering research fronts

1.2.1 Radar stealth technology

Radar stealth (invisibility) technology, also known as radar low observability technology, is professionally called as radar target signature control technology. It is used for manipulating the scattering direction, polarization, intensity, and pattern of the electromagnetic wave illuminating the target surface via synthetic designing of shape, material, circuit and other aspects, thereby reducing the probability of detection and recognition by the enemy radar system. Using radar is the most efficient method to detect remote targets; thus, radar stealth has always been the focus of stealth technology.

Considering electromagnetic wave manipulation in technology implementation, radar stealth technology includes mainly shape stealth, material stealth, active stealth, and stealth-integrated design and evaluation.

Shape stealth was the first to receive attention and development in the radar stealth technology. It regulates the incident direction and the scattering mode of electromagnetic waves to achieve stealth. The focus is to reflect the incident waves to nonthreatening directions, and to reduce or block the strong scattering sources, such as dihedral angles/trihedral angles of the target surface as well as the discontinuous structure scattering. Considering a stealth aircraft as an example, the critical technologies to be solved in the shape stealth design are the integrated design of stealth shape and aerodynamic layout, the real-time electromagnetic calculation technology of the electric large size target, and the integrated fast forming technology.

Material stealth is used to change the attenuation or radiation of the electromagnetic waves by applying and mounting special functional materials on the target surface or its key parts (such as electronic system antennas and some strong scattering points). According to the electromagnetic regulation method of materials, the stealth materials currently in research and development include mainly: absorbing type stealth materials that introduce the radar waves into the material and then dissipate their energy; surface type stealth materials represented by metamaterials that change the scattering pattern and the polarization mode of electromagnetic wave by sub-wavelength periodic geometric circuit structure design. The key technologies to be addressed in the development of material stealth technology include electromagnetic/thermal/force integrated design and analysis, micro-nano processing, and metamaterial technology. The surface electromagnetic control materials represented by metamaterials are the focus of future stealth materials development.

The active stealth technology refers to real-time generation of electromagnetic field signals opposite to the target scattering field according to the incident electromagnetic wave state (incident direction and polarization) and target state (attitude velocity), thereby achieving zero scattering through space cancellation and RCS reduction of the target. The active stealth technology is still in the stage of exploration and development. The key technologies to be solved include real-time electromagnetic spectrum sensing and measurement, real-time generation and precise control of electromagnetic field signals, information metamaterials, and so on. Intelligent skinning for active stealth is an important direction for the development of future stealth technology.

Stealth integrated design and evaluation is a technical field that must be emphasized. This is one of the important reasons why theoretical principle is basically open but the stealth technology is mastered by only a few countries. The development of multi-sensor battlefield sensing technology, stealth technology must also emphasize the integrated control technology of active and passive features such as electromagnetic, optical, infrared, and acoustic ones. Therefore, the key technologies that must be solved and developed include multi-field coupling parallel computing, simulation testing and evaluation of stealth performance, as well as related design tools and instrumentation techniques.

Currently, radar stealth technology has been successfully applied to multi-type weapons and equipment after more than 50 years of development. Taking stealth aircraft as an example, it evolves from the earliest representative F117 to the current F22, F35, and B2. China and Russia have also become two of the few countries that have mastered the design techniques of stealth aircraft. As the escalation of the game between detection and anti-detection technology, the main directions of future radar stealth technology include:

(1) Development in a very low observable and ultra-low observable direction;

(2) Development in the broadband and omnidirectional stealth direction;

(3) Development from mono-static radar stealth to dual/multi-static radar stealth direction;

(4) Stealth design in the integrated and lightweight direction;

(5) Development from scattering field reduction to disturbance field/attenuation field reduction.

The countries or regions with the greatest output of core papers, institutions with the greatest output of core papers, countries or regions with the greatest output of citing papers, and institutions with the greatest output of citing papers on "radar stealth technology" are shown in Tables 1.2.1–1.2.4. The collaboration networks among major countries or regions as well as among major institutions are shown in Figure 1.2.1 and Figure 1.2.2, respectively.

1.2.2 Interpretable deep learning

(1) Core of artificial intelligence: learning and reasoning

The intrinsic feature of AI lies in its abilities of never-ending or self-taught learning from data and experiences, intuitively reasoning, and self-adaptation. Reasoning, the basic form of thinking and simulation, is a process of obtaining new judgments or conclusions from one or several given judgments or premises. Reasoning could be categorized into deductive reasoning, inductive reasoning, analogy reasoning, presumptive or abduction reasoning, causality reasoning, synthesis reasoning, etc. Early studies towards reasoning started in areas of logicism and knowledge engineering. Logicism resorts to the formalization method to represent the objective world, e.g., using the first-order logic or predicate logic to conduct reasoning. Recently developed knowledge-graph reasoning, memory-driven reasoning, multi-agent reasoning, and cross-media synthesis reasoning receive more and more attention of researchers.

Intelligent learning follows three main paradigms: ① learning with formalization methods that first represents rules by symbolic logic and then conduct reasoning. ② Statistical learning that could be considered as learning from data or the so-called data-driven learning. First, we can construct supervised learning process on large-scale labeled data samples, such as deep learning methods. Moreover, using data distributions or prior knowledge, Bayesian learning can be effectively performed on small-size data samples. ③ Learning based on cybernetics—i.e., self-improving from experiences—that could

Table 1.2.1 Countries or regions with the greatest output of core papers on the "radar stealth technology"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	19	79.17%	606	76.90%	31.89
2	USA	4	16.67%	146	18.53%	36.50
3	Australia	2	8.33%	52	6.60%	26.00
4	Netherlands	1	4.17%	66	8.38%	66.00
5	Spain	1	4.17%	66	8.38%	66.00
6	Iran	1	4.17%	12	1.52%	12.00

Table 1.2.2 Institutions with the greatest output of core papers on the "radar stealth technology"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Southeast Univ	11	45.83%	469	59.52%	42.64
2	Cooperat Innovat Ctr Terahertz Sci	5	20.83%	165	20.94%	33.00
3	Nankai Univ	4	16.67%	173	21.95%	43.25
4	Tianjin Univ	4	16.67%	171	21.70%	42.75
5	Xidian Univ	4	16.67%	76	9.64%	19.00
6	Nanjing Univ	3	12.50%	144	18.27%	48.00
7	Arizona State Univ	2	8.33%	48	6.09%	24.00
8	Fudan Univ	2	8.33%	113	14.34%	56.50
9	Univ Elect Sci & Technol China	2	8.33%	129	16.37%	64.50
10	Peking Univ	2	8.33%	42	5.33%	21.00

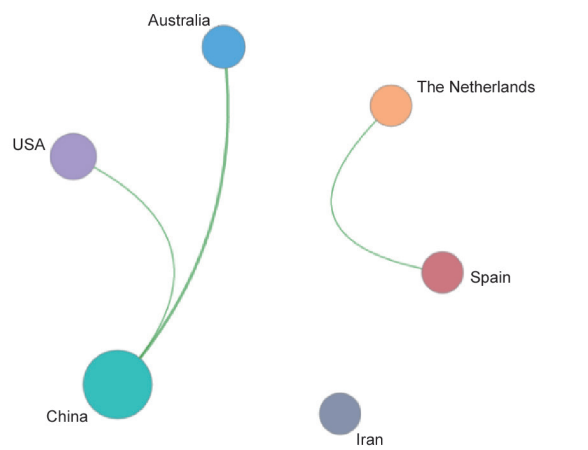

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "radar stealth technology"

be considered as the question-guided or feedback-guided learning, such as reinforcement learning.

(2) Deep learning: black box versus interpretability

Deep learning methods, such as deep convolutional neural networks (CNNs), recurrent neural networks (RNNs), generative adversarial network (GAN), and deep reinforcement learning (DRL), have recently achieved outstanding predictive performance in a wide range of applications, including visual object recognition, speech recognition and synthesis, and natural language processing. There has been an explosion of interest in interpreting the representations learned by these models.

Currently, deep neural networks obtain high discrimination

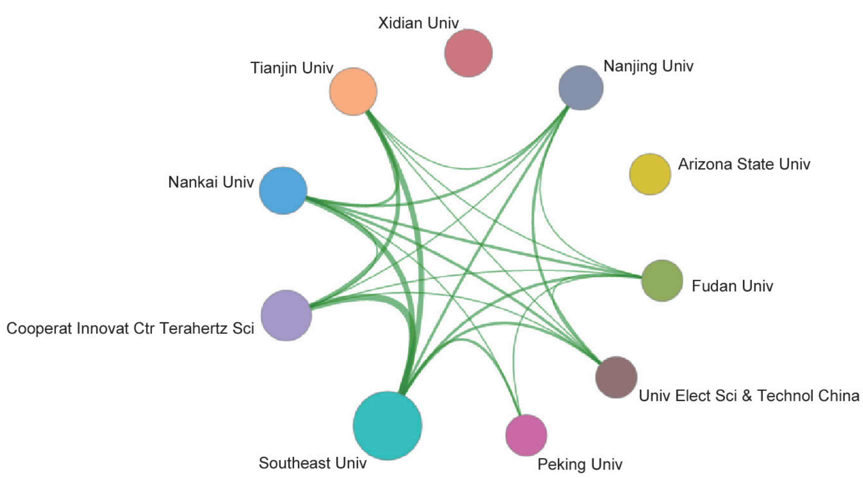

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "radar stealth technology"

Table 1.2.3 Countries or regions with the greatest output of citing papers on the “radar stealth technology”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	255	71.63%	2016.48
2	USA	36	10.11%	2016.44
3	Singapore	19	5.34%	2016.58
4	India	9	2.53%	2016.56
5	Iran	9	2.53%	2016.33
6	Canada	7	1.97%	2016.14
7	UK	6	1.69%	2016.33
8	Australia	6	1.69%	2016.50
9	Italy	5	1.40%	2016.60
10	Denmark	4	1.12%	2017.00

Table 1.2.4 Institutions with the greatest output of citing papers on the “radar stealth technology”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Southeast Univ	53	24.65%	2016.32
2	Air Force Eng Univ	51	23.72%	2016.49
3	Xidian Univ	19	8.84%	2016.79
4	Cooperat Innovat Ctr Terahertz Sci	16	7.44%	2016.19
5	Tianjin Univ	16	7.44%	2016.06
6	Nanjing Univ	15	6.98%	2016.20
7	Chinese Acad Sci	12	5.58%	2016.50
8	Nankai Univ	12	5.58%	2015.83
9	Nat Univ Singapore	11	5.12%	2016.55
10	Commun Univ China	10	4.65%	2016.40

power at the cost of low interpretability of their black-box representations. For example, the end-to-end learning strategy makes CNN representations a black-box. Except for the final network output, it is difficult for people to understand the logic of CNN predictions hidden inside the network. Though dramatic success in deep learning has led to a torrent of AI applications and systems that can perceive, learn, decide, and act on their own, the effectiveness of these systems is limited by their current inability to explain their rationale, characterize their strengths and weaknesses, predict their applicability on new task, and even convey an understanding of how they will behave in the future. A high-model interpretability may help people to break several bottlenecks of deep learning, such as learning from very few annotations, learning via human–computer interaction at the semantic level, and semantically debugging network representations.

(3) Interpretable deep learning: data-driven and knowledge-guided

As discussed above, deep neural networks’ low interpretability lies in their black-box representations. It is difficult for people to understand the relations between decision outputs and logic of predictions and parameters hidden inside the network. Current studies on understanding neural-network representations with interpretable or disentangled representations fall mainly into five directions: ① visualization of the CNN representations in intermediate networks layers, ② diagnosis of the CNN representations, ③ disentanglement of the mixture of patterns encoded in each filter of CNNs, ④ building explainable models, such as interpretable CNNs and capsule networks, and ⑤ semantic-level middle-to-end learning via human–computer interaction. Moreover, adversarial machine learning tries to explore deep learning methods' vulnerability and its robustness to adversarial attacks. Recent studies show that learning meta-predictor via imposing explainable rules to the process of constructing adversarial examples could help open up the black-box of deep neural networks and make explanations to the decision boundary of their prediction models.

As a data-driven learning paradigm, incorporating explicit reasoning rules into the deep learning models is difficult and limits their interpretability. Symbolic AI refers to a set of methods based on high-level symbolic problem representations and its goal is to dene intelligent systems in an explicit way that is understandable by humans and thus is interpretable. Recent developed abductive learning connects symbolic reasoning with neural perception. Owing to the expressive power of first-order logic, abductive learning is capable of directly exploiting general domain knowledge, so as to enhance the interpretability of the learning process. Moreover, inspired by the intelligence of human brain, perception or cognition requires brain not only to handle the data of target tasks but also to activate related information stored in the brain. Therefore, attention and memory play an important role in the process of cognitive reasoning, especially for the knowledge extraction, understanding and reasoning from sequential media data of texts, audios and videos. Based on these motivations, learning from external knowledge could be combined with the data-driven learning paradigm if we appropriately incorporate the attention mechanism and memory structures into end-to-end deep learning. Representative methods include neural tuning machine, memory networks, adaptive computation time, neural GPU, neural random-access machines, as well as random accessing to external memories via reinforcement training, and can be taken as new intelligent learning frameworks of combining data-driven and knowledge-guided paradigms. Thus, constructing deep neural reasoning on top of attention mechanism or memory structures should be a promising direction to improve the interpretability of AI's learning and reasoning abilities.

(4) Related academic endeavors and projects

Interpretable machine learning has received more and more focuses from academic community. There has been a tutorial of "Interpretable Machine Learning: The fuss, the concrete and the questions" at the International Conference on Machine Learning, 2017 (ICML 2017), organized by researchers from Harvard University and Google Brain. In 2017 conference on Neural Information Processing Systems, researchers from MIT, MPI, Microsoft, Cornell, UW-Madison, Johns Hopkins, JPL, DeepMind, UCSD, and NYU gathered together and organized an Interpretable ML Symposium. The symposium solicited more than 30 papers from areas of deep learning, kernel or probabilistic methods, automatic scientific discovery, safe AI and AI ethics, causality, human–computer interaction, quantifying or visualizing interpretability, symbolic regression, etc. This symposium was designed to broadly engage the machine learning community to discuss how to enhance the interpretability of machine learning.

The defense advanced research projects agency (DARPA) launched the program of "explainable artificial intelligence (XAI)" on Oct. 10, 2017, whose goal is to create a suite of machine learning techniques that produce more explainable models while maintaining a high level of learning performance and enable human users to understand, appropriately trust, and effectively manage the emerging generation of artificial intelligent partners. XAI is one of a handful of current DARPA programs expected to enable "third-wave AI systems," where machines understand the context and environment in which they operate, and over time build underlying explanatory models that allow them to characterize real world phenomena.

Very recently, on July 20, 2018, DARPA announced its Artificial Intelligence Exploration (AIE) program, a key component of the agency's broader AI investment strategy. AIE continues DARPA's five-decade streak of pioneering groundbreaking research and development in AI. Past DARPA investments facilitated the advancement of "first wave" (rule-based) and "second wave" (statistical-learning-based) AI technologies. DARPA-funded projects enabled some of the first successes in AI, such as expert systems and search, and more recently the agency has advanced machine learning algorithms and hardware. DARPA is now interested in researching and developing "third wave" AI theory and applications that address the limitations of first and second wave technologies by making it possible for machines to contextually adapt to changing situations.

The countries or regions with the greatest output of core papers, institutions with the greatest output of core papers, countries or regions with the greatest output of citing papers, and institutions with the greatest output of citing papers on "interpretable deep learning" are shown in Tables 1.2.5–1.2.8. The collaboration network among major countries or regions and the collaboration network among major institutions are shown in Figure 1.2.3 and Figure 1.2.4, respectively.

1.2.3 New-generation mobile communication technology

Speaking of the research paradigm, the new generation of mobile communication technology will continue to advance along the three main paradigms of the past, namely measurement modeling, performance analysis, and system design. Measurement modeling refers to the measurement, characterization, and modeling of the objective physical world; performance analysis refers to given wireless communication system and transmission mechanism, and then analyzes its system performance; system design refers to design and optimizes the mobile communication network architecture given the system design indicators. Moreover, with the advancement of big data, machine learning, and AI technology, how to combine it with mobile communication to achieve interdisciplinary integration development is one of the key research directions of the next-generation mobile communication technology, and even may become a mainstream research and an important branch in the next five years. The key technologies to be solved are: ① co-integration technology of storage, computing, and communication; ② ubiquitous network architecture and ultra-dense heterogeneous network technology supporting massive terminal access; ③ the theory and implementation of ultra-reliable low-latency mobile communication system; ④ intelligent mobile communication system design for scenes and services; ⑤ theory and implementation of data-driven mobile communication system; ⑥ optimization theory and real-time implementation of ultra-large-scale mobile communication network.

Table 1.2.5 Countries or regions with the greatest output of core papers on the "interpretable deep learning"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	2	40.00%	107	72.30%	53.50
2	Colombia	1	20.00%	60	40.54%	60.00
3	France	1	20.00%	47	31.76%	47.00
4	UK	1	20.00%	47	31.76%	47.00
5	Austria	1	20.00%	17	11.49%	17.00
6	China	1	20.00%	13	8.78%	13.00
7	Denmark	1	20.00%	13	8.78%	13.00
8	Germany	1	20.00%	11	7.43%	11.00

Table 1.2.6 Institutions with the greatest output of core papers on the "interpretable deep learning"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Case Western Reserve Univ	1	20.00%	60	40.54%	60.00
2	Univ Nacl Colombia	1	20.00%	60	40.54%	60.00
3	Cent Supelec INRIA Saclay	1	20.00%	47	31.76%	47.00
4	Univ Massachusetts	1	20.00%	47	31.76%	47.00
5	Univ Oxford	1	20.00%	47	31.76%	47.00
6	IST Austria	1	20.00%	17	11.49%	17.00
7	Shanghai Jiao Tong Univ	1	20.00%	13	8.78%	13.00
8	Univ Copenhagen	1	20.00%	13	8.78%	13.00
9	Staatliche Berufliche Oberschule Kaufbeuren	1	20.00%	11	7.43%	11.00
10	Univ Appl Sci Mittweida	1	20.00%	11	7.43%	11.00

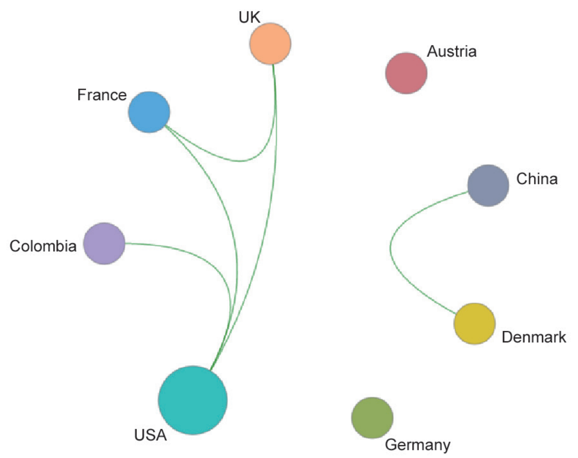

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “interpretable deep learning”

Currently, the development priorities of major countries and regions in the world are as follows: ① The United States is committed to the intellectual property protection of the fifth generation mobile communication (5G) core technology, and focuses on data-driven, AI-based mobile communication technology; ② Europe is promoting the use of 5G core technology, such as the core challenges and commercialization of large-scale antennas, at the same time, several countries, mainly Germany, pay special attention to the research of ultra-reliable low-latency mobile communication systems relying on industrialization 4.0; ③ NTT Docomo is the representative of Japan, focusing on a series of core issues of 5G commercialization, such as the implementation of large-scale antennas.

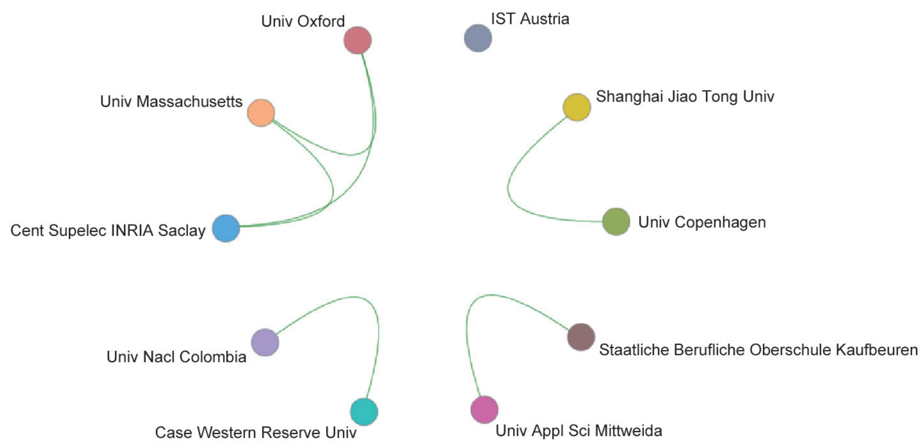

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “interpretable deep learning”

Table 1.2.7 Countries or regions with the greatest output of citing papers on the “interpretable deep learning”

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	53	26.77%	2017.11
2	USA	49	24.75%	2016.73
3	UK	16	8.08%	2017.38
4	Germany	14	7.07%	2017.29
5	Netherlands	13	6.57%	2017.00
6	Colombia	13	6.57%	2015.62
7	Canada	12	6.06%	2016.67
8	Australia	11	5.56%	2016.55
9	Singapore	9	4.55%	2017.00
10	France	8	4.04%	2016.75

Table 1.2.8 Institutions with the greatest output of citing papers on the "interpretable deep learning"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Univ Nacl Colombia	13	20.00%	2015.62
2	Case Western Reserve Univ	12	18.46%	2015.83
3	Chinese Acad Sci	8	12.31%	2017.63
4	Radboud Univ Nijmegen	5	7.69%	2016.20
5	Nanyang Technol Univ	5	7.69%	2017.00
6	Univ Adelaide	5	7.69%	2016.40
7	Wuhan Univ	5	7.69%	2017.20
8	Nanjing Univ Informat Sci & Technol	4	6.15%	2016.25
9	Univ Florida	4	6.15%	2016.75
10	Shanghai Univ	4	6.15%	2016.75

Currently, research on next-generation mobile communication technologies based on 5G focuses mainly on the following mainstream directions and branches:

(1) Channel measurement and modeling

To meet the needs of enhanced mobile broadband (eMBB) services, 5G systems communicate in high-frequency bands, so channel measurement and modeling around high-frequency bands is one of the key research directions; high-band channel modeling based on big data is also important in the future.

(2) Large-scale antenna

The 5G system further uses large-scale antennas to provide spectrum efficiency and support more user access. Currently, large-scale antennas, especially for high-frequency large-scale antennas, still have many problems. For the first time, large-scale commercialization of 5G is carried out, and the realization of the level of challenges is also one of the key research directions.

(3) Massive connection

For the needs of the Internet of Things, smart cities, smart grids, wireless communication under massive connection scenarios will still be one of the key research directions.

(4) Ultra-reliable low-latency wireless communication

Currently, there is no theory of ultra-reliable low-latency wireless communication to guide the specific design of this system, so this research direction will become one of the research priorities of the sixth-generation (6G) mobile communication in the future.

Other wireless communication technologies such as drone-based, based on energy harvesting and wireless energy transmission, especially the inter-satellite communication technology based on wireless energy transmission in space scenarios, are also the research focus of next-generation wireless communication technology.

Future mobile communication technologies will be developed in the following key directions: ① co-integration technology for storage, computing and communication; ② ubiquitous network architecture for supporting massive terminal access and ultra-dense heterogeneous network technology; ③ ultra-reliable low-latency mobile Theory and implementation of communication system; ④ intelligent mobile communication system design for scene and service; ⑤ theory and implementation of data-driven mobile communication system; ⑥ optimization theory and real-time implementation of ultra-large-scale mobile communication network; ⑦ the design and implementation of communication systems, especially the integration of terrestrial satellites with terrestrial networks.

The countries or regions with the greatest output of core papers, institutions with the greatest output of core papers, countries or regions with the greatest output of citing papers, and institutions with the greatest output of citing papers on "new-generation mobile communication technology" are shown in Tables 1.2.9–1.2.12. The collaboration network among major countries or regions and the collaboration network among major institutions are shown in Figure 1.2.5 and Figure 1.2.6, respectively.

Table 1.2.9 Countries or regions with the greatest output of core papers on the “new-generation mobile communication technology”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	8	88.89%	381	98.70%	47.63
2	Canada	7	77.78%	228	59.07%	32.57
3	UK	5	55.56%	295	76.42%	59.00
4	Singapore	1	11.11%	115	29.79%	115.00
5	Taiwan of China	1	11.11%	53	13.73%	53.00
6	Australia	1	11.11%	18	4.66%	18.00
7	USA	1	11.11%	18	4.66%	18.00

Table 1.2.10 Institutions with the greatest output of core papers on the “new-generation mobile communication technology”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Beijing Univ Chem Technol	7	77.78%	366	94.82%	52.29
2	Univ British Columbia	6	66.67%	223	57.77%	37.17
3	Tsinghua Univ	5	55.56%	344	89.12%	68.80
4	Univ Sheffield	4	44.44%	278	72.02%	69.50
5	Beijing Univ Posts & Telecommun	3	33.33%	175	45.34%	58.33
6	Kings Coll London	3	33.33%	43	11.14%	14.33
7	Univ Sci & Technol Beijing	3	33.33%	50	12.95%	16.67
8	Minist Educ China	1	11.11%	137	35.49%	137.00
9	Shanghai Jiao Tong Univ	1	11.11%	137	35.49%	137.00
10	Univ Elect Sci & Technol China	1	11.11%	137	35.49%	137.00

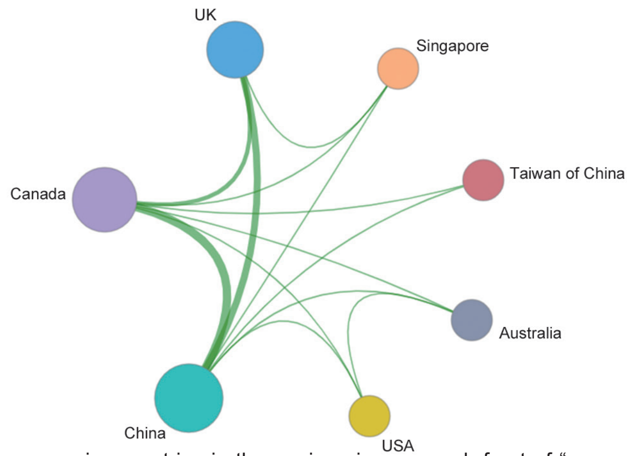

Figure 1.2.5 Collaboration network among major countries in the engineering research front of “new-generation mobile communication technology”

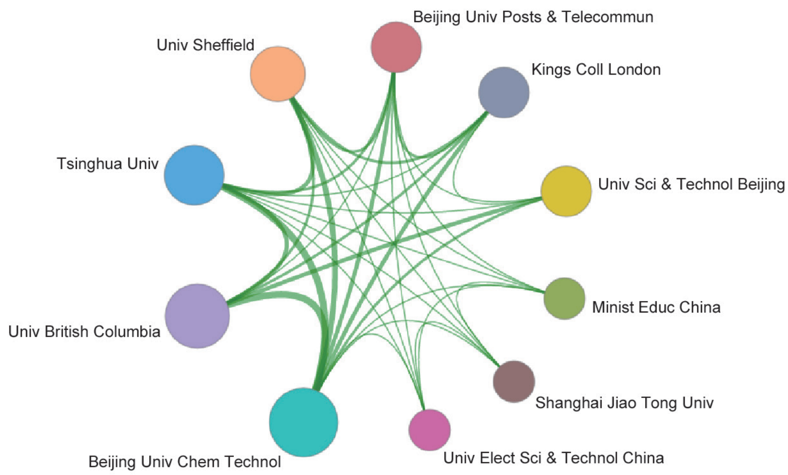

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "new-generation mobile communication technology"

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "new-generation mobile communication technology"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	157	48.61%	2016.36
2	Canada	45	13.93%	2016.02
3	USA	26	8.05%	2016.31
4	South Korea	25	7.74%	2016.68
5	UK	23	7.12%	2016.00
6	Iran	12	3.72%	2016.42
7	Australia	11	3.41%	2016.27
8	India	9	2.79%	2016.67
9	Singapore	8	2.48%	2016.25
10	Taiwan of China	7	2.17%	2016.43

Table 1.2.12 Institutions with the greatest output of citing papers on the "new-generation mobile communication technology"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Beijing Univ Posts & Telecommun	34	24.46%	2016.18
2	Univ British Columbia	23	16.55%	2015.96
3	Tsinghua Univ	17	12.23%	2016.12
4	Southeast Univ	17	12.23%	2016.29
5	Xidian Univ	12	8.63%	2016.33
6	China Univ Min & Technol	9	6.47%	2016.11
7	Nanjing Univ Posts & Telecommun	8	5.76%	2016.63
8	Chinese Acad Sci	7	5.04%	2016.43
9	Univ Essex	6	4.32%	2015.83
10	Beijing Univ Chem Technol	6	4.32%	2016.33

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The top 10 project development fronts reviewed by the Information and Electronic Engineering Group are summarized in Table 2.1.1, covering electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. The annual disclosure of core patents involved in various development fronts from 2012 to 2017 is shown in Table 2.1.2.

(1) Unmanned aerial vehicles and autonomous driving technology

An unmanned aerial vehicle is an aircraft that relies on the system's own perception, processing and operation capabilities, and changes its own decisions in real time according to the external environment to complete the established tasks. The autonomous driving technology for vehicles is based on high-precision maps, supplemented by intra-vehicle sensing equipment to collect data, makes

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	Unmanned aerial vehicles and autonomous driving technology	177	14 988	84.68	2013.80
2	Multi-dimensional image information acquisition, processing, and fusion technology	33	1 200	36.36	2013.97
3	Display, interaction, and manipulation techniques for virtual reality and augmented reality systems	45	1 980	44	2014.33
4	Optical fiber communication and all-optical network	156	6 166	39.53	2013.28
5	Identity authentication and access control in network security	23	1 278	55.57	2013.70
6	Cloud computing platform	111	9 269	83.5	2013.05
7	Human–computer interaction sensing method and application	39	1 534	39.33	2013.38
8	Array sensor and array sensing big data processing technology	64	2 800	43.75	2012.83
9	Broadband wireless communication system	83	7 121	85.8	2013.14
10	New storage system based on nonvolatile memory	50	4 480	89.6	2013.02

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	2012	2013	2014	2015	2016	2017
1	Unmanned aerial vehicles and autonomous driving technology	35	26	67	38	10	1
2	Multi-dimensional image information acquisition, processing, and fusion technology	5	9	7	8	2	2
3	Display, interaction, and manipulation techniques for virtual reality and augmented reality systems	8	5	9	12	9	2
4	Optical fiber communication and all-optical network	60	45	21	13	11	6
5	Identity authentication and access control in network security	2	10	6	3	2	0
6	Cloud computing platform	43	33	26	6	2	1
7	Human–computer interaction sensing method and application	11	9	14	3	2	0
8	Array sensor and array sensing big data processing technology	30	19	12	2	1	0
9	Broadband wireless communication system	35	25	8	9	3	3
10	New storage system based on nonvolatile memory	18	18	10	3	1	0

decisions based on the identification and calculation of intelligent algorithms with deep learning capabilities, and independently controls the vehicle driving. Unmanned driving with autonomous control can greatly improve system performance and reduce personnel burden and is the future development direction of aircraft and vehicles. With the rapid development of sensor technology, network technology, information technology and AI technology, drones and autonomous driving technologies continue to make important breakthroughs, system performance continues to improve, and practical applications are gradually being implemented.

(2) Multi-dimensional image information acquisition, processing, and fusion technology

Image information fusion enables software to combine different images of the same target or scene into an accurate description of the same target or scene. The application requirements of military, medical science, natural resource exploration, marine resource management, environment and land use management, topographical analysis, and biology have strongly stimulated the development of image processing and image fusion technologies. With the development of remote sensing technology, the means of obtaining remote sensing data is more and more abundant. The image data obtained by various sensors form image pyramids in the same area. Image fusion technology realizes the complementary advantages of multi-source data, and provides an effective way for improving the utilization efficiency of these data. A good image fusion method can lay a solid foundation for subsequent computer automated processing.

(3) Display, interaction, and manipulation techniques for virtual reality and augmented reality systems

Virtual reality technology takes advantage of computer simulation to generate a pure virtual three-dimensional environment that provides people with a perception experience being consistent with the objective world. Augmented reality technology integrates the computer-simulated virtual environment and the real environment in multiple levels. It enhances people's perception of the real environment by superimposing virtual information on the real environment or enhances users' sense of reality for virtual object experience with the integration of real objects or real scenes. Both virtual reality and augmented reality technologies greatly expand the ability of human to understand the world and space, especially for those that human physiological activities are difficult to reach. For examples, human beings can be free from the limitations of time and space to experience the events which have occurred or not in the world, to observe and study the same events in various hypothetical conditions of the occurrence and development process, to explore the macroscopic or microcosmic world, etc. Thus, it provides new tools for people to know the world and change the world. In order for people to perceive the virtual environment/object as well as the real world, it must take geometry, appearance, physical, behavioral, and other aspects into consideration for realistic modeling of virtual environment/objects. At the same time, it must generate real-time virtual environment/object to satisfy people’s visual, auditory, tactile and other sensory channels where the simulation information is needed. Therefore, the virtual reality and augmented reality system is a highly integrated computer simulation system that integrates computer graphics technology, computer simulation technology, AI, sensor technology, display technology, interaction technology and other multiple technical categories.

(4) Optical fiber communication and all-optical network

Optical fiber communication technology refers to a way to transmit information using optical signals and optical fibers. Optical signals can carry a large amount of information after being modulated by different modulation methods. The main material of the optical fiber is glass, which is an electrical insulator, and there is no need to consider the ground loop problem. Because the optical fiber communication system has the advantages of large communication capacity (currently several tens of Tbps), long transmission distance, strong anti-interference performance, good confidentiality and low cost, it has developed rapidly and has received wide attention from the industry, especially in today's information explosion. In the era, the application of optical fiber communication technology has made great contributions to the development of the communication industry and the transformation of the entire society.

All-optical network refers to all optical signal processing in the process of network transmission and exchange, because it does not need to realize electro-optical and photoelectric conversion in it, so it can greatly increase the transmission bandwidth while reducing power consumption and cost. The main technologies of all-optical network include optical fiber technology, wavelength division multiplexing technology, optical switching technology (ROADM, OXC, etc.), passive optical network technology (FTTX), optical fiber amplifier technology (EDFA, Raman amplification), and so on.

The rapid development of optical fiber communication and all-optical networks laid the foundation for the national strategy of "speeding up and reducing fees."

(5) Identity authentication and access control in network security

Identity authentication, also known as "authentication" or "identification," refers to the process of confirming the identity of an operator in a computer and computer network system to determine whether the user has access to and use of a certain resource; thereby, making the computer and the access policy of the network system can be executed reliably and effectively. Moreover, it prevents the attacker from impersonating the legitimate user to obtain the access rights of the resource, ensuring the security of the system and the data, and authorizing the legitimate interests of the visitor.

Currently, mainstream identity authentication and access control technologies include: command-based identity authentication and access control technology, smart card-based identity authentication and access control technology, password-based identity authentication and access control technology, blockchain-based identity authentication and access control, and biometric-based identity authentication and access control technologies.

The development trend of identity authentication and access control technology will break through and develop in the following aspects: ① a combination of multiple identity authentication and access control technologies to provide authentication security and effectiveness. For example, the command authentication method is simple and easy, the password-based authentication method is mature and stable, the smart card has high security features, and the biometric features such as fingerprint iris are very unique and will not be lost or fraudulent. There will be better effect to combine their respective advantages. ② The decentralized distributed verification technology based on smart contract can use Token to intelligently control the identity, authority and access control of users in the system. ③ The identity authentication and access control technology based on user attributes relies on identity encryption mechanism by using the attributes such as user mailbox and identity ID as input credentials to solve the problem that the traditional password mechanism is unfriendly and unrecoverable. ④ The standardization of authentication. By specifying a unified standard, the authentication mechanism of different application systems is compatible.

(6) Cloud computing platform

The cloud computing platform enables users to easily access configurable, shared resource pools on demand in the cloud system, such as servers, networks, storage, applications, and other services, often over networks including the Internet. At the same time, the cloud platform can provide rapid resource provision/release with minimal administrative overhead and minimal interaction with vendors. The ultimate goal of cloud computing is to provide all kinds of IT resources as a public facility to the public, enabling people to use them on demand like water and electricity, and pay for the actual usage without self-construction. To this end, cloud computing is recognized as the third revolution after the personal computing and the Internet; thus the major countries in the world have brought it into the national overall development strategies, and promoted it as the strategic commanding heights of the future informatization.

The services provided by the cloud computing platform can be divided into three levels: infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). According to the deployment form, it can be divided into public cloud, private cloud and hybrid cloud. Key technologies for cloud computing platform implementation include server virtualization technology, distributed computing technology, distributed storage, software-defined networking, and cloud security technologies. Cloud computing platform has become the main form of information technology infrastructure in the Internet era, and the hybrid cloud composed of public cloud plus private cloud or multiple private clouds is becoming the preferred choice for most enterprises and organizations in the transformation into cloud computing. The cloud computing platform itself is also evolving, and new modes such as mobile cloud and edge cloud have appeared. Meanwhile, the cloud computing platform is experiencing fusion development with the emerging applications such as big data, Internet of Things, AI, and blockchain, providing basic resource support for them.

(7) Human–computer interaction sensing methods and applications

The human–computer interaction technology establishes an interface and channel for information exchange between the user and the computing device. From the early manual paper tape, command line interface, graphical user interface, to the current multi-touch interface, physical user interface, the current human–computer interaction technology is entering the stage of high-efficiency, intelligent and invisible natural interaction. In the human-centered interaction process, the computer accurately recognizes the user's interactive instructions by sensing various information such as the user's voice, expression, posture, and physiological data, models the user's cultural background, personality habits, and emotional preferences, more accurately understands the user's interaction intentions, predicting interaction behavior, and greatly reduces the cognitive burden of users in the interaction process. The key methods of human–computer interaction sensing are: interactive sensing methods based on voice and other sound signals, interactive sensing methods based on handwriting or contact data, interactive methods based on behavioral expression understanding, interactive sensing methods based on emotion computing, interactive sensing methods based on physiological calculations, and so on.

The new interactive device will adopt one or more key sensing methods to improve the accuracy of understanding the user's interaction intentions and construct a realistic virtual environment of user experience. Through various artificial sensory technologies such as projection, body, sound, and smell, the growth of the bandwidth of information exchange with the machine and the establishment of a new human–computer interaction interface bring a new service experience to the new generation of computing systems. The human–computer interaction sensing method is a key supporting technology for wearable computing systems, intelligent living space systems, game entertainment systems, and virtual/enhanced/mixed reality systems, and is widely used in various important fields such as media, entertainment, education, medical care, and national defense.

(8) Array sensor and array sensing big data processing technology

Sensor arrays have been widely applied in radar, sonar, microphone, communication, navigation, seismology and other fields. The sensor array is formed by an array of sensors that are placed in a specific position with a specific architecture, enabling receiving multi-dimensional spatial signals. The technology of sensor array processing is developed to analyze these spatial signals, to extract the useful information. It has more flexible beamforming control, higher signal gain, and better spatial resolution over the signal processing of one-dimensional signals acquired by a single sensor. The arrangement, size, and number of the sensors of a sensor array which serves as a hardware, play a significant role in the acquisition of the valid signal. Moreover, the effectiveness and accuracy of the extracted signals are more dependent on array signal processing. The studies regarding the theory of the array signal processing started from 1960s and had focused on adaptive beamforming first and spatial spectrum estimation subsequently. In the recent two years, high-resolution spatial spectrum estimation has attracted much attention; however, it requires expensive computation, and thus the establishment of the real-time algorithm in terms of both hardware and software is increasingly demanding.

The type and number of sensors are greatly increasing and the signal acquisition technology is rapidly improving; thus, the data acquisition amount grows dramatically with widening bandwidths in both frequency and spatial domains. The technique of sensors as well as signal processing has extended its application from the traditional fields to other new fields, such as astronomy, energy, finance, geography, safety control, and social networks. The rapid development of the acquired signals in bandwidth, dimension, resolution, and cyberization has raised the growth rate of data acquisition amount higher than those of the data storage amount and the signal processing speed, indicating that signal processing has stepped into the big data era.

The signal processing with big data requires much effort in several aspects. First, smart sensors with capacity of signal acquisition, data compression, and signal pre-processing are required to reduce the data transmission amount, facilitating the extraction of the valuable information. Second, the new advanced algorithms for the multi-sensor signals are required for the information fusion of the diverse and complex signals with matched time-space dimensions. Third, the high-speed signal processing technology is necessary for extending the I/O bandwidth and enhancing real-time high-performance and high-speed data processing. Finally, the introduction of the AI technique in the signal processing with big data is an alternative way to improve the efficiency of data mining based on its ability of information integration, fusion and cooperative analysis.

(9) Broadband wireless communication system

The new-generation mobile communication system is a stage and goal in the evolution of mobile communication systems. It not only adopts the new wireless transmission technology to improve the performance of the existing communication systems, but also integrates with various existing wired and wireless networks. Further, it not only includes the existing mobile cellular systems, network structure, and some other environments, but also adopts the ad-hoc mode networking, or a combination of the two structures to form a two-hop or multi-hop network structure mode under the cellular network. In general, a cellular network is a widely covered networking approach with the goal of achieving wide-area wireless coverage with limited frequency and power resources. Compared with the cellular network structure, the ad-hoc mobile network structure is more flexible. It adopts distributed management technology, and a group of autonomous wireless nodes cooperate with each other to form a mobile communication network. The wireless node is a mobile terminal in a general sense. It can also be used as a wireless relay and routing device to forward other user data; thus, it has the functions of dynamic search, rapid network construction, and network self-recovery, and has broad application prospects. Considering the importance of ad-hoc in wireless networking and next-generation wireless networks, the Internet Engineering Task Force (IETF) has established a MANET working group to conduct ad-hoc network research. In addition, in recent years, with the development and application of ultra-wide band (UWB) technology, nodes in wireless networks can transmit a large number of very short and fast energy pulses while working, and their transmitted signal power spectral density is low, making UWB suitable as an implementation technology in personal domain networks in a new generation of mobile communication systems.

With the continuous development and maturity of the soft switch technology based on the separation of control and bearer, and the wide application of the intelligent network technologies that can quickly realize various value-added services based on the separation of switching and service control, they are in the new generation of mobile communication systems. Furthermore, with the wide application of the IP technology, the industry generally believes that the development trend of the communication network structure based on next-generation mobile communication is based on the IP network. At the same time, with the rapid development of network capacity and users, IPv6 technology will become the core protocol of the next-generation network.

Wireless communication systems tend to be integrated because of the following reasons. ① Different applicable standards in each wireless communication system begin to seek common ground while reserving differences, complementing each other, and tend to merge; ② systems are merging through integration, and systems are constantly improving; and ③ wireless communication systems and the Internet convergence between them is conducive to the transparency of IP service transmission.

(10) New storage system based on nonvolatile memory

The performance of traditional memory is much different than that of CPU and has become the biggest bottleneck restricting the entire computing system. Moreover, with the rapid development of mobile terminals, large data, cloud computing, machine learning and other emerging applications, the requirement of read-write performance, I/O speed, bandwidth and capacity of memory is constantly improving. The existing multi-layer storage architecture of cache (SRAM)/main memory (DRAM)/hard disk (Flash or HDD) is far from meeting the requirements. As the contradiction between memory and CPU becomes increasingly prominent, a new generation of nonvolatile memory with superior performance is urgently needed to replace DRAM and Flash. A new generation of nonvolatile memory with superior performance is urgently needed to replace DRAM and Flash. In response to this demand, IBM proposed a new memory concept named storage-class-memory (SCM) in 2008 that is defined as having the advantages of nonvolatile, high-capacity, low-cost hard drives. It also has the advantages of fast read/write speed, high reliability, and byte addressable DRAM. After decades of research and development, a variety of nonvolatile memory technologies have become potential for SCM, including STT-MRAM, PCRAM (including Intel's latest 3D-xPoint), ReRAM, FRAM, and so on. SCM is divided into two categories: Memory-SCM with main memory and Storage-

SCM with data storage. In terms of performance metrics, memory-SCM requires a durability greater than 10^9 and a read-write latency of less than 200 ns to be able to be used as a peer memory with DRAM (50 ns level) without having to pass through the I/O controller. Nonvolatile memory-SCM with these performance metrics can solve a series of traditional storage system problems, fully optimize the storage system, and can even completely change the entire computing architecture.

As the amount of data increases, a major development trend in computing architectures is a significant increase in cache capacity and main storage capacity. If you use traditional SRAM and DRAM to achieve capacity expansion, due to their volatility, they need to be used with more than a few orders of magnitude of external storage (Flash or HDD), in turn resulting in lower performance metrics for the entire system. The fast and nonvolatile nature of Memory-SCM can solve this contradiction well, not only to achieve memory expansion, reduce internal processing overhead, but also greatly improve overall performance. A variety of new architectures can be developed. First of all, Memory-SCM can replace the DRAM in the memory. The low cost and high density of SCM allows the memory capacity to be greatly improved. Further, the data are "nonvolatile;" thus, the data exchange efficiency with the CPU can be greatly improved. Reduced data exchange with Flash/HDD. In some specific application scenarios, all DRAMs in memory can be replaced by SCMs, especially with STT-MRAM with a durability of 10^{14}. However, in most cases, because the durability and read/write speed of the new nonvolatile memory are worse than that of the DRAM, retaining part of the DRAM in the main memory and forming a mixed main memory system with the SCM are still necessary. This hybrid main memory system requires the development of a new main memory management system, buffer management algorithm, memory interface, and interface/interconnect technology to manage two different memories simultaneously. At the same time, it is necessary to develop a fault management algorithm for the characteristics of SCM technology, as well as a wear leveling algorithm that compensates for the low durability of SCM, and transfer the frequently read and write "hot data" to the DRAM to reduce the wear of the SCM and thus extend the SCM. For example, the new start-gap algorithm can extend the service life of SCMs with a durability of only 10^7 to 3 years. The industry has developed a variety of such SCM/DRAM hybrid main memory systems, such as 16 TB of mixed memory used in Amazon's cloud computing system x1e. Another advantage of SCM replacing DRAM is to reduce power consumption because SCM does not need to be refreshed like DRAM. At least 1/3 of the power consumption in large computing systems is in the memory system, and SCM can greatly reduce power consumption by replacing DRAM. Another type of nonvolatile memory Storage-SCM application goal is to replace the hard disk. Compared with Flash, the advantages of SCM include faster speed and lower power consumption.

Although the above-mentioned new architecture is much better than the SRAM/DRAM/Flash system, there is a flaw that limits its overall performance: the data need to be transferred between different functional blocks, thereby consuming too much time and power. A more radical improvement is to overthrow the existing von Neumann computing architecture, abandon the CPU-centric architecture, transform into a new "data-centric computing architecture" (non-Von Neumann architecture), and re-start from scratch with the design software and hardware interface. In a data-centric computing architecture, data are stored in a large-capacity nonvolatile SCM memory array (called "general-purpose memory"), and the system no longer sends data to the CPU for computation, but instead uses distributed computing. The CPU lays out the CPU calculation functions around the data to perform approximate calculations on the data. IBM's analog computing shows that the performance of a data-centric computing architecture using nonvolatile SCM memory technology will be several orders of magnitude higher than that of the Von Neumann architecture in terms of speed, power consumption, and floor space.

2.2 Interpretations for three key engineering development fronts

2.2.1 Unmanned aerial vehicles and autonomous driving technology

The autonomous control of unmanned aerial vehicles (UAVs) is divided into three layers: autonomous motion, autonomous task, and autonomous cooperative control layers. The key technologies are adaptive control technology for complex environment of UAV, task-oriented autonomous control technology of UAV and cooperative control technology of UAV. Adaptive control technology for complex environment solves mainly the problem of autonomous motion control for unmanned aerial vehicles under complex conditions. Task-oriented autonomous control technology for UAVs solves mainly the problem of autonomous decision-making and control when UAVs perform complex tasks in confrontation environment. The cooperative control technology of unmanned system solves mainly the control and decision-making problems of multiple unmanned systems in cooperative task execution.

The classification of autonomous driving is divided into 0–5 levels, proposed by the Society of Automotive Engineers (Table 2.2.1). The L0 level is completely unassisted and operated by the driver; the L1 level is still operated by the driver but is embedded in individual auxiliary systems; the L2 level is still controlled by the driver, but the burden can be reduced through the active driving safety assistance system. The L3 level allows the system to take over the operation of the vehicle under certain conditions, but the driver must take over the vehicle when the system determines that a driving operation is required. Above the L4 level, the main control of the vehicle has been the auxiliary system; however, in extreme cases, the driver still needs to take over. The L5 level is a self-driving car that does not need to be driven at all. People are completely passengers.

The key technologies of autonomous driving mainly sensor include, high-precision map, vehicle and environment interaction, and self-determination technologies. A sensor is equivalent to the eye of an autonomous car. The car uses it to identify roads, other vehicles, pedestrian obstacles, and basic transportation facilities. Sensors are usually divided into laser radar, traditional radar, and camera. The high-precision map is accurately positioned by the vehicle to accurately restore the vehicle in a dynamically changing three-dimensional traffic environment. To achieve the safety of autonomous driving, high-precision maps need to be accurate to the centimeter level. The vehicle and environment interaction technology is a technology of interactive information between the vehicle and the surrounding environment, such as vehicles, transportation facilities, and cloud databases, to help the self-driving vehicle to grasp real-time driving information and road condition information, and provide information support for decision-making. The most critical part of autonomous decision-making technology supporting autonomous driving is currently implemented by the machine learning and AI algorithms.

The UAV technology has made breakthroughs in recent years. Various types of UAV are widely used in production, life and combat. In the area of high-performance UAVs, the United States has been at the forefront of the world, the development and installation of a series of high-performance military UAVs. The US MQ-9 has both reconnaissance, surveillance, and firepower strike capabilities, and has achieved good results in actual combat applications. X-47B successfully took off and landed independently on the carrier, and has the ability of multi-platform coordination. In the next step, the control of UAV will change from simple remote control and program control to man–machine intelligent integrated interactive control mode, and gradually develop to fully autonomous control mode; the architecture of the system will develop from specialization and simplification to generalization and standardization; the application mode will change from single-platform independent use to multi-platform cooperation. It is not the direction of cluster applications.

The development of autonomous driving technology is relatively lagging and is still in the auxiliary driving phase of L2. However, major automakers and technology companies have intensified their development of autonomous driving technology in recent years and are expected to make significant progress in the near future. Google began

Table 2.2.1 List of autonomous driving system levels

Grade	Name	Steering, acceleration, and deceleration control	Observation of the environment	Fierce driving response	Coping conditions
L0	Manual driving	Driver	Driver	Driver	–
L1	Assisted driving	Driver + system	Driver	Driver	Partial
L2	Semi-automatic driving	System	Driver	Driver	Partial
L3	Highly automated driving	System	System	Driver	Partial
L4	Super altitude automatic driving	System	System	System	Partial
L5	Fully automatic driving	System	System	System	All

autonomous driving technology research in 2009, and its driverless cars have completed 6 million miles of road tests and 5 billion miles of virtual road tests. The Tesla Autopilot system has reached the level of L2 and is iteratively updated. In China, Baidu launched the unmanned vehicle project in 2013. In 2015, it established a special autonomous driving division to directly develop the L4 fully automatic driving technology. In April 2018, the mass production of the world's first L4-class mass production self-driving bus “Apolong” was completed. Improving the reliability of the system, adapting to the environment, and reducing the system costs are the future development directions.

The countries or regions with the greatest output of core patents, institutions with the greatest output of core patents, collaboration network among major countries, and the collaboration network among major institutions regarding “UAV and autonomous driving technology” are shown in Table 2.2.2, Table 2.2.3, Figure 2.2.1, and Figure 2.2.2, respectively.

2.2.2 Multi-dimensional image information acquisition, processing, and fusion technology

In recent years, with the development of sensor technology, the variety of information expressions, huge amount of information, complex relationship of information, and timeliness, accuracy, and reliability of information processing are unprecedented. This is the rapid development of the use of computer technology to analyze and optimize the multi-source information obtained under certain criteria to complete the required estimation and decision-making (i.e., multi-sensor information fusion technology). Information fusion can be described as synthesizing multi-source information to obtain high-quality and useful information. Generally, various single sensors cannot extract enough information from a scene; thus, it is difficult or even impossible to obtain a comprehensive description of a scene independently. Multi-sensors are required to acquire target data for fusion analysis, so that classification and recognition decisions can be effectively performed.

As a type of information fusion, image fusion is a synthesis of multiple scene information. The image fusion technology is an advanced image processing technology that combines multiple source image information. The so-called multi-source or multi-dimensional image fusion performs appropriate fusion processing on multiple source images collected by the multiple sensors on the same scene or target to obtain a more accurate, more comprehensive and more reliable image for the same scene description. An image is a two-dimensional signal, and the image fusion technology is an important branch of the multi-source information fusion technology. Therefore, image fusion and multi-sensor information fusion have common advantages. Image fusion can enhance useful information in images, increase the reliability of image understanding, and obtain more accurate results, making the system more practical. Simultaneously, the system has good robustness, such as increasing confidence, reducing ambiguity, and improving classification performance.

Currently, the main purposes of applying image fusion technology to digital image processing are as follows:

Table 2.2.2 Countries or regions with the greatest output of core patents on the “UAV and autonomous driving technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	154	87.01%	13112	87.48%	85.14
2	Germany	6	3.39%	435	2.90%	72.50
3	Japan	6	3.39%	650	4.34%	108.33
4	China	5	2.82%	318	2.12%	63.60
5	Canada	4	2.26%	331	2.21%	82.75
6	UK	2	1.13%	131	0.87%	65.50
7	Israel	2	1.13%	148	0.99%	74.00
8	Ireland	1	0.56%	101	0.67%	101.00
9	South Korea	1	0.56%	85	0.57%	85.00

Table 2.2.3 Institutions with the greatest output of core patents on the “UAV and vehicle autonomous driving technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	FORD	26	14.69%	1700	11.34%	65.38
2	GOOG	20	11.30%	1386	9.25%	69.30
3	FLXT	15	8.47%	1964	13.10%	130.93
4	GENK	9	5.08%	632	4.22%	70.22
5	MGIN	7	3.95%	553	3.69%	79.00
6	Autoconnect Holdings LLC	6	3.39%	1102	7.35%	183.67
7	DJII	5	2.82%	318	2.12%	63.60
8	HOND	4	2.26%	510	3.40%	127.50
9	BOSC	3	1.69%	233	1.55%	77.67
10	HONE	3	1.69%	341	2.28%	113.67

FORF: Ford Global Technologies Inc.; GOOG: Google Inc.; FLXT: Lextronics Ap LLC; GENK: GM Global Technologies Operations Inc.; MGIN: Magna Electronics Inc.; AUTO: Autoconnect Holdings LLC; DJII: SZ DJI Technology Co., Ltd.; HOND: Honda Motor Co., Ltd.; BOSC: Robert Bosch Gmbh; HONE: Honeywell Int. Inc.

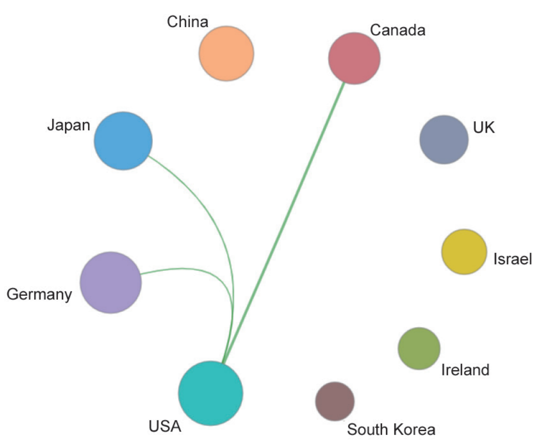

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “UAV and autonomous driving technology”

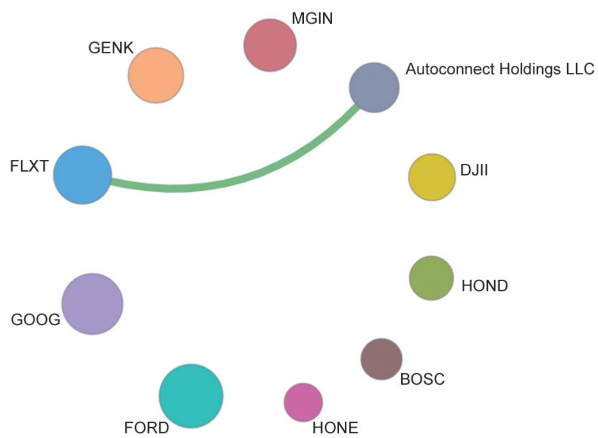

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “UAV and autonomous driving technology” project development

① increasing the content of useful information in the image, improving the sharpness of the image, and enhancing certain features that cannot be seen/visible in a single sensor image; ② improving the spatial resolution of the image, increasing the content of the spectral information, obtaining supplementary image information for improving detection/classification/understanding/recognition performance; ③ detecting the change of a scene/target through image sequence fusion at different moments; ④ producing three-dimensional images by fusion of multiple two-dimensional images with stereoscopic vision that can be used for three-dimensional image reconstruction or stereo photography, measurements, etc.; and ⑤ using images from other sensors to replace or compensate for missing or failure information in a certain sensor image.

In general, image fusion can be performed on the following three levels. ① Pixel level. This refers to fusing on the acquired image information, which can retain more information and improve the fusion precision. However, because of the large amount of processed information, the fusion efficiency is low, the real-time performance is poor, and the pixel-level fusion image is accurately registered. Furthermore, the fusion result is prone to large errors. ② Feature level. In the process of feature level fusion, the image needs to be extracted first, and then the data are analyzed and processed by the feature level fusion algorithm based on the extracted feature information. In this process, the amount of information is greatly compressed, which is conducive to real-time processing, while the fusion results maximize the information required for decision analysis. ③ Decision level. It is the highest level of integration, and the result of integration provides the basis for command, control, and decision-making. Therefore, the fusion result directly affects this decision level. Decision-level fusion can make decisions in the case of loss of some data sources, so it is fault-tolerant. In addition, compared with the first two levels, the decision-level fusion has a good real-time performance, low data requirements, and strong analytical ability. However, it has high requirements for preprocessing and feature extraction; thus, the cost of decision-level fusion is higher. Usually, level-3 fusion can be used together to achieve better fusion.

The information fusion methods used in image fusion can be divided into six categories: algebra-based, component substitution, multi-scale decomposition, statistical, variational, and learning-based methods.

Image fusion is an important topic in the field of image analysis. It has a wide range of applications, such as medical research, map drawing, and hidden weapon inspection. A good fusion image can lay a good foundation for computer automatic processing, such as target recognition and classification.

The countries or regions with the greatest output of core patents, institutions with the greatest output of core patents, collaboration network among major countries, and the collaboration network among major institutions regarding “multi-dimensional image information acquisition, processing, and fusion technology” are shown in Table 2.2.4, Table 2.2.5. Figure 2.2.3, and Figure 2.2.4, respectively.

2.2.3 Display, interaction, and manipulation techniques for virtual reality and augmented reality systems

Both virtual reality and augmented reality technologies model the real world in a virtual environment, which depends on the data acquisition and modeling technology in the real environment. The present development trends of this technology are to model more categories of objects, collect data with higher dimensions, and create a scene more precisely and efficiently. Specifically, modeled objects are no longer limited to geometric surfaces, and they also include features such as appearance, illumination, texture, and bidirectional reflectance. In terms of data dimension, it includes dynamic geometry, illumination, and texture of time dimension, aside from static data. The speed and precision of the collection also increase. The geometric

Table 2.2.4 Countries or regions with the greatest output of core patents on the “multi-dimensional image information acquisition, processing, and fusion technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	24	72.73%	940	78.33%	39.17
2	Japan	3	9.09%	80	6.67%	26.67
3	Canada	1	3.03%	33	2.75%	33.00
4	Switzerland	1	3.03%	19	1.58%	19.00
5	Germany	1	3.03%	40	3.33%	40.00
6	Finland	1	3.03%	24	2.00%	24.00
7	UK	1	3.03%	35	2.92%	35.00
8	Israel	1	3.03%	27	2.25%	27.00
9	South Korea	1	3.03%	24	2.00%	24.00
10	Sweden	1	3.03%	33	2.75%	33.00

Table 2.2.5 Institutions with the greatest output of core patents on the "multi-dimensional image information acquisition, processing, and fusion technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Pelican Imaging Corp	9	27.27%	428	35.67%	47.56
2	Fotonation Cayman Ltd	5	15.15%	241	20.08%	48.20
3	Lytro Inc	4	12.12%	157	13.08%	39.25
4	MICT	4	12.12%	165	13.75%	41.25
5	CANO	2	6.06%	57	4.75%	28.50
6	AMSH	1	3.03%	33	2.75%	33.00
7	APPY	1	3.03%	31	2.58%	31.00
8	Aspect Imaging Ltd	1	3.03%	27	2.25%	27.00
9	ETRO	1	3.03%	46	3.83%	46.00
10	GENE	1	3.03%	33	2.75%	33.00

MICT: Microsoft Corp.; CANO: Canon KK or Canon Kabushiki Kaisha; AMSH: Amersham Pharmacia Biotech Inc.; APPY: Apple Inc.; ETRO: Etron Technologies Inc.; GENE: Ge Healthcare Bio-Sci Corp.

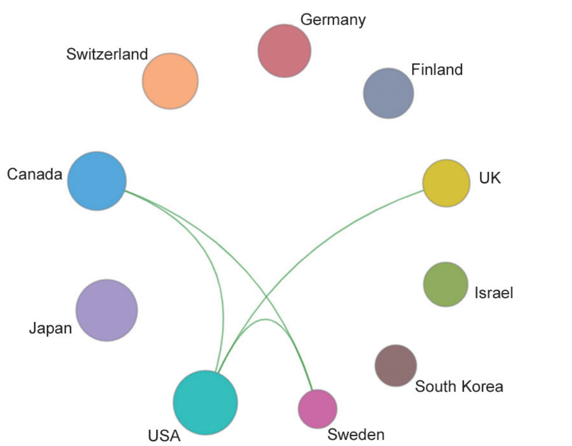

Figure 2.2.3 Collaboration network among major countries in the engineering development front of "multi-dimensional image information acquisition, processing, and fusion technology"

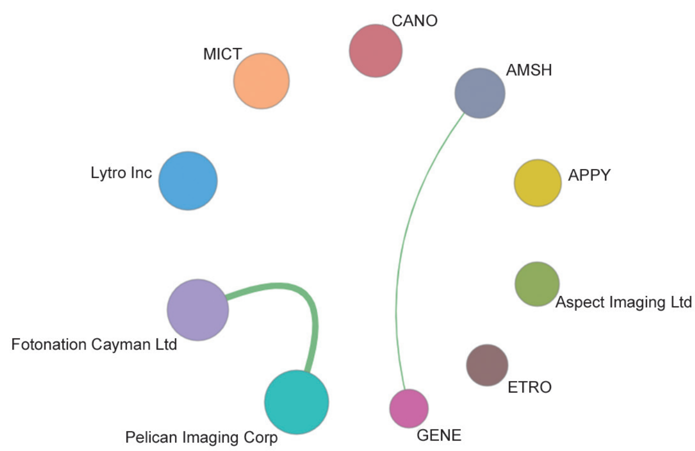

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "multi-dimensional image information acquisition, processing and convergence technology"

calculation is accurate to micron. Further, the illumination reconstruction realizes the collection of dynamic light field. For the modeling method, the means of modeling have been expanded with the comprehensive utilization of the latest acquisition equipment, and the use of new laser scanner, depth camera, and femtosecond camera. Based on vision, interaction, and AI, new methods and technologies provide a more convenient and intelligent modeling method. For example, over the past few years, modeling methods based on machine learning and geometric modeling design methods have been explored from the perspective of achieving high-level semantic understanding. Thus, it is rapidly designed in batches of models with similar styles, but different sizes and details. The emergence of these technologies provides a new technological approach for high-fidelity and high-efficiency reconstruction of the real environment.

Both virtual reality and augmented reality technologies present virtual environment/object in real time with high fidelity and provide people with realistic visual experience, which is a problem that the computer rendering technology continuously tries to improve. Though traditional graphics technology is able to construct complex and interactive virtual scenes, the accuracy and efficiency of presentation need to be improved. As the application goes deeper, the performance of the virtual scene becomes more sophisticated, leading to the rapid growth of its complexity, posing serious challenges to the interactive processing of the virtual environment. Although many effective accelerated processing technologies have been invented, such as scene simplification, sampling prediction, and parallel distribution processing, the authenticity and real-time contradictions of virtual environment perception are still the bottleneck influencing the popularization of the virtual reality technology. Currently, there are two new development trends in this field. One is regarding some special application requirements, the methods of presentation and driving of virtual scenes with low complexity and high authenticity are explored by appropriately limiting the interactive freedom. Contrary to this, new rendering technologies, such as visibility prediction, external storage, parallel distributed computing, GPU computing, and real-time light tracking, are developed specifically to achieve high-fidelity virtual environment/object rendering.

To provide an immersive virtual experience, the current display output technology of virtual reality and augmented reality is different from the traditional display methods based on the displayer. In recent years, a series of high-tech display devices have been developed, such as high-resolution large projection display device, lightweight helmet, and real 3D optical field display, by exploring new display mechanisms and methods. The recent progress in the virtual reality industry is also driven by the launch of Oculus' consumer virtual reality headset. Further, with the launch and release of a series of products such as HTC Vive virtual reality headset, Microsoft Hololens penetrating augmented reality headset, and Magic Leap optical field display helmet, and the emergence of display helmet using holographic technology, new display and devices are provided for people, greatly improving the immersive experience of virtual and augmented realities. In addition, in terms of 3D displays, the new-generation real 3D optical field displays overcome the defects of traditional naked eye 3D displays with only fixed optimal observation points and provide a natural presentation of the optical field of virtual objects and realize continuous motion parallax and binocular parallax. However, regarding display technology, for realistic rendering of virtual environments/objects, the following problems need to be resolved: contradiction among virtual and real consistent experience, limited calculation, and processing and display bandwidth.

In terms of human–computer interaction, a traditional interactive technology based on voice, pen, data glove, and 3D mouse is increasingly mature. However, there are still many problems in the nature and efficiency of interaction, especially in the aspect of tactile perception interaction. Though many researchers are continuing to perfect these interactive technologies, some new natural and harmonious human–computer interaction technologies and interfaces of virtual-real fusion have rapidly become the mainstream development directions. The new technology tries to map people's interaction of objects and environment in real life to the user interface of the interactive process in information space, and apply a life experience to the human–computer interaction system as closely as possible, to lower the learning threshold of the computer technology and increase the naturalness of the interaction. In recent years, multi-touch user interface and interactive method based on hand gestures is in-depth study of a human–computer interaction interface. Although these interactive technologies have a preliminary application, they are often limited by reliability, speed, flexibility, accuracy, convenience, and other such factors. This is still quite far from what people expect of natural and intuitive human–computer interaction technology.

The object in both virtual reality and augmented reality technologies is human; thus, realizing the consistent experience of virtual and real environment in the sense of human perception is necessary. Real perception research on the psychological and physiological aspects of people should also be conducted. Among these aspects, the first thing that needs to be solved is the physical discomfort brought by virtual environment simulation, usually referred to as "virtual reality motion sickness." There are many factors leading to virtual reality motion sickness. The first is that the visual information (the virtual image seen by the eyes) does not match the real position information perceived by the vestibular system in the ear, causing a feeling of vertigo. Another reason is that the calculation results in the delay of the visual image and a delay lag in the movement. In addition, everyone's pupil distance is different, and the three points of the eye, namely pupil center, lens center, and image center may not be in the same line. Thus, there is a phenomenon of ghosting that can also cause discomfort. Finally, it is possible to experience vertigo as the depth of field is out of sync in a virtual scene. Currently, there are many ways to solve motion sickness. One is the biosynchronous feedback technology, such as using omnidirectional treadmills to make real simulation of real responses in the virtual world. Second, the electromagnetic stimulation technology, such as using vestibular stimulation technology to stimulate users' vestibular receptors through feedback from the electrodes behind the ears, so that the user can have a strong sense of virtual environment vision and body position immersion. Third, improving the computing capacity, such as reducing delay. Fourth, adding a virtual reference object, such as a virtual nose, to reduce the perceived discomfort.

The proposal of the conception of virtual reality and augmented reality can be traced back to science fiction from the 1930s. The first virtual reality lab headset, which turned the concept parts into reality, appeared in the 1960s, while the Oculus headset that entered the consumer market and led the development of the virtual reality industry was officially released in 2016. After more than half a century of progress in modeling, rendering, display, and interaction technologies, virtual and augmented realities have finally entered the home of ordinary people and begun to affect the lives of people. The rapid development of consumer market will further promote the improvement and development of technology. Currently, internationally renowned IT enterprises (such as Microsoft, Facebook (Oculus), Google, and Apple) have increased their investment in virtual and augmented reality technologies. The achievement of mutual promotion and development between market and technology will be evident over the next five years. Further development will be achieved in the way and authenticity of virtual environment presentation, and the convenience and accuracy of man–machine interaction. In the future, a larger breakthrough is expected in the fields of vision displays helmet, realistic rendering algorithm based on ray tracing, natural gesture interaction, mobile precise positioning and position perception, and so on. Further, the authenticity of creating a virtual environment by virtual and augmented realities is further improved, thereby providing people with barrier-free, accessible, and comfortable virtual and enhanced environment.

The countries or regions with the greatest output of core patents, institutions with the greatest output of core patents, collaboration network among major countries, and the collaboration network among major institutions regarding "display, interaction, and manipulation techniques for virtual reality and augmented reality systems" are shown in Table 2.2.6, Table 2.2.7, Figure 2.2.5, and Figure 2.2.6, respectively.

Table 2.2.6 Countries or regions with the greatest output of core patents on the "display, interaction, and manipulation techniques for virtual reality and augmented reality systems"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	34	75.56%	1507	76.11%	44.32
2	Japan	7	15.56%	208	10.51%	29.71
3	Canada	2	4.44%	82	4.14%	41
4	Germany	1	2.22%	121	6.11%	121
5	South Korea	1	2.22%	62	3.13%	62

Table 2.2.7 Institutions with the greatest output of core patents on the "display, interaction, and techniques for virtual reality and augmented reality systems"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	MICT	10	22.22%	735	37.12%	73.50
2	Magic Leap Inc	7	15.56%	309	15.61%	44.14
3	DAQRI LLC	3	6.67%	54	2.73%	18.00
4	SHIH	3	6.67%	71	3.59%	23.67
5	SONY	3	6.67%	94	4.75%	31.33
6	GOOG	2	4.44%	86	4.34%	43.00
7	Microsoft Technology Licensing LLC	2	4.44%	49	2.47%	24.50
8	BOSC	1	2.22%	121	6.11%	121.00
9	ETRI	1	2.22%	62	3.13%	62.00
10	Eye Labs LLC	1	2.22%	15	0.76%	15.00

MICT: Microsoft Corp.; SHIH: Seiko Epson Corp.; SONY: Sony Corp.; GOOG: Google Inc.; BOSC: Robert Bosch Gmbh; ETRI: Electronics & Telecom Res Inst.

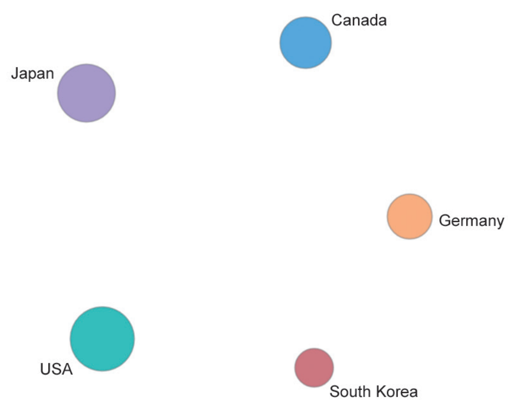

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "display, interaction, and manipulation techniques for virtual reality and augmented reality systems"

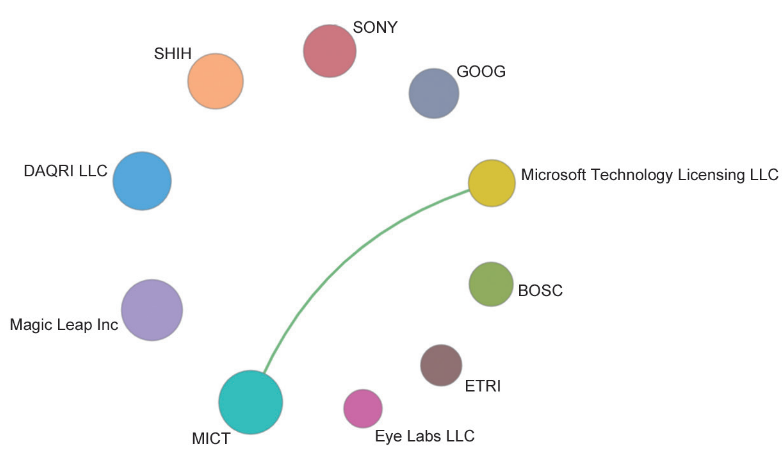

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "display, interaction, and manipulation techniques for virtual reality and augmented reality systems"

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III. Chemical, Metallurgy & Materials Engineering

1 Engineering research fronts

1.1 Development trends in the top 12 engineering research fronts

The top 12 engineering research fronts assessed by the Field Group of Chemical, Metallurgy, and Materials Engineering are shown in Table 1.1.1. These fronts include the fields of new energy materials science and engineering, functional materials, composite materials and engineering, materials physics and chemistry, and catalysis. Among these top 12 research fronts, "development of novel fuel cells," "nanoscale and high-performance metal materials," "carbon dioxide fixation," "photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis," "functionally graded nanomaterials," "design and preparation of supercapacitors," and "highly efficient electrocatalytic water splitting" are further developments of traditional existing research fields. However, "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes functionalization and composites of nanocarbon materials," "Li–O_2 and metal-air batteries," "high-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors," "new fluorescent molecular probes for bioimaging," and "controllable synthesis, functionalization, and application of metal-organic framework (MOF) materials" are emerging fronts. The numbers of core papers published each year from 2012 to 2017 for each of the top 12 engineering research fronts are listed in Table 1.1.2.

(1) Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes

There are numerous types of carbon materials, including charcoal, carbon black, graphite, diamond, linear carbon,

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes	34	2 040	60.00	2015.94	50.0%	0.00
2	Development of novel fuel cells	49	1 023	20.88	2016.31	49.0%	0.00
3	Nanoscale and high-performance metal materials	1 834	238 535	130.06	2014.00	–	–
4	Carbon dioxide fixation	19	1 195	62.89	2015.16	26.3%	0.00
5	Lithium–O_2 and metal-air batteries	37	3 019	81.59	2015.19	62.2%	0.00
6	Photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis	18	1 184	65.78	2016.28	50.0%	0.00
7	Functionally graded nanomaterials	40	2 767	69.18	2015.20	67.5%	0.00
8	Design and preparation of supercapacitors	47	2 903	61.77	2015.66	31.9%	0.00
9	Highly efficient electrocatalytic water splitting	21	2 455	116.90	2015.86	61.9%	0.00
10	High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors	130	13 521	104.01	2015.91	55.4%	0.00
11	New fluorescent molecular probes for bioimaging	38	1 139	29.97	2015.71	28.9%	0.00
12	Controllable synthesis, function-oriented modification and application of metal-organic framework (MOF) materials	31	2 314	74.65	2015.23	41.9%	0.00

Table 1.1.2 Annual number of core papers published for each of the top 12 engineering research fronts in chemical, metallurgy, and materials engineering

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes	2	1	4	1	8	18
2	Development of novel fuel cells	0	1	0	6	18	24
3	Nanoscale and high-performance metal materials	302	367	489	419	216	41
4	Carbon dioxide fixation	1	0	3	9	3	3
5	Lithium–O_2 and metal–air batteries	0	5	5	9	14	4
6	Photocatalysis for solar energy conversion, pollutant degradation, and organic synthesis	0	0	0	1	11	6
7	Functionally graded nanomaterials	0	1	4	21	14	0
8	Design and preparation of supercapacitors	1	4	5	10	7	20
9	Highly efficient electrocatalytic water splitting	0	0	0	11	2	8
10	High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors	0	0	7	36	49	38
11	New fluorescent molecular probes for bioimaging	0	0	0	17	15	6
12	Controllable synthesis, function-oriented modification and application of metal-organic framework (MOF) materials	1	3	4	6	14	3

carbon fiber, vitreous carbon, graphite intercalation compounds, fullerenes, carbon nanotubes, and graphene. Carbon nanotubes and graphene have been state-of-the-art materials in research over the past decade. Graphene nanosheet is a new material with a hexagonal scrobiculate-type lattice with a laminated structure composed of carbon atoms with an sp^2 hybridized orbit. Graphene nanosheets can be folded to form carbon nanotubes (a one-dimensional tubular nanostructured carbon material). Both graphene and carbon nanotubes have excellent mechanical, thermal, and electrical properties; however, well-proportioned composite materials cannot be produced using these materials due to their unique small-size effects, surface effects, and strong Van der Waals forces that make them prone to self-agglomeration during preparation of composite materials. On the other hand, their hydrophobic and oleophobic behavior and the chemical inertness of their surfaces result in poor compatibility with other materials, and hence, a low interfacial bonding strength of the composite materials. Thus, functional modification of the carbon materials should be conducted; i.e., introducing heteroatoms or heteroatom functional groups inside or on the surface of the graphite lattice of the nanocarbon material. Functionalization can modify and modulate the electronic structure of carbon atoms in graphite, thereby changing their physicochemical properties, and subsequently improving the processability of nanocarbon materials during the preparation of composite materials.

(2) Development of novel fuel cells

Fuel cells are chemical devices that directly convert chemical energy into electrical energy. Fuel cells are considered the fourth-generation energy technology after thermal power, hydraulic power, and nuclear power generation technology. Fuel cells are considered the most promising green power generation technology from the perspective of saving energy and protecting the ecological environment. Hydrogen is the most commonly used fuel in fuel cells as it has a high energy conversion rate, low emission, high energy density, and high power density. However, 96% of the global hydrogen production is still from nonrenewable sources; some drawbacks of hydrogen energy include transportation and storage, and a lack of supporting infrastructure, which limit large-scale application of fuel cells. Therefore, the development of fuel cells has become a hot research topic, for ① identifying new alternative fuels (e.g., glycol, acetylene glycol, and formic acid) and studying their electro-oxidation mechanism; ② investigating new methods for preparing and modifying newly developed electrocatalytic materials with high performance, long lifetime, and low cost; ③ design and development of a new type of flexible fuel cell with high energy and power densities; and ④ elucidating the mechanism and application of electrocatalysis in the production of high value-added chemicals.

(3) Nanoscale and high-performance metal materials

Development of nanoscale and high-performance metal materials (nanometals) and improvement of their comprehensive performance will greatly promote further rapid development of the industry. The mechanical, electromagnetic, and optical properties of metallic materials are closely related to their grain size. Grain nanocrystallization is an effective way to improve the overall performance of nanometals, as they are composed of nano-sized grains. Research in this area mainly includes material selection, preparation, and characterization of their properties. Currently, nanopreparation is only used for some metal materials, but the size of the prepared nanometal materials is small, have many defects inside the materials, and the preparation process is complicated. Therefore, the development of nanometal preparation processes that can be used for industrial applications will have great potential applicability.

Preparing high-performance nanometals is a hotspot for future research, especially the preparation of bulk nanomaterials. Although this involves many challenges, breakthroughs in the preparation of materials with high strength, superplasticity, and good electromagnetic and chemical properties are expected in the future. Development work is expected to focus on the preparation of surface nanomaterials and bulk nanomaterials and their application in engineering research.

(4) Carbon dioxide fixation

Although 110 million tons of CO_2 are currently used for the production of chemicals each year, and the industrial production of urea, salicylic acid, methanol, cyclic carbonates, and polycarbonates accounts for the majority. Other technologies for converting and using CO_2 are mostly in the research stage. CO_2 is the most stable carbon oxide, which easily reacts with strong nucleophiles to form C–C and C–H; however, it is still challenging to achieve efficient conversion with inactive substrates under mild conditions. The synthesis of cyclic carbonates and their polymers from CO_2 and epoxides is an effective method for CO_2 fixation; ethylene carbonate and bisphenol A polycarbonate have been industrially produced. Catalyst systems developed for this useful conversion process include metal complexes (e.g., Al, Zn, Co, and Mg), organic amines, and metal oxides. Although many homogeneous catalysts are highly efficient for the synthesis of cyclic carbonates, their limited recyclability has impeded large-scale industrial application. In order to address this problem, the development of highly efficient heterogeneous catalysts has become a research hotspot, which will further promote the industrialization of cyclic carbonate production. Ammonia methylation and carbamylation processes are other ways to fix CO_2, which involve the reduction of CO_2 and the formation of C–N. According to previous reports, the market value of methylamines (such as $MeNH_2$, Me_2NH, and Me_3N) exceeds 4000 Euro/ton. Therefore, aminomethylation using CO_2 as a C1 feedstock can create a value-added product. CO_2 can also be used in carboxylation and carbonylation processes. The former involves CO_2 activation by a nucleophilic reagent into a carboxylated product, while the latter includes in situ reduction of CO_2 to CO, followed by carbonylation. Although these two types of CO_2 fixation strategies provide new opportunities for carbonylation and carboxylation, the current catalytic systems suffer from limited activity and the need for harsh processing conditions. Therefore, it is desirable to develop highly efficient catalysts to achieve CO_2 conversion using these processes.

(5) Li–O_2 and metal–air batteries

Metal–air batteries are electrochemical energy storage/conversion devices that use metal as an anode and oxygen as a cathode. Because the oxygen is obtained from the ambient air, the metal–air battery performs at a higher energy density than traditional batteries, making it suitable for a broad range of potential applications in electric vehicles and electrical grid energy storage. Recently, research and development (R&D) advances have been mostly dedicated to Li–air, Zn–air, Al–air, and Mg–air batteries.

Research areas in metal–air batteries (lithium–air for example) include development of bifunctional oxygen reduction/evolution catalysts and explanation of the corresponding reaction mechanism; mechanism of decay of catalytic activity and stability of the catalyst; design of the architecture of the oxygen electrode, lithium/electrolyte interface, and lithium dendrite; corrosion and protection of lithium; synthesis of electrolytes; structural design and manufacture of the batteries; and system integration.

Trends in the development of metal–air batteries include elucidation of the mechanisms of the electrode reaction and ion transfer via in situ characterization techniques; improving models and algorithms to more closely replicate real conditions; creating controllable methods for preparing the material and electrode; and the development of high-efficiency integrated battery systems and low-energy-consumption smart management systems.

(6) Photocatalysts for solar energy conversion, pollutant degradation, and organic synthesis

In photocatalytic processes, highly active electrons and holes, or excited molecules, are generated by the excitation of absorbed photons, which can drive thermodynamically uphill reactions and accelerate downhill reactions. Photocatalysis (including particulate photocatalysis and photoelectrocatalysis) is extensively investigated for solar energy conversion, pollutant degradation, and organic synthesis involving redox reactions.

The total efficiency of photocatalysis is the product of the efficiencies of light absorption, separation of photogenerated carriers, and the catalytic reaction. In order to improve the efficiency of sunlight conversion, novel materials for harvesting light, such as oxides with a wide absorption band, as well as (oxy)nitride, chalcogenide, and (oxy)halide semiconductors are emerging as promising candidates. Several charge separation mechanisms have been proposed and devices are being developed based on heterojunctions, phase junctions, donor-acceptor materials, and facet charge separation. In addition to water splitting and pollutant degradation, several new catalytic reactions, such as photocatalytic CO_2 reduction, ammonia synthesis, and fabrication of high value-added organic products, are becoming research fronts. Such research includes the effects of surface structure, the function of the co-catalyst, and design of new co-catalysts.

(7) Functionally graded nanomaterials

Over the past 30 years, a novel method for developing high-strength materials has been investigated. This technique involves the nanocrystallization of structural materials with much higher strength and hardness than traditional coarse crystalline materials due to the high number of grain boundaries and other interfaces. However, along with these improvements, the plasticity and toughness of the material are greatly reduced, resulting in a degradation of the work hardening ability and stability of the structure. Therefore, further development of nanoscale materials is challenging. To address these problems, the concept of functionally graded nanomaterials has been proposed. This concept refers to continuous changes in the components, structures, and single or compound physical, chemical, and biological properties, with the aim of tailoring the properties and functions of the material to adapt to different environments. For example, a new material with particular functions can be achieved via changing the intensity, diffusion rate, and chemical reaction activity over a large range. The focus of the present research is the development of preparation methods for functionally graded nanomaterials, which can be classified as follows: ① simple and maneuverable powder metallurgy technology; ② self-propagating high-temperature synthesis method for producing high-purity nanomaterials with high efficiency; ③ a wide range of laser cladding methods; ④ gas-phase precipitation method that can produce precise shapes; and ⑤ graded plastic deformation methods that can introduce a large number of defects.

Functionally graded nanoscale materials have created new challenges and opportunities in the development of new materials and processing technologies. On the one hand, it is important to understand the relationship between the structure and performance of the functionally graded nanomaterials, the difference in the deformation mechanism at all levels, and the morphology difference between homogeneous structures. In addition, deeper understanding of the thermal, mechanical, and chemical stability is required. On the other hand, the efficiency, convenience, and cost of the preparation process will be crucial for determining potential applications and allowing further development of functionally graded nanomaterials.

(8) Design and preparation of supercapacitors

Supercapacitors contain passive energy-storage elements that have a high power density. They have many advantages, such as quick charging and discharging, high efficiency, long cycle life, a wide range of operating temperature, and good reliability. Their superior performance and broad range of potential applications have attracted worldwide attention. Electrochemical supercapacitors are energy-storage devices that rely on the principle of an electric double layer or faradaic pseudocapacitance, where their biggest advantages are excellent pulse charge and discharge performance, as well as fast charge and discharge performance. Current studies of supercapacitors are mainly divided into two groups: ① flexible miniaturized supercapacitors for wearable devices; and ② supercapacitors with a high energy density for large-scale energy storage and mobile power. The development of flexible miniaturized supercapacitors is still in its infancy, mainly focusing on the development of flexible electrode materials and electrolytes. Meanwhile, device packaging and encapsulation technology for supercapacitors need to be developed and tailored for the different electrode materials. Conventional sandwich-shaped supercapacitors (with relatively mature packaging technology) are predominantly studied for the development of high-energy-density electrode materials and high-pressure electrolytes.

(9) Highly efficient electrocatalytic water splitting

Electrocatalytic water splitting is a sustainable method for producing hydrogen, which has attracted much research attention. The process involves the two half reactions of water oxidation (evolution of oxygen) and water reduction (evolution of hydrogen). Although the overpotentials for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) are relatively high under pH neutral conditions, there is considerable interest in this system due to its mild conditions; the overpotentials can be somewhat reduced by using a pH buffer pair like phosphates and borates. On the other hand, many studies have been carried out using a low loading of noble metal catalysts and non-noble-metal catalysts, including (hydr)oxides, chalcogenides, and nitrides and phosphides of Fe, Co, and Ni. Many non-noble-metal electrocatalysts have similar HER performance to noble-metal electrocatalysts, while some even surpass noble metal electrocatalysts for the OER under alkaline conditions. There are two strategies for improving the activity of HER and OER electrocatalysts. The first is to improve the dispersion and increase the amount active sites by producing small particles with selective facets, core-shell structures, or 3D porous structures. The other strategy is to enhance the intrinsic activity of active sites via the introduction of a new crystal or surface structure, or by taking advantage of the cooperativity of metal elements and modulation of nonmetal elements.

(10) High-efficiency halide perovskite solar cells, luminescent materials, and sensitive detectors

$APbX_3$ is the typical formula of halide perovskites, where A is a cation such as methylammonium, formamidinium, or Cs^+; X refers to I, Br, or Cl; and Pb can be substituted by other metals such as Sn, Bi, Sb, and Ag. In the broad definition, non-ABX_3 type layered perovskites are also included, such as A_2PbX_4 and $A_3Bi_2X_9$. Halide perovskite solar cells have advantages of high efficiency, low cost, and simple fabrication methods, making them one of the state-of-the-art research topics in the field of solar cell. By controlling the crystal growth in the film, defects, and interfaces for electron and hole transport, the photoconversion efficiency of small-area halide perovskite solar cells have exceeded 22%. The development of large-area cells and long-term durability of the cell are key focuses in the current research. Based on the excellent photoelectric properties of halide perovskites, some new halide perovskite materials have shown excellent luminescence performance or potential as sensitive irradiation detectors; these topics are attracting increasing research attention.

(11) New fluorescent molecular probes for bioimaging

Fluorescent probes can identify and mark target molecules using fluorescence signals (e.g., wavelength, intensity, and lifetime). With the development of cell biology, molecular biology, and dye chemistry (especially considering the widespread applications and importance of fluorescent proteins in biology), the field of fluorescence probes is focusing on more precise marking of target molecules, including the use of protein labels, synthetic amino acids, biological intersection reactions (click chemistry), and other techniques. The performance of the fluorescent groups can be greatly improved considering the fluorescence intensity, optical stability, polychromatic wavelength, and Stocks shift. The understanding and use of new fluorescence response mechanisms and accurate analysis of fluorescence signals has been rapidly developing. The focus of fluorescence probe research includes achieving a breakthrough in the diffraction limit of the space resolution, increasing the time resolution for real-time live imaging, and increasing the specificity of the response. Such challenges are being addressed for practical applications, such as fluorescence-guided surgery.

(12) Controllable synthesis, functionalization, and application of MOF materials

MOF materials are composed of metal ions (or clusters) bridged by organic linkers and are a novel subclass of porous organic–inorganic hybrid materials. MOF materials have remarkable advantages over traditional inorganic porous materials considering the wide range of possible chemical compositions and architectures. The past decade has seen explosive growth in the study of MOF materials. Three topics in the MOF field are of particular interest: ① controllable synthesis of MOF materials, including computational design of the composition and architecture, high throughput synthesis and characterization of MOF crystals, and manipulation of the morphology without changing the underlying topology. ② Application-oriented post-synthesis modification of MOF materials, including metal/linker substitution, covalent post-synthesis modification, confinement, pore modulation, hybridization, and hierarchical nanostructure assemblies. ③ Application of MOF materials in fields including CO_2 capture, hydrocarbon storage, adsorption and membrane separation, catalysis, sensors, drug delivery, and photoelectrochemistry. In the future, synthesis of MOFs with reticular structures is expected to focus on the deliberate design and assembly of MOF components, rather than the haphazard trial-and-error method currently used. Efforts in this direction are already being undertaken, which are employing many different feasible strategies, including design and modification of microstructures, tailoring the pore size, and decoration of secondary building units to produce far more sophisticated MOF materials.

MOF materials have a wide range of potential uses, where two in particular are thought to be promising in the near future: ① Adsorbents and separation membranes. It is expected that substantial efforts will be devoted to constructing MOF-based adsorbents and separation membranes in the search for alternative energy-efficient and environmentally friendly separation of H_2, CO_2, CH_4, petroleum-based platform chemicals, biomass-based platform chemicals, and pharmaceutical intermediates, along with the pollutant removal and desalination. ② Functional devices. The ability to integrate MOFs with other functional materials in a miniaturized fashion would allow the development of portable multifunctional devices for applications in medicine, electronics, and optics, as well as microreactors.

1.2 Interpretations for three key engineering research fronts

1.2.1 Functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes

Research into graphene and carbon nanotubes is a hotspot in materials science and related fields. Studies have shown that graphene, carbon nanotubes, and their composite materials have broad potential applications in the fields of electronics, information technology, energy, materials, and biomedicine, and are expected to initiate a new technological revolution in the 21st century. Nanocarbon composites mainly include carbon/polymer composites, carbon/nanoparticle composites, and carbon/carbon composites. Neither graphene nor carbon nanotubes can produce well-proportioned composite materials due to their unique small size effect, surface effect, and strong Van der Waals forces, which make them prone to self-agglomeration during the preparation of composite material. On the other hand, their hydrophobic and oleophobic behavior, as well as the chemical inertness of their surfaces result in poor compatibility with other materials and hence, a low interfacial bonding strength of the composite materials. Thus, functional modification of the carbon materials should be conducted; that is, introducing heteroatoms or heteroatom functional groups inside or on the surface of the graphite lattice of the nanocarbon material. Functional modification can modify and modulate the electronic structure of carbon atoms in graphite, thereby changing their physicochemical properties, and subsequently improving the processability of nanocarbon materials during the preparation of composite materials.Recently, many innovations in the preparation of graphene and carbon nanotube composite materials have been related to the modification of the carbon materials in order to optimize the structures (and hence, performance) of the composite materials. The functionalization of graphene can be broadly divided into mechanisms involving covalent bonding or noncovalent bonding. Covalent-bonding functionalization is mainly used to oxidize carbon materials, producing a large number of oxygen-containing groups (e.g., carboxyl, hydroxy, and epoxy groups), which are highly reactive and facilitate covalent modification. To date, surface functionalization of graphite has been achieved using reagents such as isocyanate, silane coupling agents, and organic amine. Noncovalent bonding functionalization changes the surface properties of a carbon material and improves its dispersibility in water or nonpolar solutions by facilitating physical adsorption or polymer encapsulation on the surface. Since physical adsorption and polymer encapsulation have no detrimental effects on the inherent structure of graphene or carbon nanotubes, their structure and properties can be maintained to a large extent.

Carbon nanocomposites using graphene and carbon nanotubes have excellent performance and show unique advantages for various applications. However, industrial application of these materials is still relatively limited as the preparation of the corresponding composite materials needs further development. The limitations of the current preparation methods for composite materials are a major bottleneck in the development of carbon materials science. The research institutions predominantly involved in this research are in China, the United States, and India. The institutes are collaborating and analyzing relevant laws in the preparation of composite materials from different perspectives. This is expected to greatly improve their output and lay the foundation for the industrial production and application of graphene, carbon nanotubes, and other nanocarbon composite materials, allowing these materials to enter the daily life of the consumer.

Countries or regions and institutions with the greatest output of core papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes” are listed in Table 1.2.1 and Table 1.2.2, respectively. Countries or regions and institutions with the greatest output of citing papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes” are summarized in Table 1.2.3 and Table 1.2.4. The collaboration network among major countries or regions and institutions in the engineering research front of “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes” are illustrated in Figure 1.2.1 and Figure 1.2.2.

1.2.2 Development of novel fuel cells

Fuel cells are the fourth generation of power produce technology after thermal power, hydropower, and nuclear power technology. Fuel cells are considered as the top ten “high-tech” field of the 21st century in the USA, and have been hailed as a new global power source. A fuel cell converts chemical energy directly into electricity via an electrochemical reaction within the cell. In addition, there is no mechanical transmission of energy within fuel cells; therefore, they produce little noise and have high reliability. In theory, continuous conversion of chemical energy to electric energy can be achieved in fuel cells if the fuel and oxidizer can be constantly supplied.

Hydrogen is an ideal fuel for fuel cells as it has a high energy conversion rate, high energy and power densities, and fast electric oxidation rate. However, 96% of the global hydrogen production is from nonrenewable resources. In addition, the transportation and storage of hydrogen are problematic, and there is a lack of supporting infrastructure, which greatly

Table 1.2.1 Countries or regions with the greatest output of core papers on the “functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	13	38.24%	356	17.45%	27.38
2	China	12	35.29%	367	17.99%	30.58
3	Australia	10	29.41%	1 371	67.21%	137.10
4	India	5	14.71%	272	13.33%	54.40
5	South Korea	4	11.76%	377	18.48%	94.25
6	Italy	3	8.82%	72	3.53%	24.00
7	Germany	2	5.88%	23	1.13%	11.50
8	Spain	2	5.88%	24	1.18%	12.00
9	France	2	5.88%	22	1.08%	11.00
10	Israel	1	2.94%	16	0.78%	16.00

Table 1.2.2 Institutions with the greatest output of core papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Tennessee	11	32.35%	334	16.37%	30.36
2	Univ Sydney	10	29.41%	1 371	67.21%	137.10
3	Shandong Univ Sci & Technol	9	26.47%	251	12.30%	27.89
4	Univ Ulsan	4	11.76%	377	18.48%	94.25
5	Shandong Univ	3	8.82%	352	17.25%	117.33
6	Pusan Natl Univ	2	5.88%	227	11.13%	113.50
7	Humboldt Univ	2	5.88%	23	1.13%	11.50
8	Avanzare Innovac Tecnol SL	2	5.88%	24	1.18%	12.00
9	Instit Italiano Tecnol	2	5.88%	24	1.18%	12.00
10	Politecn Torino	2	5.88%	24	1.18%	12.00

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	409	49.34%	2016.78
2	India	102	12.30%	2016.80
3	USA	99	11.94%	2016.96
4	Iran	53	6.39%	2016.91
5	South Korea	50	6.03%	2016.06
6	Spain	26	3.14%	2016.42
7	Australia	25	3.02%	2016.40
8	Italy	25	3.02%	2016.04
9	UK	20	2.41%	2016.85
10	Turkey	20	2.41%	2016.95

Table 1.2.4 Institutions with the greatest output of citing papers on the "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Univ Tennessee	41	20.20%	2017.24
2	Chinese Acad Sci	38	18.72%	2016.71
3	Shandong Univ Sci & Technol	28	13.79%	2017.29
4	Sichuan Univ	20	9.85%	2017.24
5	Harbin Inst Technol	16	7.88%	2016.94
6	Univ Sydney	13	6.40%	2015.92
7	Shandong Univ	13	6.40%	2017.24
8	Tsinghua Univ	12	5.91%	2016.75
9	Tianjin Univ	11	5.42%	2017.29
10	Indian Inst Tech	11	5.42%	2016.55

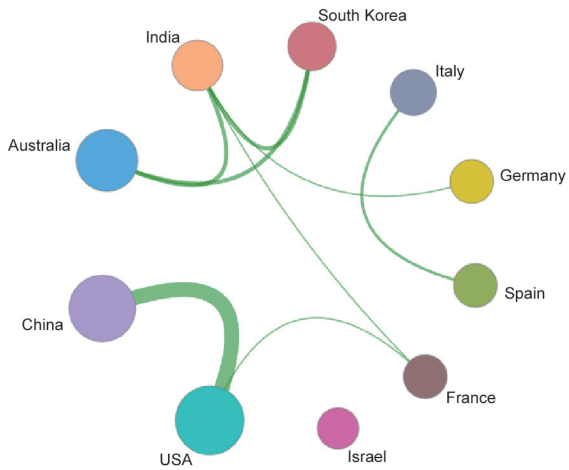

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

limits the promotion and popularization of hydrogen fuel cell applications. Therefore, the development of new types of fuels has become a research hotspot in the field. Toyota has begun developing a fuel-cell system using natural gas as a fuel. The first step in using natural gas as a fuel is to decompose it into hydrogen and carbon monoxide. Then, compressed air is added to the gas mixture, and electricity is generated via a chemical reaction in the fuel cell stack. This process produces some hydrogen and carbon monoxide, which is burnt using a small gas turbine to produce more electricity. Finally, additional electricity is generated using the waste heat via an automotive power generation system. The efficiency of this natural gas fuel cell system was predicted to be 65%. In addition, ethylene glycol, acetylene glycol, formic acid, and other fuels are widely used and studied as alternatives to hydrogen fuel.

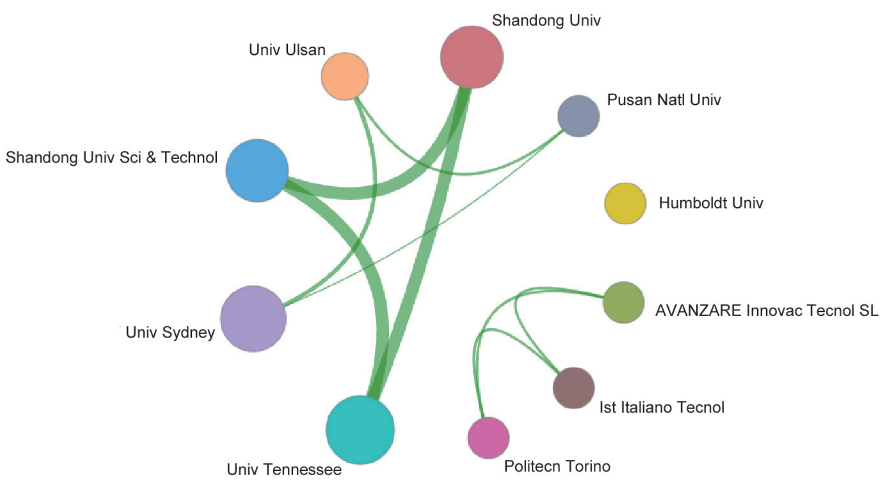

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "functionalization and composites of nanocarbon materials such as graphene and carbon nanotubes"

The catalyst is another key material for fuel cells. The most widely used fuel-cell catalyst is platinum, which has two fatal drawbacks, it is expensive and easy to poison; therefore, there is an urgent need to develop novel alternative catalysts in order to promote the development of fuel cell technology. In 2017, Nisshinbo developed a new catalyst using carbon alloy instead of platinum, which decreased the material cost of the fuel cell by a factor of 1000. For the first time, they successfully realized practical application of a fuel cell without a platinum catalyst. Electrocatalytic oxidation and reduction is a key step to energy conversion in fuel cells, where it is of great significance to exploit the synthesis of highly value-added chemicals using electrocatalysis. For example, the preparation of chemicals and energy materials via electrocatalytic reduction of CO_2 can enable the use of CO_2 as a feedstock and effective storage of clean electric energy.

China has recently issued several policies to support the development of fuel cell technology, including the *Made in China 2025* document published by the Ministry of Industry and Information Technology, China's 13th Five-Year Development Plan, *Action Plan for Energy Technology Revolution and Innovation (2016–2030)*, and *Road Map for Key Innovation Initiatives in the Energy Technology Revolution* documents released by the National Development and

Reform Commission and the National Energy Administration. These policies clearly supported hydrogen energy and fuel cell innovation, and promoted increasing the engineering and industrial capacity of core technologies, such as fuel cells.

Countries or regions and institutions with the greatest output of core papers on the "development of novel fuel cells" are listed in Table 1.2.5 and Table 1.2.6, respectively. Countries or regions and institutions with the greatest output of citing papers on the on the "development of novel fuel cells" are summarized in Table 1.2.7 and Table 1.2.8. The collaboration network among major countries or regions and institutions in the engineering research front of "development of novel fuel cells" are illustrated in Figure 1.2.3 and Figure 1.2.4.

1.2.3 Nanoscale and high-performance metal materials

The preparation of metal materials with improved performance is responding to the needs of the ever-expanding industrial sector. Since the 1980s, nanometals have gradually attracted global attention due to their unique performance and broad range of potential applications, and are expected to be a core part of the industrial revolution of the next century. Currently, the development focus in the nanometal materials field is related to metal surface nanocrystallization and preparation of bulk nanomaterials, resulting in the development of a series of high-performance metal materials. The core technology of nanometal research is the nanopreparation of metal materials, including electrolytic deposition, powder metallurgy, and mechanical processing (e.g., large plastic deformation and shot peening) methods. However, these preparation processes can be complicated and easily produce defects in the material. Currently, many groups are investigating surface modification of nanometals (i.e., graded nanometal materials), which improve the mechanical, friction, wear, and corrosion properties of the materials to some extent. However, there are still limitations in the processing of bulk nanometal

Table 1.2.5 Countries or regions with the greatest output of core papers on the "development of novel fuel cells"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	44	89.80%	914	89.35%	20.77
2	Japan	7	14.29%	63	6.16%	9.00
3	USA	5	10.20%	217	21.21%	43.40
4	India	2	4.08%	53	5.18%	26.50
5	Canada	2	4.08%	16	1.56%	8.00
6	Denmark	1	2.04%	13	1.27%	13.00
7	Spain	1	2.04%	15	1.47%	15.00

Table 1.2.6 Institutions with the greatest output of core papers on the "development of novel fuel cells"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Soochow Univ	22	44.90%	431	42.13%	19.59
2	Chinese Acad Sci	10	20.41%	227	22.19%	22.70
3	Univ Chinese Acad Sci	6	12.24%	146	14.27%	24.33
4	Taiyuan Univ Technol	5	10.20%	180	17.60%	36.00
5	Tokyo Univ Sci Yamaguchi	5	10.20%	41	4.01%	8.20
6	Zhejiang Normal Univ	4	8.16%	47	4.59%	11.75
7	Shandong Univ	4	8.16%	156	15.25%	39.00
8	Peking Univ	4	8.16%	156	15.25%	39.00
9	Xiamen Univ	2	4.08%	57	5.57%	28.50
10	SUNY Stony Brook	2	4.08%	98	9.58%	49.00

Table 1.2.7 Countries or regions with the greatest output of citing papers on the “development of novel fuel cells”

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	354	64.48%	2016.80
2	USA	66	12.02%	2016.76
3	Japan	25	4.55%	2016.56
4	India	20	3.64%	2016.90
5	South Korea	20	3.64%	2016.85
6	Iran	18	3.28%	2016.50
7	Canada	17	3.10%	2017.24
8	Australia	10	1.82%	2016.70
9	Germany	10	1.82%	2016.30
10	France	9	1.64%	2016.56

Table 1.2.8 Institutions with the greatest output of citing papers on the “development of novel fuel cells”

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Soochow Univ	52	22.81%	2016.96
2	Chinese Acad Sci	51	22.37%	2016.76
3	Univ Chinese Acad Sci	24	10.53%	2016.54
4	Zhejiang Normal Univ	19	8.33%	2017.11
5	Shandong Univ	19	8.33%	2016.50
6	Univ Sci & Technol China	15	6.58%	2017.00
7	Peking Univ	14	6.14%	2017.00
8	Xiamen Univ	12	5.26%	2016.83
9	Beijing Univ Chem Technol	11	4.82%	2017.18
10	Univ Toronto	11	4.82%	2017.27

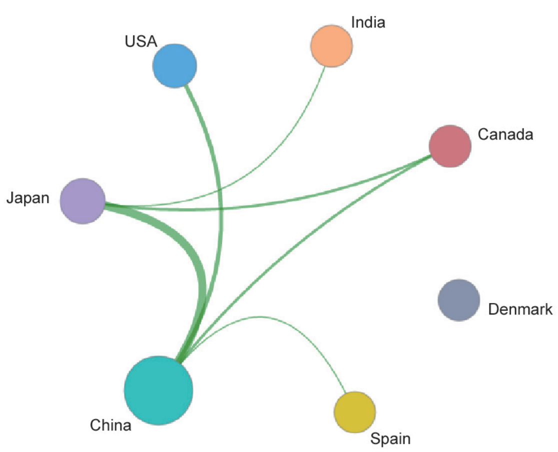

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “development of novel fuel cells”

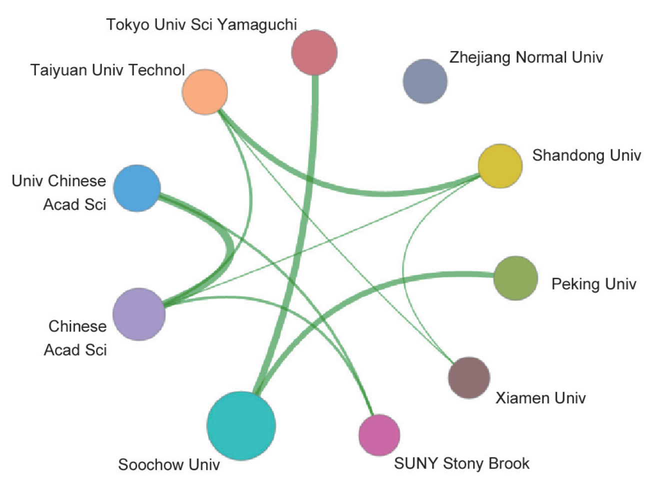

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “development of novel fuel cells”

materials and development of preparation processes that can be up-scaled to provide opportunities for industrial applications.

The top ten countries and institutions producing core papers in the “nanoscale and high-performance metal materials” field since 2012 are listed in Table 1.2.9 and Table 1.2.10, respectively. The cooperation between these countries and institutions are shown in Figure 1.2.5 and Figure 1.2.6, respectively. The top countries or institutions that have cited the chosen core papers are shown in Table 1.2.11 and Table 1.2.12, respectively. Nanometal research mainly focuses on nanofabrication and characterization of metal materials, while a few groups have studied nanofabrication of bulk materials. The majority of the core papers were published by the top three countries (China, the USA, and Singapore). China’s output of core papers accounted for 48.80% of the total, while the number of core papers from the USA accounted for 28.90%. China and the USA have the highest level of collaboration, followed by Singapore, Australia, and China, then South Korea, Japan, and the USA. The Chinese Academy of Sciences has the most core papers of any institute, followed by Nanyang Technological University in Singapore. There is also a lot of collaboration between the Chinese Academy of Sciences with University of Science and Technology of China, Tsinghua University; between National University of Singapore with Zhejiang University, and Nanyang Technological University. The top country with the greatest output of citing papers is the same as the country that

Table 1.2.9 Countries or regions with the greatest output of core papers on the “nanoscale and high-performance metal materials”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	895	48.80%	109 180	45.77%	121.99
2	USA	530	28.90%	76 486	32.06%	144.31
3	Singapore	139	7.58%	23 576	9.88%	169.61
4	South Korea	137	7.47%	18 388	7.71%	134.22
5	Australia	110	6.00%	14 207	5.96%	129.15
6	Germany	104	5.67%	17 550	7.36%	168.75
7	Japan	99	5.40%	13 131	5.50%	132.64
8	UK	70	3.82%	9 074	3.80%	129.63
9	India	58	3.16%	5 315	2.23%	91.64
10	Saudi Arabia	41	2.24%	4 963	2.08%	121.05

Table 1.2.10 Institutions with the greatest output of core papers on the “nanoscale and high-performance metal materials”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	164	8.94%	22 160	9.29%	135.12
2	Nanyang Technol Univ	97	5.29%	19 330	8.10%	199.28
3	Univ Sci & Technol China	53	2.89%	6 653	2.79%	125.53
4	Tsinghua Univ	46	2.51%	6 014	2.52%	130.74
5	Zhejiang Univ	38	2.07%	5 182	2.17%	136.37
6	Natl Univ Singapore	37	2.02%	4 158	1.74%	112.38
7	Fudan Univ	37	2.02%	3 720	1.56%	100.54
8	Stanford Univ	35	1.91%	7 042	2.95%	201.20
9	Argonne Natl Lab	33	1.80%	5 248	2.20%	159.03
10	Univ Calif Berkeley	33	1.80%	4 061	1.70%	123.06

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "nanoscale and high-performance metal materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	24 269	45.61%	2015.66
2	USA	10 946	20.57%	2015.53
3	South Korea	4 440	8.34%	2015.48
4	Germany	2 459	4.62%	2015.57
5	Japan	2 279	4.28%	2015.51
6	UK	1 949	3.66%	2015.71
7	Australia	1 931	3.63%	2015.71
8	Singapore	1 927	3.62%	2015.43
9	India	1 910	3.59%	2015.65
10	France	1 102	2.07%	2015.55

Table 1.2.12 Institutes with the greatest output of citing papers on the "nanoscale and high-performance metal materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	4 449	36.19%	2015.57
2	Univ Chinese Acad Sci	1 174	9.55%	2015.89
3	Nanyang Technol Univ	1 142	9.29%	2015.38
4	Tsinghua Univ	1 028	8.36%	2015.69
5	Univ Sci & Technol China	820	6.67%	2015.68
6	Peking Univ	783	6.37%	2015.70
7	Zhejiang Univ	780	6.34%	2015.58
8	Soochow Univ	745	6.06%	2015.78
9	Huazhong Univ Sci & Technol	717	5.83%	2015.68
10	Natl Univ Singapore	657	5.34%	2015.46

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "nanoscale and high-performance metal materials"

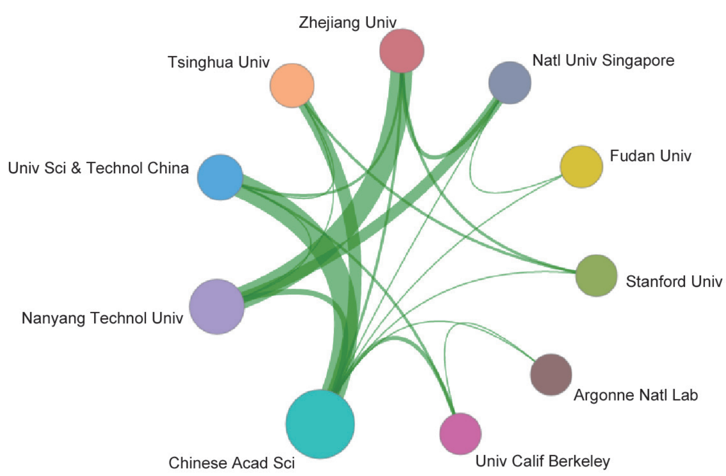

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "nanoscale and high-performance metal materials"

published the highest number of core papers, China. Similarly, the top institute with the greatest out of citing the core papers is the same one that published the highest number core papers, Chinese Academy of Science.

Countries or regions and institutions with the greatest output of core papers on the "nanoscale and high-performance metal materials" are listed in Table 1.2.9 and Table 1.2.10, respectively. Countries or regions and institutions with the greatest output of citing papers on the on the "nanoscale and high-performance metal materials" are summarized in Table 1.2.11 and Table 1.2.12. The collaboration network among major countries or regions and institutions in the engineering research front of "nanoscale and high-performance metal materials" are illustrated in Figure 1.2.5 and Figure 1.2.6.

2 Engineering development fronts

2.1 Development trends in the top 12 engineering development fronts

The top 12 engineering development fronts assessed by the Field Group of Chemical, Metallurgy, and Materials Engineering are shown in Table 2.1.1. These topics include new energy materials science and engineering, functional materials, composite materials and engineering, metal materials engineering, catalysis engineering, metallurgical engineering, and cell biology engineering. Among these development fronts, "green and intelligent metallurgical manufacturing processes," "preparation and application of light metal alloys," "advanced processing of rare and precious metals," "catalytic conversion of fossil resources and biomass," "key materials and technology for large-scale energy storage," "key technologies and materials for supercapacitor," "new-generation high-energy Li–S batteries and solid-state Li batteries," and "preparation, structural connections, and applications of advanced composites" are further developments of traditional fields. However, "crystal engineering and large-scale applications of metal-organic framework (MOF) materials," "key methods for preparing graphene-based functional materials and their application in energy storage," "development and application of additive manufacturing (3D printing)," and "cell therapy" are emerging fronts. The annual numbers of patents published within these fields from 2012 to 2017 are shown in Table 2.1.2.

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Key materials and technology for large-scale energy storage	503	991	1.97	2014.68
2	Catalytic conversion of fossil resources and biomass	154	310	2.01	2014.73
3	Green and intelligent metallurgical manufacturing processes	981	1 103	1.12	2014.57
4	Development and application of additive manufacturing (3D printing)	338	8 417	24.90	2014.12
5	Preparation, structural connections, and applications of advanced composites	196	6 487	33.10	2013.91
6	Key technologies and materials for supercapacitors	609	1 573	2.58	2015.12
7	New-generation high-energy Li–S batteries and solid-state Li batteries	579	991	1.71	2015.67
8	Key methods for preparing graphene-based functional materials and their application in energy storage	853	1 825	2.14	2015.33
9	Preparation and application of light metal alloys	165	2 967	17.98	2013.52
10	Crystal engineering and large-scale applications of metal-organic framework (MOF) materials	590	1 084	1.84	2015.67
11	Advanced processing of rare and precious metals	170	333	1.96	2014.67
12	Cell therapy	237	398	1.68	2014.73

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

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Key materials and technology for large-scale energy storage	66	77	91	84	87	98
2	Catalytic conversion of fossil resources and biomass	17	30	25	26	28	18
3	Green and intelligent metallurgical manufacturing processes	118	185	193	159	155	171
4	Development and application of additive manufacturing (3D printing)	54	60	87	86	29	22
5	Preparation, structural connections, and applications of advanced composites	43	42	32	49	28	2
6	Key technologies and materials for supercapacitors	63	61	93	121	98	138
7	New-generation high-energy Li–S batteries and solid-state Li batteries	28	43	57	107	125	166
8	Key methods for preparing graphene-based functional materials and their application in energy storage	58	85	97	143	216	254
9	Preparation and application of light metal alloys	43	53	32	18	16	3
10	Crystal engineering and large-scale applications of metal-organic framework (MOF) materials	20	44	64	119	131	160
11	Advanced processing of rare and precious metals	24	31	26	23	28	38
12	Cell therapy	32	39	28	40	58	40

(1) Key materials and technology for large-scale energy storage

Currently, large-scale energy storage technologies mainly include pumped hydro storage, compressed air, flow batteries, lithium-based batteries, phase-change energy storage, lead-acid batteries, thermal storage, superconductors, flywheels, supercapacitors, and Na–S batteries. Among these technologies, pumped hydro is currently the only technology that has achieved large-scale use. However, it is limited by geographical conditions; there is a mismatch between the geographical position of wind and solar resources and locations suitable for pumped hydro in China. In addition, it cannot meet the required energy storage for future large-scale development of wind and solar energy. Hence, it is imperative to develop alternative energy storage technologies. There are three essential requirements for large-scale energy storage systems: ① high reliability; ② cost-effective life cycle; and ③ low environmental impact over its life cycle. Many of the proposed energy storage technologies have limitations with respect to scale, cost, and lifetime. Among the solutions, compressed air and flow batteries are relatively mature technologies and have become development priorities for current large-scale energy storage systems. Li polymer batteries and phase-change energy storage have advantages of high energy density, easy management, combined heat and power, and are suitable for regional energy supplies. With the rapid growth of the global energy demand, many countries have introduced a number of scientific and technological plans to meet this need, where the developed countries have taken the lead in energy storage technology. For example, the scale of compressed air energy storage systems is currently over 100 MW; the lifetime of flow battery is about ten years; the lifetime of flywheels and supercapacitors has exceeded twenty years; the cost of superconductor, thermal, and compressed air energy storage systems is less than 1000 USD/kW; and various energy storage technologies have entered the stage of large-scale demonstration and commercial applications.

(2) Catalytic conversion of fossil resources and biomass

Energy is a common global concern and diversification of the global energy structure is a present trend. It is predicted that by 2040, oil, gas, and coal will still account for three-quarters of the total energy supply, although a rapid increase in renewable energy production is underway. Therefore, the clean and efficient transformation and use of petroleum, coal, natural gas, and biomass is an important direction in the current energy field. A breakthrough in modern coal chemical technology is the key for future coal use. In the future, the fuel market will be affected by new energy policies, and the direct conversion of oil to chemicals will be developed to adapt to changes in the market. Biomass is an important part of the renewable energy supply, and its large-scale, low-cost, and efficient transformation and use is expected to be a future development trend. In recent years, the rapid development of catalysis science has played an important role in the growth of new technologies and the improvement of existing ones.

(3) Green and intelligent metallurgical manufacturing processes

The large scale of the metallurgy industry results in high total energy consumption and emission of pollutants. This industry is subject to increasing environment constraints and pressure to reduce energy use. Hence, it is imperative to promote green development and intelligent manufacturing in the metallurgy industry and achieve harmonious development with society. In the case of manufacturing in the metallurgy industry, green manufacturing refers to the principle of "reduce, reuse, and recycle," with the goal of zero emissions, and total reuse of waste heat, residual pressure, residual gas, waste water, and solid waste produced during the process, finally achieving a clean and environmentally friendly process. The state-of-the-art green manufacturing technologies developed to date include: waste heat recovery and use of slag, new composite ferrous coke technology, combined optimization of material, energy, and information flow (big data) in iron and steel works, and CO_2 capture, storage, and use. The metallurgy industry, in particular the steel industry, has highly automated processes. The development of intelligent manufacturing has a good foundation and widespread potential. With the help of intelligent manufacturing technologies, such as Internet + and the Internet of Things, the customization, flexibility, greening, networking, and intelligence of steel production can be improved, which will promote transformation and upgrade of the steel industry. The key technologies for intelligent manufacturing in the steel industry include: intelligent expert systems based on industrial big data, the use of robotic systems, multi-objective real-time optimization of on-line technologies in production, use of big data for intelligent fault diagnosis and maintenance of key technology and equipment, optimization of supply chains, and integration of information technology for cooperative manufacturing.

(4) Development and application of additive manufacturing (3D printing)

Additive manufacturing, also known as 3D printing, is an advanced manufacturing technology which has nearly 30 years of development. It is used for rapid manufacturing due to its advantage of 3D freedom of movement, and is widely used in the development of new products and small batch manufacturing. The system uses alloy powder or wire as a raw material and the product is deposited layer-by-layer using in situ high-power laser melting and rapid solidification. Additive manufacturing technology can be classified into two categories according to the different states of the metal during the deposition process: ① a molten pool of the metal is produced during processing; for example, laser engineered net shaping (LENS) and direct metal deposition (DMD); ② the metal powder is distributed before deposition of the following layer, including direct metal laser sintering (DMLS), selective laser melting (SLM), fused deposition modeling (FDM), and selective laser sintering (SLS) methods. In general, this technology has several advantages, including fast manufacturing and efficient material use, where no molds are required; this reduces the manufacturing cost by 15%–30% and reduces the production cycle by 45%–70%. Functional metal parts with complex shapes can be produced that are difficult or even impossible to fabricate using traditional methods. In addition, graded functional structures with different components and textures can be formed in the same part without repeat molding and intermediate heat treatments. Furthermore, rapid solidification results in metal parts that are completely compact with a fine structure, and tensile performance exceeding that of cast materials. The near-net-shape parts can be used directly or only require a small amount of subsequent machining. Additive manufacturing is a green transformative technology based on digital manufacturing that is characterized by its low cost, short cycle time, and ability to control the shape and performance of a product. This technology has huge development potential and broad prospects in future aviation and aerospace, nuclear power, petrochemical, marine, and manufacturing industries. In the past 20 years, this technology has become a research hotspot in the interdisciplinary field between materials process engineering and advanced manufacturing, attracting worldwide attention from government, industry, and academia.

(5) Preparation, structural connections, and applications of advanced composites

Advanced composite materials with high-performance fibers as reinforcing materials (e.g., carbon, boron, aramid, and silicon carbide fibers) have advantages of low density, high specific strength and specific stiffness, and good fatigue resistance, vibration damping, and mechanical properties. Such materials are the first choice for designing lightweight structural materials and are widely used in aerospace, automotive, wind power generation, machinery manufacturing, and medical fields. The research focus for advanced composite materials includes optimizing the design of the composite structure, along with developing large-scale integral molding technology, regenerative functions, composite connection methods, self-healing properties, and the combination of intelligence, stealth, and other functionality. The bonding methods for advanced composite materials include adhesive, mechanical, and hybrid connections. In the future, the connection modes for composite materials are expected to include a variety of new connection techniques in addition to mechanical and adhesive bonding. The overall trend is to optimize the design of the bonds to achieve integration of composite structural parts to achieve enhanced stability and reliability of the joints.

(6) Key technologies and materials for supercapacitors

Supercapacitors (also known as electrochemical capacitors, gold capacitors, and farad capacitors) include electric double layer capacitors and pseudocapacitors, which store energy by polarizing electrolytes. Although supercapacitors are electrochemical systems, they do not undergo a chemical reaction during energy storage, and the process is reversible; hence, supercapacitors can be repeatedly charged and discharged billions of times. Supercapacitors are expected to replace traditional chemical batteries as they have large capacity, high power, long lifespan, and low cost, in addition to being environmentally friendly. Hence, they have a broader range of applications than traditional batteries. This technology is constantly evolving, driving applications from the initial field of electronic equipment into power and energy storage. The core challenge in supercapacitor technology is preparing low-cost supercapacitors with high energy density while maintaining the high power density, long cycle life, and environmentally friendly properties of traditional capacitors. These requirements can be realized through the development of key electrode materials, highly compatible capacitor separators, and high-pressure electrolytes, while optimizing the system design and integration of supercapacitors.

(7) New-generation high-energy Li–S batteries and solid-state Li batteries

Lithium–sulfur (Li–S) batteries are a new generation of high-energy density secondary battery, employing Li as the anode and S as the cathode. To date, the reported specific energy of Li–S batteries is more than 600 Wh/kg, which is three times that of Li-ion batteries. However, development challenges include poor cycle stability of the battery due to polysulfide shuttle effect, where polysulfides generated during the discharge of Li–S batteries diffuse to the anode. In addition, the lithium metal becomes powered and generates dendrites during the cycling. Recent directions in technical research include optimization of the cathode composition and structure, such as the addition of anchoring agents for polysulfides to inhibit the shuttle effect; addition of a catalyst to enhance conversion of polysulfide to lithium sulfide; deposition of artificial solid electrolyte interphase films on the surface of the Li anode and construction of a 3D network structure to uniformly deposit Li ions, thereby improving the cycle stability of the Li-S batteries.

In solid-state Li batteries, the liquid electrolyte is replaced by a solid-state electrolyte and Li metal acts as the anode. Since the solid-state electrolyte has a high melting point and excellent mechanical properties, which can inhibit the formation of lithium dendrites, solid-state Li batteries are expected to become the next generation battery system with high specific energy and good safety. Recent directions in technical research include: preparation of solid-state electrolytes with high ionic conductivity at room temperature and good compatibility with metallic Li; and modification and optimization of the interface between the solid-state electrolyte and electrodes, thereby improving the electrochemical performance of solid-state Li batteries.

(8) Key methods for preparing graphene-based functional materials and their application in energy storage

Graphene is a hexagonal scrobiculate-lattice two-dimensional carbon nanomaterial composed of carbon atoms in an sp^2 hybridized orbit. The scientific community has been studying graphene for more than a decade. Although graphene was proved to exist alone in 2004, patents using this material only increased sharply after 2010. A large number of inventions and technologies are emerging every year, predicting that the industrial application of graphene technology will enter a period of rapid development in the next few years. The crucial research directions of graphene are expected to focus on the preparation of graphene suspensions or powders, macroscopic graphene (such as fibers, films, aerogels, and foams), and graphene composite materials. Graphene is expected to be widely used in supercapacitors and various new types of batteries, and will gradually be used as an active energy storage medium instead of only as a conductive agent (as used in the early applications). This requires functionalization of the graphene and preparation of suitable functional or composite materials, such as 3D graphene, and graphene-coated silicon for Li battery anodes, which can also be used as a capacitor or the positive electrode of Li–S batteries.

(9) Preparation and application of light metal alloys

With the rapid development of high-tech fields, such as aerospace, high-speed rail, nuclear power, automotive, and biomedical, the demand for high-performance metal alloys is significantly increasing. Most development work involves Al-, Mg-, Ti-, and Zr-based alloys, including: high-performance Al alloy for structural and wire applications; Mg alloys with high strength and toughness, and wear and corrosion resistance; biodegradable and biomedical Mg alloys; medical titanium alloys; high-strength, high-toughness Zr-based amorphous alloys and ceramic materials.

The high performance of Al alloys is due to the micro-alloying effect. The current research focus in this area is selecting and controlling the types and quantities of elements that play different roles in the alloy. To date, the hotspot for Mg alloy research is achieving high strength and toughness. In order to achieve this goal, design of the alloy composition and preparation process is used to optimize the material performance. Currently, the tensile strength at room temperature of advanced high-strength cast magnesium alloys and cast wrought magnesium alloys is $\geqslant$400 MPa and $\geqslant$550 MPa, respectively. Improvement of the plasticity and toughness of high-strength lightweight alloys is a current hotspot. Improving the plastic toughness of high-strength lightweight alloys through grain refinement, new phases, new structures (e.g., the long-period stacking order structure), and optimization of the interface and texture is the focus of development in several countries. In addition to being a structural material, Mg alloys are used for medical applications. In particular, biodegradable biomedical Mg alloys are a future development trend, where improving their corrosion resistance is a research focus. Systematic research on Ti alloys is underway, where lowering the production cost and developing new Ti-based materials are expected to further expand their application. Zr-based amorphous alloys have excellent mechanical properties, good corrosion resistance, and high catalytic performance; these properties have resulted in their widespread use in electronics and military applications.

(10) Crystal engineering and large-scale application of MOF materials

MOF materials, composed of metal ions (or clusters) bridged by organic linkers, are a novel subclass of porous organic–inorganic hybrid materials. The flexibility with which the metal nodes and organic linkers can be varied has led to thousands of compounds with permanent and regular porous networks. MOFs have a wide range of potential uses, including gas storage, separation, catalysis, and energy technology. Crystal engineering using both modeling and experimental methods is an efficient strategy to design and synthesize MOF materials. Substantial efforts in this direction have already been undertaken, including: ① high throughput synthesis, screening, and characterization of MOF crystals; ② systematic investigation of the nucleation and growth of MOF crystals; and ③ scaled-up synthesis of MOF materials. Considering the cost and environmental impact, an impending challenge is improving the space-time-yield of MOF synthesis while greatly reducing the consumption of organic solvents. Thus, the development of aqueous synthesis methods or solvent-free processes with high space-time-yield has been demonstrated as a feasible solution to overcome these issues. In addition, precise control of the nucleation and growth of MOF crystals is expected to yield MOF materials with uniform particle size distributions on a large scale. In the future, the field will focus on two aspects of large-scale application of MOF materials; namely, adsorbents/separation membranes and functional devices. An alternative energy-efficient and environmentally friendly separation pathway will be established using MOF-based adsorbents and membranes. Meanwhile, on-going development combining different areas of expertise (including chemistry, engineering, medicine, biology, electronics, and optics) will promote commercialization of MOF-based devices. The poor stability of MOF materials is of particular concern; the use of MOF materials in demanding conditions remains a challenge (although MOF crystals are constructed from metal-containing inorganic units and organic linkers connected by relatively strong bonds). Substantial efforts have already been undertaken to resolve this problem using a series of feasible strategies, such as the integration of MOFs with functional protective materials, or using functional decorations to improve their stability.

(11) Advanced preparation of rare and precious metals

Rare and precious metals generally include rare and refractory metals, such as titanium, zirconium, hafnium, vanadium, niobium, tantalum, molybdenum and tungsten; rare light metals such as lithium, rubidium, and cesium; scattered metals such as gallium, indium, thallium, germanium, rhenium, selenium, and tellurium; rare earth metals such as scandium, yttrium, and lanthanide; rare radioactive metals such as scandium, yttrium, polonium, actinide, thorium, and uranium; and precious metals such as gold, silver, and platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum). Rare and precious metals are important basic materials for the national economy, social development, and national defense, and are widely used in the energy, metallurgy, petrochemical, machinery, aerospace, information, marine, biomedical, and transportation sectors and for building materials and textiles. Due to their low abundance in the Earth's crust and their distinct physical and chemical properties, rare and precious metals are difficult to extract and process. Developed countries attach great importance to the R&D of rare and precious metals and almost monopolize the international market of high-end and high value-added products. For a long time, China lacked the core technology of independent intellectual property rights for the preparation and processing of some high-purity rare and precious metal products. Because of the high manufacturing cost, large-scale production has not been realized, which has restricted the development of emerging industries, such as optoelectronics. With increasing demand for rare metals in high-end equipment manufacturing, strategic emerging industries, and major projects, advanced processing methods for rare and precious metals has become a global R&D focus. The key technologies include: preparation methods for ultra-high-purity rare metals; large-scale manufacturing technology for rare and precious metals for target high-end functional components; large-scale and deep processing technology for high-purity rare metal products for high-end equipment manufacturing; methods for producing high-quality rare and precious metal powder; welding technology for rare and precious metals to achieve various specifications; and methods for combining the rare and precious metals with conductive materials.

(12) Cell therapy

Cell therapy encompasses many technologies where certain cells are injected or transplanted into the human body to trigger cell-mediated immunity, anti-cancer or tissue/organ regeneration, improved immune function, wound repair and regeneration, disease treatment, and anti-aging effects. Although cell therapy has a history of more than 500 years, the development of modern technologies, such as inducible stem cell cultures, tissue engineering, and genetic engineering, are now resulting in commercialization of the method. Based on the host of cells used, cell therapy can be classified as autogeneic or allogeneic cell therapy. Depending on the sources or targets of the cells (e.g., embryonic, neural, mesenchymal, or hematopoietic stem cells), the method can target diseases of the immune system or blood, diabetes, and neurological conditions. Cell therapy has already shown huge potential in such fields.

In addition to the application of cell therapy, investigation of the underlying mechanisms is also a focus, including control of cell differentiation, dedifferentiation, and inducible differentiation, and study of the signal factors and epigenetic mechanisms involved.

2.2 Interpretations for three key engineering development fronts

2.2.1 Key materials and technology for large-scale energy storage

Energy is fundamental for the sustainable development of human society and the economy. With the development of society, the demand for energy is increasing, causing a shortage of fossil energy and deterioration of the environment. Promoting changes to the energy structure, efficient use of fossil fuels, and large-scale use of renewable energy are important strategies for global energy security and sustainable economic development. However, the production of renewable energies, such as wind and solar, is intrinsically discontinuous and unstable. Therefore, large-scale energy storage technology is required in order to realize large-scale access to renewable energy, which is a key supporting technology for modifying the energy system. Existing large-scale energy storage technologies, such as vanadium flow batteries, compressed air storage, and gel polymer battery/phase-change thermal storage, are characterized by their high safety, low cost, large capacity, and long lifetime. Such technologies are expected to effectively meet current needs and have made important progress in fundamental research, trial production of devices, and small-scale demonstration. There is an urgent need for further multidisciplinary academic research in order to achieve the leap from research to engineering applications.

The development of energy storage technologies has attracted attention from governments and become a research focus. As of the end of 2016, the cumulative installed capacity of commissioned global energy storage projects was 168.7 GW, a year over year growth of 2.4%. Among the different technologies, the cumulative installed capacity of electrochemical energy storage ranked third, with a scale of 1769.9 MW, a year over year growth of 56%. According to the third edition of the *Rethinking Energy 2017* report released by the International Renewable Energy Agency, the future use of batteries for energy storage will increase significantly. It is expected that the global battery energy storage market will increase to 14 billion USD by 2020. The USA has long supported and focused on the development of energy storage, and convened the Summit on Renewable Energy and Energy Storage in the Smart Grid in 2016. The Obama administration announced the *Federal and Private Sector Action Plan for Expanding Renewable Energy and Energy Storage*, which defines the energy storage needs and allocation targets for more than eight states in the following five years, where investors will provide 130 million USD for energy storage. With the aim of making renewable energy the core of Germany's future power supply, the German government is implementing an ambitious energy transformation strategy that will increase the renewable energy power supply to 35% by 2020 and more than 50% and 80% by 2030 and 2050, respectively; the rapid development of energy storage technology plays a critical support role in this strategy. Japan has been continuously funding R&D of energy storage technology since the 1970s. Over the past ten years, Japan has invested more than 40 billion JPY (more than 3 billion CNY) in the R&D of energy storage technology. Japan’s current installed capacity of energy storage is ranked first in the world and occupies about 11% of the total installed capacity of electricity. In 2012, South Korea launched the *Strategy for Energy Storage Technology R&D and Industrialization*, and will invest 6.4 trillion KRW (about 32 billion CNY) for energy storage technology research, development, and application by 2020.

The Chinese government is paying increasing attention to energy storage. Various national science and technology, and energy strategic plans, such as the *Development Outline of National Medium and Long-term Science and Technology (2006–2020)*, *Development Plan of the 13th Five-Year National Strategic Emerging Industry*, and *13th Five-Year National Science and Technology Innovation Plan* have highlighted energy storage technology as one of the key development directions. In addition, with support from Technology Plans, such as those from the National Natural Science Foundation (Program 973 and Program 863), and national key R&D plans, many energy storage technologies in China have made progress in basic research, key technology R&D, trial production of devices, and small-scale demonstration. Energy storage technology research in China started relatively late; thus, there is still a considerable gap between the level of research produced in China and that of the rest of the world, especially in terms of system integration, demonstration of devices, and comprehensive management of energy systems.

Countries or regions and institutions with the greatest output of core patents on the “key materials and technology for large-scale energy storage” are listed in Table 2.2.1 and Table 2.2.2, respectively. The collaboration network among major countries or regions and institutions in the engineering development front of “key materials and technology for large-scale energy storage” are illustrated in Figure 2.2.1 and Figure 2.2.2.

2.2.2 Catalytic conversion of fossil resources and biomass

Energy is one of the most important issues attracting global concern and is crucial for domestic economic and social development. According to the 2018 edition of BP Energy Outlook, the global energy structure is diversified. Demand for oil will continue to increase in the near future, where most of the growth in demand is driven by petrochemical products, while natural gas will become the second largest resource of

Table 2.2.1 Countries or regions with the greatest output of core patents on the "key materials and technology for large-scale energy storage"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	149	29.62%	180	18.16%	1.21
2	Japan	110	21.87%	140	14.13%	1.27
3	USA	105	20.87%	409	41.27%	3.90
4	Germany	54	10.74%	100	10.09%	1.85
5	South Korea	52	10.34%	58	5.85%	1.12
6	Taiwan of China	8	1.59%	13	1.31%	1.63
7	France	6	1.19%	5	0.50%	0.83
8	India	5	0.99%	0	0.00%	0.00
9	Russia	3	0.60%	0	0.00%	0.00
10	Canada	2	0.40%	35	3.53%	17.50

Table 2.2.2 Institutions with the greatest output of core patents on the "key materials and technology for large-scale energy storage"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	YUAS	Japan	64	12.72%	53	5.35%	0.83
2	MATU	Japan	24	4.77%	21	2.12%	0.88
3	BOSC	Germany	17	3.38%	46	4.64%	2.71
4	SGCC	China	17	3.38%	22	2.22%	1.29
5	BATT	USA	12	2.39%	111	11.20%	9.25
6	CHWE	China	12	2.39%	21	2.12%	1.75
7	HITB	Japan	11	2.19%	42	4.24%	3.82
8	LITE	Germany	11	2.19%	16	1.61%	1.45
9	OCIO	Korea	10	1.99%	3	0.30%	0.30
10	MINN	US	9	1.79%	4	0.40%	0.44

YUAS: GS Yuasa Corp; MATU: Panasonic Corp; BOSC: Bosch GmbH Robert; SGCC: State Grid Corp China; BATT: Battelle Memorial Inst; CHWE: Chilwee Power Co Ltd; HITB: Hitachi Chem Co Ltd; LITE: Li-Tec Battery GmbH; OCIO: OCI Co Ltd; MINN: 3M Innovative Properties Co.

energy. The share of coal in primary energy consumption will decline, but China is still the largest coal market, expected to account for 40% of global demand in 2040. In addition, China's renewable energy consumption will grow rapidly.

A vital mission of the current energy R&D is to create new technologies for clean and efficient use of oil, coal, natural gas, and biomass, in order to solve the increasingly prominent problems related to energy and environment. In particular, the clean and efficient use of coal is of great significance to China. The modern coal chemical industry has shown to be quite promising in clean and efficient use of coal. The successful implementation of large coal chemical demonstration projects, i.e. coal to olefins, coal to liquid, and coal to ethylene glycol, has shown that the China is leading the innovations of clean coal technology in the world. Recent breakthroughs in the coal-to-ethanol and syngas to-olefins technologies further demonstrated China's capability for sustainable innovations regarding to

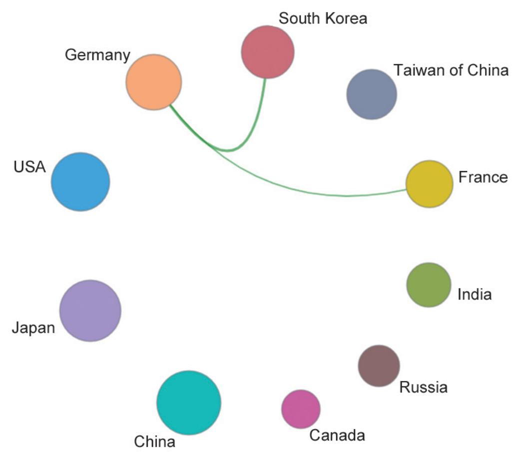

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “key materials and technology for large-scale energy storage”

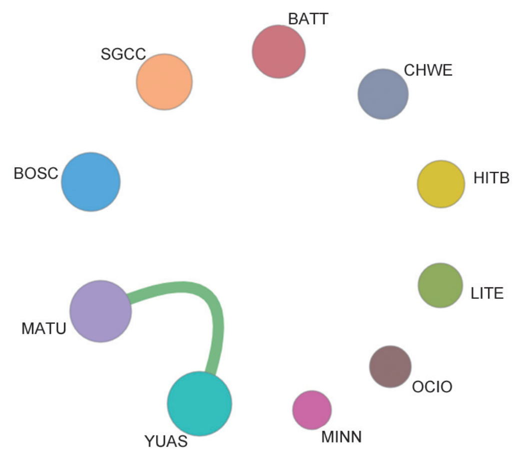

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “key materials and technology for large-scale energy storage”

R&D and industrialization of coal to chemical technologies. The integration of large-scale refineries and chemical industries has become a notable trend in the chemical industries. Developing new processes for more efficiently converting crude oil to high-value chemicals is also important for changing future oil consumption. The breakthrough of methane conversion technology provides important support for the use of unconventional gas resources, such as shale gas. For biomass transformation, biodiesel, biomass pyrolysis oil, ethanol/butanol by fermentation, gasification-syngas Fischer-Tropsch synthesis, and cellulose to ethylene glycol have shown significant progress. Large-scale, low-cost, efficient conversion of biomass to chemicals is expected to be the most likely breakthrough in the near future.

In most of these energy transformation processes, catalysis plays a very important role. Most breakthroughs in new technology depend on the application of new catalytic materials and the development of high performance catalyst. Precise control of the active sites and reaction paths is of great significance for enhancing the excellent properties of traditional catalytic materials (e.g., molecular sieves) and improving the efficiency of catalytic processes. Innovations in the synthesis of catalysts, developing green processes, and catalyst recovery remain important directions of catalyst engineering.

Countries or regions and institutions with the greatest output of core patents on the “catalytic conversion of fossil resources and biomass” are listed in Table 2.2.3 and Table 2.2.4, respectively. The collaboration network among major countries or regions and institutions in the engineering development front of “catalytic conversion of fossil resources and biomass” are illustrated in Figure 2.2.3 and Figure 2.2.4.

2.2.3 Green and intelligent metallurgical manufacturing processes

The metallurgy industry is a fundamental basic industry for the China’s national economy, providing important raw materials that guarantee social development, and strongly supporting the development of related industries. As the situation regarding global climate change and carbon emissions becomes increasingly serious, the development of the metallurgy industry is facing increasing environmental pressure. In particular, as the steel industry is a major consumer of resources and energy, environmental problems related to steel production are increasingly concerning for the society at large. Developing the steel industry using green and intelligent technologies is thought to be critical for transforming and upgrading the industry.

Promoting the “greening” of the manufacturing process is a major priority in the steel industry. Clean production and greening of the entire manufacturing process will be realized via the following three functions in the steel manufacturing process: steel product manufacturing, energy conversion, and treating the produced waste. These processes will follow the

Table 2.2.3 Countries or regions with the greatest output of core patents on the "catalytic conversion of fossil resources and biomass"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	78	50.65%	258	83.23%	3.31
2	China	48	31.17%	63	20.32%	1.31
3	Netherlands	10	6.49%	2	0.65%	0.20
4	South Korea	6	3.90%	7	2.26%	1.17
5	India	5	3.25%	2	0.65%	0.40
6	Saudi Arabia	5	3.25%	4	1.29%	0.80
7	Germany	4	2.60%	0	0.00%	0.00
8	France	3	1.95%	7	2.26%	2.33
9	Japan	3	1.95%	0	0.00%	0.00
10	Australia	1	0.65%	2	0.65%	2.00

Table 2.2.4 Institutions with the greatest output of core patents on the "catalytic conversion of fossil resources and biomass"

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	ESSO	USA	22	14.29%	111	35.81%	5.05
2	UNVO	USA	16	10.39%	8	2.58%	0.50
3	SNPC	China	12	7.79%	16	5.16%	1.33
4	SABI	USA	10	6.49%	4	1.29%	0.40
5	SHEL	Netherlands/USA	6	3.90%	24	7.74%	4.00
6	CACP	China	5	3.25%	1	0.32%	0.20
7	LUMM	USA	5	3.25%	11	3.55%	2.20
8	CALI	USA	4	2.60%	4	1.29%	1.00
9	CELA	USA/China	3	1.95%	28	9.03%	9.33
10	UNCZ	China	3	1.95%	2	0.65%	0.67

ESSO: Exxonmobil Chem Patents Inc; UNVO: Universal Oil Prod Co; SNPC: SINOPEC Corp; SABI: SABIC Global Technologies BV; SHEL: Shell Oil Co; CACP: CAS Dalian Chem & Physical Inst; LUMM: Lummus Technology Inc; CALI: Chevron USA Inc; CELA: Celanese Int Corp; UNCZ: Univ Changzhou.

principle of "reduce, reuse, and recycle", where waste heat, residual pressure, residual gas, waste water, and solid waste will be fully recycled with the goal of zero emissions. In recent years, various technologies have been developed and applied to advance green development of steel manufacturing, including: the "three dry" technology (dry coke quenching, dry gas cleaning in the blast furnace, and dry gas cleaning in the converter); comprehensive use of waste water; use of by-product gas (in the coke oven, blast furnace, and converter) as a secondary energy source; and comprehensive use of solid waste (e.g., blast furnace slag and converter slag). These technologies have effectively achieved energy savings and emission reductions in the steel industry. Currently green manufacturing frontier technologies include: waste heat recovery and use of slag; novel use of carbon-iron composites; combined optimization material, energy, and information flow (big data) in iron and steel works; and carbon dioxide capture, storage, and use.

Intelligent manufacturing is an important trend in the future development of manufacturing industries, and is also an important way to transform and upgrade the steel industry.

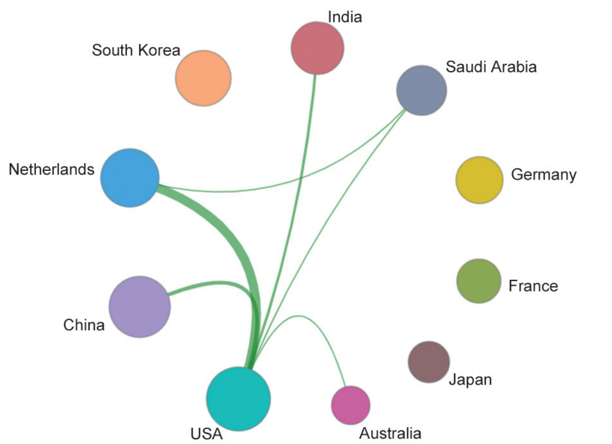

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “catalytic conversion of fossil resources and biomass”

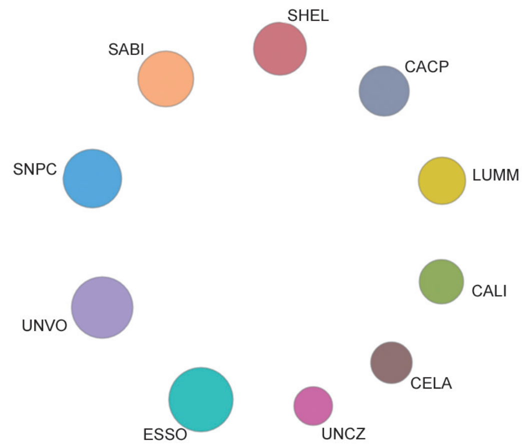

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “catalytic conversion of fossil resources and biomass”

The steel industry is highly automated and the development of intelligent manufacturing has good foundation and broad prospects in this field. With the help of intelligent manufacturing technologies, such as Internet + and the Internet of Things, we will promote the customization, flexibility, greening, networking, and intelligence of steel production methods, and promote the transformation and upgrading of the steel industry. In recent years, intelligent manufacturing methods have been increasingly applied to steel manufacturing, business management, logistics and distribution, and product sales. Demonstration of intelligent factories and digital workshops has been built around intelligent manufacturing processes and mass customization. The application of technology and equipment, such as human-machine interfaces, industrial robots, and intelligent logistics management in the production process has been achieved. The application of simulation optimization, digital control, real-time monitoring, and adaptive control of iron and steel manufacturing processes is promoted. However, intelligent manufacturing in the steel industry is still in its infancy and key technologies need to be developed in the future, including intelligent expert systems based on

Table 2.2.5 Countries or regions with the greatest output of core patents on the “green and intelligent metallurgical manufacturing processes”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	914	93.17%	1039	94.20%	1.14
2	Japan	20	2.04%	38	3.45%	1.90
3	Russia	10	1.02%	1	0.09%	0.10
4	USA	10	1.02%	21	1.90%	2.10
5	South Korea	8	0.82%	2	0.18%	0.25
6	India	3	0.31%	0	0.00%	0.00
7	Taiwan of China	3	0.31%	0	0.00%	0.00
8	Australia	2	0.20%	1	0.09%	0.50
9	UK	2	0.20%	0	0.00%	0.00
10	Poland	2	0.20%	0	0.00%	0.00

industrial big data, application of intelligent robots, multi-objective real-time optimization of on-line operations, use of big data for intelligent fault diagnosis and maintenance of key systems, intelligent optimization of the supply chain, and integration of information technology for cooperative manufacturing.

The countries and institutions publishing the most core patents in the field of "green and intelligent manufacturing in the metallurgy industry" since 2012 are given in Table 2.2.5 and Table 2.2.6, respectively. The cooperation between these countries and institutions are shown in Figure 2.2.5 and Figure 2.2.6, respectively. China is the main publisher of the core patents, accounting for 93.17% of the total number of patents. The number of citations for the core patents and the main research institutes are mainly concentrated in China, indicating that China's R&D in this field is leading the world. According to the average cited frequency of core patents, the USA and Japan are higher than China, indicating that these countries have well-developed basic technology and strong R&D programs, as recognized by other researchers around the world. There is little cooperation between the major countries and institutions, indicating that most of the research is performed independently.

Table 2.2.6 Institutions with the greatest output of core patents on the "green and intelligent metallurgical manufacturing processes"

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CMEG	China	59	6.01%	78	7.07%	1.32
2	BAOS	China	21	2.14%	14	1.27%	0.67
3	SHGG	China	19	1.94%	34	3.08%	1.79
4	ANSH	China	13	1.33%	9	0.82%	0.69
5	JGJT	China	12	1.22%	38	3.45%	3.17
6	HBIS	China	10	1.02%	9	0.82%	0.90
7	BJSW	China	9	0.92%	3	0.27%	0.33
8	UYDB	China	9	0.92%	42	3.81%	4.67
9	JGHX	China	8	0.82%	8	0.73%	1.00
10	WSGC	China	8	0.82%	26	2.36%	3.25

CMEG: Metallurgical Corp China; BAOS: Baoshan Iron & Steel Co Ltd; SHGG: Beijing Shougang Int Eng Technology Co; ANSH: Angang Steel Co Ltd; JGJT: Shandong Iron & Steel Co Ltd; HBIS: Hebei Iron & Steel Co Ltd; BJSW: Jiangsu Province Metallurgical Design; UYDB: Univ Northeastern; JGHX: Gansu Jiu Steel Group Hongxing Iron & Steel Co Ltd; WSGC: Wuhan Iron Steel (Group) Corp.

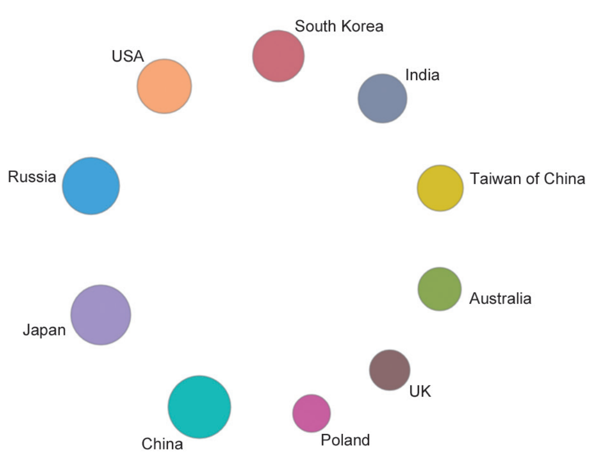

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "green and intelligent metallurgical manufacturing processes"

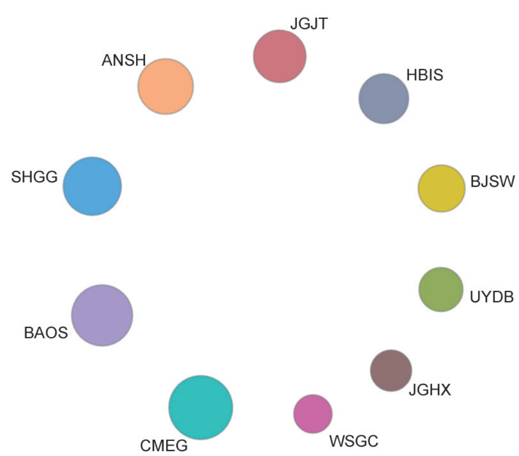

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "green and intelligent metallurgical manufacturing processes"

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IV Energy & Mining Engineering

1 Engineering research fronts

1.1 Development trends in the top 13 engineering research fronts

The top 13 engineering research fronts assessed by the Field Group of Energy & Mining Engineering are shown in Table 1.1.1. These fronts include the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; mining science, technology, and engineering.

Among these top 13 research fronts, "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies," "microgrids and smart distribution systems," "critical technical issues in advanced high-performance fuel cells," "in situ upgrading mechanism and key technologies for large-scale development of shale oil," "seepage mechanism and efficient development of unconventional oil and gas," and "deep space and deep sea nuclear reactors and power supply technology" are emerging ones. "Efficient and clean processing and transformation of coal," "3D seismic data analysis and reconstruction technology," and "fully intelligent integrated small modular reactor technology" are further developments of traditional research fields. "New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells" is the subversive front. "Advanced nuclear energy technology: fusion-fission hybrid reactor technology," "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation," and "spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory" are the fronts of interdisciplinary integration. The numbers of core papers published each year from 2012 to 2017 for each of the top 13 engineering research fronts are listed in Table 1.1.2.

(1) Advanced nuclear energy technology: fusion-fission hybrid reactor technology

The fusion-fission hybrid reactor (referred to as the hybrid reactor) is a nuclear energy technology that combines the advantages of, and overcomes the shortcomings of, fusion and fission. The main difference between a hybrid reactor and a pure fusion reactor is that the cladding contains fissile fuel. The fission fuel has better neutron proliferation ability and energy amplification capability than Be or Pb, which helps reduce the difficulty of fusion engineering. From the perspective of the enthalpy cycle, it is conducive to the achievement of self-sustainability and reduction of the initial amount of investment; from the perspective of energy balance, it can reduce the fusion power and reduce the radiation damage of high-energy neutrons on materials. Compared with a fission reactor, a hybrid reactor is a deep subcritical system driven by a fusion neutron source, which has outstanding safety performance, and can solve the problem of proliferation of fission fuel and metamorphism of transuranic element at the time of energy output. The main research directions of hybrid reactor include driver technology (including tokamak, laser inertial confinement fusion, and Z-pinch inertial confinement fusion), subcritical reactor technology (including pupa, proliferation, transmutation, and energy supply), and high-gain fusion target design technology (for inertial confinement fusion). The development trend of hybrid reactors is based on the recently achieved fusion parameters and draws on mature fission reactor technology to promote the early application of fusion energy and explore ways to solve the sustainable development of fissile energy.

(2) Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies

As an effective way to solve the problems of energy utilization and environmental pollution in the world, a power generation system based on renewable energy is an inevitable choice and an effective measure for the sustainable development of energy utilization. Focusing on the efficient and clean utilization of renewable energy, technologies for renewable energy generation and energy storage are rapidly developing and attracting increasing attention worldwide.

Based on the current resource status and technological development level of renewable energy sources, the utilization of wind, solar, and hydropower is considered the most realistic and promising method to generate electricity.

Table 1.1.1 Top 13 engineering research fronts in energy and mining engineering

No	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Advanced nuclear energy technology: fusion-fission hybrid reactor technology	802	35 451	44.20	2013.43	–	–
2	Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies	687	37 042	53.92	2013.76	–	–
3	Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation	75	146	1.95	2014.75	–	–
4	Microgrids and smart distribution systems	10	130	13.00	2016.60	50.0%	0.00
5	Critical technical issues in advanced high-performance fuel cells	595	30 669	51.54	2013.27	–	–
6	Efficient and clean processing and conversion of coal	810	36 477	45.03	2013.46	–	–
7	In situ upgrading mechanism and key technologies for large-scale development of shale oil	75	452	6.03	2015.20	–	–
8	3D seismic data analysis and reconstruction technology	37	403	10.89	2016.49	0.0%	0.00
9	Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory	147	1 507	10.25	2014.88	–	–
10	Seepage mechanism and efficient development of unconventional oil and gas	1 100	9 872	8.97	2015.16	–	–
11	Fully intelligent integrated small modular reactor technology	573	25 436	44.39	2013.52	–	–
12	Deep space and deep sea nuclear reactors and power supply technology	97	1 117	11.52	2014.43	–	–
13	New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells	120	6 395	53.29	2015.85	22.5%	0.00

Table 1.1.2 Annual number of core papers published for each of the top 13 engineering research fronts in energy and mining engineering

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Advanced nuclear energy technology: fusion-fission hybrid reactor technology	253	188	192	108	52	9
2	Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies	150	173	161	117	69	17
3	Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation	6	15	12	16	11	15
4	Microgrids and smart distribution systems	0	0	0	0	4	6
5	Critical technical issues in advanced high-performance fuel cells	201	165	126	75	25	3
6	Efficient and clean processing and conversion of coal	230	213	193	115	57	2
7	In situ upgrading mechanism and key technologies for large-scale development of shale oil	5	8	9	14	23	16
8	3D seismic data analysis and reconstruction technology	0	0	0	1	17	19
9	Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory	11	22	25	32	30	27
10	Seepage mechanism and efficient development of unconventional oil and gas	96	116	137	206	256	289
11	Fully intelligent integrated small modular reactor technology	164	145	124	89	46	5
12	Deep space and deep sea nuclear reactors and power supply technology	13	22	16	15	18	13
13	New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells	1	2	7	28	48	34

Renewable energy generation technologies can be classified into two types: single and hybrid energy generation systems. A single renewable energy system is relatively independent of other power systems and is susceptible to the limitations of the renewable energy source itself. Hybrid renewable energy systems are mainly classified into two categories: the first one is a combination of several renewable energy sources such as wind, solar, and hydropower to complement each other, which can overcome the discontinuous and unstable supply of a single type of renewable source; the second one is a combination of renewable energy with existing fossil fuels in a hybrid power generation system.

Energy storage is a kind of technology that stores electricity when electricity demand is low and discharges it when electricity demand is high to enable better integration of wind power, hydro, solar, and other renewable energy sources with the grid. From the perspective of storage media, there are some energy storage technologies, including mechanical, electrical, electrochemical, thermal, and chemical energy storage.

Current studies are mainly focused on renewable energy materials, components and thermal cycle characteristics of new energy systems, maximum use of renewable energy and minimum use of natural gas in the region, balance between multi-energy supply and demand across a full range, planning of large-scale energy storage facility and coordination with renewable energy systems, and optimization of energy flow based on energy storage and management.

(3) Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation

The intelligent extraction of coal, oil, and gas is based on massive data collection, and integrates intelligent environmental perception, intelligent equipment control, self-sustaining operation, intelligent analysis and feedback, etc. Its objective is to achieve unmanned coal mining operation and self-adjustment of oil and gas production. The intelligent extraction of coal, oil, and gas is an integration of environmental perception, intelligent decision, and automatic control. The related five sub-disciplines are engineering perception, digital mine, mine Internet of Things, big data and cloud computing, and equipment automation. The future developments of coal mining intelligentization are: ① Intelligent exploration, which refers to the automatic search and measurement of unknown mining spaces—e.g., coal-rock boundary location, coal gangue detection, and advanced detection; ② Intelligent navigation, which refers to the utilization of computer technology, photoelectric technology, and navigation technology for the automatic positioning of equipment and operator; ③ Intelligent manipulation, which refers to the integration of intelligent equipment and automatic scheduling; it features multiple technologies including longwall shearer memory cutting, hydraulic support automation, coal flow balance of conveying system, hydraulic system generalization, coal mining face visualization, remote control, 3D virtual reality, and one-key start and stop. Intelligentization of oil and gas exploitation involves intelligent well drilling, intelligent well completion, and intelligent production. Intelligent well drilling is essential for well completion and production. The active involvement of multiple technologies such as big data, artificial intelligence, closed loop control, and precise guidance will effectively avoid drilling risk and increase drilling rate. Intelligent well completion requires real-time monitoring and control, which can be achieved through advanced sensing technology, communication technology, equipment automation, big data, and artificial intelligence. Intelligent production is the big-data-based management and optimization of an oil and gas field during its life period. Intelligentization of oil and gas exploitation can be primarily approached through the cooperative work between multiple sub-disciplines, and requires the integration of data, equipment, and operation. The intelligentization of oil and gas field requires considering big data as the foundation. The development plan must be determined using intelligent analysis. The real-time optimization requires intelligent adjustment. Therefore, the integration of intelligent data collection, communication, analysis, and equipment manipulation is necessary and is the direction of future development. Moreover, the deep integration of equipment and material with artificial intelligence can monitor the real-time state of an oil and gas field, thereby enhancing recovery and supporting the data collection, staged fracturing, layered production, and data mining.

(4) Microgrids and smart distribution systems

Microgrids and smart distribution systems are composed of distributed generation units, energy storage system, energy conversion equipment, monitoring and protection devices, and loads. They are autonomous systems with self-control and energy management. They are flexible in operation and control, and can seamlessly access various AC and DC equipment and can work in multiple modes such as grid-tied and off-grid. Therefore, it greatly improves the power system capability to integrate distributed energy sources, improves system operation efficiency, and ensures continuous and reliable power supply of critical loads. In recent years, comprehensive planning and design, multi-time scale energy management, optimized operation, high-performance hybrid simulation, and new power electronic equipment and control have gradually attracted significant attention. In addition, with the continuous improvement of technologies such as big data, artificial intelligence, and new energy storage, the future microgrids and smart distribution systems will be more open and flexible to achieve integration and interaction with other types of energy systems such as cold, heat, and transportation systems.

(5) Critical technical issues in advanced high-performance fuel cells

A fuel cell directly converts the chemical energy in fuels and oxidants into electrical energy via an electrochemical reaction, and possesses the advantages of being high-efficiency, and pollution- and noise-free, etc. Very recently, significant improvements have been achieved in hydrogen proton-exchange membrane fuel cell (PEMFC) technologies, thus greatly promoting the global industrialization of fuel cell electric vehicles. So far, the specific power, efficiency, and cold start of automotive fuel cells have already technically satisfied commercialized requirements. However, there remains an urgent need to further improve the service life and greatly lower the cost of fuel cell stacks. Correspondingly, four key research interests should be pursued, including the synthesis of highly active and stable ultra-low/low platinum oxygen reduction reaction electrocatalysts and their mass production; fabrication of high-performance and durable ultra-low/low platinum membrane electrode assemblies and their mass production; development of high-performance anti-corrosion coatings for metallic bipolar plates; improvement of mass transport and water management in the cathodes. When breakthroughs are obtained in the aforementioned aspects, it is expected that the cell performance of PEMFCs will be greatly enhanced, the cost will be significantly reduced, and independent intellectual property rights on these key materials and components will also be attained.

(6) Efficient and clean processing and conversion of coal

The efficient utilization of coal is based on the needs of the end-user. Clean processed coal can be used as a fuel or a raw material. Efficient utilization of coal includes efficient combustion and efficient conversion. The cleaning of coal is designed to improve the quality of raw coal in order to fulfill the needs of users, so as to provide efficient matching and stable coal products for their efficient utilization. The clean transformation of coal is the use of coal as a raw material. It can be classified into gaseous, liquid, and solid fuels, or into chemical products and carbon materials with special uses.

The main task for the efficient utilization of coal is to improve its consumption structure. At present, scientific research is focused on the in situ conversion of coal, which is beneficial to cleaning secondary energy sources (electricity, fuel gas, and fuel oil). This includes the strengthening of deep processing to obtain chemical raw materials or products (gaseous, liquid, or solid). The main task of clean coal processing is to improve the quality of merchantable coal. The current research focuses on the development of new coal dressing technologies, especially for high-efficiency ash reduction, desulphurization, and dry coal preparation technology, focusing on the washing of steam coal. Coal conversion technology includes all kinds of chemical transformations of coal besides combustion. Scientific research focuses on five coal conversion technologies: coal gasification, coal liquefaction, coal-to-natural gas, coal-to-chemicals, and the pyrolysis of low-rank coal.

Considering the current situation of coal utilization technology and the rising requirements of environment, future coal-efficient processes, with clean processing and transformation, will involve the combination of high-efficiency combustion of coal, power generation technology, coal-fired pollutant control technology, high-efficiency coal-fired generator set and circulating fluidized bed combustion technology, and integrated coal gasification technology, based on coal gasification technology. The development of capture and seal-up technology for the safekeeping of CO_2, and oxygen-enriched combustion separation of CO_2, will be emphasized.

(7) In situ upgrading mechanism and key technologies for large-scale development of shale oil

In situ transformation of shale oil is a physical and chemical process of transforming unconverted organic matter and retained hydrocarbon in organic-rich shale into light hydrocarbon by using in situ heating technology, which can be referred to as "underground refinery." The basic principle of the technology is to heat the shale formation to generate high-quality petroleum and natural gas, which exists in a gaseous state under high-temperature conditions in the underground, thus greatly improving the fluidity. The shale will produce micro-fractures and high pressure during the in situ transformation process, and form an artificial seepage system to increase the seepage capacity. The high-quality petroleum produced via the in situ transformation of shale oil can reach the aviation kerosene level after simple processing, which significantly saves the cost of crude-oil refining, and the residues are stored underground, which can reduce environmental pollution, eliminate hydrofracture, save water resources, and reduce carbon dioxide emissions by comprehensively utilizing new energy sources such as wind and solar energy. At present, the technology is potentially feasible for industrial application, but it has not yet reached the industrialization level. Therefore, we should increase the support and investment for the technology, and develop in situ transformation technology suitable for continental organic-rich shale oil in China. Promoting the industrialization process of this technology is crucial for significantly reducing the external dependence of national crude oil and guaranteeing energy security.

(8) 3D seismic data analysis and reconstruction technology

In seismic data acquisition, owing to the influence of actual environment (such as mountains, rivers, and buildings) and financial constraints, the collected original data are often irregular, and consequently, the effect of subsequent processing (such as offset, multiple wave suppression, and seismic imaging) is not ideal. As an important step in seismic data processing, 3D seismic data analysis and reconstruction can effectively solve this problem. The main research direction of this technology is how to improve the regularity of field-derived data to enhance noise immunity and imaging accuracy. At present, the main research trends focus on the seismic channel interpolation method of F-K domain for sparse seismic data and the unsteady seismic data reconstruction method for irregular missing data, including data reconstructions based on predictive filtering, mathematical transformation, and wave equations. The current development trend is to apply these core technologies to the detection of weak microseismic signals, improvement of the signal-to-noise ratio, oil and gas detection, high-precision hydraulic fracturing monitoring, and full-waveform inversion of logging constraints.

(9) Spatial distribution prediction of residual oil and gas resources based on big data and cognitive theory

Technologies for predicting remaining hydrocarbon resources aim to satisfy the following two characteristics. First, the distribution of the remaining conventional hydrocarbon resources is disperse and subtle. Second, the distribution of unconventional hydrocarbon resources is heterogeneous. They are important supplements and extensions of traditional resource assessment methods. The traditional studies on the distribution of remaining resources have been conducted from the perspective of resource management, i.e., the systematic management of hydrocarbon resource-play-target. The new technologies for predicting remaining hydrocarbon resources can realize the space localization of remaining resources and visualization of exploration risks. Big data and cognitive theory offer conditions for these technologies. Big data refer to the collection of data that cannot be captured, managed, and processed with conventional software and tools within a certain period of time. They are massive, high-growing, and diversified information assets, which require new processing modes to achieve stronger decision-making power, insight ability, and process optimization. Cognitive theory is related to the internal processing of organism learning, such as the acquisition and memory of information, knowledge, and experience, the realization of insight, the interrelation of concepts and terms, and the various psychological theories of resolving problems. With the deepening of hydrocarbon exploration and development, petroleum industry accumulates data related to mass hydrocarbon production, such as statistical data of exploration and development, geophysical data of earthquakes and well-logging, wireline-log and well-testing data, and lab data related to geology research. Based on the quantitative evaluation of hydrocarbon resources through traditional methods such as genetic method, statistical method, and analogy method, the development trends of future technologies for the prediction of hydrocarbon resources include the prediction of distribution of hydrocarbon resources, clarification of resource distribution law, and determination of favorable hydrocarbon accumulation zones or specific locations. All these actions should be undertaken according to cognitive theory during the exploration geological processing and development geological processing of big data.

(10) Seepage mechanism and efficient development of unconventional oil and gas

The seepage mechanism of unconventional oil and gas mainly involves the flow characteristics of oil and gas in nanoscale pores and micro cracks. It can be used to analyze the production dynamics in the reservoir and provide important support for the accurate description and evaluation of the unconventional oil and gas reservoirs. However, the geological characteristics of unconventional oil and gas reservoirs are complex, and the development of nanoscale pore oil and gas is difficult. There is an urgent need to improve the development efficiency of unconventional oil and gas, and realize major breakthroughs in the field of unconventional oil and gas. This mainly involves the research direction of reservoir reconstruction, production control, and automation exploitation.

China’s shale gas, shale oil, tight gas, tight oil, coal-bed methane, heavy oil, and other unconventional oil and gas resources are abundant, which are important strategic replacement resources. However, as the reservoirs are complex and the related theory and technology are not mature, it is difficult to realize economic and effective exploitation through conventional means. There is an urgent need to study the seepage mechanism and provide a scientific basis for the regulation and real-time optimization of the unconventional oil and gas production. Therefore, regarding the microscopic percolation characteristics of unconventional oil and gas, the attention degree of non-Darcy percolation, multiphase seepage, and multi-scale percolation will be hot topics in the future. Furthermore, the research on high-efficiency technology, such as waterless fracturing, multilevel fracturing, synchronous fracturing, partial fracturing and combined exploitation, “multi-layer and multi well type” mixed well network mining, and “factory” exploitation, has become the future development trend. It can significantly reduce the cost of mining and improve the recovery of oil and gas.

(11) Fully intelligent integrated small modular reactor technology

Since the International Atomic Energy Agency (IAEA) announced in June 2004 that it has launched an innovative small- and medium-sized reactor (SMR) development program featuring integrated technology and modular technology, the total number of participating member states has reached 30. More than 45 innovative SMR concepts have become hotspots in international research and development. Small nuclear reactors generally refer to reactors with a single stack of thermal power below 1000 MW (300 MW), with carbon-free emissions, small capacity, flexible site selection, low construction investment, short construction period, and system equipment that can be assembled at the factory. It is easy to transport and can be upgraded and economically improved through modular design. From the perspective of the modular small-stack technical solutions that have been proposed at home and abroad, there are various types of reactors such as pressurized water reactors (PWRs), high-temperature gas-cooled heat reactors, high-temperature gas-cooled fast reactors, lead-bismuth-cooled fast reactors, and molten salt reactors. The modular small reactor that can be deployed in the short-term, without exception, follows the integrated PWR route, and its design and development progress far exceeds those of other reactor types, which is mainly due to the good PWR technology and industrial foundation built over several decades. Research and development features of international main small-sized reactor models are that based on the recently promoted integrated PWR model, design measures to eliminate large loss-of-coolant accidents or projectile accidents are adopted, and design optimization is adopted to improve economy; marine modularity or circuit type of PWR adopts inherent safety features and passive safety system, draws on the experience of nuclear icebreakers and submarines, and adopts standardized design, and batch production and loading to enhance market competitiveness. The small-sized reactor belongs to military and civilian dual-use technology, which can be used as military power, applied to ship power and border defense construction, and can also be used in national economic construction fields (such as residential power supply, icebreaker, urban heating, industrial process heating, and seawater desalination). It has broad application prospects in the military and civilian fields.

(12) Deep space and deep sea nuclear reactors and power supply technology

Deep space and deep sea contain rich strategic resources.

They are new and valuable territories for the sustainable development of human beings in the 21st century. Their strategic position in national development and international competition is becoming increasingly prominent. Along with the continuous improvement of various deep-space and deep-sea technological capabilities, the issue of energy and power has gradually become a bottleneck for the further improvement of the performance of various deep-sea equipment, and must be rectified. Compared with conventional energy sources, nuclear reactor power sources have the natural advantages of high energy density, no air requirement, and long running time. They can fundamentally solve the shortcomings of deep-sea equipment and become the best choice for future deep-sea energy. The main technologies include: ① Heat-pipe-cooled reactor technology: In contrast to the traditional loop cooling reactor, the heat of this reactor is removed through the heat pipe, which has the advantages of being simple, safe, and reliable, and avoiding single point failure. It is very suitable as the preferred stack type for the power supply unit of a deep-sea small nuclear reactor; ② Free piston Stirling generator technology: regenerative thermal power generation technology, through the linear motor to output electrical energy. It has many advantages such as long life, high reliability, high conversion efficiency, no pollution, and low noise. It is widely used in space power, solar thermal power generation, small-scale cogeneration, portable power supply, biomass power generation system, etc.; ③ Reactor fully autonomous operation technology: the fully autonomous operation of a reactor indicates that it relies on its own physical thermal feedback and instrument control system to adjust and realize automatic operation. It does not require personnel to monitor and intervene online, and can automatically respond to fluctuations in working conditions. It has the advantage of long-term stable maintenance-free operation; ④ Reactor safety technology: special research on the safety technology of deep-sea nuclear reactors, focusing on the safety features, accident mechanisms, and threats of nuclear proliferation that are unique to deep-sea nuclear reactors.

(13) New-generation solar cells, including perovskite, perovskite/Si heterojunction tandem, $Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells

Perovskite materials are a class of compounds that have a special molecular structure (ABX_3) and originate from calcium titanium oxide mineral ($CaTiO_3$). Perovskite materials have the advantages of high absorption coefficient, sharp absorption edge, and large adjustable bandgap, and hence, the efficiency of perovskite solar cells has been enhanced from 3.8% to 22.7% in only seven years. At present, scientific research in this regard mainly focuses on efficiency, stability, and large-scale industrialization. Among the research topics, inorganic substitution of organic and tin elements to replace lead elements is the most effective method to solve the stability and toxicity problems of perovskites, and has gradually become a new research trend. Furthermore, the unique crystal structure and photoelectric properties of perovskite materials are very suitable for monolithic solar cells. Perovskite/silicon monolithic solar cell technology utilizes different bandgap materials to absorb photons of different energies, thus fully utilizing sunlight, and is expected to become an emerging technology that breaks the efficiency limit of silicon solar cells. The current research and development of this technology focuses on optimizing material preparation processes and reducing parasitic absorption and reflection losses. In only three years, the efficiency of perovskite/silicon monolithic solar cells has increased from 13.7% to 25.2%, which is close to the highest efficiency of silicon cells. Perovskite/silicon monolithic solar cell technology will become a research hotspot in both academia and industry.

$Cu_2ZnSnSe_4$ thin film, polymer, and quantum dot sensitized solar cells are other types of novel solar cells studied in recent years. Compared with the CuInGaSe thin film, $Cu_2ZnSnSe_4$ has an energy gap closer to the ideal bandgap for solar cells. Moreover, it has abundant sources, is non-toxic and inexpensive, and is expected to achieve higher conversion efficiency. The main focus of related research is to raise its efficiency by improving the fabrication method and application of doping. The representative advances include achieving efficiency of 12.3% using metal precursors and 8.7% using a co-evaporation method (reached 10.4% subsequently, certified). The polymer solar cell is a type of solar cell based on organic semiconductors. It can be easily fabricated as large-area flexible solar cells via a spray method. So far, it could achieve efficiency higher than 13% (single junction) and close to 15% (tandem cell). The typical functional layers are a polymer electron donor layer and a fullerene electron acceptor layer. The recent research hotspots include the development of non-fullerene acceptor-based solar cells, optimization of the electron donor via chemical treatment (for instance, chlorization), and fabrication of tandem solar cells by combining different electron donor layers so as to increase the full spectrum absorption. A quantum dot sensitized solar cell is a type of photo-electrochemical solar cell not based on junction structures such as p-n junction and heterojunction. It uses semiconductor quantum dots (can be compound semiconductors such as PbS and CdSe or single semiconductors such as Si) adsorbed on photo-anodes (normally nanostructured oxide semiconductors such as porous TiO_2 and nanowire arrays of ZnO) as a light absorber and realizes electron–hole separation through carrier exchange between them and the oxidation/reduction ion pair in the solid or liquid electrolyte in contact with them. Bandgap modulation can be easily realized through the content and size control of the quantum dot to create spectrum-matched solar cells. Furthermore, it does not require good interfacial condition and very high purity of precursors, which are important to achieve high efficiency with low cost. Recently, a record efficiency of 4.72% has been achieved in the PbS/TiO_2 system doped with Hg, whereas an efficiency of 8.0% has been realized in the In_2S_3+$CuInS_2/TiO_2$ system.

1.2 Interpretations for three key engineering research fronts

1.2.1 Advanced nuclear energy technology: fusion-fission hybrid reactor technology

(1) Conceptual explanation and key technologies

The fusion-fission hybrid reactor (referred to as the hybrid reactor) is a nuclear energy technology that combines the advantages of, and overcomes the shortcomings of, fusion and fission. The main difference between a hybrid reactor and a pure fusion reactor is that the cladding contains fissile fuel. The fission fuel has better neutron proliferation ability and energy amplification capability than Be or Pb, which helps reduce the difficulty of fusion engineering. From the perspective of the enthalpy cycle, it is conducive to the achievement of self-sustainability and reduction of the initial amount of investment; from the perspective of energy balance, it can reduce the fusion power and reduce the radiation damage of high-energy neutrons on materials. Compared with a fission reactor, a hybrid reactor is a deep subcritical system driven by a fusion neutron source, which has outstanding safety performance, and can solve the problem of proliferation of fission fuel and metamorphism of transuranic element at the time of energy output. The main research directions of hybrid reactor include driver technology (including tokamak, laser inertial confinement fusion, and Z-pinch inertial confinement fusion), subcritical reactor technology (including pupa, proliferation, transmutation, and energy supply), and high-gain fusion target design technology (for inertial confinement fusion). The development trend of hybrid reactors is based on the recently achieved fusion parameters and draws on mature fission reactor technology to promote the early application of fusion energy and explore ways to solve the sustainable development of fissile energy.

(2) Development status and future development trend

The research on hybrid reactors involves two major nuclear energy fields: fusion and fission. Based on the recently realized fusion technology and mature fission technology, the application of fusion energy and the sustainable development of fission energy are promoted.

The fusion field is divided into magnetic confinement fusion and inertial confinement fusion. In terms of magnetic confinement fusion, Tokamak research is in a leading position. China officially participated in the construction and research of the international thermonuclear experimental reactor (ITER) project; simultaneously, as a bridge between the ITER device and the fusion demonstration reactor (DEMO), China is independently designing and developing the China Fusion Engineering Experimental Reactor (CFETR) project. In terms of inertial confinement fusion, Z-pinch has more potential as an energy source and is likely to develop into a competitive fusion-fission hybrid energy (Z-FFR) scheme. The Z-FFR consists of a Z-pinch drive, energy target, and sub-critical energy cladding. The following focuses on the key technologies to be addressed by Z-FFR.

Z-pinch inertial confinement fusion covers multiple physical processes and complex physical effects such as magnetohydrodynamics, radiation transport, atomic physics, plasma microscopic instability, and transport mechanisms under strong pulsed magnetic fields. China has focused on the research of Z-pinch plasma implosion kinetics and its radiation source physics, and has obtained a wealth of research results. The research on the overall conceptual design of Z-FFR has made significant progress. However, there are few studies on key issues such as the relationship between current front and Z-pinch load parameters and implosion dynamics, Z-pinch plasma source calibration law and Z-pinch dynamic black cavity radiation field (temperature) calibration law, and Z-pinch inertia, and the energy conversion efficiency of several important physical processes in the process of constrained fusion.

The super-pulsed magnetic field is the most prominent feature of the Z-pinch process. Under this condition, plasma formation and magnetic Rayleigh–Taylor instability development have a decisive influence on the implosion process and implosion quality. Owing to the strong nonlinearity, the energy exchange between the electromagnetic energy of the load zone, the internal energy of the Z-pinch plasma, and the radiant energy is very complicated. The Spitzer resistivity does not accurately describe the characteristics of Z-pinch plasma resistivity, and its anomalous mechanism is unclear. The description and explanation of the generation process and physical mechanism of the radiation source are extremely important. A high-current device can provide a wider range of parameters for conducting Z-pinch plasma physics experiments.

The typical Z-pinch process has a cylindrical implosion feature, whereas the fusion target is a spherical implosion, and a suitable black cavity configuration is designed to effectively separate the loaded plasma Z-pinch process from the target implosion in time and space. This is the core issue of Z-pinch drive inertial confinement fusion. It is not feasible to carry out this experimental study on the existing devices in China. Compared with laser fusion, Z-pinch radiation source has a long time scale and large spatial scale, which makes it difficult to finely adjust the waveform. A new fusion target design is required to effectively compress the fuel and obtain higher energy gain.

The construction of a new-generation high-current pulse power experimental platform is beneficial to the experimental research and verification of the key physical problems of Z-pinch radiation source, black cavity, and target implosion, and other Z-pinch drive inertial confinement fusion processes. It is recommended to have national-level support for the construction of a Z-pinch drive with a peak current of 50–70 MA in 2018–2025 to achieve fusion ignition as soon as possible. Once the ignition target is achieved, the subsequent step is to start building Z-FFR. Z-FFR is equipped with a large ultra-high-power repetitive frequency driver, the preferred fast pulse linear transformer driver, with capacitor nominal energy storage $\leqslant$ 100 MJ, peak current 60–70 MA, rising edge 150–300 ns, and operating frequency 0.1 Hz; adopts the concept of "local overall ignition," and designs high-gain fusion target pellets with energy gain Q $\geqslant$ 100; and designs natural uranium fission cladding to achieve self-sustaining energy amplification of 10–20 times and fission fuel proliferation.

(3) Analysis of comparisons and cooperation between countries/regions and institutions

According to Table 1.2.1, the countries with the largest number of core papers in this research direction are the USA, Germany, the UK, France, Japan, Italy, and China. Among them, the USA holds the first place, with more than 50% of core papers, and the proportion of core papers from Germany, the UK, France, Japan, Italy, and China exceeds 10%.

As evident from Table 1.2.2, the most core papers in this research direction are from Lawrence Livermore National Laboratory, University of Rochester, Los Alamos National Laboratory, Massachusetts Institute of Technology (MIT), General Atomics, Istituto Nazionale di Fisica Nucleare, Sandia National Laboratories, University of Oxford, and Chinese Academy of Sciences, with at least 20 papers each.

According to Figure 1.2.1, the USA, Japan, Germany, the UK, France, and China are more concerned about the cooperation between countries or regions in this field. China has published numerous papers, mainly in cooperation with USA, Japan, Germany, France, the UK, and Russia.

According to Figure 1.2.2, there is cooperation among Lawrence Livermore National Laboratory, MIT, General Atomics, Los Alamos National Laboratory, and University of Rochester.

In Table 1.2.3, the percentage of citing papers from the USA has reached 29.75%; the percentage of citing papers from China has reached 16.81%; and the percentage of citing paper from Germany exceeds 10%.

In Table 1.2.4, the institution that accounts for the highest output of core papers is Chinese Academy of Sciences, with nearly 20%. Lawrence Livermore National Laboratory accounts for more than 16% of the core papers.

According to the analysis of the above data, the core paper output and the number of quotations regarding fusion-fission hybrid reactors in the USA and China are among the highest in the world, and the number of core papers cited by Chinese institutions is large.

1.2.2 Renewable energy power generation and energy storage: energy-saving and environment-friendly technologies

(1) Concept description

As an effective way to solve the problems of energy utilization and environmental pollution in the world, an energy system based on renewable energy is an inevitable choice and an effective measure for the sustainable development of energy utilization. Focusing on the efficient and clean utilization of renewable energy, technologies for renewable energy generation and energy storage are rapidly developing and attracting increasing attention worldwide.

• Renewable energy generation system

Based on the current resource status and technological development level of renewable energy sources, the utilization of wind, solar, and hydropower is considered the most realistic and promising method to generate electricity.

Table 1.2.1 Countries or regions with the greatest output of core papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	434	54.11%	20 456	57.70%	47.13
2	Germany	130	16.21%	6 250	17.63%	48.08
3	UK	116	14.46%	6 518	18.39%	56.19
4	France	111	13.84%	5 468	15.42%	49.26
5	Japan	90	11.22%	5 166	14.57%	57.40
6	Italy	87	10.85%	4 316	12.17%	49.61
7	China	84	10.47%	3 326	9.38%	39.60
8	Spain	53	6.61%	2 359	6.65%	44.51
9	Russia	49	6.11%	2 234	6.30%	45.59
10	Switzerland	46	5.74%	2 647	7.47%	57.54

Table 1.2.2 Institutions with the greatest output of core papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Lawrence Livermore Natl Lab	116	14.46%	5 810	16.39%	50.09
2	Univ Rochester	74	9.23%	2 935	8.28%	39.66
3	Los Alamos Natl Lab	72	8.98%	3 661	10.33%	50.85
4	MIT	44	5.49%	2 674	7.54%	60.77
5	Gen Atom Co	41	5.11%	1 933	5.45%	47.15
6	Ist Nazl Fis Nucl	29	3.62%	1 116	3.15%	38.48
7	Sandia Natl Labs	25	3.12%	1 323	3.73%	52.92
8	Univ Oxford	21	2.62%	1 553	4.38%	73.95
9	Chinese Acad Sci	20	2.49%	988	2.79%	49.40
10	Univ Calif Berkeley	19	2.37%	1 568	4.42%	82.53

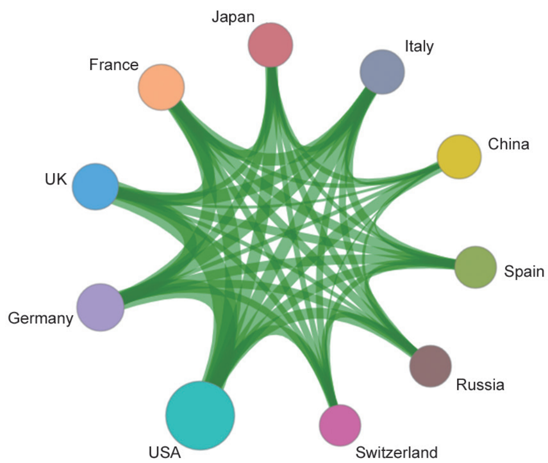

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

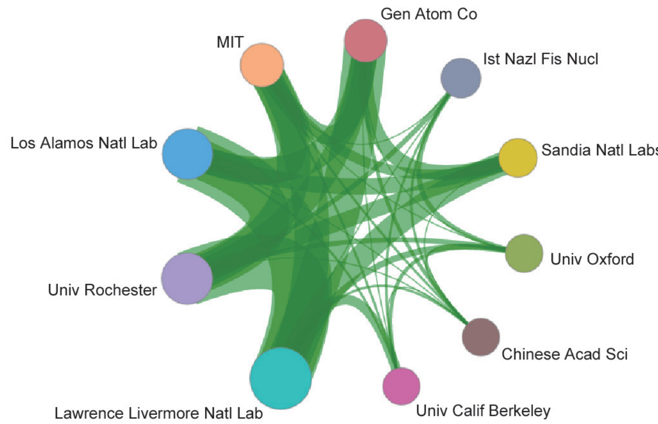

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	9 956	29.75%	2015.78
2	China	5 626	16.81%	2016.10
3	Germany	3 919	11.71%	2015.77
4	UK	2 873	8.58%	2015.85
5	France	2 542	7.59%	2015.70
6	Italy	2 480	7.41%	2015.77
7	Japan	2 267	6.77%	2015.81
8	Spain	1 418	4.24%	2015.88
9	Russia	1 207	3.61%	2015.71
10	Canada	1 183	3.53%	2015.81

Table 1.2.4 Institutions with the greatest output of citing papers on the "advanced nuclear energy technology: fusion-fission hybrid reactor technology"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	1 208	19.58%	2016.09
2	Lawrence Livermore Natl Lab	1 015	16.45%	2015.31
3	Univ Calif Berkeley	613	9.94%	2015.56
4	Los Alamos Natl Lab	591	9.58%	2015.51
5	Ist Nazl Fis Nucl	541	8.77%	2015.38
6	MIT	473	7.67%	2015.56
7	Univ Rochester	449	7.28%	2015.43
8	Russian Acad Sci	446	7.23%	2015.62
9	Univ Calif Los Angeles	419	6.79%	2016.03
10	CALTECH	415	6.73%	2015.63

Renewable energy generation technologies can be classified into two types: single and hybrid energy generation systems. A single energy generation system is relatively independent of other power systems and is susceptible to the limitations of the renewable energy source itself. Hybrid renewable energy power generation systems are mainly classified into two categories: the first one is a combination of several renewable energy sources such as wind, solar, and hydropower to complement each other, which can overcome the discontinuous and unstable supply of a single type of renewable source; the second one is a combination of renewable energy with existing fossil fuels (natural gas, biogas, biomass, geothermal, etc.) in a hybrid power generation system.

Guaranteeing a continuous, stable, and qualified power output is the key aspect of renewable energy generation. Current studies are focused on dynamic modeling and thermal cycle characteristics of energy system, maximum use of renewable energy and minimum use of natural gas in the region, balance between multi-energy supply and demand across a full range, and controlling system of energy storage and management.

The future development direction of renewable energy is a multi-energy complementary system composed of wind, solar, hydro, heat, and storage through a distributed renewable energy system and intelligent microgrid. Terminal integrated systems designed for multiple user-side needs such as electricity, heat, cold, and gas will be rapidly developed in China. Hybrid renewable energy power generation systems have been used in developed countries such as the United States and Europe.

• Advanced energy storage technology

An energy storage system operates by storing electricity when electricity demand is low and discharging when electricity demand is high to enable better integration of wind power, hydro, solar, and other renewable energy sources with the grid. The general concept of energy storage technology can be defined as a one-way or bi-direction storage between electricity and other types of energy such as heat, chemical, and mechanical energy.

From the perspective of storage media, energy storage technology includes mechanical, electrical, electrochemical, thermal, and chemical energy storage. Pump water storage, compressed air, and flywheel belong to the category of mechanical energy storage. Electric energy storage mainly includes supercapacitor and superconducting energy storage. Electrochemical energy storage mainly refers to batteries, such as lead-acid battery, lithium-ion battery, sodium sulfur battery, and liquid flow battery. Thermal energy could be stored through special media (such as phase change material) in a heat insulation container. The thermal energy can be converted into electricity when required or directly used. Chemical energy storage technology refers to the second utilization of hydrogen or natural gas from the electrolysis of water.

Pumped water storage is currently the most installed energy storage technology in the world, accounting for 98% of the total energy storage capacity. Moreover, compressed air energy storage, lead-acid, and lithium batteries have been developed rapidly in recent years, and have been the most competitive energy storage technologies in the world.

The key technologies of energy storage include planning of large-capacity energy storage and coordination with renewable energy systems, energy system optimization and management based on energy storage, and integrated design and coordination of energy storage and conversion devices.

(2) Development status and future development trend

• Renewable energy generation technologies

According to "Renewable 2018 Global Status Report," published by Renewable Energy Policy Network for the 21st Century (REN21), renewable energy generation accounted for 70% of the net increase in global power generation in 2017, which is the largest increase in renewable energy generation in modern history.

At present, the increase in the global investment in renewable energy has exceeded two times the total investment in both fossil fuels and nuclear power generation. Owing to the increase in cost competitiveness, the proportion of renewable energy investment in the power industry in 2017 is more than 2/3, and the percentage of renewable energy in the power industry will continue to rise.

According to the statistics provided by the National Energy Administration, in 2017, the renewable energy power generation capacity of China was 1.7 trillion kWh, with a year-on-year increase of 150 billion kWh; renewable energy has accounted for 26.4% of the total power generation, with a year-on-year increase of 0.7%. Among various renewable power sources, hydropower generation capacity was 1,194.5 billion kWh, with a year-on-year increase of 7%; wind power generation capacity was 305.7 billion kWh, with a year-on-year increase of 26.3%; photovoltaic power generation was 118.20 billion kWh, with a year-on-year increase of 78.6%; biomass power generation was 79.4 billion kWh, with a year-on-year increase of 22.7%. The annual abandonment of hydropower was 51.5 billion kWh. As the amount of incoming water was greater than that in the last year, the water utilization rate reached 96%; the amount of abandoned wind power was 41.9 billion kWh, and the abandoned wind rate was 12%, with a year-on-year decrease of 5.2%; the abandoned solar power was 7.3 billion kWh, and the abandoned rate was 6%, which is 4.3% lower than that in 2016. Thus, the proportion of renewable energy power generation in China has steadily increased.

At present, the research on renewable energy technologies mainly includes the following three aspects: advanced power generation technology, grid connection technology, and multi-energy complementary system of renewable energy.

For the advanced power generation technology of renewable energy, as the most important output characteristic of photovoltaic power generation is randomicity, tracking the maximum active output power point of photovoltaic power generation is one of the research priorities. As the maximum power point tracking requires high accuracy, rapidity, and stability, effective adjustment of active output is the key aspect of photovoltaic power generation. Wind power generation technologies are mainly classified into two categories: the first employs constant speed and constant frequency, mainly adopting active stall regulation or capable generator equipment; the second employs variable speed and constant frequency, mainly equipped with an asynchronous induction generator. Of the two categories, variable-speed and constant-frequency power generation can capture and utilize wind energy to the utmost extent, and the speed running range is relatively loose with the adjustment system more flexible.

In terms of grid connection technologies for renewable energy generation, renewable resources are affected by ambient temperature and weather factors, which result in relatively large fluctuations and intermittence. This characteristic could easily cause flashover or fluctuations in the grid voltage. Therefore, grid connection and consumption of renewable energy are key aspects for access to existing energy systems. ① Advanced inverter technology: Considering photovoltaic energy as an example, power grids and photovoltaic power plants are mainly connected by inverters. Therefore, inverters are required to be capable of expandable communication functions, controlling reactive power and active power, reducing active power rate, and achieving harmonic compensation. The inverters should guarantee the stability of power output quality and anti-interference ability. Moreover, the interaction between grid and energy sources should satisfy the requirements of the smart grid. ② Accurate and fast grid voltage signal locking technology is required for grid connection of renewable energy, which could accurately lock the phase of voltage under high-power asymmetric operation and voltage sampling fluctuations of grid. ③ System anti-interference technology: The island detection technology requires reliable anti-interference ability from the renewable energy system. Moreover, the low-voltage ride-through (LVRT) performance has become a necessary index for ensuring the safe and stable operation of a power system under the condition of large-scale new energy access. For a centralized wind power and photovoltaic station, LVRT is realized based on inverter control, and the command of island detection can be realized by using the energy from the transmission and transformation of electricity system. For a distributed wind power and photovoltaic station, island detection should be achieved through the control system, and signal command is given based on the energy management platform of the power distribution system.

As for a multi-energy complementary system of renewable energy, compared with traditional power grids, this kind of hybrid system typically has system complexity and uncertainty. ① Planning of system integration, including deterministic and uncertainty analysis: The deterministic analysis indicates that the wind, light, and other resource conditions and load requirements are derived from historical record data. Uncertainty analysis mainly refers to modeling of renewable energy and load variations based on probability statistics, considering several factors such as natural conditions and cold and heat loads of users. ② Comprehensive system modeling: Notably, the time scales and dynamic characteristics of the subsystems in the renewable energy complementary system are different. For example, grid power should be instantaneously balanced, and its dynamic characteristics should be described using differential-algebraic equations. Cold and heat conversion processes are the slowest and are usually expressed in dynamic processes by minute and hour. ③ Optimizations of system design: At present, the calculating methods used by researchers include power flow calculation based on Newton–Raphson method, lowest cost optimization of life cycle analysis, and multi-objective chaotic quantum genetic algorithm. To achieve the optimal use of energy and long-term economic operation, a renewable energy complementary system requires scientific system integration and energy management.

• Advanced energy storage technology

By the end of 2017, the cumulative installed capacity of energy storage projects in the world reached 175.4 GW, a year-on-year increase of 4%. The cumulative installed capacity of pumped water storage still accounted for the largest proportion, i.e., 96%, but with a decrease of 1 percentage point from the previous year. The cumulative installed capacity of electrochemical energy storage was the second largest, with a scale of 2926.6 MW, an increase of 45% from the previous year. The proportion of electrochemical energy storage was 1.7%, an increase of 0.5 percentage points over the previous year. Among the various types of electrochemical energy storage technologies, the cumulative installed capacity of lithium-ion batteries had the largest proportion, accounting for more than 75%.

In 2017, the installed capacity of newly added chemical storage projects in the world was 914.1 MW, a year-on-year increase of 23%. The planned installed capacity of the electrochemical energy storage project under construction is 3063.7 MW. It is expected that the global installed capacity of electrochemical energy storage will experience rapid growth in the short term.

By the end of 2017, the cumulative installed capacity of the energy storage projects of China has reached 28.9 GW, a year-on-year increase of 19%. In 2017, the total capacity of newly invested energy storage projects in China was 121 MW, involving three areas: centralized renewable energy grid connection, auxiliary services, and user-side projects. In the field of centralized renewable energy integration in 2017, the projects undertaken include Qinghai DC photovoltaic and energy storage demonstration project and Jilin wind thermoelectric hybrid energy storage project. The commercialization of solar energy storage is accelerated, and the application of combined electricity and heat storage has become a new research direction to reduce the electricity peaking of power systems and increase the consumption of renewable energy.

Although there are many different types of energy storage technologies, only pumped storage is relatively widely used in large-scale energy storage devices. However, owing to geographical constraints, the usage of pumped storage is very limited. Moreover, other energy storage methods are still in experimental or initial research stages, and the reliability, service life, manufacturing cost, and application capability of these energy storage devices must be improved. In general, the research on energy storage technology in China is still in its initial period and it is not suitable for comprehensive application to the power grid. Moreover, there are still several problems such as incomplete research institutions, uncertain economic benefits, and the lack of operational data support. At present, the key technical fields of energy storage technology research are mainly distributed in the following aspects.

The planning of energy storage systems includes the following fields: ① The wide-area layout of energy storage systems and cogeneration method for conventional power supply and renewable energy; the integration of an energy storage device of hundreds of megawatts in the power transmission and distribution processes of the new energy generation system; ② Research on the selection and configuration method of energy storage in new technology and power supply business mode; the convergence effect, operation mode, and controlling strategy of a distributed energy storage system in the power grid; ③ The policy requirements to realize market application of energy storage technology, including electricity price, market access institution, and electricity market mechanism, which could promote energy storage development; the coordinated operation mechanism of energy storage and other energy resources under various types of electricity market transactions.

As for the technologies of energy storage devices, current research mainly includes: ① The key material modification, low-cost preparation, energy density improvement, and industrialization technology of lithium ion, lead carbon, liquid flow, and other types of energy storage batteries under the current power system; high-security battery materials based on ionic liquid and solid electrolyte; low-cost and high-reliability membrane production technology of liquid flow battery; ② Development of supercapacitor, including porous graphene electrode and high-pressure electrolyte salt, electrolyte, and cellulose separator; ③ Research on air compressor and expander technology; study of high-efficiency and low-cost cold and heat storage technology; 4Research on next-generation energy storage technology, including high-specific-energy-density battery technology such as lithium sulfur and lithium air batteries; research on hydrogen production and storage equipment, and technologies of large-scale hydrogen energy storage device with low cost and high efficiency; research and development of heat and cold storage devices with high capacity and energy density; key materials of thermal phase change energy storage.

In terms of integration and applications of energy storage systems, studies in this field mainly include: ① System integration, controlling technology, and engineering demonstration of an energy storage and power station of hundreds of megawatts; ② Architecture of battery energy storage system including energy storage battery pack, battery management system, power conversion system, microgrid control center, and energy management system; research on cascade utilization and safety management techniques such as battery reorganization, integration, and heat grooming; ③ Development of energy storage converter based on new device, topology, and control method; control of energy storage converter, energy storage battery management, and energy monitoring and scheduling system; ④ System integration and engineering application technologies of hydrogen, phase change, and flywheel energy storage; integration and test technology of seawater pumped storage and cryogenic energy storage system.

Physical energy storage will still be dominant. According to China's National 13th Five-Year Plan, by the end of 2020, the cumulative installed capacity of pumped storage in China will be 40 GW. By the end of 2017, 28.49 GW has been completed, and the scale of projects under construction is 38.71 GW. It is expected that this target will be achieved by 2020.

Electrochemical energy storage will maintain steady growth. High-density distributed energy storage systems such as electric vehicles will fundamentally change the structure of the power grid. With the promotion and application of new energy vehicles, the performance and cost of battery systems have gradually become the main bottleneck delaying their rapid development. Future electrochemical energy storage will focus on battery systems with higher energy density, lower cost, better security, and longer lifetime.

Energy storage technology will be deeply integrated with renewable energy systems. Energy storage technology can achieve smooth power fluctuation, reduction of electric peaking, frequency modulation, and voltage regulation, and is considered an important means to achieve the large-scale integration of renewable energy systems to the power grid. With the development of smart microgrid and energy Internet, more flexible power-peaking resources will be developed to satisfy urgent demand, and the promotion of renewable energy grid connection will increase in the market.

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

According to Table 1.2.5, the countries with the largest output of core papers in this research direction are the USA, China, Iran, and India. Among them, the core papers from USA and China account for 26.78% and 19.51% respectively, and the core papers from India and Iran account for more than 6%.

As evident from Table 1.2.6, the organizations with the largest output of core papers in this research direction are MIT, Imperial College of Science, Technology and Medicine, University of Malaya, Chinese Academy of Sciences, and Huazhong University of Science and Technology—each of them with more than 10 core papers.

According to Figure 1.2.3, China, the USA, Australia, the UK, and Germany are more concerned about the cooperation between countries or regions in this field. Among them, China has a large number of published papers, mainly in cooperation with the USA, Australia, and the UK.

According to Figure 1.2.4, Imperial College of Science, Technology and Medicine has a cooperative relationship with University of Malaya in certain areas.

In Table 1.2.7, among the countries that cite the most core papers, China accounts for more than 33%, and the USA accounts for nearly 20%. The percentages of cited core papers from India, the UK, Iran, Spain, Australia, Germany, and Italy all exceed 5%.

In Table 1.2.8, the institution that cites the most core papers is the Chinese Academy of Sciences, whose citing proportion is nearly 25%. The proportion of cited core papers from Tsinghua University and North China Electric Power University is more than 10%.

According to the analysis of the above data, the USA and China are at the forefront of the world's core output and quotation for renewable power generation, and Chinese institutions have cited numerous core papers in recent years.

1.2.3 Key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation

(1) Concepts of research fronts

Intelligent mining began in the 1980s with automated mining and telemining/distance mining. In 1992, Finland proposed the Intellimine program, and the concept of intelligent coal mining was introduced. At present, oil and gas exploitation in China urgently requires intelligent dynamic control using intelligent equipment and technology to reduce production costs and improve the production and recovery of oil and gas. Intelligent mining refers to the mining operation process without manual intervention, independently completed using

Table 1.2.5 Countries or regions with the greatest output of core papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	184	26.78%	9 997	26.99%	54.33
2	China	134	19.51%	7 261	19.60%	54.19
3	Iran	46	6.70%	1 908	5.15%	41.48
4	India	43	6.26%	2 382	6.43%	55.40
5	Spain	40	5.82%	2 172	5.86%	54.30
6	UK	39	5.68%	2 289	6.18%	58.69
7	Australia	39	5.68%	2 158	5.83%	55.33
8	Germany	33	4.80%	1 580	4.27%	47.88
9	Canada	33	4.80%	1 419	3.83%	43.00
10	Malaysia	26	3.78%	1 517	4.10%	58.35

Table 1.2.6 Institutions with the greatest output of core papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	MIT	15	2.18%	713	1.92%	47.53
2	Imperial Coll Sci Technol & Med	13	1.89%	798	2.15%	61.38
3	Univ Malaya	13	1.89%	643	1.74%	49.46
4	Chinese Acad Sci	12	1.75%	633	1.71%	52.75
5	Huazhong Univ Sci & Technol	12	1.75%	495	1.34%	41.25
6	Tech Univ Denmark	10	1.46%	717	1.94%	71.70
7	Indian Inst Technol	9	1.31%	491	1.33%	54.56
8	Univ New S Wales	9	1.31%	443	1.20%	49.22
9	King Fahd Univ Petr & Minerals	9	1.31%	440	1.19%	48.89
10	Univ Tehran	9	1.31%	368	0.99%	40.89

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

mining equipment through intelligent perception of mining environment, intelligent control of mining equipment, and autonomous cruising of mining operations. The intelligent mining of coal, oil, and gas is a revolutionary technology based on mechanized mining and automated mining, through the deep integration of informatization and industrialization to improve production efficiency and economic benefits.

(2) Fronts of engineering science branches

Key engineering technologies, equipment, and materials for intelligent coal mining. They are the deep integration of three technical units: environmental perception, intelligent decision, and automatic control, involving five branches of engineering science: engineering environmental perception, digital mining, mine Internet of things, big data and cloud computing, and automatic control. Engineering environment

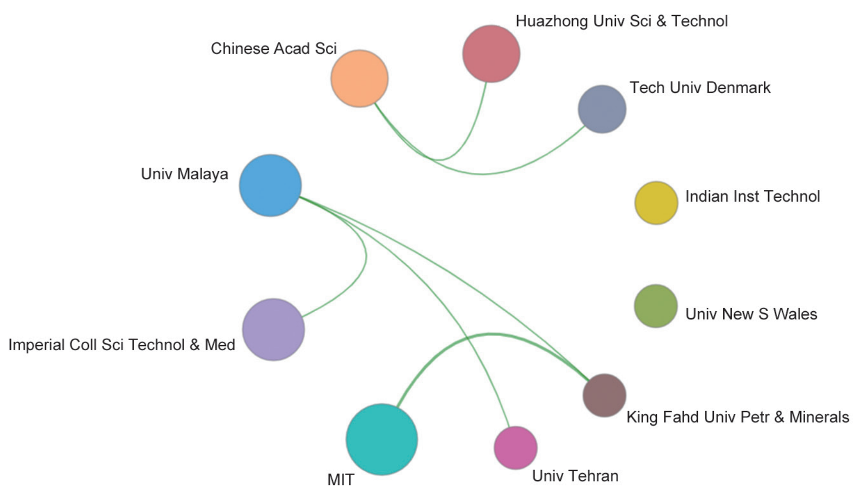

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	China	7 544	33.96%	2016.27
2	USA	4 244	19.11%	2015.90
3	India	1 920	8.64%	2016.21
4	UK	1 414	6.37%	2016.10
5	Iran	1 294	5.83%	2016.18
6	Spain	1 232	5.55%	2015.81
7	Australia	1 205	5.42%	2015.98
8	Germany	1 183	5.33%	2015.98
9	Italy	1 150	5.18%	2015.90
10	South Korea	1 027	4.62%	2016.11

Table 1.2.8 Institutions with the greatest output of citing papers on the "renewable energy power generation and energy storage: energy-saving and environment-friendly technologies"

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	870	24.47%	2016.11
2	Tsinghua Univ	417	11.73%	2016.27
3	North China Elect Power Univ	416	11.70%	2016.08
4	Univ Chinese Acad Sci	300	8.44%	2016.47
5	Xi'an Jiao Tong Univ	299	8.41%	2016.12
6	Nanyang Technol Univ	268	7.54%	2016.12
7	Huazhong Univ Sci & Technol	259	7.29%	2016.23
8	Shanghai Jiao Tong Univ	250	7.03%	2016.21
9	Islamic Azad Univ	243	6.84%	2015.81
10	Zhejiang Univ	233	6.55%	2016.14

perception is an automatic detection and transmission technology for underground equipment, personnel, and disasters. It aims to achieve automated meticulous monitoring of the whole mining process in underground complex geological conditions. In this field, Australia focuses on intelligent detection of coal seam geological structures based on thermal infrared imaging whereas China focuses on intelligent detection of the position and pose of mining equipment. The equipment level of intelligent mining in China is equivalent to that of foreign countries. Chinese mining machines have online awareness of fault parameters and operation parameters, shearer drum cutting memory program, and wireless remote control system, which realize a remote monitoring system of mining machines. Foreign mainstream hydraulic supports can achieve remote control and system fault diagnosis whereas the reliability of hydraulic support electro-hydraulic control systems in China still has a certain gap with foreign technology. At present, the intelligence of Chinese independent development conveyors is mainly reflected in soft start control, chain automatic tensioning, and monitoring of operating conditions. The intelligent integrated system of a fully mechanized mining face can realize intelligent integrated control and cooperative interlocking of mining machine, hydraulic support, conveyor, and other equipment in the mining face. Automatic control indicates that the mining machine can achieve self-regulation and autonomous cruising through pre-programming without manual intervention to complete the mining operation independently. In this field, Australia focuses on the development of mining machine memory cutting and autonomous navigation technology, whereas China focuses on remote control technology of mining equipment.

Key engineering technologies, equipment, and materials for digital mines and mine system network. Focusing on mine spatial data and models, it is a concentrated expression of spatial information technology, network technology, and visualization technology in the comprehensive application of mining enterprises. Its basic task is to provide data security and technical support for the visualization, refinement, and intelligent control of the whole process of mine production through unified space-time benchmarks, unified data standards, unified network structure, and unified integration platform. The main directions of the future of digital mines include mine spatial data warehouse and data update technology, mine data mining and knowledge discovery technology, true 3D solid modeling, and virtual mining technology. The mine system network consists of the perception layer, transport layer, analysis layer, and application layer. The mine sensor network is built on a high-speed network covering the mine ground surface and underground. The mine environment, equipment, and personnel are connected in real time through various sensors to the real-time monitoring, sensing, communication, and control of the environment, equipment health, and personnel safety posture. The future development of the mine system networks is focused on multi-network convergence transmission technology and multi-parameter information analysis and processing technology. As the scope of coverage of mine system networks becomes increasingly wider, the amount of generated data of the "human, machine, and physical" ternary worlds interacting and integrating in the information space and available on the Internet is also increasing, and the data are inherent. The extraction and utilization of value must be supported by ultra-large-scale and highly scalable cloud computing technology. Large data cloud computing technology for coal mines is still in its infancy. Moreover, it needs to focus on the development of unified technical standards and data modeling.

Key engineering technology, equipment, and materials for intelligent drilling. Intelligent drilling combines large data and artificial intelligence, and uses advanced detection, closed-loop control, and precision guidance, which can effectively avoid drilling risks, form high-quality wellbore, improve drilling speed and drilling ratio, and reduce drilling cost. It is the basis for the smooth development of well completion and production. Intelligent drilling uses the big data of the drilling process to adaptively optimize the drilling rock-breaking parameters and intelligently regulate the well trajectory by analyzing the real-time working conditions. The key engineering technology of intelligent drilling involves data bidirectional efficient transmission technology, closed-loop intelligent regulation technology, and intelligent drilling guidance technology. The drilling process generates massive data. To ensure the dynamic interaction between the ground control system and the downhole information, it is necessary to use an intelligent drill pipe and other equipment for more efficient data transmission. The use of intelligent analysis of drilling data, optimization of drilling parameters through signal feedback, and formation of closed-loop control of drilling information significantly improves the efficiency of drilling data processing, specifically involving unmanned drilling rigs, intelligent pressure control, integrated driller control, and other equipment. Intelligent guidance uses strata conditions and ground control commands to control the drilling speed of the drill bit for targeted directional drilling, specifically involving intelligent drill bits and other equipment. To improve the performance of tools under complex conditions, carbon fiber composites, high-entropy alloys, super steels, pure phase polycrystalline diamond, and other materials have received extensive attention at home and abroad. Furthermore, bionic drilling fluids and supramolecular polymer drilling fluids have been extensively studied at home and abroad as important carriers for wellbore drilling and smooth progress. Currently, Norway has applied highly flexible, executable multi-task unmanned rigs to the field. Baker Hughes' first TerrAdapt adaptive drill bit has dramatically reduced the frequency of downhole faults through automated controls. The British North Sea Babbage Oilfield used intelligent closed-loop control and intelligent drill pipe to efficiently transmit data through the intelligent drill pipe, which has increased the penetration rate by nearly 200%. Schlumberger, Baker Hughes, Weatherford, Halliburton, etc. have used intelligent steering technology for drilling sites.

Key technology, equipment, and materials for intelligent well completion. Intelligent well completion uses advanced sensing, transmission, and automatic control equipment, combined with large data, artificial intelligence, etc. It can monitor and control the production of oil and gas in real time including interlayer isolation, permanent monitoring, flow control, and sand control, and provide strong support for the intelligent production. The key technology of intelligent well completion is mainly related to oil-well inflow control and intelligent optimization of completion parameters. At present, an integrated well management control system integrates downhole monitoring, data transmission, and stratified flow control. It can realize reservoir information management, dynamic data sharing, and intelligent flow control. It is widely studied at home and abroad. It involves downhole sensors, downhole production controller, multi-channel packer, etc. At present, the Beck Hughes InCharge completion system can control up to 12 production layers using an electric hydraulic drive and achieve stepless throttling. The Schlumberger Manara well completion system can conduct data wireless transmission, multi-channel separation, and hierarchical monitoring. In addition, Halliburton and China National Petroleum Corporation (CNPC) launched SmartWell and EIC-Riped completion systems. Furthermore, the multi-function intelligent nano completion fluid system of nanomaterials and completion fluids can automatically identify and deal with complicated conditions or accidents in the downhole, which has become the trend of future development.

Key engineering technology, equipment, and materials for intelligent production. Intelligent production is the dynamic management and optimization of the whole life cycle of oil and gas field based on big data and trail learning. Intelligent production of oil and gas can be achieved using the effective integration of data, instruments and equipment, and field operation through the collaborative work of research branches. Intelligent production utilizes a sensing device to collect the downhole data, subsequently transmits it to the ground system for intelligent analysis and signal feedback, and carries out the control instruction through the ground and downhole equipment to continue the intelligent management and optimization to the well work condition. The key engineering technology of intelligent production involves the dynamic real-time four-dimensional interpretation technology of reservoir production, intelligent displacing technology to improve oil recovery, and intelligent analysis and utilization technology of multivariate massive data. The intelligent production of oil and gas mainly involves the intelligent monitoring of oil and gas fields, capturing the dynamic information of each link to provide the support for the real-time interpretation of oil and gas reservoir, and the intelligent analysis of gas and oil exploitation. Moreover, the massive data produced during the field operation must be analyzed intelligently using deep learning and data mining, which impose stringent requirements on the performance of big-data storage and computing equipment. The nano intelligent oil displacement agent has attracted increasing attention at home and abroad because it can remarkably improve the recovery rate of a low-permeability reservoir. To analyze the production dynamics of oil and gas reservoirs, Anadarko Petroleum is building a huge monitoring database based on microbial DNA in Delaware Basin. Oil reservoir robot, which has become a hot research topic globally, can monitor the temperature and pressure data under complex conditions, and Saudi Aramco has carried out active research in this field. Shell used big data and cloud computing to establish an oil field management system, which initially achieved automatic control of production. To improve oil recovery, CNPC and Sinopec Group have been actively exploring the improvement of oil recovery using intelligent fine water injection and an intelligent nano flooding agent. The Natural Resources Corp., Canada also carried out a pilot test to enhance the recovery rate of polymer nano microspheres. In addition, China has developed supercomputers rapidly and has reached the international advanced level, which lays an important foundation for the study of massive data storage, calculation, and analysis of oil and gas exploitation.

(3) Development status and future development trend

The development direction of intelligent mining is to achieve a real-time and intelligent full life cycle regulation of the coal and oil-gas production process, based on the dynamic information of the production process, relevant engineering technology, equipment, and material. At present, a significant amount of research has been carried out in the key fields of intelligent mining at home and abroad. However, the entire process of intelligent mining has not been realized. The following major breakthroughs must be achieved in the future.

Deep integration of engineering equipment, materials, and artificial intelligence. Efficient intelligent development of coal, oil, and gas is realized through effective data acquisition, hierarchical intelligent production, and data mining and intelligent analysis. Advanced computer, optoelectronic, and navigation technology are used to automatically locate mining equipment and personnel in order to achieve safety monitoring and accurate mining. Moreover, the deep integration of materials and artificial intelligence will help improve the performance of engineering equipment in all directions, realize the automatic exploration and detection of the unknown area of mining stopes, and even automatically identify and deal with the complicated production conditions or accidents in underground mines.

Integration technology of intelligent data acquisition, efficient transmission, intelligent analysis, and intelligent control. Intelligent analysis is adopted to determine the real-time production dynamics and use intelligent control in the mine production process based on the acquisition of multivariate data to achieve data collection, transmission, analysis, control, and coordination work in all aspects.

(4) Countries, institutions, and the comparison and cooperation between them

According to Table 1.2.9, the countries with the largest numbers of core papers in this research direction are China, India, Canada, Australia, and the UK. Among them, the core papers from China exceed 50%, and the core papers from other countries account for less than 10%. According to Table 1.2.10, the institutions with the largest number of core patents in this research direction are Xi'an University of Science and Technology, Luohe Medical College, and China University of Mining and Technology, Beijing. Among them, Xi'an University of Science and Technology and Luohe Medical College have a core patent ratio exceeding 5%.

According to Figure 1.2.5, countries such as China, Australia, USA, UK, and Italy have paid more attention to the cooperation among nations or regions in this research direction. Among them, China has built a cooperative relationship with Australia, the USA, and the UK, with the largest number of co-published core paper. Although India and Canada have a high number of core papers, they have no cooperative relationship with other countries.

According to Figure 1.2.6, the institutions with a cooperative relationship with other institutions are Luohe Medical College, Chinese Academy of Sciences, Henan Vocational College of Quality Engineering, Henan Polytechnic Institute, and Commonwealth Scientific and Industrial Research Organisation (CSIRO). Among them, Luohe Medical College has built a cooperative relationship with Henan Vocational College of Quality Engineering and Henan Polytechnic Institute. Furthermore, they have the largest number of co-published core papers. Xi'an University of Science and Technology of Xi'an, China has the largest number of publications. However, it has no co-published papers.

According to Table 1.2.11, China, Australia, the USA, the UK, and India have produced the largest number of cited core papers in this research direction. Among them, more than 50% of the core papers from China have been cited, whereas only 10.2% from Australia have been cited. According to Table 1.2.12, the most productive institutions in terms of the

Table 1.2.9 Countries or regions with the greatest output of core papers on the “key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	43	57.33%	75	51.37%	1.74
2	India	6	8.00%	5	3.42%	0.83
3	Canada	5	6.67%	9	6.16%	1.80
4	Australia	3	4.00%	24	16.44%	8.00
5	UK	3	4.00%	9	6.16%	3.00
6	USA	3	4.00%	8	5.48%	2.67
7	Romania	2	2.67%	11	7.53%	5.50
8	Iran	2	2.67%	2	1.37%	1.00
9	Italy	2	2.67%	2	1.37%	1.00
10	Thailand	2	2.67%	1	0.68%	0.50

Table 1.2.10 Institutions with the greatest output of core papers on the “key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Xi’an Univ Sci & Technol	6	8.00%	0	0.00%	0.00
2	Luohe Med Coll	4	5.33%	0	0.00%	0.00
3	China Univ Min & Technol Beijing	3	4.00%	3	2.05%	1.00
4	Henan Qual Engn Vocat Coll	3	4.00%	0	0.00%	0.00
5	Chinese Acad Sci	2	2.67%	27	18.49%	13.50
6	Shiraz Univ	2	2.67%	2	1.37%	1.00
7	Henan Polytech Inst	2	2.67%	0	0.00%	0.00
8	Univ Alberta	2	2.67%	0	0.00%	0.00
9	Shandong Univ Sci & Technol	1	1.33%	35	23.97%	35.00
10	CSIRO	1	1.33%	24	16.44%	24.00

number of core papers published in this research direction are China University of Mining and Technology, Chinese Academy of Sciences, and Shandong University of Science and Technology. Among them, the core paper outputs of China University of Mining and Technology and Chinese Academy of Sciences are more than 20%.

2 Engineering development fronts

2.1 Development trends in the Top 14 engineering development fronts

The top 14 engineering development fronts assessed by the Field Group of Energy & Mining Engineering are shown in Table 2.1.1. These fronts include the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; mining science, technology, and engineering. Among these top 14 development fronts, "research and application of wireless power transmission and its related equipment," "green mining technology (coal, oil, gas, ores)," and "safe, intelligent, and precise mining technology and equipment" are emerging fronts. "Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment," "spent fuel reprocessing and nuclear facility instrumentation," "renewable resources generation system and its operation and control," "advanced reactor technology and equipment development," "new tools and materials for petroleum engineering," "logging identification of unconventional reservoirs," and "3D geological modeling technology" are further developments of traditional research fields. "Advanced nuclear fuel technology research and development" is the subversive front. "High-voltage and high-power power electronic devices and equipment in power systems," "advanced energy storage technology in energy and power systems," and "using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources" are the fronts of interdisciplinary integration. The numbers of core papers published each year from 2012 to 2017 for each of the top 14 engineering development fronts are listed in Table 2.1.2.

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

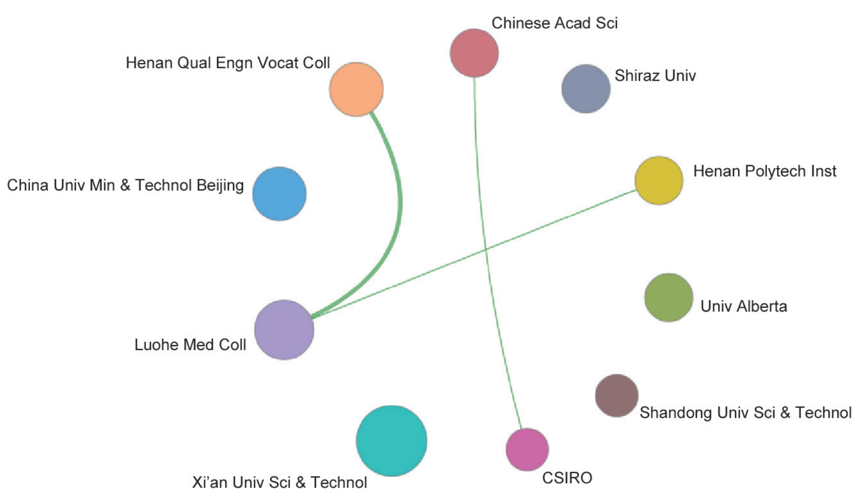

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	78	53.06%	2017.04
2	Australia	15	10.20%	2016.47
3	USA	11	7.48%	2016.36
4	UK	10	6.80%	2017.30
5	India	10	6.80%	2016.70
6	South Korea	6	4.08%	2017.33
7	Italy	5	3.40%	2014.80
8	Malaysia	4	2.72%	2016.00
9	Japan	4	2.72%	2016.25
10	Taiwan of China	4	2.72%	2017.25

Table 1.2.12 Institutes with the greatest output of citing papers on the "key engineering technologies, equipment, and materials for the intelligentization of coal, oil, and gas exploitation"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	China Univ Min & Technol	24	32.88%	2017.83
2	Chinese Acad Sci	17	23.29%	2015.71
3	Shandong Univ Sci & Technol	10	13.70%	2017.90
4	CSIRO	5	6.85%	2016.80
5	Newcastle Univ	5	6.85%	2017.00
6	China Univ Geosci	3	4.11%	2016.33
7	Univ Sydney	3	4.11%	2016.67
8	New Jersey Inst Technol	2	2.74%	2017.00
9	Univ Malaya	2	2.74%	2015.50
10	Petru Maior Univ Tirgu Mures	2	2.74%	2016.50

(1) Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment

The key technology and equipment of coal exploitation can be divided into two aspects: mining and tunneling. Complete fully mechanized automation, and intelligent and unmanned mining technology and equipment generally refers to the application of automation and intelligent technology in fully mechanized mining equipment to achieve the same work with only a few people, or with unmanned mining on the working face. Developing fully mechanized automation and intelligent technology to achieve unmanned mining on the coal face is the developmental direction of coal mining technology. The main technical orientations include hydraulic-powered support and surrounding rock-coupling adaptive technology; automated top coal caving control systems based on intelligent decision-making, sequential control, memory coal caving, and manual intervention cooperative control; reliable, real-time, and safe working face multi-machine cooperative control systems; automation of the working face end support system and the advanced support system.

Intelligent rapid tunneling technology and equipment for coal roadways refers to the driving equipment for coal roadways, such as tunneling machines, anchor machines, crushing transfer machines, and belt conveyors, which have the ability to perceive, memorize, learn, and perform decision-making tasks, controlled by a hubbed automatic control system, with remote visual monitoring, as a means to ensure safe and efficient tunneling technology of "full face rapid excavation and parallel operation of excavation support

Table 2.1.1 Top 14 engineering development fronts in energy & mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment	7 570	19 467	2.57	2014.51
2	High-voltage and high-power power electronic devices and equipment in power systems	30 142	93 793	3.11	2014.02
3	Spent fuel reprocessing and nuclear facility instrumentation	6 868	6 162	0.90	2014.97
4	Advanced energy storage technology in energy and power systems	34 878	112 316	3.22	2014.26
5	Research and application of wireless power transmission and its related equipment	1 700	32 763	19.27	2014.47
6	Renewable resources generation system and its operation and control	23 387	55 280	2.36	2014.56
7	Advanced reactor technology and equipment development	1 147	6 231	5.43	2013.65
8	Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources	5 821	19 950	3.43	2014.40
9	New tools and materials for petroleum engineering	10 890	52 436	4.82	2013.77
10	Green mining technology (coal, oil, gas, ores)	400	1 080	2.70	2014.30
11	Logging identification of unconventional reservoirs	4 766	17 227	3.61	2014.51
12	3D geological modeling technology	3 072	5 108	1.66	2016.51
13	Advanced nuclear fuel technology research and development	46 462	244 048	5.25	2013.69
14	Safe, intelligent, and precise mining technology and equipment	3 932	5 379	1.37	2014.83

Table 2.1.2 Annual number of core patents published for the top 14 engineering development fronts in energy & mining engineering

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment	599	747	848	1 819	1 796	1 116
2	High-voltage and high-power power electronic devices and equipment in power systems	3 203	4 236	4 377	4 812	4 750	5 115
3	Spent fuel reprocessing and nuclear facility instrumentation	620	841	938	1 145	1 556	1 651
4	Advanced energy storage technology in energy and power systems	4 039	4 882	5 309	5 355	5 627	6 614
5	Research and application of wireless power transmission and its related equipment	140	192	234	255	312	392
6	Renewable resources generation system and its operation and control	2 468	3 501	3 656	4 064	4 251	4 394
7	Advanced reactor technology and equipment development	127	102	144	161	160	232
8	Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources	492	811	831	804	1 006	1 308
9	New tools and materials for petroleum engineering	1 077	1 246	1 473	1 608	1 719	1 890
10	Green mining technology (coal, oil, gas, ores)	34	46	48	56	80	86
11	Logging identification of unconventional reservoirs	273	590	608	713	669	880
12	3D geological modeling technology	15	44	157	259	622	1 151
13	Advanced nuclear fuel technology research and development	5 150	5 667	6 509	6 113	6 723	8 068
14	Safe, intelligent, and precise mining technology and equipment	336	528	553	762	907	747

and transportation" in the driving working face. Intelligent rapid tunneling technology has created a new type of rapid tunneling, which is the "trinity" of driving, support, and transportation. It allows for the centralized and coordinated control of the equipment, and provides the foundation for an unmanned driving working face. The main technical directions and key technologies include intelligent cutting technology, intelligent anchor technology, multi-point drive power balance technology for conveyor belts, automatic control technology of tension forces, auxiliary process automation technology, integration technology for the "Internet of Things," and adaptability research of the system. The development trend of intelligent and rapid tunneling technology for coal roadways has progressed from the "trinity" of driving, support, and transportation, to the "quaternity" of driving, support, transportation, and auxiliary services. In addition, a large database of tunneling machines and a cloud-computing center will be constructed. This platform will effectively solve the problem of the intelligent control and remote service of tunneling machines. "Unattended and intelligent tunneling" will become a reality.

Unconventional oil and gas resources in China are abundant, and they are important strategic alternative resources. However, owing to the characteristics of low porosity, low permeability, large seepage resistance, and the low recovery rate of unconventional oil and gas reservoirs, it is difficult to achieve economical and efficient development of unconventional oil and gas industries through traditional means. There is an urgent need to improve the production and recovery of unconventional oil and gas resources, and to reduce their development cost, through the innovation of engineering systems and core technology equipment for long horizontal well technology, large-scale volume fracturing technology, and high-efficiency "well factory" technology. In turn, it will promote the realization of major breakthroughs in China's unconventional oil and gas fields, and contribute to the security of China's energy strategy. Long horizontal well technology is an effective method for expanding unconventional oil and gas reservoir drainage areas, improving the wellbore control volume, and carrying out staged fracturing transformation, which can significantly improve single-well production and recovery. The key technologies for long horizontal drilling and completion include rotary steerable drilling technology, efficient drilling fluid technology, and wellbore integrity control. Volume fracturing transforms the reservoir by fracturing to form one or more main cracks. Furthermore, through segmented multi-cluster perforation, high displacements, large liquid volumes, low-viscosity liquids, and steering materials and technologies interact with natural cracks and artificial cracks to increase the volume of the reforms and increase the initial yields and ultimate recoveries. "Factory-based" drilling uses robotized automatic drills, through the standardization and specialization of all drilling operations, using a streamlined "factory" production model to complete drilling operations in batches, to improve the construction efficiency of equipment, personnel, and organization, and to reduce overall drilling time and development costs. Therefore, long horizontal well technology, volume fracturing, and "well factory" drilling can significantly improve the production and recovery of unconventional oil and gas and reduce operating costs, which have become a hotspot for research and development at home and abroad.

(2) High-voltage and high-power power electronic devices and equipment in power systems

High-voltage high-power power electronic devices are the core for the transmission assignment and transformation of electric energy. For example, in ultra-high-voltage (UHV) power transmission and smart grids, there are large amounts of high-power semiconductor devices, flexible alternative current transmission systems (FACTS) based on power electronic devices, static synchronous compensators (STATCOM), static var compensators (SVC), power electronic transformers (PET), and energy routers. With the development of energy structures and the ever-increasing demand for energy, power devices and equipment achieve higher power and higher switching, and become more intelligent. The investigation of high-power electronic devices such as gate turn-off thyristors (GTO), insulated gate bipolar transistor (IGBT), and integrated gate commutated thyristors (IGCT) is required for long-distance power transmission including nationwide interconnection, sending power from west to east, and mutual supply between south and north. The key issues of high-power devices that must be resolved include their reliability, the current sharing and reduction of thermal resistance in the high-voltage module, and drive protection. SiC and GaN are considered the most promising power semiconductor devices for smart grids and new energy technology. The main related technologies include high-quality epitaxial layer, the reliability of gate oxide, current collapse, and high-voltage terminal. The development of UHV power transmission relies on the performance of power electronic equipment. In the future, intelligent and digitized power electronic equipment will be combined more closely with smart grids.

(3) Spent fuel reprocessing and nuclear facility instrumentation

Spent fuel reprocessing refers to the treatment and disposal of nuclear fuel (called "spent fuel") after it is discharged from the reactor. These methods include intermediate storage of spent fuel, post-treatment of spent fuel, treatment of radioactive waste, and final disposal. Spent fuel reprocessing is the core of the latter part of the nuclear fuel cycle. It treats spent fuel components discharged from nuclear power plants, separates and recovers unburned uranium and newly formed plutonium, and treats radioactive waste to satisfy disposal requirements. The post-treatment technique is classified into a wet method (also referred to as "water method") and a dry method in accordance with the existing state of spent fuel in the main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purexium uranium recovery through extraction involves converting the spent fuel components of the reactor into an aqueous solution of nitric acid via appropriate pretreatment, and thereafter using an organic solvent. The commonly used kerosene solution of tributyl phosphate is used in extraction separation for recovering nuclear fuel and removing fission products. Dry post-processing has certain advantages for dealing with high fuel consumption and spent fuel, especially in a fast reactor, and is an important research direction at present.

To ensure safe and efficient nuclear power operation, automatic operation monitoring of key systems and equipment of nuclear power should be strengthened to improve the reliability of systems and equipment; availability of nuclear power plant operation should be improved, thus to improve economic efficiency; maintenance in unreachable areas should be carried out by robots to reduce the exposure dose of the staff; and eventually, technical conditions are created for serious accident handling and decommissioning including digital technology, artificial intelligence, nuclear instrumentation, and other key instrument technologies related to nuclear safety.

(4) Advanced energy storage technology in energy and power systems

Energy storage technology can be implemented at any stage in the energy production and consumption chains. This is especially important for new energy and modern power systems because energy requirements do not match in space and time. Taking advantage of energy storage technology, energy can be stored and be made available later wherever or whenever it is required. This technology enables otherwise wasted energy streams to be reused, energy efficiency to be improved, and fluctuating renewable energy inputs to be managed. Each of these benefits will be increasingly important and necessary in future smart power systems.

In general, most of the developed and developing energy storage technologies can be applied to electricity networks, depending upon their energy and power ranges. These technologies can be classified based on their physical-chemical properties. They are electrochemical energy storage, such as various conventional and emerging secondary chemical batteries and flow batteries; chemical energy storage, such as hydrogen storage technology; thermochemical energy storage, such as ammonia dissociation-recombination and methane dissociation-recombination; thermal energy storage, such as sensible heat and latent heat utilization technology; kinetic energy storage, such as flywheel energy storage; potential energy storage, such as pumped hydro and compressed air energy storage; electrical and magnetic storage, such as superconducting magnetic energy storage and super capacitors.

The most suitable storage technology must be chosen considering the intended application and economic parameters such as cost of investment, energy or power densities, life cycle, and impact on the environment.

(5) Research and application of wireless power transmission and its related equipment

Wireless power transfer techniques apply near-field resonant coupling, electromagnetic wave, or acoustic wave to wirelessly transmit power from the transmitter side to the receiver side. The near-field inductive resonant coupling technique is widely adopted in many applications such as uniform wireless charging platform for various portable electronics, stationary electric vehicle wireless charging device, dynamic wireless charging system for electric vehicles, wireless charging facility for industrial robots, wireless charging device for implantable electronics, wireless charging facility for monitoring devices or aerial surveillance drones of power grid, and underwater wireless charging system for unmanned submarines. Space solar power station, which is based on microwave or laser wireless power transfer technique, is a promising solution for future renewable power generation. High-power far-field wireless power transfer, high-power high-frequency power conversion, high-power high-frequency power devices, maximum efficiency point tracking, dynamic control techniques, coupled-field analysis, and metamaterials have become the research focus. Future wireless power transfer techniques, with longer power transfer distance, higher power, higher efficiency, higher safety, and miniature size, will play important roles in transportation electrification, aeronautics and astronautics, implantable medical devices, underwater detection, and smart homes.

(6) Renewable resources generation system and its operation and control

The operation and control of renewable generation system is a comprehensive technology based on advanced power electronics, control theory, and information and communication technology that aims at the secure, efficient, and flexible operation of renewable generation systems (such as wind farms and PV plants) under variable capacity and integration modes.

Centralized and distributed modes could be adopted in renewable generation. Centralized generation could achieve large-scale utility of renewable energy and centralized integration as well as a long-distance delivery with the construction of clustered renewable generation stations. The centralized mode of renewable generation could solve the conflict between renewable energy and load center distribution in China and it conforms to the future development trends of power systems in China. However, the centralized renewable generation system is faced with several technical challenges, such as fault ride-through, grid-connection stability, flexible operation control, efficient delivery, and prediction-based grid dispatching. In distributed mode, renewable energy is converted, integrated, and utilized locally with the assistance of distributed generation units and power converters. It has the technical advantages of economy, efficiency, flexibility, and reliability. The main challenges for distributed renewable generation are the coordination with the distribution network, fault location and protective relay in the DC system, and the stability issue with system control.

The main goal and trend of operation and control of renewable energy generation are to upgrade the primary energy structure and build a clean, low-carbon, secure, and efficient power system. Different scales and operation modes for different local conditions may be adopted so that all kinds of renewable energy can be utilized and consumed efficiently. The negative effects on power system security and stability operation caused by random, intermittent, and volatile characteristics should be avoided.

Present studies mainly focus on the following topics: stability control technology of DC delivery systems of renewable energy generation bases; integration of distributed generation with microgrids and active distribution networks; DC grid-connection and consumption of high-proportion distributed generation; optimal dispatching and intelligent control of multiple renewable energy generation; coordinated operation technology of clustered power electronics devices in renewable energy generation for secure and stable grid connection.

(7) Advanced reactor technology and equipment development

In response to the research and development of advanced reactor technology and equipment, the International “Fourth-generation Nuclear Energy International Forum” proposed six types of reactors (including their respective fuel cycles) for research and development for the fourth-generation nuclear power and research and development “road map” in 2002; The International “Global Nuclear Energy Partnership” is committed to promoting joint research and development of advanced nuclear energy technologies for safety, sustainable development, economy, and nuclear non-proliferation; the IAEA launched an international project dedicated to the development of sustainable and innovative nuclear energy systems. The goal of the development of the fourth-generation nuclear power plant is to have inherent safety, fully utilize nuclear resources, improve thermal efficiency, develop nuclear energy for hydrogen, metallurgy, chemical, and other purposes, dispose of nuclear waste, prevent nuclear proliferation, and counter terrorism. Currently, six of the most promising reactor systems have been selected internationally, namely sodium-cooled fast reactor, ultra-high-temperature reactor, gas-cooled fast reactor, lead-cooled or lead-bismuth eutectic cooled reactor, lead-cooled fast reactor, molten salt reactor, and supercritical water reactor. The fourth-generation reactor chooses fast-spectrum reactors because of its ability to proliferate nuclear fuels. Sodium-cooled fast reactors, lead-cooled fast reactors, gas-cooled fast reactors, and molten salt reactors all have this capability, significantly improving the utilization of uranium resources, which can be transformed to minimize waste. The role of ultra-high-temperature gas-cooled reactor is to achieve high-temperature hydrogen production and improve the power generation efficiency of nuclear power plants. Furthermore, its high-temperature heat can expand the application of nuclear energy in the industrial field. The United States launched a traveling wave reactor for its nuclear energy characteristics, and China and the United States jointly developed this project. The traveling wave reactor is a special design of a fast neutron reactor. Using high-performance fuel and material technology, the long life and deep fuel consumption make the majority of the natural uranium ^{238}U undergo in situ proliferation and incineration in the heap, reducing the demand for spent fuel after treatment.

(8) Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources

Using wide spectral remote sensing techniques to explore the mineral deposits and geothermal resources is very efficient, for aiding national industrial development. With the increasing degree of resource exploration, prospecting for new deposits becomes more difficult, and advanced techniques are required. The remote sensing techniques have gradually become effective for the exploration and assessment of resources. Many nations are eager to launch various exploration satellites which can carry equipment receiving a wide spectrum, such as visible to near infrared, shortwave infrared, thermal infrared, and microwaves. Remote sensing techniques can effectively explore resources in the arid-semiarid and shallow coverage areas. The earth surface is half covered by vegetation, which causes difficulty in exploration. However, remote sensing can discover deposits underneath the areas covered by vegetation, using techniques of suppression of vegetation information and spectral chromatography. Clean geothermal resources, highly appreciated by international society, are covered by the vegetation. However, the identified temperature field by using thermal infrared spectrum and the structure interpretation by microwave mapping reveal the information of covering areas. Information enhancement and extraction avoid messy information, which effectively guide exploration and yield accurate prediction. In brief, for the exploration of mineral deposits and geothermal resources, remote sensing is effective, by using various wide spectral data. Enhancing and extracting key information are also critical techniques. The all goals are for providing the guidance of exploration, locating the targets of deposits, and achieving breakthrough of resource quantities.

(9) New tools and materials for petroleum engineering

As the exploration and development of oil and gas reservoirs have become more complex, there is an urgent need to develop new tools and materials for petroleum engineering for dealing with the complex conditions in a wellbore, which include high temperature and high pressure. This can help accelerate the exploration and exploitation of hydrocarbon reservoirs and ensure successful drilling. New tools for petroleum engineering mainly involve the fields of drilling, completion, production, etc., and new materials are applied to improve the performance of petroleum tools, drilling fluids, fracturing fluids, proppants, etc.

Currently, the exploration and development of oil and gas in the world are progressing from shallow ground to deep ground, from shallow sea to deep sea, and from conventional to unconventional fields. There is an urgent need to conduct research on tools and materials in petroleum engineering, which aims at improving the scale and efficiency of exploration and development under the strategies of being innovation-driven and made in China 2025. At present, the research hotspots of new tools for petroleum engineering include intelligent steerable tools, rotary steerable tools, single-well injection-production tools, and separate-layer water injection tools. Advanced materials, which include nanometer materials, functional gradient materials, and carbon fiber composite materials, can be used to improve the performance of tools. Furthermore, nano drag reducing agent, nano oil displacement agent, and self-healing polymer materials can play an important role in increasing the performance of drilling fluids, fracturing fluids, proppants, and other fluids.

(10) Green mining technology (coal, oil, gas, ores)

Green mining controls the mining disturbance to the mining environment within a regional environmental capacity, and optimizes the utilization of resources, while minimizing the impact on the ecological environment. In the process of mining, scientific and orderly mining must be strictly implemented, and the disturbance to the mining area and the surrounding environment should be controlled within the controllable range of environment. Green mining of coal, oil, and gas, as well as ore, indicates that all the available energy resources, such as coal, oil, gas, ore, mash gas, water, land, and gangue should be understood and treated from a perspective of the mining activity, preventing or mitigating adverse effects to the environment or other resources during the mining of energy resources, and realizing the economic benefits that accompany the optimum environmental and social benefits.

Green mining of coal resources, a direction borne out of the environment problems caused by coal mining in large quantities, is still the focus of research on energy resources. The techniques of exploitation and innovation should be employed from the beginning of the coal mining method; moreover, research on corporate mining and the utilization of associated resources, as well as technology and equipment, should be improved. The research topics are as follows: water preserved from mining, land and building protection, ecological reconstruction, simultaneous extraction of coal and gas, surface subsidence that retards mining, reduction of gangue emissions, concentration and utilization of marsh gas, utilization of solid waste, clean exploitation and processing of ore resources, ecological restoration of mine lot wastelands, the benefit-and-effect evaluation of mineral exploitation, the safety as well as monitoring and early warning of mine lot environments, etc. The key points of metal and nonmetal green mining include the integration of mining and processing, non-waste mining, breakthroughs in mechanization for continuous tunneling and mining, and innovations in tunneling and mining techniques with high-pressure water jets, lasers, or plasma.

Green oil exploitation is an integrated and systematic concept, aiming at environmental, social, and economic benefits, through a sustainable method. Clean oil exploitation or non-pollution product systems by means of ecological research with modern techniques should be realized; furthermore, they can be transformed into ecological products in the market. Therefore, a switch from a high-consumption development mode with high energy consumption and high pollution to a sustainable development mode with ecological and economic integration is required. The key innovations involve water conditioning to improve the quality of injection water, fine filters for injection water, improvement of resource utilization through the creation of key equipment, and increased production with the innovation of production and process control.

(11) Logging identification of unconventional reservoirs

Unconventional reservoirs refer to the reservoirs that cannot be economically explored using traditional techniques to obtain natural productivity, and require new technologies to improve reservoir permeability or fluid viscosity. Conventional logging methods have poor applicability in unconventional reservoirs, which require new logging technology to develop logging identification techniques for unconventional reservoirs. At present, the main technologies include elemental capture spectroscopy (ECS) logging, imaging logging, nuclear magnetic resonance logging, and other special logging techniques, as well as rapid identification of overlapping logging images, natural gamma and tri-porosity logging identification, electromagnetic resistivity and resistivity-fluid properties method, and effective fracture interval detection technology of shale oil and gas. These technologies have high recognition accuracy and speed, which can improve the accuracy of prediction of effective reservoirs of unconventional reservoirs by determining the continuous identification depth of effective reservoir and non-reservoirs, and satisfy the production requirements of effective fracturing intervals in the exploration and development of effective reservoirs in unconventional reservoirs. Future logging identification of unconventional reservoirs is still a difficult and hot topic, which will be optimized through collection technology, petrophysical research, processing and interpretation methods, and reservoir evaluation. It is expected that the digital petrophysical technology will play a more important role in logging evaluation and analysis in the future. In addition, the logging interpretation evaluation software is being developed toward multidisciplinary integration, and more attention is being paid to the comprehensive evaluation of oil and gas reservoirs; further, the research on the logging basic theory is intensified and the analysis techniques are more abundant.

(12) 3D geological modeling technology

3D geological modeling technology is a method to combine the spatial information management, geological interpretation, spatial analysis and prediction, geostatistics, physical content analysis, and graphical visualization in a virtual 3D environment by using computer technology and is applied to geological analysis. Data sources include borehole data, profile data, 3D seismic data, and other geological data. Modeling methods include phased geological modeling, petrographic modeling of sedimentary microfacies constraints, and parameter modeling of porosity, permeability, and saturation. Kriging method, stochastic modeling method, sequential Gaussian simulation method, dual-mode iteration technique, sedimentary-facies-coupled petrophysics modeling, well-to-seismic modeling, 3D reservoir parameter modeling, and 4D seismic technology have become the research hotspots. 3D seismic modeling software will become more mature and will be widely used in the future, from focus on shape modeling only to equal attention on form and physical property, and will be more closely combined with the geophysical data in the seismic, logging, electrical, gravity, and magnetic aspects, as well as drilling and geological data. It will be more closely integrated with various professional models (mineral description, accumulation simulation, 3D inversion of gravity and magnetic field, sedimentary environment analysis, etc.), which indicates that the mainstream IT technologies such as big-data analysis, cloud computing, and Internet of things will become the main techniques used in this regard.

(13) Advanced nuclear fuel technology research and development

After the Fukushima nuclear accident in Japan in 2011, countries began to accelerate the research and development of advanced nuclear fuels represented by accident tolerance fuels (ATF). Compared with conventional fuels, ATF fuels enhance the safety of reactors and spent fuel pools in the event of an accident by enhancing the ability of fuel-bearing fission products and cladding materials to resist oxidation, providing longer incident response times, and therefore potentially proactively or passively mitigating the consequences of the accident, achieving deeper fuel consumption, and improving fuel economy. ATFs can be used in new and in-service nuclear power plants, and hence, the development of ATF fuels is of great significance for the safe development of nuclear power. The research and development direction focuses on innovative cladding and new fuels. It can be classified into three directions: improving the high-temperature oxidation resistance and strength of the zirconium alloy cladding; developing a non-zirconium alloy with high strength and oxidation resistance; and developing a new fuel with better performance and retention of fission products than UO_2. The extended ATF should also include changes in geometry, such as ring fuel. The related research includes materials, processes, and inspection and verification techniques.

(14) Safe, intelligent, and precise mining technology and equipment

By means of different technologies including “intellisense,” intelligent control, the Internet of Things, and cloud computing and big data, intelligent precise mining technology and equipment for mining safety are proposed as a new mining mode that integrates the intelligent mining technique requiring few workers (unmanned), and it has the functions of risk identification, monitoring, and early warning. This mode is based on transparent spaces and geophysics, as well as multi-field coupling to achieve spatiotemporal accuracy and efficiency. At present, the main research directions are as follows: the innovation of geophysical sciences with transparent functions, a new type of intellisense, a multi-internet fusion transmission method and technical equipment, dynamic complex mining analysis of multi-field and multi-parameter information and fusion processing technologies, theoretical models on precise coal mining based on big data and cloud technology, multi-field-coupling composite disaster warning, remote-controlled intelligent coal mining technology and equipment requiring few workers (unmanned), disaster communication, personnel orientation, disaster detection technology and equipment, and intelligent coal mine construction based on cloud technology—all of which provide a technological path for a mode of future mining that requires few workers (unmanned), based on the Internet and scientific mining. China has concentrated on safety mining that requires few workers (unmanned), and it will further accelerate the intensity of innovation for mining technology, with plans to break through the basic and full implementation of a safe-intelligent-precise mining mode in the years 2020, 2035, and 2050, respectively, indicating a full realization of high-tech industrial upgrades that will boost the Chinese dream of powerful energy technology.

2.2 Interpretations for three key engineering development fronts

2.2.1 Development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment

(1) Complete fully mechanized automation, and intelligent and unmanned mining technology and equipment for coal mines

Fully mechanized longwall mining is the main mining method for coal mines. The technological advancement of fully mechanized mining equipment is the engine for promoting the development of safe, efficient, and green mining technology for coal. The deep integration of modern automation, informatization, intelligent technology, advanced manufacturing technology, and coal mining technology makes it possible to produce fully mechanized automation, and intelligent and unmanned mining technology and equipment. Research on intelligent mining technology and equipment is required, as outdated mining methods and equipment must be eliminated, in order to achieve safe, efficient, and green mining of coal resources. Improving the automation and intelligence level of equipment, and requiring few people or using unmanned mining is the only possible way for the development of fully mechanized mining and the modernization of mines.

To better describe the technical connotations and the level of automation technology required for a fully mechanized mining face that operates according to the level of perception, decision, and execution of the fully mechanized mining equipment control system, the terms defined are automatic fully mechanized mining face, intelligent fully mechanized mining face, and unmanned fully mechanized mining face. An automatic fully mechanized mining face indicates that the equipment is electromechanically integrated; this includes the adoption of hydraulic supports, coal mining machines, and scraper conveyors with automatic functions, which requires few people as operators, and allows safe and efficient mining. An intelligent, fully mechanized mining face is an electromechanically integrated equipment system with the adoption of comprehensive perception, self-learning, decision-making, and automatic execution functions, which allows for a highly automated mining face that requires few people for remote monitoring, and allows for safe and efficient mining. An unmanned, fully mechanized mining face indicates that the mining face adopts remote intelligent integrated control systems, and is a complete automated, intelligent, and highly reliable system with electromechanical integration, which achieves completely unmanned (within both face ends), safe, and efficient mining.

Fully mechanized, automatic, and intelligent mining is the basis for the mining of unmanned working faces, which is the ultimate target of mine technology development. The technology orientations and the key technologies to be developed are as follows.

1) The study of hydraulic-powered supports and surrounding rock coupling adaptive technology, and automated top coal caving control systems, based on intelligent decision-making, sequential control, memory coal caving, and a manual intervention cooperative control, for a reliable, real-time, and safe working face multi-machine cooperative control system.

2) The study of the sensitivity of coal rock characters to the cutting head load; the establishment of on-line monitoring of the cutting head load, with abrupt changes and detection of the criteria of the cutting state; the development of intelligent control technology of the precise location of the autonomous shearer, including self-learning, and intelligent adjustment from memory. Research on the multi-source information fusion method of the integrated system of shearer cutting–hydraulic powered support–transportation, aiming at the elimination of conflict for collaborative work, and the establishment of prevention of the collision algorithm and its technology; finally, the development of a reliable, real-time, and safe collaborative working system in the working faces.

3) The study of the failure mode and the fault mechanism of key components of the fully mechanized mining equipment; the establishment of an evaluation system for fully mechanized equipment key components and system reliability, aiming at automatic, intelligent, and unmanned working faces.

4) Strengthening of the automation study on the working face end and advanced support to solve the constraints caused by the above places.

With the development and popularization of fully mechanized, automatic technology, high-efficiency technology is the fundamental solution to achieving safe, high-yield, and high-efficiency mines. The reliability and adaptability of complete equipment in a fully mechanized working face are improved with integration with automatic, intelligent technology. At present, unmanned mining operation has been achieved in some advanced coal mines, or under limited conditions. Continual technical research on fully mechanized, automatic, and intelligent technology is the developing orientation for mine technology science.

(2) Intelligent rapid tunneling technology and equipment for coal roadways

Mining and tunneling coordination has always been an important issue in the coal production process. With the increase in the automation and intelligence level of the equipment in the fully mechanized coal mining face, the unbalance of mining and tunneling owing to excavation efficiency has become a difficult problem in the modern large mine. In the last few decades, the level of driving technology for coal roadways has been greatly improved in China. Especially in recent years, the Taiyuan Research Institute, China Coal Technology & Engineering Group Corp (CCTEG), and Shendong have co-developed an efficient and rapid driving system. This system was applied to the fully mechanized coal mining faces in Coal Seam 5-2 in the Daliuta Coal Mine in Shendong mining areas from July 2014 to November 2015, and it allowed for full-section rapid excavation, a parallel operation of tunneling, supporting, and transportation, remote monitoring operation, and an auxiliary operation. Currently, it is the fastest driving system with the highest degree of mechanization, automation, and informatization in China. However, there are still shortcomings in this highly efficient and rapid driving system, including the following issues: ① The system is only adaptable to mines with better geological conditions, such as Shendong, and the adaptability of the system is not high; ② The mechanization, automation, and intellectualization of the supporting equipment are generally not high, and should be further improved; ③ The reliability of single machines must be improved; ④ The system did not achieve parallel operation. Therefore, it is necessary to further study the problems related to the rapid tunneling of coal roadways, and to explore intelligent rapid tunneling technology, in order to further improve the technical indexes of the tunneling operation, and to satisfy the needs of safe and efficient coal mining.

The intelligent rapid tunneling technology and equipment for coal roadways refer to the driving equipment of coal roadways, such as the tunneling machine, anchor machine, crushing transfer machine, and belt conveyor, which have the ability to perceive, memorize, learn, and perform decision-making tasks. They use a hubbed automatic control system, and also use remote visual monitoring as a means to realize safe and efficient tunneling technology of “full face rapid excavation, parallel operation of excavation support, and transportation” in driving the working face. Intelligent rapid tunneling technology has created a new type of rapid tunneling, which is the “trinity” of driving, support, and transportation. This has achieved centralized and coordinated control of equipment, and it provides the foundation for an unmanned driving working face.

Foreign excavator and full-section boring machines have automatic cutting technology, transmission equipment monitoring, and automatic control technology, which enable full-function remote control and monitoring of the cutting section. Germany, the United States, and Austria have mastered multi-point drive technology for the line friction of the flexural belt conveyor, and for the turning technology of the conveyer belt. However, at present, the automated single machine equipment is mostly used in non-coal mines such as metal ore, salt mines, and other non-coal mines. The technology and equipment of the coal mining face in foreign countries are still at the semi-automation level, and there is no complete set of technology and equipment for intelligent rapid tunneling at present.

The main technical directions and key technologies include intelligent cutting technology, intelligent anchor technology, multi-point drive power balance technology of the conveyor belt, automatic control technology of the tension force, auxiliary process automation technology, integration technology for the Internet of Things, and the adaptability research of the system.

The development trend of intelligent and rapid tunneling technology for coal roadways is based on the “trinity” of driving, support, and transportation, progressing to the “quaternity” of driving, support, transportation, and auxiliary services. In addition, a large database of tunneling machines and the cloud-computing center will be constructed. This platform will effectively solve the problem of the intelligent control and remote service of tunneling machines. “Unattended and intelligent tunneling” will become a reality.

(3) Unconventional oil and gas development and utilization systems, and core technology and equipment

Unconventional oil and gas are characterized by a difference in reservoir characteristics and accumulation mechanisms from conventional oil and gas reservoirs. Such oil and gas accumulation can only be developed economically by using advanced technology, large-scale stimulation measures, and/or special recycling processing, owing to its special reservoir rock properties (low matrix permeability and natural cracks), special infill injection (absorbed gas and methane hydrate from self-generated and self-reserved rock), and/or special fluid properties (high viscosity). The key parameters are that the porosity of the reservoir is generally less than 10%, and that the permeability is less than $1\times10^{-3}\,\mu m^2$. The key indicators are the “continuous distribution of large areas of oil and gas, no apparent trapping limits” and “no natural industrial stable outputs, no apparent Darcy seepage flow.” With the increasing difficulty in the exploration and development of conventional oil and gas, unconventional oil and gas resources have increasingly attracted attention worldwide. It can be said that unconventional oil and gas is an inevitable trend and choice for the development of the world oil and gas industry. Therefore, accelerating the development and utilization of unconventional oil and gas resources is of great strategic significance to compensate the energy gap, and to ensure national energy security.

The branch engineering technologies for unconventional oil and gas exploration mainly include drilling technology (horizontal well drilling technology is the leading mainstream technology), fracturing technology, and platform-type “factory” mining technology.

Horizontal well drilling technology. Compared with vertical wells, horizontal wells have the advantages of large oil and gas drainage areas, high single-well production, high penetration, high employing reserves, saving land occupation, and avoidance of obstacles and harsh environments. This plays an important role in improving single-well oil and gas production, and recovery of oil and gas, and it has become a key technology for the efficient exploration and development of unconventional oil and gas resources. With the development of horizontal wells and process technologies, new horizontal well technologies have been developed, such as extended-reach horizontal wells, sidetracking horizontal wells, multi-branch horizontal wells, pinnate horizontal multilateral wells, cluster horizontal wells (PAD), under-balanced horizontal wells, and coiled tubing drilling.

Fracturing technology. In recent years, the scale of fracturing has developed from miniaturization to maximization. The number of fracturing layers has progressed from a single layer to multiple layers. Fracturing wells have progressed from vertical wells to horizontal wells, with the development of various fracturing technologies and supporting processes, such as vertical well segmental fracturing, horizontal well segmental fracturing, repeated fracturing, and simultaneous fracturing, which have become the core technologies for the economic and effective development of unconventional oil and gas resources, and have played a key role in the rapid development of unconventional oil and gas. At present, fracturing technology is being developed in the following three aspects: ① The existing fracturing technology is being continuously developed and integrated, such as continuous tubing fracturing, slim hole fracturing, downhole mixing fracturing, and other technologies; ② fracturing equipment develops to be high-power, modular, miniaturized, and portable; ③ efficient, low-cost, environment-friendly fracturing technology will be an important development direction in the future, such as volumetric fracturing transformation, high-speed channel fracturing, and other technologies being tested.

Platform-style “factory” mining technology. This is mainly based on a cross-well superseding strategy, using cluster horizontal well drilling, simultaneous fracturing, or cross-fracturing operation, where dozens of wells are synchronized in a well site, saving land and reducing costs. This breaks through the problem of poor efficiency of single-well mining in a well site, and provides an efficient operation mode for the economic development of unconventional oil and gas resources, such as shale gas.

At present, unconventional oil and gas development technology is complicated and expensive. In the future, we should investigate how to reduce costs, in order to achieve the expected mining targets on the basis of ensuring the smooth exploration and exploitation of unconventional oil and gas resources. The main research trends includes adhering to long-term basic theoretical innovation, to provide a solid theoretical basis and technical guidance for the exploration and development of unconventional oil and gas; adhering to core technology advancement and large-scale application, which is the key to breakthroughs in the field of unconventional oil and gas; focusing on horizontal well-scale fracturing and platform-type “factory” mining; strengthening process technologies and developing low-cost supporting technologies as soon as possible; strengthening the regulation and control of development of unconventional oil and gas resources; formulating scientific development plans; developing, utilizing, establishing, and planning the required talent team training system; forming a talent organization composed of researchers and technical experts to ensure the rational development of unconventional oil and gas resources.

(4) Comparisons and cooperation between countries and institutions

According to Table 2.2.1, the countries with the largest number of core patent outputs in this research direction are China, the USA, Japan, Russia, and Germany. Among them, the proportion of China’s patents exceeds 80%, and the proportion of patents of the other countries is less than 5%. According to Table 2.2.2, the institutions with the largest number of core patent outputs in this research direction are UYMT, UYMB, SHGR, UYHP, and SNPC. Among them, only UYMT, UYMB, and SHGR have a core patent ratio exceeding 2%.

According to Figure 2.2.1, countries such as USA, China, Australia, Canada, and Germany have paid more attention to cooperation among nations or regions in this research direction. Among them, China and USA have formed a cooperative relationship, and have a much larger number of co-authored core patents. Although Japan and Russia have a high number of core patents, they have cooperative relationship with no more than two countries or regions, and they have no cooperative relationship with China.

According to Figure 2.2.2, the institutions with a cooperative relationship with other institutions are UYMT, UYMB, SHGR, SNPC, and Xi'an University of Science and Technology. Among them, UYMT, UYMB, and SHGR have a cooperative relationship with each other, and have the largest number of co-published core patents. Xi'an University of Science and Technology has a cooperative relationship with UYMB and SHGR; however, they have a lower number of co-published core patents.

2.2.2 High-voltage and high-power power electronic devices and equipment in power systems

(1) Concept description and key techniques

High-power power electronic technology uses high-power semiconductor devices to realize effective power conversion and transmission through the accurate energy flow control with information flow, and to improve the conversion efficiency and accuracy of high-power power electronic equipment. Nowadays, China is at a critical stage owing to the development of energy structures and the ever-increasing demand for energy. Thus, UHVAC transmission and smart grids are attracting widespread attention. Hence, power converters and semiconductor devices face new challenges and opportunities. However, there are still some important issues that must be solved in achieving high power, high frequency, and intelligentization.

(2) State-of-the-art and future development trends

Power devices with high voltage and high power. To achieve long-distance power transmission including nationwide interconnection, sending power from west to east, and mutual supply between south and north, IGBT and IGCT with higher energy capability are urgently required. ABB and Mitsubishi have reported 8500V/4240A thyristor and 4500V/2100A IGBT, respectively. At present, 6-inch 8000V/4000A thyristor, 4500V/4000A IGCT, 3300V/2400A IGBT are in mass production in China. In 2018, the first 4500V/3000A crimping IGBT has been proposed by CRRC. The key issues of high-power devices that must be resolved include the fast switching and reliability of GTO, current sharing and reduction of thermal resistance in the IGBT module, and drive protection.

Novel high-voltage devices with high frequency. To satisfy the requirements of the development of smart grid and new energy technology, novel high-voltage devices with high frequency are required to realize converters with high efficiency and power density. Currently, SiC and GaN are considered the most promising power semiconductor devices. The 900 V–1700 V SiC and 30 V–650 V GaN devices are already industrialized in Europe, USA, and Japan. Furthermore, 10 kV SiC MOSFET, 27 kV SiC IGBT, and 22 kV SiC GTO samples have been reported. So far, 10 kV SiC MOSFET and 10 kV SiC IGBT samples have already been reported in China. The key issues that must be resolved include high-quality epitaxial layer, the realization of gate oxide, and high-voltage terminal.

Table 2.2.1 Countries or regions with the greatest output of core patents on the “development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	6 330	83.62%	10 363	53.23%	1.64
2	USA	364	4.81%	5 646	29.00%	15.51
3	Japan	227	3.00%	679	3.49%	2.99
4	Russia	132	1.74%	111	0.57%	0.84
5	Germany	82	1.08%	612	3.14%	7.46
6	South Korea	78	1.03%	45	0.23%	0.58
7	Australia	64	0.85%	287	1.47%	4.48
8	France	50	0.66%	359	1.84%	7.18
9	India	48	0.63%	139	0.71%	2.90
10	Canada	41	0.54%	786	4.04%	19.17

Table 2.2.2 Institutions with the greatest output of core patents on the “development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment”

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYMT	China	247	3.26%	1 221	6.27%	4.94
2	UYMB	China	189	2.50%	356	1.83%	1.88
3	SHGR	China	153	2.02%	440	2.26%	2.88
4	UYHP	China	141	1.86%	332	1.71%	2.35
5	SNPC	China	91	1.20%	374	1.92%	4.11
6	UYTL	China	85	1.12%	150	0.77%	1.76
7	Univ Xi’an Sci & Technology	China	79	1.04%	128	0.66%	1.62
8	KOBM	Japan	74	0.98%	225	1.16%	3.04
9	BJSW	China	73	0.96%	67	0.34%	0.92
10	SDST	China	69	0.91%	108	0.55%	1.57

UYMT: Univ China Mining & Technology; UYMB: Univ China Mining & Technology Beijing; SHGR: Shenhua Group Corp. Ltd.; UYHP: Univ Henan Polytechnic; SNPC: China Petroleum & Chem Corp.; UYTL: Univ Taiyuan Technology; KOBM: Kobe Steel Ltd.; BJSW: Beijing Shenwu Environment & Energy Tech; SDST: Univ Shandong Sci & Technology.

Intelligent high-power electronic equipment. The capacity improvement of power transmission relies on the performance of power electronic equipment such as FACTS, STATCOM, SVC, PET, and energy router. The key issues that must be resolved include power electronic equipment with high capacity and high reliability, and high-efficiency equipment technology.

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

The core technology of high-voltage power devices and equipment for power systems in China is advancing satisfactorily overall but the quality and quantity in certain institutions still need to be improved. As shown in Table 2.2.3 & 2.2.4, the number of enterprises operating in the field of high-power electronic devices and equipment in China is considerably large. However, the average number of citations and cited proportion of the related patents from China are much less than those from the USA, Europe, and Japan. As shown in Figure 2.2.3, there is a strong cooperative relationship among these developed countries and regions

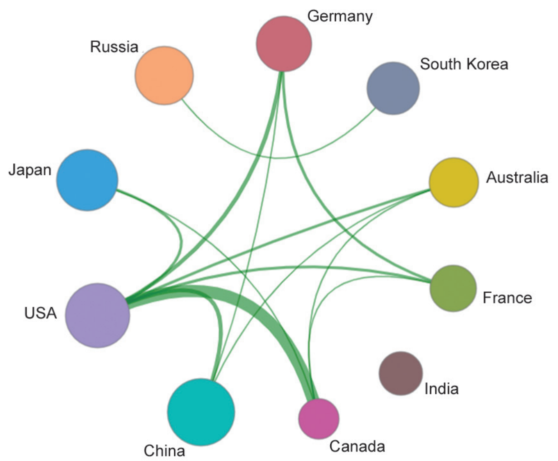

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

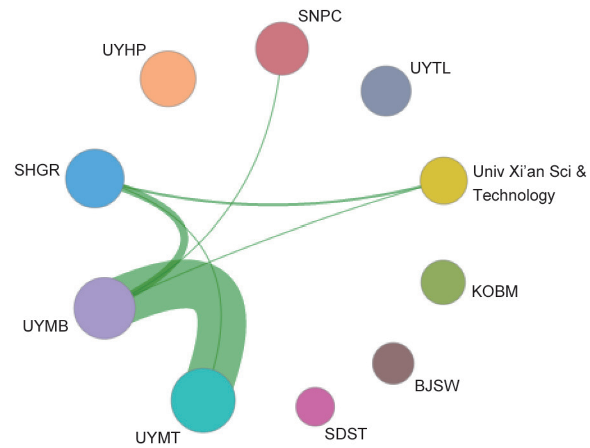

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "development and utilization system of fossil energy (coal, and unconventional oil and gas) and core technology and equipment"

in the field of high-power electronic devices and equipment. Moreover, many enterprises take part in the research through division of labor and collaboration. Among them, the semiconductor enterprise and foundry are also included as shown in Figure 2.2.4.

2.2.3 Spent fuel reprocessing and nuclear facilities instrumentation

(1) Conceptual explanation and key technologies

1) Spent fuel reprocessing refers to the treatment and disposal of nuclear fuel (called "spent fuel") after being discharged from the reactor. These methods include intermediate storage of spent fuel, post-treatment of spent fuel, treatment of radioactive waste, and final disposal. Spent fuel reprocessing is the core of the latter part of the nuclear fuel cycle. It treats spent fuel components discharged from nuclear power plants, separates and recovers unburned uranium and newly formed plutonium, and treats radioactive waste to satisfy disposal requirements. The post-treatment technique is classified into a wet method (also referred to as "water method") and a dry method in accordance with the existing state of spent fuel in the main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purexium uranium recovery through extraction involves converting the spent fuel components of the reactor into an aqueous solution of nitric acid via appropriate pretreatment, and thereafter using an organic solvent. The commonly used kerosene solution of tributyl phosphate is used in extraction separation for recovering nuclear fuel and removing fission products. Dry post-processing has certain advantages for dealing with high fuel consumption and spent fuel, especially in a fast reactor, and is an important research direction at present.

2) To ensure the safe and efficient operation of nuclear power operation during the whole life, the automatic operation monitoring of key systems and equipment of nuclear power should be strengthened, thus to improve the reliability of systems and equipment; the availability of nuclear power plant operation should be improved, thus to improve economical efficiency; robot maintenance is carried out in unreachable areas, to reduce the exposure dose of workers; and ultimately technical conditions for serious accident handling and decommissioning is created. Digital technology, artificial intelligence and nuclear instrumentation, and other key instrument technologies related to nuclear safety are included.

(2) Development status and future development trend

1) The medium treated by the spent fuel reprocessing plant of the power reactor is highly radioactive, toxic, and corrosive, and has outstanding problems such as nuclear criticality safety and radiation safety. The requirements for engineering technology, special equipment, online control and monitoring, and far-distance operation and maintenance are high, and

Table 2.2.3 Countries or regions with the greatest output of core patents on the "high-voltage and high-power power electronic devices and equipment in power systems"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	19 056	63.22%	21 726	23.16%	1.14
2	Japan	4 897	16.25%	30 528	32.55%	6.23
3	USA	1 643	5.45%	22 001	23.46%	13.39
4	South Korea	1 200	3.98%	2 995	3.19%	2.50
5	Germany	1 139	3.78%	5 953	6.35%	5.23
6	Switzerland	469	1.56%	3 607	3.85%	7.69
7	Russia	403	1.34%	125	0.13%	0.31
8	Austria	256	0.85%	2 126	2.27%	8.30
9	Taiwan of China	221	0.73%	822	0.88%	3.72
10	France	196	0.65%	1 087	1.16%	5.55

Table 2.2.4 Institutions with the greatest output of core patents on the "high-voltage and high-power power electronic devices and equipment in power systems"

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	SGCC	China	2 186	7.25%	3 583	3.82%	1.64
2	FJIE	Japan	771	2.56%	5 982	6.38%	7.76
3	INFN	Austria	673	2.23%	4 827	5.15%	7.17
4	MITQ	Japan	590	1.96%	3 980	4.24%	6.75
5	CRRC	China	497	1.65%	802	0.86%	1.61
6	ALLM	Switzerland	438	1.45%	3 161	3.37%	7.22
7	TOKE	Japan	437	1.45%	2 232	2.38%	5.11
8	NPDE	Japan	419	1.39%	3 037	3.24%	7.25
9	TOYT	Japan	419	1.39%	2 187	2.33%	5.22
10	CSPG	China	274	0.91%	311	0.33%	1.14

SGCC: State Grid Corp China; FJIE: Fuji Electric Co., Ltd.; INFN: Infineon Technologies AG; MITQ: Mitsubishi Electric Corp.; CRRC: Zhuzhou CRRC Times Electric Co., Ltd.; ALLM: ABB Technology Co., Ltd.; TOKE: Toshiba Corp.; NPDE: Nippondenso Co., Ltd.; TOYT: Toyota Jidosha KK; CSPG: China Southern Power Grid Co., Ltd.

nuclear fuel reprocessing technology is difficult to study. It is necessary to develop a series of special engineering techniques, special equipment, and instruments. The development of post-processing processes generally includes laboratory process conditions and cascade experiments, laboratory-scale bench warming tests, and pilot-scale thermal verification processes; the development of key equipment requires experience prototype development, equipment amplification research and development of prototypes, and engineering prototype development; the typical unit process, equipment, layout, and maintenance program also requires 1:1 scale engineering verification under non-release (or cold uranium) conditions. Thus, the engineering design of the nuclear fuel reprocessing plant can be carried out to improve the reliability, operability, and maintainability of the reprocessing plant, thus ensuring the operating rate, economy, and safety.

Sustainable development of nuclear energy must address the two major problems of uranium resources: optimization of utilization and minimization of radioactive waste. Returning of the uranium and thorium extracted via post-treatment to a

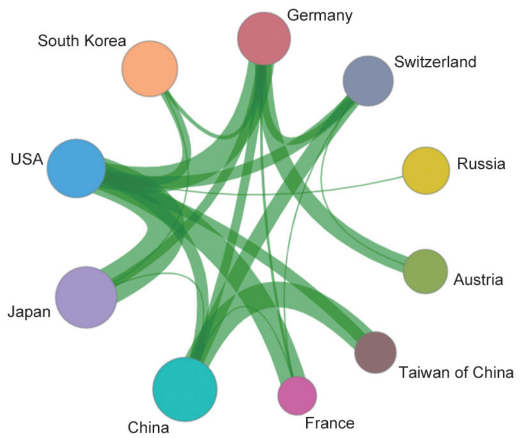

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "high-voltage and high-power power electronic devices and equipment in power systems"

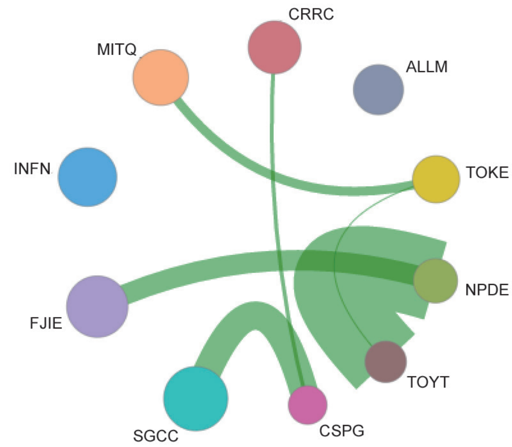

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "high-voltage and high-power power electronic devices and equipment in power systems"

thermal reactor for reuse can only increase the utilization rate of uranium resources by 30%; returning to a fast reactor for reuse can increase the utilization rate of uranium resources by 60 times. Furthermore, long-lived, highly radiotoxic secondary lanthanides and fission products separated via post-treatment are consumed in the fast reactor through incineration and metamorphism, which can effectively reduce not only the impact of spent fuel on the environment, but also the supervision time, thus significantly reducing economic and social costs. Therefore, the closed cycle of nuclear fuel, especially in fast reactors, is the only possible way for the sustainable development of nuclear energy.

2) Instrumentation in nuclear facilities includes digital technology, artificial intelligence and nuclear instrumentation, and other key instrument technologies related to nuclear safety. Among them, nuclear measuring instruments use certain characteristics of radiation to measure radiation types and related physical parameters. Instrumentation in nuclear facilities mainly includes three parts: reactor control, safety protection, and environmental monitoring. According to the type of instrument, it includes nuclear instrumentation and key instruments related to nuclear safety. China has established a nuclear instrumentation equipment manufacturing system that is relatively complete in product variety and can satisfy general needs. However, with the development of advanced nuclear power technology, the safety and reliability of nuclear power plants are being continuously improved, and the subsequent nuclear instrumentation requirements and measurement accuracy, operating environment, and product reliability requirements of key instruments related to nuclear safety are also constantly improving; thus, product replacement is imperative. Owing to the gaps in testing and inspection capabilities among key materials and the design and manufacturing levels and conditions, the existing products of domestic manufacturers have been unable to satisfy the technical requirements of the third-generation nuclear power plants.

The USA, France, UK, Russia, India, Japan, and other countries have all the aspects of the nuclear fuel cycle. Except for the United States, they all adhere to the post-development and nuclear fuel closed cycle. At present, the total post-processing capacity of the world is approximately 4 850 tons per year, and more than 90 000 tons of spent fuel has been reprocessed. France's UP3, UP2-800, and UK THORP reprocessing plants are state-of-the-art commercial reprocessing plants. Internationally, research and development on the post-processing of spent fuel in fast reactors is actively carried out, and finally, an integrated fuel reactor (fuel manufacturing-reactor-post-treatment at the same site) closed fuel cycle (U, Pu, MA recycling) is realized.

To gain intelligence and wisdom, and to upgrade the high-tech strategic industry level of the nuclear industry, it is necessary to deeply and widely apply a new type of artificial intelligence technology represented by industrial robots, image recognition, deep self-learning systems, adaptive control, autonomous manipulation, human–machine hybrid intelligence, and virtual reality intelligence. The measures also include the use of intelligent instrument intelligent controllers for the establishment of nuclear power plant digital control system; the use of Internet+ to establish a big-data system to develop digital nuclear power plants; (three-dimensional dynamic) development of virtual reality technology; operational guidance and accident handling guidance; intelligent maintenance of equipment system in a nuclear power plant; using robots or robotic systems to repair unreachable areas in highly radioactive areas.

(3) Focus on the analysis of countries and institutions and the comparison and cooperation between them

According to Table 2.2.5, the countries with the largest number of core patent outputs in this research direction are Japan, the USA, China, the Netherlands, Germany, South Korea, France, and Russia. Among them, the proportion of core patents from Japan exceeds 30%, the proportion of core patents from the USA and China exceeds 20%, the proportion of core patents from the Netherlands is approximately 6%, and the proportion of core patents from the other countries is less than 6%.

As evident from Table 2.2.6, the institutions with the largest number of core patent outputs in this research direction are GENE, PHIG, CGNP, and MITQ, and their proportion of core patent output exceeds 5%.

According to Figure 2.2.5, the USA, the Netherlands, Germany, France, Japan, and Russia are more concerned about the cooperation between countries or regions in this field.

According to Figure 2.2.6, the institutions with a cooperative relationship with other institutions include CGNP and CNNU, and the number of core patents published by means of the cooperation is also the largest; HITA has a cooperative relationship with two research institutes, TOKE and GENE.

Table 2.2.5 Countries or regions with the greatest output of core patents on the “spent fuel reprocessing and nuclear facilities instrumentation”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	193	30.54%	700	18.37%	3.63
2	USA	170	26.90%	1 921	50.42%	11.30
3	China	153	24.21%	182	4.78%	1.19
4	Netherlands	38	6.01%	767	20.13%	20.18
5	Germany	28	4.43%	289	7.59%	10.32
6	South Korea	21	3.32%	42	1.10%	2.00
7	France	16	2.53%	115	3.02%	7.19
8	Russia	14	2.22%	3	0.08%	0.21
9	Canada	9	1.42%	54	1.42%	6.00
10	Poland	6	0.95%	2	0.05%	0.33

Table 2.2.6 Institutions with the greatest output of core patents on the “spent fuel reprocessing and nuclear facilities instrumentation”

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GENE	USA	38	6.01%	404	10.60%	10.63
2	PHIG	Netherlands	34	5.38%	571	14.99%	16.79
3	CGNP	China	32	5.06%	68	1.78%	2.13
4	MITQ	Japan	32	5.06%	71	1.86%	2.22
5	HITA	USA	29	4.59%	120	3.15%	4.14
6	SHMA	Japan	29	4.59%	146	3.83%	5.03
7	TOKE	Japan	25	3.96%	38	1.00%	1.52
8	CNNU	China	17	2.69%	17	0.45%	1.00
9	USGO	USA	12	1.90%	47	1.23%	3.92
10	WESE	USA	10	1.58%	76	1.99%	7.60

GENE: General Electric Co.; PHIG: Konink Philips NV; CGNP: China Guangdong Nuclear Power Group Co., L; MITQ: Mitsubishi Electric Corp.; HITA: Hitachi Ltd.; SHMA: Shimadzu Corp.; TOKE: Toshiba Corp.; CNNU: China National Nuclear Corporation; USGO: National Nuclear Security Administration, which is an agency within the U.S. Department of Energy and is closely related to U.S. Department of Homeland Security; WESE: Westinghouse Electric Co., LLC.

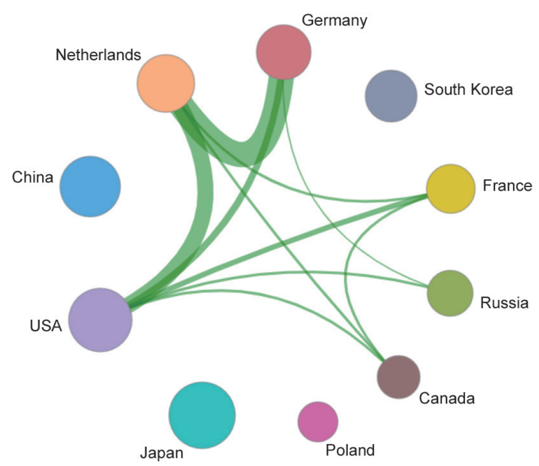

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “spent fuel reprocessing and nuclear facilities instrumentation”

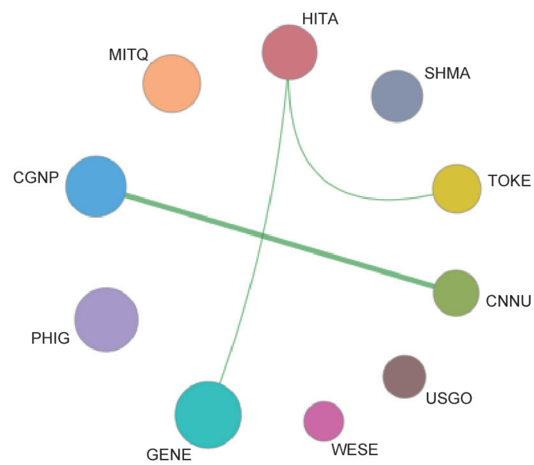

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “spent fuel reprocessing and nuclear facilities instrumentation”

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V. Civil, Hydraulic & Architecture Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts related to the field of civil, hydraulic & architecture engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering; construction materials; roads and railway engineering; architecture; heating, ventilation, air conditioning, and gas supplying; municipal engineering; surveying and mapping engineering; and hydraulic engineering. Among these research fronts, “intelligent control systems for building environment,” “migration and transformation mechanisms of microplastics in wastewater treatment,” and “dynamic fusion of geographical spatiotemporal big data for smart cities” are the emerging fronts, while the others are extended from conventional disciplines.

Table 1.1.2 presents the annual statistical data of the core papers published between 2012 and 2017 relevant to the top 10 research fronts. The increasing rate of core papers on intelligent control systems for building environment is the highest among the top 10 research fronts.

(1) Lifecycle reliability of civil engineering structures and systems

This research front refers to the time-dependent reliability of civil-engineering structures and resulting systems considering the random distribution of loads and the degrading performances of materials, components, and structures during their service life. Under long-term environmental and mechanical loads, structural properties experience stochastic and time-dependent degradation. Based on the theory of stochastic processes, time-dependent structural reliability can be determined through use of probabilistic models of load effects and structural properties. Major issues concerning

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic & architecture engineering

No.	Engineering research fronts	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Lifecycle reliability of civil engineering structures and systems	215	4 440	20.65	2014.57	–	–
2	Ultrahigh-performance and smart cement-based composite materials	64	2 594	40.53	2013.59	–	–
3	Highway pavement renewable materials and pavement materials rejuvenation	27	601	22.26	2013.74	–	–
4	Green vernacular architecture	317	9 213	29.06	2013.89	–	–
5	AI-based architectural design methodology	107	3 704	34.62	2013.92	–	–
6	Intelligent control systems for building environment	31	1 244	40.13	2015.32	38.7%	0.00
7	Migration and transformation mechanisms of microplastics in wastewater treatment	7	243	34.71	2016.14	28.6%	0.00
8	Fusion and processing of multilevel space-air-ground remote-sensing data	141	7 023	49.81	2014.39	–	–
9	Dynamic fusion of geographical spatiotemporal big data for smart cities	52	1 244	23.92	2015.50	–	–
10	Lifecycle safety of water-related engineering	49	913	18.63	2013.78	–	–

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

No.	Engineering research fronts	2012	2013	2014	2015	2016	2017
1	Lifecycle reliability of civil engineering structures and systems	30	39	31	39	45	31
2	Ultrahigh-performance and smart cement-based composite materials	14	17	17	13	3	0
3	Highway pavement renewable materials and pavement materials rejuvenation	7	3	9	6	2	0
4	Green vernacular architecture	56	76	76	70	34	5
5	AI-based architectural design methodology	17	26	27	25	10	2
6	Intelligent control systems for building environment	1	0	4	11	13	2
7	Migration and transformation mechanisms of microplastics in wastewater treatment	0	0	0	2	2	3
8	Fusion and processing of multilevel space-air-ground remote-sensing data	25	21	21	32	32	10
9	Dynamic fusion of geographical spatiotemporal big data for smart cities	1	1	6	18	15	11
10	Lifecycle safety of water-related engineering	10	9	18	6	6	0

this research front include the evolution of structural performance under environmental actions, quantification of the time-dependent reliability index, and reliability of structural systems. Evolution of structural performance has a direct impact on quantification of the reliability index, and introduction of related random variables into the deterministic models of resistance degradation has been widely accepted. The time-dependent reliability index at a component level can be calculated through use of such approaches as the first-passage method, time-independent reliability index for an equivalent series system, Monte Carlo simulation method, and probability-density-evolution method. That said, reliability analysis of systems remains a challenging task. Between 2012 and 2017, 215 core papers have been published relevant to this research front, and these papers have received 4440 citations with an average of 20.65 citations per paper published.

(2) Ultrahigh-performance and smart cement-based composite materials

Ultrahigh-performance materials refer to composites with superior mechanical properties and durability. Accordingly, smart cement-based composite materials refer to composites with smart functions, such as self-sensing, self-thermal insulation, self-cleaning, and self-damping. With the development of civil engineering structures, the complexity of upgrading structures raises an increasing demand for novel construction materials. Compared with conventional concrete, the ultrahigh-performance concrete (UHPC) demonstrates high compressive strength, excellent toughness, super-high abrasive resistance, antiknock property, and significantly increased durability. The workability and mechanical properties of UHPC have attracted increased research attention in recent years. Owing to the development of carbon-based materials and phase change materials, it is possible to produce smart cement-based composite materials capable of performing intelligent functions, such as self-sensing, self-thermal insulation, and self-cleaning. The use of carbon-based materials, such as carbon nanotubes, graphene, and nano-carbon fiber, improves the mechanical as well as electrical performance of such materials. Upgraded materials can, therefore, ensure safety and reliability of structures and functionalize resulting structures with smart monitoring properties. Between 2012 and 2017, 64 core papers have been published relevant to this research front, and these papers have received 2594 citations in total with an average of 40.53 citations per paper published.

(3) Highway pavement renewable materials and pavement materials rejuvenation

Concepts of circular economy and sustainable development have drawn increased attention in the field of highway paving, and the use of renewable materials in highway-paving applications and their rejuvenation have become hot topics of research in recent years. Renewable materials are those that follow the principle of bionics and perform dual functions of perception and excitation. Active self-sensing, automatic healing, and self-healing are basic features of such materials. Developing innovative renewable materials, revealing appropriate regeneration mechanisms, and establishing design theories for renewable composite materials are important issues concerning the realization of sustainable development of highway-pavement materials. Material rejuvenation refers to the recycling of industrial and civil wastes, such as steel slags, plastic granules, construction wastes, reclaimed pavement materials, and other materials. Relevant research topics include development of new material recycling technologies, physical and chemical properties of rejuvenated materials, and mechanisms for blending of new and old materials. Between 2012 and 2017, 27 core papers have been published relevant to this research front and have received 601 citations in total with an average of 22.26 citations per paper.

(4) Green vernacular architecture

Contemporary green vernacular architecture is based on modern building technologies and materials whilst still featuring regional environmental adaptability and cultural continuity. Over the course of its long-term development, vernacular architecture has developed a clear adaptive relationship with its environment. On one hand, such architecture needs to critically absorb the characteristics of climatic adaptation within conventional construction systems while on the other hand, it must respond to requirements of contemporary life and form a sustainable development system that is benign to circumstances and the social environment. Green vernacular architecture not only focuses on the application of technologies concerning modern environmental control, structural safety, culinary and sanitary facilities, and intelligent communication systems to the existing conventional architectural heritage but also devotes itself to discovering the wisdom and experience of vernacular architecture with respect to environmental coordination, climatic adaptation, cultural heritage, and functional organization. Research endeavors in this field pay special attention to the contribution of local architectural forms, construction of national cultural landscapes within environmental adaption, self-adjustment, and self-improvement. Between 2012 and 2017, 317 core papers have been published relevant to this research front and have received 9213 citations with an average of 29.06 citations per paper published.

(5) AI-based architectural design methodology

The AI-based architectural design methodology considers the architectural design process as its object, artificial intelligence (AI) as its engine, and various virtual reality (VR) technologies as its interface. It brings into full play a combination of the human ability of creating and dealing with uncertainty issues, accurate perception of machines, and high-speed computing ability via intelligent machine systems via real-time interaction. This new concept is superior to conventional ones in three aspects. First, conventional architectural design methodologies are based on monism that sees the architect as the sole subject, whereas the modern approach emphasizes on interaction between human beings and intelligent machines to complete a design, thereby breaking through the monistic mindset of the theoretical framework. Second, the field of AI—with breakthroughs based on the deep neural network technology as its highlight—can recognize and analyze images with accuracies that far exceed human perception and has already outplayed human beings in various game problems through application of enhanced learning algorithms. All these factors enable machines to possess a certain degree of intelligence. Lastly, the light weight and popularization of VR technology in hardware greatly broadens its applications. Compared with the conventional two-dimensional graphical user interface of the screen, its immersive real-time three-dimensional environment greatly enhances the efficiency of information interaction. Simultaneously, with the development of various real-time scanning and projection technologies, the tangible user interface has become popular, got rid of the perception agent mode of both the screen and virtual environment, directly enabled architects to implement various operations with computable information in real objects, and realized direct interactions between humans and machines. Between 2012 and 2017, 107 core papers have been published relevant to this research front and have received 3704 citations with an average of 34.62 citations per paper published.

(6) Intelligent control systems for building environment

By monitoring the indoor thermal, acoustic, lighting, and air-quality parameters, building intelligent systems (BISs) are primarily used to automatically control and manage mechanical and electrical systems, such as cooling and heating, ventilation, lighting, shading, and façade within residential and corporate buildings, thereby providing, adjusting, and maintaining the desired indoor environment. Presently, major research trends relevant to this front include ① monitoring and transmission of environmental parameters; ② intelligent analysis, identification, and diagnosis of control systems; and ③ intelligent control and optimization of mechanical and electrical systems. BISs are essentially derived and upgraded from building automation systems, which initially play a supplementary role in monitoring and managing the cooling and heating, elevator, water-supply, security, fire-extinguishing, and power-supply and distribution systems within buildings. Following the rapid development of computers and sensors as well as increasing popularization of intelligent terminals (e.g., smartphones, smart wearable devices, and display screens), BIS offers more possibilities and opportunities for providing an appropriate, customizable, and comfortable indoor environment. For example, the subjective perception of an indoor environment by occupants can be first collected via intelligent terminals and subsequently used as input to BIS to integrate personalized preferences with regard to indoor temperature, humidity, airflow, lighting, etc. Between 2012 and 2017, 31 core papers have been published relevant to this research front and have received 1244 citations with an average of 40.13 citations per paper published.

(7) Migration and transformation mechanisms of microplastics in wastewater treatment

Microplastics correspond to plastic particles and textile fibers with tiny particle sizes. These are generally considered plastic particles measuring less than 5 mm in dimension. The primary source of these particles is plastics, which are widely used in daily life, and after being exposed to the natural environment, gradually reduce in size owing to the effect of the wind and sun. Additionally, there exists a large quantity of frosted particles in cosmetics or cleansing products in addition to the large number of fibers contained in the wastewater discharged from household washing machines. These microplastics possess small volumes, large specific surface areas, and a strong ability to adsorb pollutants. They are, therefore, likely to form organically contaminated spheres with persistent organic pollutants, such as hydrophobic polychlorinated biphenyls and bisphenol A. Microplastics cannot be effectively removed in conventional urban wastewater treatment plants because they tend to float on the water surface during treatment. Wandering microplastics can easily be swallowed by such organisms belonging to the lower end of the food chain as mussels and zooplanktons. These plastics, however, cannot be digested, thereby causing disease and mortality in such organisms. If microplastics containing organic contaminants are eaten, the contaminants tend to be released—under the action of enzymes—within the organisms' bodies, thereby exacerbating their damaging impacts. If the said microplastics and organic pollutants enter bodies of organisms belonging to the upper part of the food chain, the "enrichment" effect of the food chain can cause widespread mortality of a larger organism community. Researches concerning mechanisms of migration and transformation of microplastics relevant to sewage treatment focus on determination of ① the composition of microplastics present within sewage via use of various approaches—observations, experiments, theoretical models, and numerical simulations; and ② migration pathways, conversion products, transformation, and distribution of microplastics and other pollutants within sewage-treatment systems using various techniques. The said researches target elimination of microplastics, persistent organic pollutants, heavy metals, endocrine disruptors, emerging pollutants, etc. Between 2012 and 2017, 7 core papers have been published relevant to this research front and have received 243 citations with an average of 34.71 citations per paper published.

(8) Fusion and processing of multilevel space-air-ground remote-sensing data

Fusion and processing of multilevel space-air-ground remote-sensing data refers to a deep fusion of remote-sensing big data, including multisource and multilevel aerospace and ground remote-sensing data, to analyze image features and discover inherent regularities between multisource data based on physical characteristics of ground objects. Using the hybrid multi-level fusion technology, desired information can be extracted by combining the pixel, feature, and decision-making layers and integrating professionally constructed models. Major issues encountered in this research front include ① high-precision preprocessing of multisource remote-sensing data, including radiometric calibration, geometric correction, atmospheric correction, and co-accurate correction of multisource heterogeneous data; ② spatial fusion of multisource remote-sensing data, major methods of which include combined block adjustment and image registration; the former method converts a spatial fusion problem into a joint block-adjustment problem involving multisource remote-sensing data from the perspective of photogrammetry, whereas the latter converts a spatial fusion problem into an image registration problem from the perspective of image processing and computer vision; and ③ the informational fusion of spatially fused multisource remote-sensing data to extract new and meaningful information. The process of informational fusion can, in general, be divided into three levels—pixel level, feature level, and decision level. Development trends in this research front include ① support of combined block adjustment of multisource data to enable automatic search and joint adjustment of corresponding points among various sources, phases, and resolutions; ② in-depth informational fusion based on multilayer blending; and ③ information extraction based on deep learning and neural networks. Between 2012 and 2017, 141 core papers have been published relevant to this research front and have received 7023 citations with an average of 49.81 citations per paper.

(9) Dynamic fusion of geographical spatiotemporal big data for smart cities

With the construction of smart cities, numerous widespread sensors generate PB, EB, or even ZB levels of urban geographical spatiotemporal datasets. Dynamic fusion of geographical spatiotemporal big data of a smart city aims at automatically discovering and extracting implicit and non-obvious patterns, rules, and knowledge from real-time, multiplatform, multitemporal, multisensor, multitype, high-resolution, hyper-spectral, and massive multisource geographical spatiotemporal big data followed by a quick transformation of geographical spatiotemporal big data to valuable information via efficient, intelligent, and dynamic processing. The proposed fusion process, is believed, would greatly improve the spatial cognition ability of smart cities. Major issues concerning this research front include basic theories and methods for representation, measurement, and understanding of geographical spatiotemporal big data of smart cities along with revelation of relationships between spatiotemporal big data and real objects, behaviors, and events. Worldwide research endeavors being undertaken relevant to this topic have resulted in multidisciplinary studies being performed for collecting geospatial and temporal data of physical objects and human activities within smart cities via various methods and integrated approaches, information extraction, network management, knowledge mining, spatial knowledge perception, and provision of intelligent location services. Between 2012 and 2017, 52 core papers have been published relevant to this research front and have received 1244 citations with an average of 23.92 citations per paper.

(10) Lifecycle safety of water-related engineering

Water-related engineering is a key component of infrastructure systems and plays an irreplaceable role in ensuring water safety as well as social and economic development. In recent years, water-related construction activities have expanded from inland regions into the deep sea, and higher safety requirements are being specified to be met during deep-sea construction and operation with the working environment becoming more complex and diverse within deep water. Lifecycle safety of water-related engineering is a concept raised in view of security threats and changes in surrounding environments encountered during all stages of a structure's service life. Major research endeavors in this regard are concerned with ① development of anti-vibration, anti-corrosion, and anti-seismic technologies for water-related engineering structures; ② nondestructive detection, damage identification, and rapid repair technologies for underwater structures; ③ diagnostic evaluation of safety of water-related structures; and ④ optimization of lifecycle safety design of water projects. Compared to hydraulic structures, port structures, and offshore engineering, deep-sea engineering operations are confronted with more complex environmental factors, including both normal (e.g., wind, wave, current, and salinity) and extreme factors (e.g., typhoons and earthquakes). In order to ensure the safety of deep-sea engineering operations, the combined action of various environmental factors must be taken into consideration. Response and failure mechanisms of deep-sea engineering structures under complex environments could be analyzed via experiments as well as numerical simulations, on the basis of which lifecycle performance monitoring and damage repair systems could be established. This would ultimately lead to satisfaction of lifecycle safety assessment and design criteria concerning deep-sea operations. Consequently, researches concerning catastrophic mechanisms, intelligent monitoring, and automatic repair technologies under complex conditions, lifecycle safety evaluations, and optimization design of the structural system will remain the major focus in this research front. Between 2012 and 2017, 49 core papers have been published relevant to this research front and have received 913 citations with an average of 18.63 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Lifecycle reliability of civil engineering structures and systems

Owing to rapid industrialization, large-scale infrastructure constructions have been undertaken in many countries since the middle of the twentieth century. Meanwhile, the durability and service life of civil-engineering structures have become topics of concern for the entire society. Certain structures tend to degrade prematurely owing to insufficient knowledge concerning the evolution of structural performance. Structural engineers have, over the years, realized the significance of the service life of structures and proposed a series of design methods, including the allowable stress, ultimate strength, and limit state design methods, all relating to the service life of structures. Presently, the limit-state design method, based on the probability theory, has been examined and adopted in several engineering practices. This approach, however, considers a structure to demonstrate a state of construction completion with loads varying over the target service life whilst ignoring performance degradation of the structure itself over a period of time.

In an attempt to determine more appropriate approaches, researchers proposed stochastic-process-based reliability-analysis methods by introducing time-dependent probabilistic models for degradation resistance of structures. However, there continues to exist the lack of an in-depth understanding of performance evolution of various structures subjected to environmental and mechanical loads. This is because the available models often provide results largely deviating from observations in actual scenarios. Based on the different resistance degradation models, time-dependent reliability-analysis techniques have been proposed, such as the first-passage method, time-dependent reliability of an equivalent series system, and Monte Carlo simulation. The first two methods are either inapplicable to time-dependent reliability-index calculation or limited to specific stochastic physical systems. The Monte Carlo simulation method is relatively time-consuming, although it has been widely employed with high accuracy without being limited to stochastic physical systems and limit state equations.

Currently, major topics of research concerning the lifecycle reliability of civil engineering structures and systems include

(1) Improved methods for time-dependent reliability analysis. Examples under this topic include the Poisson-process-based analytical and Monte-Carlo-simulation-based stochastic methods, both of which have been proposed to reduce the high computational cost associated with the direct simulation method and resolve the difficulty in sampling events with a small probability. Additionally, the probability density evolution method—based on the principle of probability conservation—has been extended to applications involving time-dependent reliability analysis.

(2) Improved time-dependent state functions of structures and systems. Related studies include a) assessment of the reliability of reinforced concrete (RC) structures considering time-dependent corrosion rate of steel bars and spatially varying distribution of corrosion current density and corrosion morphology; and b) establishment of equivalent extreme events and performing associated reliability analysis considering complex structural failure modes.

(3) Design and maintenance of structures and systems based on time-dependent reliability.

As listed in Table 1.1.1, 215 core papers have been published between 2012 and 2017 concerning "lifecycle reliability of civil engineering structures and systems," and each paper has been cited an average of 20.65 times. The top 3 nations in terms of core-paper output in this regard are China, USA, and Italy (Table 1.2.1). China is one of the most active players in this topic, publishing 33.49% of core papers and ranking first in terms of quantity. In terms of core-paper citation, papers published by the Chinese have each been cited 21.15 times on average, slightly exceeding the corresponding global average number. This indicates that researchers from China are gradually gaining more attention. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation has been observed among the most productive top 10 countries/regions except Czech Republic.

As listed in Table 1.2.2, the top 3 institutions publishing the most number of core papers are Hunan University (China), Dalian University of Technology (China), and Tongji University (China). As illustrated in Figure 1.2.2, collaborative studies are rare among the top 10 most productive institutions in this regard.

As listed in Table 1.2.3, the top 3 most productive countries/regions (i.e., China, USA, and Italy) are also the most active ones in terms of the most number of citing papers between 2012 and 2017. Note that approximately 40% citations of core papers are contributed by China, thereby indicating that Chinese researchers pay increased attention to researches performed concerning this front. As presented in Table 1.2.4, the top 3 institutions citing the most number of core papers are Hunan University (China), Tongji University (China), and Lehigh University (USA).

Summarizing the above statistical data, it can be stated that China is, at present, the leading player in terms of research trends concerning "lifecycle reliability of civil engineering structures and systems." As such, continuous support at the national and provincial levels is important for sustaining dedicated studies to maintain China's leading position concerning this topic.

Table 1.2.1 Countries or regions with the greatest output of core papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	72	33.49%	1 523	34.30%	21.15
2	USA	40	18.60%	911	20.52%	22.78
3	Italy	24	11.16%	528	11.89%	22.00
4	Australia	19	8.84%	396	8.92%	20.84
5	UK	18	8.37%	421	9.48%	23.39
6	Iran	18	8.37%	303	6.82%	16.83
7	Czech Republic	12	5.58%	124	2.79%	10.33
8	Singapore	11	5.12%	254	5.72%	23.09
9	France	9	4.19%	279	6.28%	31.00
10	Germany	9	4.19%	151	3.40%	16.78

Table 1.2.2 Institutions with the greatest output of core papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Hunan Univ	13	6.05%	342	7.70%	26.31
2	Dalian Univ Technol	12	5.58%	207	4.66%	17.25
3	Tongji Univ	10	4.65%	240	5.41%	24.00
4	Lehigh Univ	9	4.19%	256	5.77%	28.44
5	Univ Sydney	8	3.72%	199	4.48%	24.88
6	Univ Zabol	8	3.72%	118	2.66%	14.75
7	Natl Univ Singapore	6	2.79%	183	4.12%	30.50
8	Tech Univ Munich	6	2.79%	103	2.32%	17.17
9	VSB Tech Univ Ostrava	6	2.79%	48	1.08%	8.00
10	Politecn Milan	5	2.33%	149	3.36%	29.80

Figure 1.2.1 Collaborative network among major countries or regions in the engineering research front of "lifecycle reliability of civil engineering structures and systems"

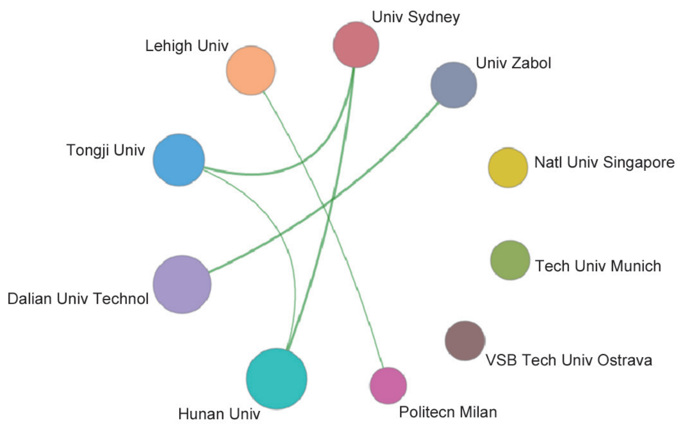

Figure 1.2.2 Collaborative network among institutions in the engineering research front of "lifecycle reliability of civil engineering structures and systems"

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1 191	38.72%	2016.48
2	USA	645	20.97%	2016.00
3	Italy	241	7.83%	2015.86
4	UK	216	7.02%	2016.23
5	Australia	182	5.92%	2016.42
6	Iran	167	5.43%	2016.54
7	Germany	132	4.29%	2016.47
8	India	112	3.64%	2016.23
9	Singapore	96	3.12%	2016.07
10	France	94	3.06%	2016.30

Table 1.2.4 Institutions with the greatest output of citing papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hunan Univ	150	18.82%	2016.40
2	Tongji Univ	131	16.44%	2016.37
3	Lehigh Univ	90	11.29%	2015.42
4	Dalian Univ Technol	76	9.54%	2016.50
5	Politecn Milan	66	8.28%	2016.02
6	Beihang Univ	65	8.16%	2016.74
7	Huazhong Univ Sci & Technol	57	7.15%	2016.60
8	Univ Sydney	55	6.90%	2016.33
9	Wuhan Univ	54	6.78%	2015.70
10	Northwestern Polytech Univ	53	6.65%	2016.43

1.2.2 Ultrahigh-performance and smart cement-based composite materials

With the advancement in social economy, structural design theory, and construction technology, engineering structures have grown higher, longer, and deeper in recent years. To enable construction of complicated engineering structures, there exists an increasing demand for development of non-conventional construction materials, such as ultrahigh-performance composite (UHPC) materials with superior mechanical properties, toughness, abrasive resistance, antiknock property, and durability. Meanwhile, there also exists a need for structures capable of performing delicate and intelligent functions to meet the objective of realizing reliable and safe living and traffic conditions. The smart cement-based composite material is one such material capable of demonstrating the said intelligent functions. It has great potential for use in the monitoring stress, strain, and temperature within important structural components. It could serve as a useful nondestructive tool to estimate structural damage as well as to achieve timely recovery of such damages. Moreover, this smart material can also be specially functionalized to relieve impacts from typhoons and earthquakes as well as manipulate temperature, humidity, and energy consumption within indoor environments. As a highly technical material, the use of smart cement-based composite has opened new avenues with regard to future development of conventional construction materials as well as new research opportunities. Further studies concerning basic theories and applications are required to realize breakthrough development concerning novel structural materials, which in turn, would help researchers create a huge market with great social and economic benefits.

Major research topics concerning ultrahigh-performance and smart cement-based composite materials include the following.

(1) Preparation technology and performance control of UHPC. This topic mainly covers two aspects, the first of which concerns determination of UHPC characteristics whilst focusing on the rheology and pumping ability of UHPC and aims at its successful applications in complex high, long, and deep structures. The second aspect relates to investigations concerning macroscopic mechanical properties and durability of UHPC as well as the relationship between UHPC microstructures and said macroscopic properties.

(2) Engineering applications of UHPC. In addition to ensuring its own performance requirements, UHPC applications in engineering structures require a comprehensive study concerning mechanical properties of various structural members made of this material. Such studies are potentially useful in the establishment of mature reliability design calculation methodologies. There, however, exist many challenges with regard to extensive applications of this material to engineering structures, such as buildings, bridges, roadbeds, and dams.

(3) Intelligent monitoring characteristics of smart cement-based composite materials. An important area of research concerning smart cement-based composite materials is to functionalize conventional cement-based materials with self-monitoring and self-diagnosis abilities. More attention is paid to the self-monitoring ability of structures with regard to stress, deformation, and temperature monitoring. Against a background of rapid development of carbon-based materials, such as carbon fiber, carbon nanotubes, and graphene, improving the sensitivity, stability, application range, and durability of smart cement-based materials holds great potential.

(4) Intelligent adjustment characteristics of smart cement-based composite materials. Another intelligent direction of smart cement-based composites is self-regulation and self-healing abilities. These materials adapt to changes in the service environment as well as their own structures, such as self-adjustment to temperature and humidity, self-control of shape and damping, and self-healing of microcracks. Researches performed in this direction have a broad future market.

As listed in Table 1.1.1, 64 core papers have been published between 2012 and 2017 concerning “ultrahigh-performance and smart cement-based composite materials,” and each paper has been cited 40.53 times on average. The top 3 countries in terms of core paper output are the USA, South Korea, and China (Table 1.2.5). China is one of the most active players in this context, producing 17.19% of the core papers. In terms of core-paper citations, papers published by China have each been cited 42.45 times on average, slightly exceeding the global average number. This indicates that researchers from China are gradually gaining increased attention. As illustrated by the international collaborative network depicted in

Figure 1.2.3, a relatively close cooperation is noted among China, USA, and UK.

As listed in Table 1.2.6, the top 3 institutions publishing the most number of core papers are Korea University (South Korea), the University of Michigan (USA), and the University of Connecticut (USA). As illustrated in Figure 1.2.4, domestic cross-organization collaborations are frequent in USA and South Korea, whereas crossover collaborations between different countries are rare.

As listed in Table 1.2.7, the top 5 countries/regions citing the most core papers are China, USA, South Korea, Australia, and Italy. Note that 31.45% citations of core papers have been contributed by China, indicating that Chinese researchers pay close attention to researches performed in this regard. As presented in Table 1.2.8, the top 3 institutions citing the most core papers are Korea University (South Korea), Harbin Institute of Technology (China), and Hanyang University (South Korea).

Summarizing the above statistical data, China is currently among leading players with regard to research endeavors concerning "ultrahigh-performance and smart cement-based composite materials." Enhanced support at national and provincial levels is, therefore, significant in promoting China's contribution towards creating greater awareness concerning the topic.

Table 1.2.5 Countries or regions with the greatest output of core papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	18	28.13%	721	27.79%	40.06
2	South Korea	13	20.31%	552	21.28%	42.46
3	China	11	17.19%	467	18.00%	42.45
4	UK	6	9.83%	225	8.67%	37.50
5	Netherlands	4	6.25%	215	8.29%	53.75
6	Italy	4	6.25%	174	6.71%	43.50
7	France	4	6.25%	119	4.59%	29.75
8	Canada	4	6.25%	106	4.09%	26.50
9	Malaysia	3	4.69%	89	3.43%	29.67
10	India	1	1.56%	102	3.93%	102.00

Table 1.2.6 Institutions with the greatest output of core papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Proportion of citations	Citations per paper
1	Korea Univ	8	12.50%	299	11.53%	37.38
2	Univ Michigan	7	10.94%	297	11.45%	42.43
3	Univ Connecticut	6	9.38%	271	10.45%	45.17
4	Korea Inst Construct Technol	4	6.25%	233	8.98%	58.25
5	Eindhoven Univ Technol	4	6.25%	215	8.29%	53.75
6	Univ Liverpool	4	6.25%	150	5.78%	37.50
7	Daegu Univ	4	6.25%	126	4.86%	31.50
8	Sejong Univ	3	4.69%	185	7.13%	61.67
9	Univ Perugia	3	4.69%	140	5.40%	46.67
10	Univ Suwon	3	4.69%	108	4.16%	36.00

Figure 1.2.3 Collaborative network among major countries or regions in the engineering research front of "ultrahigh-performance and smart cement-based composite materials"

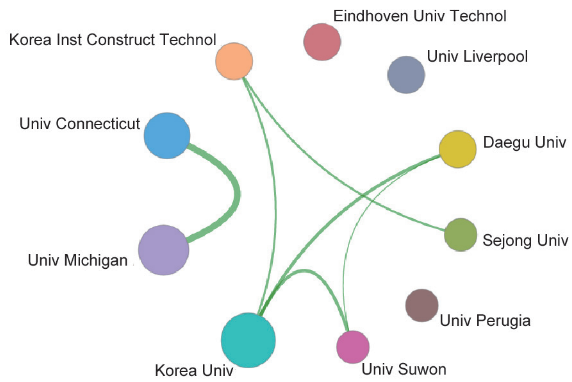

Figure 1.2.4 Collaborative network among major institutions in the engineering research front of "ultrahigh-performance and smart cement-based composite materials"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	452	31.45%	2016.52
2	USA	310	21.57%	2016.34
3	South Korea	142	9.88%	2016.15
4	Australia	107	7.45%	2016.64
5	Italy	96	6.68%	2016.51
6	Canada	73	5.08%	2016.49
7	India	72	5.01%	2016.28
8	UK	66	4.59%	2016.23
9	Iran	60	4.18%	2016.45
10	Malaysia	59	4.11%	2016.41

Table 1.2.8 Institutions with the greatest output of citing papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Korea Univ	51	13.67%	2015.59
2	Harbin Inst Technol	41	10.99%	2016.61
3	Hanyang Univ	40	10.72%	2016.85
4	Southeast Univ	39	10.46%	2016.33
5	Dalian Univ Technol	37	9.92%	2016.57
6	Hunan Univ	35	9.38%	2016.51
7	Univ British Columbia	33	8.85%	2016.27
8	Northwestern Univ	33	8.85%	2015.88
9	Iowa State Univ	32	8.58%	2016.31
10	Missouri Univ Sci & Technol	32	8.58%	2016.91

1.2.3 Highway pavement renewable materials and pavement materials rejuvenation

Concepts of circular economy and sustainable development have drawn increased attention in the field of highway paving. Renewable materials in highway-paving applications and pavement materials rejuvenation have become hot topics of research in recent years. Renewable materials are those that follow the principle of bionics and perform dual functions of perception and excitation. Active self-sensing, automatic healing, and self-healing are basic features of such materials. Developing innovative renewable materials, revealing appropriate regeneration mechanisms, and establishing design theories for renewable composite materials are important issues concerning the realization of sustainable development of highway-pavement materials. Material rejuvenation refers to the recycling of industrial and civil wastes, such as steel slags, plastic granules, construction wastes, reclaimed pavement materials, and other materials. Relevant research topics include development of new material recycling technologies, physical and chemical properties of rejuvenated materials, and mechanisms for blending of new and old materials.

Researches concerning use of recycled materials for pavements mainly focus on the application of self-healing materials. Currently available self-healing materials can repair millimeter-scale cracks, but self-repair of wide and deep cracks requires theoretical innovations and development of related technologies. Some smart materials, such as self-aware materials and shape memory polymers, have been successfully employed in aerospace and other niche applications. Although these materials have found applications in the highway-pavement industry within Europe and USA, the overall technology is still in its infancy. Researches concerning material regeneration primarily focus on sustainable utilization of solid wastes in highway pavement engineering, but the blending mechanism of the regeneration process is unclear, thereby resulting in degrading road performance. It is, therefore, necessary to further investigate scientific issues concerning renewable materials and materials rejuvenation.

Sustainable development of global transportation infrastructure promotes research endeavors concerning highway pavement whilst focusing on both renewable materials and materials rejuvenation. Owing to the self-repairing and shape-memory functions of new recycled materials, realization of effective improvement in pavement performance, prolonged pavement life, reduction in pavement maintenance costs can now be made possible. Material regeneration can effectively alleviate problems concerning global resource shortage and environmental pollution. Researches concerning highway pavement through use of renewable materials and their regeneration are, therefore, conducive to the improvement of technology and the economy as well as environmental protection, which is in accordance with the objective of sustainable development.

Major areas of the research concerning “highway pavement renewable materials and pavement materials rejuvenation” include the following.

(1) Revelation of physicochemical properties, intelligent perception, and self-repair mechanism of renewable materials; development of new renewable highway pavement materials; establishment of synergistic models of composite renewable materials; analysis of the synergistic mechanism between regenerated and original materials; development of intelligent and adaptive renewable materials; and performance optimization of renewable materials under multi-physics coupling conditions.

(2) Revelation of long-term cooperative working mechanism of various components of material regeneration, such as the synergy between new and old asphalt mixtures, synergy between external components and original materials, and synergistic effect of various components of new cement-based materials; establishment of industrial and civil waste materials gene database; exploration of advantages and defects of waste materials; and application of material calculation design theory to facilitate realization of green, refined, and efficient material regeneration processes.

As listed in Table 1.1.1, 27 core papers were published between 2012 and 2017 concerning "highway pavement renewable materials and pavement materials rejuvenation", and each paper was cited 22.26 times on average. The top 5 countries in terms of core-paper publishing are Spain, Australia, USA, Italy, and Portugal (Table 1.2.9). The top 5 countries/regions receiving the highest citations are Sweden, USA, Canada, Spain, and Switzerland. International collaboration is not very common among the most productive countries/regions with regard to this research front, as illustrated in Figure 1.2.5.

As listed in Table 1.2.10, the University of Córdoba (Spain) has published the most number of core papers. As illustrated in Figure 1.2.6, collaborative studies are rare among the top 10 most productive institutions.

As indicated in Table 1.2.11, the top 5 countries/regions citing the most number of core papers include China, USA, Spain, Australia, and UK. It can, therefore, be inferred that Chinese researchers pay keen attention to researches performed in this field. As presented in Table 1.2.12, the top 3 institutions citing the most number of core papers are the Swinburne University of Technology (Australia), University of Córdoba (Spain), and University of Nottingham (UK).

Summarizing the above statistical data, it can be said that China is catching up and paying keen attention to researches concerning "highway pavement renewable materials and pavement material rejuvenation," and that enhanced support at the national and provincial levels is important for promoting China's contribution to this topic.

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

Top 10 engineering development fronts in the field of civil,

Table 1.2.9 Countries or regions with the greatest output of core papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Spain	9	33.33%	222	36.94%	24.67
2	Australia	5	18.52%	82	13.64%	16.40
3	USA	3	11.11%	88	14.64%	29.33
4	Italy	3	11.11%	64	10.65%	21.33
5	Portugal	3	11.11%	51	8.49%	17.00
6	Canada	2	7.41%	52	8.65%	26.00
7	Switzerland	2	7.41%	47	7.82%	23.50
8	UK	2	7.41%	45	7.49%	22.50
9	France	2	7.41%	34	5.66%	17.00
10	Sweden	1	3.70%	31	5.16%	31.00

Table 1.2.10 Institutions with the greatest output of core papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Córdoba	6	22.22%	156	25.96%	26.00
2	Univ Granada	3	11.11%	57	9.48%	19.00
3	Univ Palermo	2	7.41%	46	7.65%	23.00
4	Univ Beira Interior	2	7.41%	35	5.82%	17.50
5	Swinburne Univ Technol	2	7.41%	34	5.66%	17.00
6	Paradox Access Solut Inc	1	3.70%	35	5.82%	35.00
7	Univ Kansas	1	3.70%	35	5.82%	35.00
8	Empa	1	3.70%	33	5.49%	33.00
9	KTH Royal Inst Technol	1	3.70%	31	5.16%	31.00
10	Univ Nottingham	1	3.70%	30	4.99%	30.00

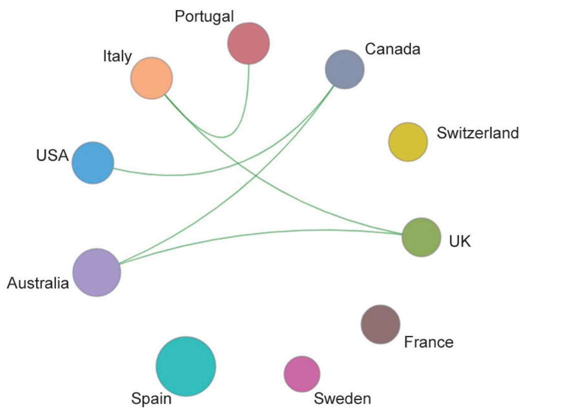

Figure 1.2.5 Collaborative network among major countries or regions in the engineering research front of "highway pavement renewable materials and pavement materials rejuvenation"

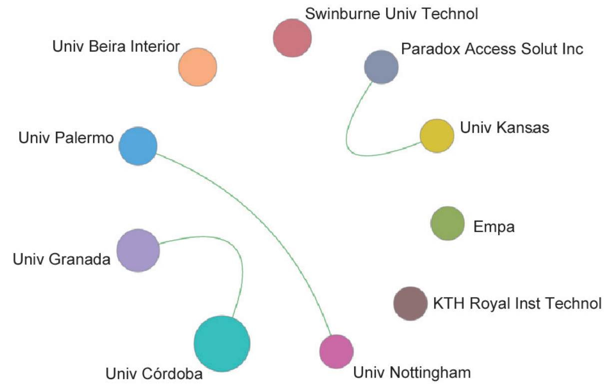

Figure 1.2.6 Collaborative network among major institutions in the engineering research front of "highway pavement renewable materials and pavement materials rejuvenation"

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	151	18.48%	2016.83
2	USA	146	17.87%	2016.44
3	Spain	123	15.06%	2016.22
4	Australia	88	10.77%	2016.47
5	UK	74	9.06%	2016.24
6	Italy	64	7.83%	2016.52
7	India	49	6.00%	2016.80
8	Portugal	47	5.75%	2016.15
9	France	39	4.77%	2016.08
10	Thailand	36	4.41%	2016.36

Table 1.2.12 Institutions with the greatest output of citing papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Swinburne Univ Technol	37	16.30%	2015.86
2	Univ Córdoba	34	14.98%	2015.18
3	Univ Nottingham	30	13.22%	2015.93
4	Suranaree Univ Technol	29	12.78%	2016.00
5	Tongji Univ	20	8.81%	2016.65
6	Southeast Univ	19	8.37%	2016.89
7	KN Toosi Univ Technol	16	7.05%	2015.56
8	Univ Politecn Valencia	16	7.05%	2016.81
9	Univ Melbourne	13	5.73%	2016.77
10	Chang'an Univ	13	5.73%	2016.62

hydraulic & architecture engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including structural engineering, urban and rural planning and landscape, roads and railway engineering, geotechnical and underground engineering, bridge engineering, construction materials, municipal engineering, hydraulic engineering, and surveying and mapping engineering. Among these development fronts, "intelligent construction and 3D printing technology," "green planning and building technology" and "collaborative development and utilization of urban underground space" are emerging fronts, whereas other fronts have been extended from conventional subjects. Table 2.1.2 presents annual statistical data of core patents published between 2012 and 2017 concerning the top 10 development fronts.

(1) Intelligent construction and 3D printing technology

Intelligent construction refers to use of a cyber-physical system (CPS) with advanced construction technologies deeply integrated with information technology. Developed from industrial construction and digital construction systems, intelligent construction comprises a combination

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

No.	Engineering development fronts	Published patents	Citations	Citations per patent	Mean year
1	Intelligent construction and 3D printing technology	65	951	14.63	2014.45
2	Green planning and building technology	49	245	5.00	2015.41
3	Key technological systems in intelligent transportation	85	1 022	12.02	2013.44
4	Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels	14	34	2.43	2014.50
5	Collaborative development and utilization of urban underground space	135	49	0.36	2016.61
6	Novel deepwater foundation and wind resistance of cable-supported bridges	179	240	1.34	2015.09
7	Eco-friendly building materials	254	380	1.50	2015.28
8	Advanced treatment of urban water	153	1 757	11.48	2013.67
9	Regulation technology for urban storm-water	67	542	8.09	2014.28
10	High-precision positioning navigation and spatiotemporal big data	570	20 781	36.46	2013.42

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

No.	Engineering development fronts	2012	2013	2014	2016	2016	2017
1	Intelligent construction and 3D printing technology	9	7	15	17	14	3
2	Green planning and building technology	4	3	3	11	15	13
3	Key technological systems in intelligent transportation	22	31	16	8	5	3
4	Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels	4	1	2	1	3	3
5	Collaborative development and utilization of urban underground space	0	3	0	3	34	95
6	Novel deepwater foundation and wind resistance of cable-supported bridge	21	10	32	36	28	52
7	Eco-friendly building materials	22	20	39	43	44	86
8	Advanced treatment of urban water	39	29	43	30	9	3
9	Regulation technology for urban storm-water	9	12	10	25	9	2
10	High-precision positioning navigation and spatiotemporal big data	205	127	112	57	57	12

of physical and cyber systems. The physical system includes members, components, and systems of buildings and infrastructure, whereas a twin model is established within the cyber system. During the entire lifecycle of the physical system (including project approval, design, manufacture, transportation, assembling, maintenance, and service), intelligent construction performs information perception and analysis, data mining and modeling, state assessment and prediction, and intelligent optimization as well as decision making of the physical system using the twin model embedded within the cyber system. Via that process, knowledge reasoning, intelligent sensing and precision control, and execution of the construction target and corresponding construction process, construction facilities and construction systems can be realized. An intelligent construction system can be composed of three subsystems—design and planning, equipment and construction, and maintenance and service—and involves advanced technologies, such as AI, 3D printing, digital construction, robotics, big data, Internet of things, and cloud computing. With increased industrialization of the construction activity, productivity of the construction industry has become increasingly dependent on inter-disciplinary research, and new disciplines, such as intelligent construction, have been further established. An intelligent construction system can only be realized by performing in-depth interdisciplinary investigations concerning architecture, civil engineering, computer science, machinery, telecommunications, materials, management, and other disciplines. Meanwhile, corresponding research endeavors result in greater requirements of joint ventures in terms of innovation mechanism and capability between universities and enterprises. Between 2012 and 2017, 65 patents on this topic have been published with 951 patent citations and an average of 14.63 citations per patent.

(2) Green planning and building technology

Green planning and building technology has received great attention in recent years owing to increasing recognition of the significance of protecting the Earth's limited resources in the process of urban and rural development. A common consensus has been arrived at in the sense that "we only have one Earth," and the planning and building strategy for realizing sustainable development of the human society and community is a demanding need. Major research directions concerning green planning and building technology include not only green ecology and open-space planning but also lifecycle urban planning, management, development, and building construction. Under the premise of ensuring functional requirements, the following points have been advocated: ① conservation of resources and energy; ② improvement in efficiency of energy resource utilization; ③ effective extraction and use of renewable energy; and ④ utilization of methods integrating data analysis, parametric design, and AI. Specific applications include sponge city construction (low-impact development, water-sensitive cities), adaptive climate planning, and construction involving sunshine, daylighting, ventilation, and thermal-comfort regulation. Current research scales considered in researches concerning this front include individual buildings, local parts of cities, or entire urban or rural areas. Between 2012 and 2017, 49 patents concerning this topic have been published with 245 citations and an average of 5 citations per patent.

(3) Key technological systems in intelligent transportation

Based on advanced technologies and new theories, such as information technology, communication technology, control technology, intelligent technology, and system technology, intelligent transportation systems (ITSs) discover and solve traffic problems with regard to different factors, including humans, vehicles, roads, and the environment, thereby aiming at an efficient, safe, ecological, and intelligent yet comprehensive transportation system. The development of ITSs in different countries differs in terms of emphasis; the main contents, however, remain roughly the same, including such intelligent systems as traffic information, traffic management, public transportation, traffic control, commercial vehicle management, electronic toll collection, security assurance, and emergency management and rescue. With the advent of new technologies, ITS development has been rejuvenated; cross-border integration and innovation have led to creation of new development patterns and service contents, which in turn, has promoted the update of technology as well as development patterns of ITS. At present, ITS technical innovations mainly concentrate on aspects, such as accurate perception and interaction of traffic status, intelligent and cooperative management and service of comprehensive transportation systems, scheduling and service of sharing transportation, transportation vehicle intellectualization and intelligent eco-driving, and cooperative vehicle–infrastructure systems and active traffic-safety assurance. Between 2012 and 2017, 85 patents concerning this topic have been published with 1022 citations and an average of 12.02 citations per patent.

(4) Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels

Ultra-long and ultra-deep tunnels generally refer to those with lengths exceeding 10 km, depths exceeding 500 m (mountain tunnels), or water pressures exceeding 0.5 MPa (underwater tunnels). With the development of tunnel construction technology and equipment, tunnels with lengths exceeding 50 km and water pressures of more than 1 MPa have appeared when crossing mountains, rivers, and lakes. Because of the considerable length and buried depth, great technical challenges are encountered during construction of ultra-long and ultra-deep tunnels. Major technical issues faced relate to ① geological and hydrogeological refinement and detection technologies and equipment used in construction of ultra-deep buried tunnels; ② load- and structural-design methods of ultra-deep buried tunnels; ③ use of intelligent materials and structural forms for ultra-long, ultra-deep buried tunnels; ④ use of modern construction technologies and equipment for tunnels with high stresses, ground temperatures, and water pressures; ⑤ use of construction technologies and equipment for constructing tunnels with super-high operating pressures in water and soil as well as those spanning ultra-long distances; ⑥ use of intelligent and high-performance construction equipment with small disturbances adapted to complex environments; ⑦ use of modern waterproofing and water-controlled technologies and equipment during operation and maintenance of ultra-deep tunnels; ⑧ use of intelligent sensing and maintenance technologies to ensure safety and efficient service performance of ultra-long tunnels; ⑨ operational security of ultra-long, ultra-deep buried tunnels along with development of intelligent disaster prevention and rescue technologies; and ⑩ dynamic risk management and monitoring of the entire process of ultra-deep-tunnel construction. Between 2012 and 2017, 14 patents on this topic have been published with 34 citations and an average of 2.43 citations per patent.

(5) Collaborative development and utilization of urban underground space

Collaborative development and utilization of urban underground space is based on overall urban planning along with relevant laws and regulations. This concept aims at conducting planning, layout, development, and utilization of the urban underground space in an integrated manner to meet the requirements of different functions, scales, and properties; establish a resource-sharing development and utilization model for underground spaces; develop a collaborative technology for urban underground spaces with different functions; and ultimately achieve sustainable development of the underground space. Technical directions in this regard include suitability evaluation of urban underground spaces; mutual adaptation of underground spaces with different functions, scales, and properties via collaborative development and utilization; creation of development and utilization models for different functions and forms of underground spaces, rational structures, and co-construction technologies concerning collaborative development of the urban underground space; collaboratively developing models and methods for operation and maintenance management of underground spaces; and multifunctional collaborative development and utilization, safety management, and disaster control of underground spaces. Rapid expansion of cities and strict regulations to protect cultivable lands would lead to insufficient land availability for construction of cities in the near future. Collaborative development and utilization of urban underground spaces can switch the development pattern of underground spaces from the single-function isolated type to multifunctional, diversified, and shared development. Under conditions of urban land shortage, collaborative development and utilization techniques could be employed to achieve an overall orderly development and utilization of the urban underground space, thereby enhancing its sustainable development. Between 2012 and 2017, 135 patents have been published on this topic with 49 citations and an average of 0.36 citations per patent.

(6) Novel deepwater foundation and wind resistance of cable-supported bridges

Deepwater foundations and long-span cable-supported bridges are usually adopted in construction of bridges across deep bays. The structural form of deepwater foundations and the wind-resistance measures of cable-supported bridges are key factors in controlling the long-term performance evolution of structures. Major technical challenges concerning this research front include time-varying mechanical behavior analysis and control of deepwater foundations, deterioration analysis and control of the long-term bearing capacity of deepwater foundations under wave and current actions, analysis and control of scouring characteristics of deepwater foundations, wind characteristics and simulation of the near-surface boundary layer, identification of aerodynamic admittance of bridge structure components, refined analysis and control of flutter and buffeting of bridges, and turbulent vortex analysis and structural effects. Correspondingly, key technical issues relevant to this field of study include the scouring mechanism and method of protection of gravel cushion caisson foundations, analysis and optimization of nonlinear vibration characteristics of composite foundations with piles and caissons, observation and optimization of long-term bearing and settlement behavior of suction foundations, spatial distribution of wind fields and non-stationary buffeting analysis under typhoon-prone climatic conditions, theoretical method for active flutter control and its verification under different inflows, process simulation of wind-induced vibration, and aerodynamic limit of long-span bridges. Between 2012 and 2017, 179 patents have been published on this topic with 240 citations and an average of 1.34 citations per patent.

(7) Eco-friendly building materials

Eco-friendly building materials refer to green civil engineering materials produced considering energy saving and environmental protection via material performance optimization and comprehensive utilization of wastes. Urban construction and industrial processes produce a large quantity of wastes, and consequently, the contradiction between environmental protection and urban development has become increasingly severe. Recycling of wastes is an effective material circulation solution. Large amounts of construction wastes, such as waste concrete and abandoned blocks, generated during urban construction practices can be utilized to produce renewable aggregates, which in turn, could be used as substitutes for ordinary or high-performance or even ultrahigh-performance concrete through use of certain preparation processes. Industrial wastes, such as steel slag, nickel slag, fly ash, and waste gypsum, can be used to prepare concrete with desired mechanical properties and high durability through use of reasonable active excitation and component compatibility techniques. Additionally, by optimizing material properties, ultrahigh-performance concrete can be produced to achieve excellent mechanical properties, high durability, high wear resistance, and excellent explosion resistance. The abovementioned eco-friendly building materials can be used in various types of structures and possess a broad market. Between 2012 and 2017, 254 patents on this topic have been published with 380 citations and an average of 1.5 citations per patent.

(8) Advanced treatment of urban water

Rapid urbanization has caused an increasing demand for water and intensified the problem of water shortage. Discharged industrial and domestic wastewater leads to pollution of water supply sources. Pollutants in water sources mainly include trace organic pollutants, tiny particulate pollutants, and water eutrophication elements, such as nitrogen and phosphorus. Conventional water purification processes (e.g., coagulation, sedimentation, and filtration) are no longer adequate to meet quality requirements of drinking water. Thus, there exists an urgent need to develop advanced technologies and equipment for treatment of tap water. Examples of the third generation of advanced drinking-water treatment technologies include the advanced oxidation, raw water pretreatment, and purification processes based on membrane filtration.

As one of the unconventional water resources, urban wastewater can be reused as non-direct drinking water after appropriate advanced treatment. Recycling wastewater is effective not only for alleviating water shortage and disruption in ecological environment but also with regard to improving the quality and economic value of recycled water. Sewage water can be treated by physical, chemical, biological, and combined processes to attain a usable standard. Representative technologies for these processes include bio-enhancement treatment, catalytic oxidation, and membrane filtration. Between 2012 and 2017, 153 patents on this topic have been published with 1757 citations and an average of 11.48 citations per patent.

(9) Regulation technology for urban storm-water

With rapid growth in urbanization and social economy, urban rainwater control becomes a significant concern owing to the associated risk of flooding, loss of enormous rainwater resources, intensified pollution in urban rivers, and increasingly degraded urban ecological environment. The concept of urban storm-water control and utilization has been proposed to deal with urban rainwater and flood-related issues. Measures pertaining to infiltration, storage, stagnation, purification, utilization, and drainage have been taken for managing urban rainwater and runoff to effectively control rainwater floods and non-point pollution at the source, halfway, and end. Source-control technologies involve construction of roof greening, low-elevation greenbelts, permeable pavements, rainwater gardens, grassed swales, and rain barrels. Halfway-control technologies, on the other hand, include sewage wells, infiltration pipes and channels, and rainwater filters. End-control technologies include use of rain pools, rainwater wetlands, buffer zones, ecological embankments, and biological floating islands. These technologies have been used in many aspects, such as water resource utilization, flood control and disaster mitigation, and ecological environment protection. The present need of the hour is to speed up the construction of large-capacity drainage systems, develop multiscale water quantity and quality coupled simulation software and digital rainwater resource-management platforms, and study the classification and regulation of storm-water resources. Between 2012 and 2017, 67 patents have been published on this topic 542 citations and an average of 8.09 citations per patent.

(10) High-precision positioning navigation and spatiotemporal big data

High-precision navigation positioning and spatiotemporal big data plays an important role in the fields of Internet of things, smart earth, energy savings and emission reduction, and disaster mitigation. High-precision positioning navigation can be used to realize the location, navigation, and supervision of various targets based on data concerning position, speed, and time provided by navigation and positioning systems. It requires wide-area coverage, and the positioning and navigation accuracy must be of the decimeter-level or even higher. Spatiotemporal big data technology improves spatial positioning, perception, and cognition via data processing, analysis, fusion, and mining. Major techniques include ① global continuous coverage real-time precise satellite navigation and positioning technology, such as the third-generation GNSS technology; ② indoor and outdoor high-precision seamless positioning and navigation technologies, such as Wi-Fi/WSN/RFID/UWB indoor positioning technology; ③ spatiotemporal big data technologies—such as statistical analysis of time series and spatial trend, data mining, and knowledge discovery—for providing knowledge services to spatial decision support systems. Between 2012 and 2017, 570 patents have been published on this topic with 20 781 citations and average of 36.46 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent construction and 3D printing technology

Conventional construction industries around the world still exist in the labor-intensive stage and consume a large quantity of social resources. This is especially true with regard to energy utilized in the construction of buildings and treatment of construction materials, which accounts for 46% of the total energy consumption of the society, and has become a huge burden on national economy. The development of a green, low-carbon, and environmentally protected construction industry has, therefore, become imperative. Intelligent construction systems based on advanced construction and information technologies through use of CPS can effectively solve aforementioned problems by transforming and upgrading the construction industry. Construction of an efficient and intelligent building system requires effective integration of advanced technologies (e.g., AI, 3D printing, digital manufacturing, robots, big data, Internet of things, and cloud computing) to ensure correct coordination between individual stages, disciplines, and players during the lifecycle of a building and enhance individual functions in physical as well as virtual spaces. The ultimate goal here is to upgrade the overall production mode and productivity of the construction industry.

Presently, major topics of research concerning intelligent construction and 3D printing technology include

(1) Structural systems and intelligent design

Architectural and structural designs in conventional construction industries are mostly created for individual projects, thereby leading to repetitive works and low efficiency of coordination between different aspects of work. To ensure material saving, parts and components are project-specified and varied in dimensions, thereby causing difficulties related to industrialization, intellectualization, and managing of construction processes whilst maintaining high operational efficiency. The basic characteristics of intelligent construction include intelligent planning and design, automation of processing and manufacturing, intelligent assembly of field construction, information-based operational and maintenance management, and recycling of dismantled waste. The ultimate objective of intelligent construction is to ensure construction quality and efficiency, reduce labor demand, and facilitate lifecycle maintenance of buildings and infrastructure. Systematization of structural design, and modularization/standardization of structural parts and components form the basis of intelligent architectural designs. In addition, efficient structural systems and joint connection technologies form key issues concerning the fulfillment of intelligent designs; the level of associated technologies available within a country is an important index of its level of intelligence with regard to the construction industry.

(2) Intelligent equipment and construction

Modern construction technologies encompass standardized product manufacturing, prefabricated construction, intelligent construction technologies, and information process management. The construction mode significantly changes to meet the requirements for evolution in the conventional construction industry. Modern construction equipment finds wide applications in the construction of underground spaces, installation of large-scale earthworks and structures, emergency rescue, modern transportation networks, and deep-space and deep-ocean explorations. Efficient construction technologies and equipment rely on extensive collaborations between experts from different fields. They, therefore, possess great potential for promoting simultaneous developments in multiple fields. Modernization of construction equipment and technology is an important indicator of the overall strength of a nation. Therefore, researches performed concerning this topic has received increased attention worldwide, and these have been included under high-tech development plans or key national technologies in many countries.

Presently, conventional methods of building construction are being taken over by advanced modern technologies. The construction industry is rapidly upgraded from the labor-intensive mode to the technology-, knowledge-, and management-intensive mode. The *Information Development Report of the Chinese Construction Industry (2016): Internet Application and Development* thoroughly addresses the current situation and future development trends concerning the application of the Internet in the construction industry. It is believed that transformation of the construction industry strongly relies on the support and extensive application of the Internet. Intelligent construction and intelligent enterprises will be the future trend of transforming the construction industry.

(3) Intelligent maintenance and services

Integrated intelligent construction can achieve the desired safety, durability, fast construction, and low-carbon and friendly environment through factory production and then field assembling. It can minimize construction waste and sewage production, reduce construction noise, and enhance construction quality and efficiency. Meanwhile, a variety of sensors, smart homes, and related management software can be employed to realize lifecycle health monitoring and effective maintenance of building systems. Via efficient construction system management, one can reduce the cost, shorten the time limit, and ensure quality and safety exclusively through management of information and intelligence and standardization of production processes, thereby fully realizing the advantages of construction technology. Meanwhile, production efficiency of the entire construction industry can be further improved, and intelligent construction realized. Over lifecycles of buildings and infrastructure, information channels, such as communication networks and electronic equipment, can be employed to optimize the management process; realize standardization of production processes; and perform real-time, refined, and intelligent management of the design, construction, acceptance, maintenance, and management, dismantling, and recycling of buildings. These will play an important role in promoting rapid development of intelligent construction technologies.

As listed in Table 2.1.1, 65 core patents have been published on this topic between 2012 and 2017, and each patent has been cited an average of 14.63 times. The top 3 countries/regions publishing the most core patents are USA, China (excluding Taiwan of China), and South Korea (Table 2.2.1), among which, USA has contributed 41.54% of the core patents and received, on average, 22.41 citations per patent, thereby ranking first in terms of the total number of core patents. China, being one of the key players with regard to this development front, has contributed 40% of core patents published and received, on average, 8.69 citations per patent. As depicted in Figure 2.2.1, international cooperation is rare among the top 10 core patenting countries/regions.

As listed in Table 2.2.2, the top 3 organizations publishing the most number of core patents are MakerBot Industries LLC (USA), China Construction Group Co. (China), and Samsung Electronics Co., Ltd. (South Korea). Cooperation among the most productive organizations in this regard is also rare (Figure 2.2.2).

2.2.2 Green planning and building technology

Green planning and building technology is an inevitable development trend and a key strategy for sustainable development. The core principle here is to save resources and energy, improve the efficiency of energy-resource utilization, actively develop and utilize renewable energy, and achieve harmony with nature along with environmentally sustainable development under the premise of ensuring a healthy and comfortable living environment over the entire lifecycle of urban development and construction practices. Research endeavors concerning green construction begin from development of energy-saving ecological technologies for

Table 2.2.1 Countries or regions with the greatest output of core patents on the “intelligent construction and 3D printing technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	27	41.54%	605	63.62%	22.41
2	China	26	40.00%	226	23.76%	8.69
3	South Korea	5	7.69%	27	2.84%	5.40
4	Netherlands	1	1.54%	22	2.31%	22.00
5	India	1	1.54%	21	2.21%	21.00
6	Finland	1	1.54%	20	2.10%	20.00
7	Japan	1	1.54%	13	1.37%	13.00
8	Denmark	1	1.54%	12	1.26%	12.00
9	Russia	1	1.54%	3	0.32%	3.00
10	Germany	1	1.54%	2	0.21%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on the “intelligent construction and 3D printing technology”

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Proportion of citations	Citations per patent
1	STTS	USA	8	12.31%	243	25.55%	30.38
2	CSCE	China	3	4.62%	19	2.00%	6.33
3	SMSU	South Korea	3	4.62%	17	1.79%	5.67
4	IROB	USA	2	3.08%	92	9.67%	46.00
5	Aprecia Pharm Co	USA	2	3.08%	77	8.10%	38.50
6	GENE	USA	2	3.08%	32	3.36%	16.00
7	CISC	USA	2	3.08%	17	1.79%	8.50
8	GLDS	South Korea	2	3.08%	10	1.05%	5.00
9	UYTJ	China	1	1.54%	41	4.31%	41.00
10	View Inc	USA	1	1.54%	37	3.89%	37.00

STTS: MakerBot Ind. LLC; CSCE: China State Construction Engrg. Corp. Ltd; SMSU: Samsung Electronics Co., Ltd.; IROB: Irobot Corp.; GENE: General Electric Co.; CISC: Cisco Technology Inc.; GLDS: LG Display Co., Ltd.; UYTJ: Tongji University.

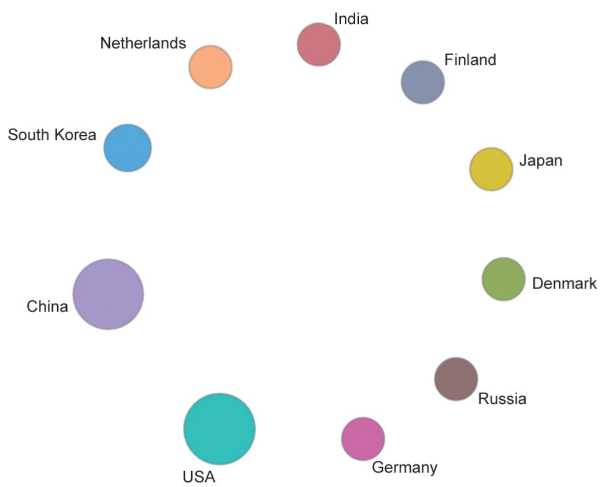

Figure 2.2.1 Collaborative network among countries or regions in the engineering development front of “intelligent construction and 3D printing technology”

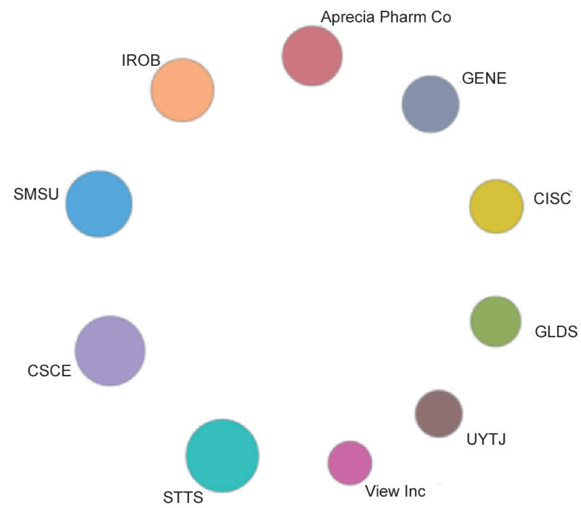

Figure 2.2.2 Collaborative network among institutions in the engineering development front of “intelligent construction and 3D printing technology”

the built environment, and actively develops the utilization of green energy and the comprehensive technological innovation of green buildings on the basis of making full use of passive technologies to achieve building consumption reduction. From the perspective of global green-building development, research and development activities must closely concentrate on green cities and green buildings; and through focusing on ecological cities, climate environment, natural resources, passive technologies, energy efficiency technologies, human comfort and health, comprehensive evaluation technologies, etc., a complete set of consulting frontier technology will be formed. Technical developments in this regard include research on high-density urban climate and energy-consumption assessment methods and information mapping, green building performance optimization based on climatic response, the technology of Internet of energies in urban buildings, application and innovation of passive technologies in green buildings, resident comfort and behavioral pattern assessment and evaluation, and active and passive technology complementary and coordinated green building synergy technology systems.

Development and application of green planning and building technologies are in full swing in China. Eighty percent of its cities with new national districts are developing demonstration projects concerning low-carbon planning. Green energy systems, blue–green ecological patterns, green transportation systems, green buildings, and green infrastructure have been developed in the new district pilots, and the *Assessment Standard for Green Eco-District* has been issued.

As listed in Table 2.1.1, 49 core patents have been published on this topic between 2012 and 2017, and each patent has been cited an average of 5 times. The top 3 countries/regions publishing the most number of core patents are China (excluding Taiwan of China), USA, and Japan (Table 2.2.3), among which, China has contributed over 95% of the core patents published and received, on average, 4.96 citations per patent, thereby ranking first in terms of the total quantity of core patents. As depicted in Figure 2.2.3, international cooperation is rare among the top 10 core patent output countries/regions in this regard.

As listed in Table 2.2.4, the top 3 organizations producing the most number of core patents are the Beijing Taikong Panel Ind. Corp. (China), Changzhou Lvjian Plate Ind. Co., Ltd. (China), and Hengyuan Building Board Ind. Co., Ltd. (China). Cooperation among these organizations is also rare (Figure 2.2.4).

2.2.3 Key technological systems in intelligent transportation

ITSs are based on new theories and such advanced technologies as information, communication, systems and controls, and intelligence. Research endeavors concerning this topic involve discovering and solving traffic problems from different perspectives, including those of humans, vehicles, roads, and the environment, whilst aiming at establishing an efficient, safe, ecological, and intelligent yet comprehensive transportation system. The development of ITSs in different countries differs in terms of emphasis; the main contents, however, remain roughly the same, including such intelligent systems as traffic information, traffic management, public transportation, traffic control, commercial vehicle management, electronic toll collection, security assurance, and emergency management and rescue.

With the advent of new technologies, ITS development has been rejuvenated; cross-border integration and innovation have led to creation of new development patterns and service contents, which in turn, has promoted the update of technology as well as development patterns of ITS. Currently, technical innovations concerning the ITS technology mainly concentrate on the following aspects.

(1) Accurate perception and interaction of traffic status. This involves realizing the intellectualization of and connection between terminal devices; accurate, simultaneous, and comprehensive attainment of the overall operational status of traffic networks; and providing traffic-related clues to both travelers and traffic management departments.

(2) Intelligent and cooperative management and service

Table 2.2.3 Countries or regions with the greatest output of core patents on the “green planning and building technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	47	95.92%	233	95.10%	4.96
2	USA	1	2.04%	8	3.27%	8.00
3	Japan	1	2.04%	4	1.63%	4.00

Table 2.2.4 Institutions with the greatest output of core patents on the “green planning and building technology”

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Taikong Panel Ind Corp	China	3	6.12%	9	3.67%	3.00
2	Changzhou Lvjian Plate Ind Co Ltd	China	3	6.12%	9	3.67%	3.00
3	Hengyuan Building Board Ind Co Ltd	China	3	6.12%	9	3.67%	3.00
4	Shandong New Century Municipal Eng Co	China	2	4.08%	10	4.08%	5.00
5	Univ Northeast Petroleum	China	2	4.08%	6	2.45%	3.00
6	CNPW	China	2	4.08%	4	1.63%	2.00
7	Shenzhen Inst Building Res Co Ltd	China	2	4.08%	3	1.22%	1.50
8	Lifengwang Shishi Environmental Protection Building Material	China	1	2.04%	13	5.31%	13.00
9	CRTC	China	1	2.04%	10	4.08%	10.00
10	Dongguan Yueyuan Packaging Co Ltd	China	1	2.04%	9	3.67%	9.00
11	Guangdong Yuansheng Eco-Environment Prot	China	1	2.04%	9	3.67%	9.00
12	UYZH	China	1	2.04%	9	3.67%	9.00

CNPW: Power Construction Corporation of China; CRTC: Railway Eng Res Inst China Academy Railway Sciences; UYZH: Zhejiang University.

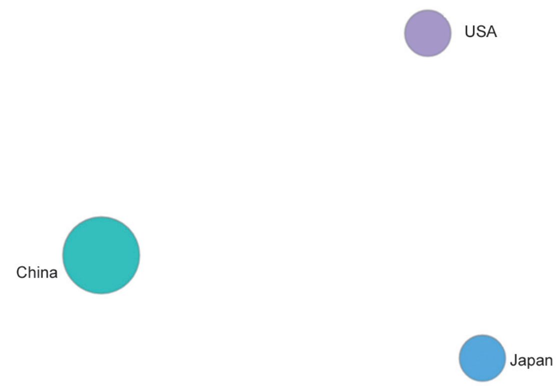

Figure 2.2.3 Collaborative network among countries or regions in the engineering development front of "green planning and building technology"

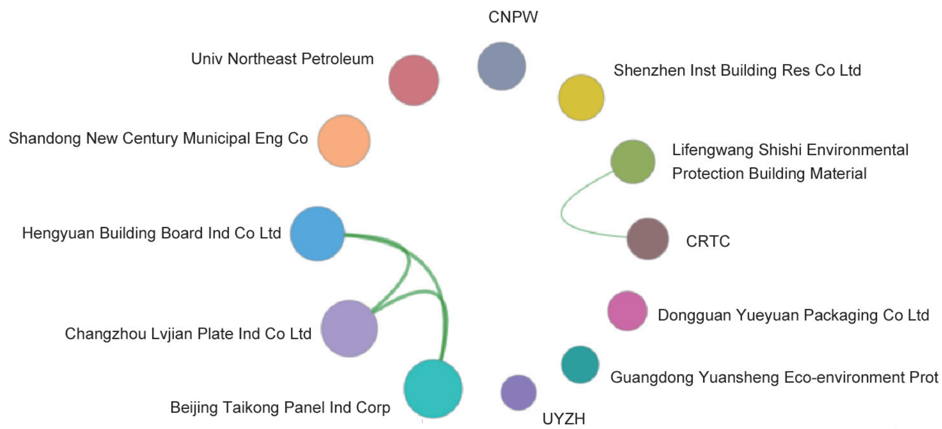

Figure 2.2.4 Collaborative network among institutions in the engineering development front of "green planning and building technology"

of comprehensive transportation systems. This field of study concerns new technologies, including big data, cloud computing, autonomous driving, connected vehicles, and AI, thereby generating new levels of intelligent management of ITSs, realizing accurate guidance and control of each individual, and improving the efficiency and capacity of traffic facilities.

(3) Scheduling and service of sharing transportation. This field of study involves transportation sharing and considers "travel is service" as its orientation, thereby designing multimodal transportation sharing systems and realizing an effective integration of management, organization, scheduling, and service principles.

(4) Transportation vehicle intellectualization and intelligent eco-driving. Intelligent vehicles represent the developing trend of future technologies and high strategic level of industrial upgradation. Related technologies are already in the testing phase with due consideration of revolutions as well as challenges concerning traffic systems.

(5) Cooperative vehicle infrastructure systems (CVISs) and active traffic safety assurance. Based on wireless and sensor technologies, road and vehicle information can be acquired. In addition, vehicles and infrastructure can be intellectually coordinated via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, thereby realizing the goal of optimizing system resources, improving road safety, and alleviating congestion. Cooperative vehicle–infrastructure system (CVIS) represents cutting-edge research in the field of transportation engineering, thereby attracting extraordinary investments in many countries, such as the IntelliDriveSM program in USA, Smartway in Japan, and eSafety in Europe.

As listed in Table 2.1.1, 85 core patents have been published on this topic between 2012 and 2017, and each patent has, on average, been cited 12.02 times. The top 4 countries/regions publishing the most number of core patents are China (excluding Taiwan of China), USA, Japan, and Australia (Table 2.2.5), among which, China—being one of the key players with regard to this development front—has contributed over 70% of the core patents published and has, on average, received 10.31 citations per patent. As depicted in Figure 2.2.5, international cooperation is rare among the top 10 core patent output countries/regions.

As listed in Table 2.2.6, Qualcomm Incorporated (USA) has published the most number of core patents on this topic. Cooperation among the most productive organizations is also rare (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents on the "key technological systems in intelligent transportation"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	62	72.94%	639	62.52%	10.31
2	USA	17	20.00%	301	29.45%	17.71
3	Japan	2	2.35%	24	2.35%	12.00
4	Australia	2	2.35%	23	2.25%	11.50
5	Netherlands	1	1.18%	39	3.82%	39.00
6	Finland	1	1.18%	23	2.25%	23.00
7	India	1	1.18%	16	1.57%	16.00
8	Saudi Arabia	1	1.18%	16	1.57%	16.00
9	Sweden	1	1.18%	10	0.98%	10.00

Table 2.2.6 Institutions with the greatest output of core patents on the "key technological systems in intelligent transportation"

No.	Institution	Country/ Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	QCOM	USA	5	5.88%	61	5.97%	12.20
2	UYQI	China	2	2.35%	35	3.42%	17.50
3	UYXN	China	2	2.35%	25	2.45%	12.50
4	ZGTH	China	2	2.35%	25	2.45%	12.50
5	HAIT	China	2	2.35%	24	2.35%	12.00
6	IBMC	USA	2	2.35%	23	2.25%	11.50
7	Xi'an Feisida Automation Eng Co Ltd	China	2	2.35%	21	2.05%	10.50
8	Wuhan Fenghuo Zhongzhi Digital Technology	China	2	2.35%	17	1.66%	8.50
9	Bravioz OY	Finland	1	1.18%	40	3.91%	40.00
10	TTTA	India	1	1.18%	39	3.82%	39.00

QCOM: Qualcomm Incorporated; UYQI: Tsinghua University; UYXN: Xidian University; ZGTH: China Railway Signal & Communication Corporation Limited; HAIT: Harbin Institute of Technology; IBMC: International Business Machines Corporation; TTTA: TATA Consultancy Service Co., Ltd.

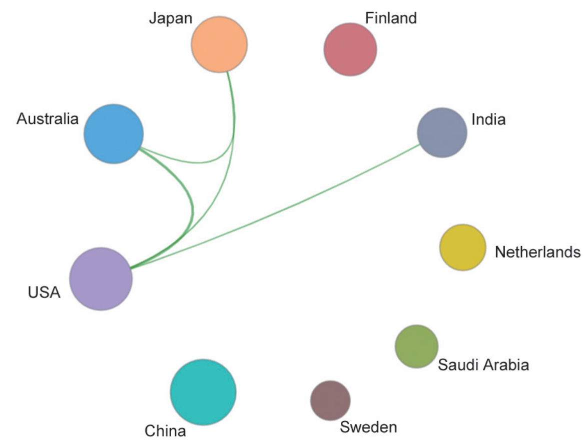

Figure 2.2.5 Collaborative network among countries or regions with the greatest output of core patents in the engineering development front of "key technological systems in intelligent transportation"

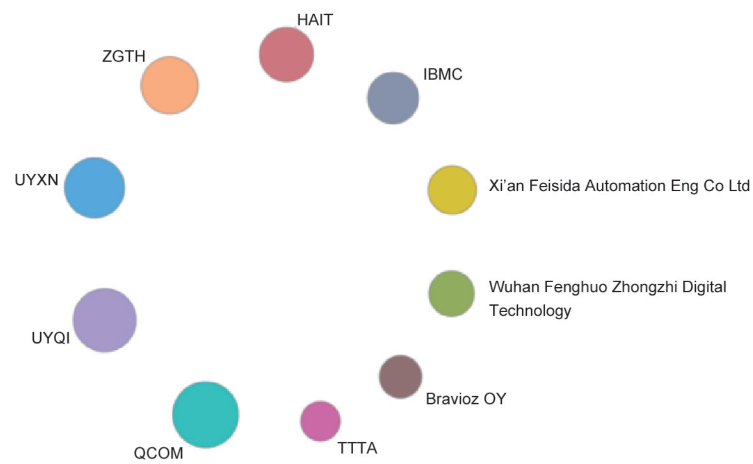

Figure 2.2.6 Collaborative network among institutions in the development front of "key technological systems in intelligent transportation"

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Members of Expert Group

Academicians

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Other Experts

CHEN Renpeng, CHI Mingmin, FAN Jiansheng, GAO Jun, GU Chongshi, GUO Ronghuan, HAN Jihong, HONG Kairong, LI Angui, LI Deying, LI Hui, LIU Jiaping, LIU Renyi, LUO Yaozhi, MA Jun, MENG Fanchao, QIAO Pizhong, QU Shaoxing, REN Weixin, SHEN Guoyi, SHI Peiling, SUN Jian, TAN Guangming, TANG Haiying, WANG Fazhou, WANG Weidong, WU Hao, XIONG Luxia, XU Bin, XU Zhaodong, YANG Feng, ZHANG Luoxian, ZHAO Tiejun, ZHAO Feifei, ZHENG Gang, ZHU Ruolin

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TANG Haiying, XING Huixian

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Bridge Engineering: GE Yaojun, SUN Zhi

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Other Experts

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Urban and Rural Planning and Landscape: ZHANG Shangwu, PANG Lei

Structural Engineering: GU Xianglin, ZHANG Weiping, LV Xilin, LI Guoqiang, ZHOU Ying

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Geotechnical and Underground Engineering: HUANG Hongwei, DING Wenqi, JIANG Mingjing, YUAN Yong

Heating, Ventilation, Air Conditioning, and Gas Supplying: ZHANG Xu, ZHOU Xiang

Construction Materials: JIANG Zhengwu, CHEN Qing

Municipal Engineering: XIA Siqing

Engineering Mechanics: LI Yan, WANG Huaning

Surveying and Mapping Engineering: TONG Xiaohua, CHEN Peng

Hydraulic Engineering: LIU Shuguang

Tongji Library: CHEN Xin, YAO Junlan

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Road and Railway Engineering: XIAO Feipeng

Construction Materials: JIANG Zhengwu, CHEN Qing

Surveying and Mapping Engineering: CHEN Peng

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VI. Environmental & Light Textile Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts in the field of environmental and light textile engineering (hereafter referred to as environmental engineering), which includes the subfield of environmental science, environmental engineering, meteorological science, marine science engineering, food science and engineering, textile science and engineering, and light industry technology and engineering, are summarized in Table 1.1.1. The annual number of core papers for individual research fronts between 2012 and 2017 is summarized in Table 1.1.2.

(1) Transport and transformation mechanisms of contaminants under multi-media and multi-interface

The transport of contaminants refers to the spatial migration and the process of enrichment, diffusion, and disappearance of contaminants into the environment. The transformation of contaminants indicates a change in the form of pollutants, or a conversion into another substance, through physical, chemical, or biological processes. Environmental systems consist of multiple media and have different environmental interfaces. Therefore, the transport of contaminants between media leads to contamination and the transformation at the interface of the media determines the level of pollution.

The research focuses on the transport, transformation, distribution, and fate behavior of carbon, nitrogen, phosphorus, sulfur, heavy metals, and organic contaminants in water–gas, water–soil, gas–soil and their biological interfaces, as well as their mechanisms for impacting the environment and ecosystems. Due to the multi-media, multi-interface, multi-component, and multi-fluid characteristics of the environmental system, the transport and transformation process of contaminants in the system is extremely complicated; while qualitatively describing this process is relatively easy, quantitatively describing it is challenging. The primary research directions include the distribution 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	Percentage of consistently-cited papers	Patent-cited papers
1	Transport and transformation mechanisms of contaminants under multi-media and multi-interface	483	22 579	46.75	2013.24	–	–
2	The mechanisms of combined air pollution	182	12 610	69.29	2014.02	–	–
3	The health effects of air pollution	1 119	68 394	61.12	2013.49	–	–
4	Performance and mechanism of decontamination technologies based on environmental nanocomposites	11	291	26.45	2016.27	27.3%	0.00
5	High-resolution ocean circulation models	29	655	22.59	2014.48	27.6%	0.00
6	Ocean acidification	38	1 852	48.74	2013.66	15.8%	0.00
7	Weather and climate predictability and model development	14	731	52.21	2014.14	14.3%	0.00
8	Mechanism of food nutrition metabolism based on intestinal microbiomics	20	2 112	105.60	2013.10	–	–
9	Intelligent wearable materials	152	6 221	40.93	2015.01	16.4%	0.02
10	Deep treatment of dyeing and finishing effluents	14	402	28.71	2016.07	14.3%	0.00

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	2012	2013	2014	2015	2016	2017
1	Transport and transformation mechanisms of contaminants under multi-media and multi-interface	175	138	79	68	18	5
2	The mechanisms of combined air pollution	31	28	58	39	24	2
3	The health effects of air pollution	324	287	258	157	74	19
4	Performance and mechanism of decontamination technologies based on environmental nanocomposites	0	0	0	2	4	5
5	High-resolution ocean circulation models	7	2	5	4	7	4
6	Ocean acidification	9	9	11	4	5	0
7	Weather and climate predictability and model development	1	3	4	5	1	0
8	Mechanism of food nutrition metabolism based on intestinal microbiomics	8	5	4	3	0	0
9	Intelligent wearable materials	9	17	28	33	40	25
10	Deep treatment of dyeing and finishing effluents	0	0	0	4	5	5

fate behavior of contaminants in environmental media, the transport and transformation mechanisms of contaminants in multi-media, the control and influence that micro-interfaces exert on pollutant transport and transformation, and the process simulation of pollutant transport and transformation in complex systems.

Traditional research on environmental pollution and control has been primarily limited to the properties of media. Scientists in the environmental field are often distinguished according to the studied medium. With a deepening of the concept of the environmental system, the study of pollution in a single medium (i.e., water, gas, soil, or organisms) is considered to be incapable of solving complex environmental problems. Future research of environmental pollution, and how to effectively control it, will increasingly move beyond the inertial thinking of transferring contaminants from one medium to another. Instead, by comprehensively considering water, gas, and soil pollution problems, the transport process of contaminants between the media and their transformation mechanism at the interface will be studied in depth, which will enable an accurate depiction and effective control of environmental pollution.

(2) The mechanisms of combined air pollution

"Combined air pollution" refers to a complicated air pollution system in which a variety of pollutants from various sources have coupling interactions between multiple interfaces under certain atmospheric conditions (temperature, humidity, illumination, etc.). Such a system features an increase in both the oxidizing capacity of the atmosphere and fine particulate matter (PM) concentrations, as well as a reduction in atmospheric visibility. Alongside China's rapid economic growth and urbanization, urban and regional air quality has deteriorated rapidly, characterized at first by high concentrations of sulfur dioxide (SO_2) and PM resulting from coal-dominated energy production and consumption. This was followed by a significant increase in nitrogen oxides (NO_x) and volatile organic compounds (VOCs) triggered by an increase in vehicle use. These primary pollutants and secondary pollutants, which are generated by the complex reactions of primary pollutants in the atmosphere, interact with the weather and climate systems, leading to a higher level and a wider range of pollution that eventually results in the reduction of visibility, frequent occurrence of haze, and formation of regional air pollution. The main research topics in this field include: revealing the key chemical and physical processes that cause the combined air pollution complex, establishing a theoretical system of combined air pollution, and developing new principles for the monitoring and source apportionment of atmospheric pollutants. The research on air pollution complex will provide a more scientific basis for solving global air pollution problems and climate issues.

(3) The health effects of air pollution

The complex and extensive effects of air pollution on human health have become a pressing issue facing the development of global society. The Global Burden of Disease (GBD) identifies air pollution among the leading risk factors for the global disease burden, responsible for 3.1% of disability-adjusted life years alone. Air pollution is a complex and ubiquitous mixture of pollutants including airborne PM, heavy metal elements, and VOCs. A significant amount of epidemiological and pathophysiological data support the claim that air pollution, especially particles with respirable aerodynamic diameters less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$), increases respiratory disease (such as asthma, chronic obstructive pulmonary disease, and lung cancer) and cardiovascular and cerebrovascular diseases (such as myocardial infarction, heart failure, and stroke). The elderly, pregnant women, babies, and people with similar diseases are more susceptible to the adverse effects of air pollution. Therefore, it is important to address China's human health issues by improving atmospheric conditions through a wide range of studies and comprehensive analyses of the impact of air pollution on human health.

(4) Performance and mechanism of decontamination technologies based on environmental nanocomposites

Nanomaterials refer to materials that have at least one dimension with a size of 1–100 nm. Nanomaterials have exhibited huge advantages in the efficient purification and treatment of pollutants (e.g., adsorption and catalytic degradation) due to their large specific surface area and high reactivity, and thus, have been important to the development of new technologies for environmental protection and remediation. However, technological bottlenecks, including aggregation, deactivation, and poor operability, have significantly limited the practical application of these materials. Fabrication of nanocomposites via the immobilization of nanoparticles is a promising strategy to address these problems. For example, nanosized metal oxides (e.g., Fe and Mn oxides) have satisfactory capabilities in removing contaminants such as heavy metals from water. Meanwhile, carbonaceous materials (e.g., graphene and carbon nanotubes) and porous materials (e.g., zeolites, clay minerals, and activated carbon) are promising hosts for nanoparticles due to their suitable conductivity, confinement, and supporting effects. In recent years, scientists around the world have developed various types of environmental nanocomposites for decontamination. The environmental nanocomposites reported recently in prominent research papers include various types such as nano metal oxides–chitosan, nano ZnO–montmorillonite, nano Mn-oxide–activated carbon, Co-impregnated carbon nanotubules, nano CuO–zeolite, and nano metal oxides–porous resins. The corresponding decontamination processes mainly include the adsorptive removal of aqueous contaminants (e.g., heavy metals, As, F, and P) from water, catalytic degradation of organic pollutants, and desulfurization of gasoline. Currently, research of decontamination technologies based on environmental nanocomposites is generally limited to lab-scale explorations, with limited instances of full-scale application. To promote environmental nanotechnologies moving from lab investigation to practical application, it is necessary to further develop novel nanocomposites with millimeter-sized hosts, upgraded operability, and sustainable reusability.

(5) High-resolution ocean circulation models

High-resolution ocean circulation models that include multiple temporal and spatial scale physical processes are a primary method for investigating and predicting ocean multi-scale dynamic processes in the marine environment. In recent years, with the development of ocean circulation modeling and the improvement of computing power, ocean numerical models have been able to simulate large-scale circulations more accurately and also have the capability to characterize ocean mesoscale processes. However, current ocean circulation models are unable to effectively simulate key dynamic processes in the ocean's mesoscale to small-scale, because of the relatively slow progress in theoretical research and the absence of a deep understanding of the dynamics of these scales. With regard to bottlenecks and frontier issues, the primary research directions and development trends include: developing a ultra-high-resolution ocean circulation model that utilizes high-resolution ocean observation, promoting theoretical innovation in small and mesoscale ocean dynamics, and enhancing the capability to simulate small and mesoscale dynamic processes and marine environment through the improvement of parameterization schemes based on physical processes; and further developing technologies for the data assimilation of satellite remote sensing observations and field measurements based on the high-resolution ocean circulation model, to reduce the models simulation error for marine environment elements with assimilating observation data, and to improve the forecast accuracy of the ocean circulation models in multi-scale processes and environmental elements.

(6) Ocean acidification

The dramatic rise of anthropogenic CO_2 emissions has led to ocean acidification, an increase in the acidity (pH) of seawater resulting from the increased absorption of CO_2 by oceans and changes in the terrestrial inputs and oceanic upwelling caused by climate change. Presently, global oceans are experiencing their fastest rate of acidification in 55 million years. Based on the current, increasing rate of anthropogenic CO_2 emission, it is estimated that the pH of the ocean surface will drop by 0.3–0.4 (to a pH of about 7.8) by 2100, an acidification increase of 1–1.5 times the level found in 1800. To assess the harm and risk associated with ocean acidification, the main research directions of ocean acidification include the following. ① Research will be conducted on the causes, processes, and reaction mechanisms of ocean acidification, the relationship between ocean acidification and biogeochemical variations in the ocean, and the parameter changes and modeling analysis of ocean acidification. ② Sensitive organisms that are vulnerable to ocean acidification will be targeted in research to study the effects of ocean acidification on the early life process, evolutionary adaptation, and pathological response of calcifying organisms. ③ Additionally, representative species, such as coral and algae, will be selected in the early research stages. ④ Finally, research will be conducted to trace the earth's history and investigate past climate change and acidification events through geological mineral research.

Ocean acidification is a topic at the forefront of international marine research. In addition to the research topics mentioned above, there are also a number of other trends in this field. ① Research is gradually expanding from directly affected, vulnerable organisms to other species such as large mammals. ② Research methods in the field are upgrading from simple laboratory research to near in situ containment tests with advanced technical equipment. ③ The research contents are shifting from early life stages, such as breed and larval growth, to life processes, physiological responses, functional behaviors, and gene expression. ④ The research scope of the assessment is expanding from the individual to the group level and multi-level response. ⑤ The study area is expanding beyond coastal areas to the open ocean and even the deep sea. ⑥ The study parameters are developing from a single pH test to a multi-factor joint test and a synergistic effect analysis.

(7) Weather and climate predictability and model development

The accuracy of short-term weather forecasting and medium- and long-term climate predictions is important to many people and is a key frontier in the field of atmospheric science. Presently, numerical models are the main tool for weather forecasting and climate prediction. The European Centre for Medium-Range Weather Forecasts (ECMWF), the UK, and the USA possess the world-class forecasting systems and models. The horizontal resolution of the high-resolution global model of the ECMWF is currently 9 km; the resolution of the global ensemble prediction system has been increased to 18 km, which can be used for ensemble prediction 15 days in advance. The ECMWF's model also leads the way in short- and medium-term forecasting techniques for global atmospheric circulation and severe weather. For example, Hurricane Sandy in October 2012 was successfully forecasted 15 days in advance. The UK (through its Met Office) is currently the only country in the world that has developed and implemented a unified weather and climate model (i.e., using the same model system framework for short- and medium-term global and regional weather forecasts, extended forecasts, month to seasonal predictions, and 100-year climate projections). The USA's global numerical weather prediction technology, which successfully forecasted the winter snowstorm that struck New York City in 2015, is ranked third in the world.

Based on GRAPES, a unified global and regional framework for numerical weather forecasting, China has independently improved and developed relevant technologies such as data assimilation, model dynamic physics, and ensemble forecasting. It has also established a comprehensive GRAPES technical system to achieve numerical deterministic and ensemble predictions over China with a regional resolution of 3 km and global resolutions of 10–25 km, narrowing the gap with advanced international systems.

(8) Mechanism of food nutrition metabolism based on intestinal microbiomics

The intestine, which contains many kinds of microbes, is an important organ for digestion, immunity, and nerve perception within the human body. In recent years, studies have found that the intestinal microbiome is closely related to various diseases of the human body. There has been a worldwide surge in research examining how the use of probiotics and other dietary measures can improve intestinal health by regulating intestinal microbes. To gain a better understanding of human nutrition and health, it is important to clarify the effects of dietary structure and its components on intestinal micro-ecology. It is also necessary to fully understand the regularity and mechanism of dietary nutrients affecting the occurrence and development of metabolic diseases mediated by intestinal microorganisms, establish the relationship between intestinal micro-ecological changes and human health status, predict the risk of metabolic diseases associated with different dietary compositions, and to design new dietary combination formulas and treatment strategies based on risk analysis.

(9) Intelligent wearable materials

The research of intelligent wearable materials aims to manufacture and process flexible materials into functional and intelligent electronic devices. These devices can sense changes in their external environment; the information processor evaluates the signal produced by a given change and then the driver adjusts the state of the material to adapt to the external environment. Through this process, these materials may eventually achieve self-diagnosis, self-adjustment, self-repair, and other functions. The materials used for manufacturing require high-speed electron mobility, good electrical conductivity, practical mechanical properties, safety features, and environmental stability. Appropriate material selection and manufacture processes are key to achieving these goals. Intelligent wearable materials have enormous potential across a wide range of applications, including intelligent electronic clothing, wearable computer clothing, wireless remote sensing and communication clothing, and leisure and entertainment clothing, etc.

(10) Deep treatment of dyeing and finishing effluents

The dyeing and finishing industries are on the list of the top dischargers of industrial effluents. The wastewater generated by dyeing and finishing processes is characterized by a complex composition, high organic content, high salt content, and significant discoloration. The emergence of newer generations of dyes and functional finishing agents has aggravated the bio-degradability of dyeing and finishing wastewater. Conventional biochemical and physicochemical treatment of these effluents is insufficient for lowering the chemical oxygen demand and chromaticity to the standard levels for discharge or reuse. Therefore, efficient and cost-effective techniques for the deep purification of dyeing and finishing wastewater must be developed urgently. Treatment by catalytic oxidation, which breaks down organic pollutants in wastewater to small non-toxic molecules or CO_2 and water through a catalyst that takes advantage of light, electricity or green oxidants, has emerged as a promising method in the field.

The catalytic oxidation treatment of wastewater is a collective term that includes electrochemical oxidation, Fenton oxidation, photocatalytic oxidation, and catalytic ozone (O_3) oxidation, all of which have certain limitations. Therefore, future developments in this field will center on addressing these corresponding limitations and integrating existing technologies for improved performance. Specifically, these include the development of highly-efficient, low-cost, and exudation-resisted electrode materials, conveniently-recyclable supported photocatalysts that utilize a broader range of the electromagnetic spectrum, pretreatment and new designs of photoreactors for improved efficiency in catalysis, the development of multiphasic O_3 catalyzed oxidation, and integrated treatment techniques that take advantage of two or more existing oxidative methods, such as electrochemical + O_3 and photochemical + O_3.

1.2 Interpretations of three key engineering research fronts

1.2.1 The health effects of air pollution

In recent years, China has faced serious environmental problems as a result of air pollution. The complexity of air pollution also causes severe health problems; in 2013, the International Agency for Research on Cancer officially listed air pollution as a primary carcinogen. An estimated 92% of the world's population live in areas with air quality that exceeds certain healthy limits. Approximately 3 million deaths each year are related to air pollution and nearly 90% of them occur in low- and middle-income countries. Air pollutants mainly include respirable particulate matter ($PM_{2.5}$, PM_{10}, etc.), SO_2, NO_x, O_3, carbon monoxide (CO), and VOCs.

A number of epidemiological and pathophysiological studies have shown that air pollution is correlated with cardiovascular diseases, respiratory diseases, and some cancers. Among the different air pollutants, aerosol particles smaller than 2.5 μm pose the greatest risk to human health because they are small enough to be inhaled deeply into the lungs and, in some cases, enter the bloodstream. Any harmful substances carried by the particles, such as bacteria, viruses, or heavy metals, can then be absorbed by the human body.

Nations are increasingly regarding the impact of air pollution on human health as a key area for research. Presently, research on this topic is mainly focused on the relationship between atmospheric pollutant concentration and exposure-response, the acute and chronic health effects of atmospheric pollutants, and genotoxic and non-genotoxic pathogenesis, among other aspects. However, due to the lack of long-term systematic monitoring and data accumulation, the academic study of the impacts of air pollution on human health in China still has much room for further development compared to that of western countries.

A review of 1119 core papers on the health effects of air pollution revealed that these studies were cited as many as 68 394 times, with a per paper citation frequency of 61.12—mostly from 2012 to 2015 (Table 1.1.1). Almost all 1119 core studies were conducted in the USA and China, and the citations per paper for both countries are 71.26 and 84.89, respectively (Table 1.2.1). Harvard University and the University of California, Berkeley, are the 2 major producers of the core papers, publishing 7.42% and 6.88% of the papers which were cited 11 212 and 9938 times, respectively.

When analyzing the engineering research front of "the health effects of air pollution", the top three countries or regions that published the highest number of core papers are the USA (556), China (228), and the UK (168); the top 3 countries or regions with the highest average citations are Switzerland (149.60), Germany (139.42), and the Netherlands (134.87) (Table 1.2.1). Among these countries or regions, China, and the USA extended the highest level of cooperation to each other, followed by the UK, Canada, and Germany (Figure 1.2.1).

The 3 institutions that published the highest number of core papers are Harvard University (83), the University of California, Berkeley (77), and Peking University (53), and the top 3 cited institutions per core paper are the University of British Columbia (197.93), Health Canada (195.91), and Fudan University (195.18) (Table 1.2.2). The institutions with the highest number of published papers in China include Peking University, the Chinese Academy of Sciences, and Fudan University (Table 1.2.2). The University of California, Berkeley has the largest cooperation with Health Canada and Peking University has significant cooperation with the Chinese Academy of Sciences, Fudan University, and the University of British Columbia (Figure 1.2.2).

The major research institutions with regard to citing core papers include the Chinese Academy of Sciences, Peking University, and Tsinghua University in China; Harvard University, the University of Washington, the University of California, Berkeley, and Columbia University in the USA; and the Imperial College of Science, Technology and Medicine in the UK (Table 1.2.3 and Table 1.2.4).

Table 1.2.1 Countries or regions with the greatest output of core papers on the "health effects of air pollution"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citation per paper
1	USA	556	49.69%	39 618	57.93%	71.26
2	China	228	20.38%	19 356	28.30%	84.89
3	UK	168	15.01%	17 229	25.19%	102.55
4	Canada	130	11.62%	13 335	19.50%	102.58
5	Italy	106	9.47%	8 740	12.78%	82.45
6	Germany	102	9.12%	14 221	20.79%	139.42
7	Spain	92	8.22%	11 044	16.15%	120.04
8	France	90	8.04%	10 580	15.47%	117.56
9	Netherlands	86	7.69%	11 599	16.96%	134.87
10	Switzerland	72	6.43%	10 771	15.75%	149.60

Table 1.2.2 Institutions with the greatest output of core papers on the “health effects of air pollution”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	83	7.42%	11 212	16.39%	135.08
2	Univ Calif Berkeley	77	6.88%	9 938	14.53%	129.06
3	Peking Univ	53	4.74%	3 292	4.81%	62.11
4	Univ Utrecht	50	4.47%	8 923	13.05%	178.46
5	US EPA	47	4.20%	8 512	12.45%	181.11
6	Hlth Canada	43	3.84%	8 424	12.32%	195.91
7	Chinese Acad Sci	43	3.84%	3 074	4.49%	71.49
8	Univ British Columbia	42	3.75%	8 313	12.15%	197.93
9	Ctr Res Environm Epidemiol CREAL	42	3.75%	2 830	4.14%	67.38
10	Fudan Univ	40	3.57%	7 807	11.41%	195.18

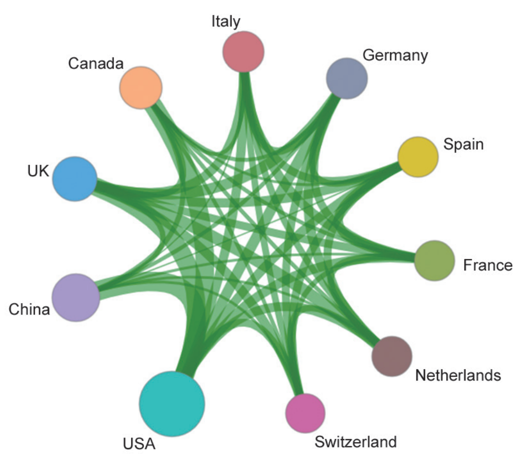

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “the health effects of air pollution”

In summary, China is gradually taking the global lead in research on the topic of “the health effects of air pollution.” Therefore, the country should continue to invest in this research area and promote research that will accelerate the progression that will allow it to remain at the forefront of the field

1.2.2 High-resolution ocean circulation models

Marine environment forecasting forms the basis of human maritime activities which in turn drive the development of ocean circulation models. Since the 1990s, progress made in ocean observation, data assimilation, and high-performance computer technology has enabled high-resolution ocean circulation models to develop rapidly to meet an increasing

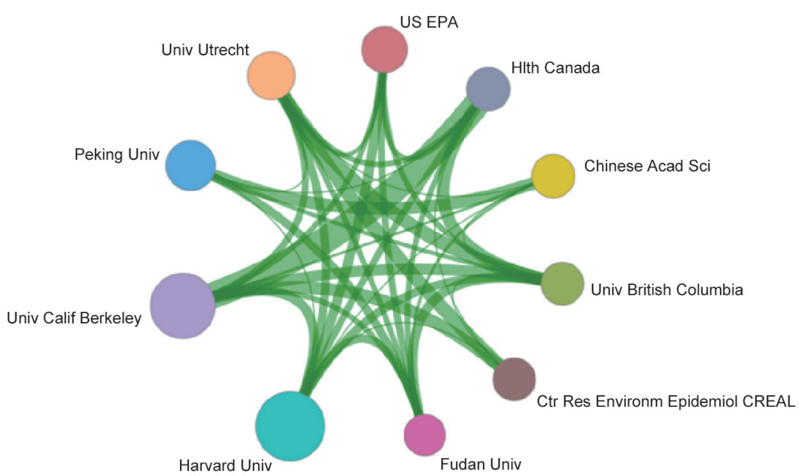

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “the health effects of air pollution”

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "health effects of air pollution"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	1 852	31.13%	2014.38
2	China	890	14.96%	2014.66
3	UK	752	12.64%	2014.48
4	Germany	445	7.48%	2014.64
5	Canada	412	6.93%	2014.52
6	Australia	368	6.19%	2014.65
7	Netherlands	327	5.50%	2014.55
8	Italy	315	5.30%	2014.54
9	Spain	298	5.01%	2014.51
10	Switzerland	290	4.87%	2014.55

Table 1.2.4 Institutions with the greatest output of citing papers on the "health effects of air pollution"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Harvard Univ	278	18.42%	2014.40
2	Chinese Acad Sci	217	14.38%	2014.81
3	Univ Washington	180	11.93%	2014.56
4	Univ London Imperial Coll Sci Technol & Med	139	9.21%	2014.05
5	Univ Calif Berkeley	137	9.08%	2014.15
6	Peking Univ	119	7.89%	2014.45
7	Columbia Univ	114	7.55%	2014.65
8	Univ British Columbia	111	7.36%	2014.81
9	Univ Utrecht	110	7.29%	2014.31
10	Tsinghua Univ	104	6.89%	2014.63

demand for global operational ocean forecasting. A number of internationally renowned ocean circulation models have been generated, including HYCOM, POM, ROMS, NLOM, HAMSOM, LICOM, NEMO, and MOM. Ocean circulation involves multi-scale dynamic processes ranging from large-scale circulation over thousands of kilometers to small-scale turbulent mixing over centimeters, and interactions and coupling between these multi-scale processes. Nonlinear interactions between different scales lead to the mass and energy transferring in multi-scale dynamic space. Although high-resolution ocean numerical models have been able to simulate large-scale circulation structures relatively accurately and have a certain ability to characterize the ocean mesoscale process, there is still a lack of theoretical research to provide an in-depth understanding of small-scale dynamic processes and their interactions in the ocean. The dynamic frames and mixed parameterization schemes of current mainstream circulation models determine that the mesoscale energy in models tends to reverse cascade, which cannot accurately describe the forward cascade and dissipation of mesoscale energy. This is one of the main bottlenecks that currently restricts the development of marine environmental forecasting and it is an international frontier for developing high-resolution ocean circulation models.

In view of these bottlenecks and frontier issues, the primary research directions and development trends at present include: carrying out in-depth research on ocean mesoscale processes and promoting theoretical innovation with regard to marine dynamics and parameterization schemes for physical processes by developing ultra-high-resolution ocean circulation models combined with high-resolution satellite remote sensing and field observation. The simulation and forecasting capability of ocean mesoscale dynamic processes and marine environment is also improved by the progress of the parameterization schemes of ocean circulation models. Currently, this work is primarily undertaken by the global ultra-high-resolution circulation model of the Jet Propulsion Laboratory in the USA and NASA's Surface Water and Ocean Topography satellite program. On the other hand, there is also a need to further develop data assimilation technologies based on satellite remote sensing and field observation. Assimilating the observation data by using the three-dimensional variation, multi-scale coupling and other technologies could reduce the error happened in calculation of marine environmental elements. This work is primarily undertaken by the global HYCOM data assimilation model jointly developed by Florida State University, the Naval Postgraduate School, and the University of Miami.

Table 1.2.5 shows the main output countries or regions of the core papers published in the research front "high-resolution ocean circulation models." It is evident that the USA ranks first in the proportion of both the number of papers published and citation frequency and there is a large gap between the other countries. This indicates that the USA holds significant research advantages in this field. China has a small number of core papers in this area, ranked eighth; however, it is worth noting that it ranks second in citation frequency with 31. In terms of the cooperative networks of major output countries or regions (Figure 1.2.3), there is extensive cooperation and exchange among the USA, Australia, Canada, and the UK, while China only cooperates with the USA.

Table 1.2.6 is the main output organization of core papers in the engineering fronts. The top 10 institutions in terms of the number of core papers produced are predominantly concentrated in the USA, while the Chinese research institutions do not appear in the top 10. According to the major inter-agency cooperation network (Figure 1.2.4), four institutions, the University Michigan, the University of

Table 1.2.5 Countries or regions with the greatest output of core papers on "high-resolution ocean circulation models"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	24	82.76%	560	85.50%	23.33
2	UK	9	31.03%	237	36.18%	26.33
3	Australia	6	20.69%	160	24.43%	26.67
4	France	4	13.79%	71	10.84%	17.75
5	Canada	4	13.79%	89	13.59%	22.25
6	Japan	1	3.45%	30	4.58%	30.00
7	China	1	3.45%	31	4.73%	31.00

Table 1.2.6 Institutions with the greatest output of core papers on "high-resolution ocean circulation models"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Michigan	8	27.59%	152	23.21%	19.00
2	Univ Calif San Diego	5	17.24%	128	19.54%	25.60
3	Univ Southampton	5	17.24%	173	26.41%	34.60
4	Woods Hole Oceanog Inst	5	17.24%	191	29.16%	38.20
5	MIT	3	10.34%	29	4.43%	9.67
6	USN	3	10.34%	96	14.66%	32.00
7	Univ New S Wales	3	10.34%	131	20.00%	43.67
8	Portland State Univ	3	10.34%	41	6.26%	13.67
9	Naval Res Lab	3	10.34%	30	4.58%	10.00
10	Bangor Univ	3	10.34%	30	4.58%	10.00

California, San Diego, the U.S. Naval Research Laboratory, and Bangor University, have cooperative relationships with each other. Three institutions, the University of Southampton, Woods Hole Oceanography Institute, and the University of New South Wales, also have cooperative relationships.

China ranks fourth in terms of citation frequency of its core papers (Table 1.2.7). There is still a significant gap between China and the USA, the leader in the category. The Ocean University of China and Chinese Academy of Sciences rank sixth and seventh, respectively, in the rankings of institutions from which core papers were cited (Table 1.2.8). Institutions in the USA still occupy the majority of the institutional rankings.

It is evident that the USA is a world leader in the field, not only in terms of the development of "high-resolution global ocean circulation models", but also with regard to its cooperation with other countries. In contrast, China is still following in this field; to overcome this China should strengthen exchange and cooperation with other countries and institutions, continue to increase research investment, and promote research in the innovative fields that will enable it to become a world leader.

1.2.3 Intelligent wearable materials

As electronic information systems have become indispensable to our daily lives, intelligent wearable materials have received significantly more attention in the engineering field. They are the combination of electronic components and textiles, but their properties are vastly different: the former is hard

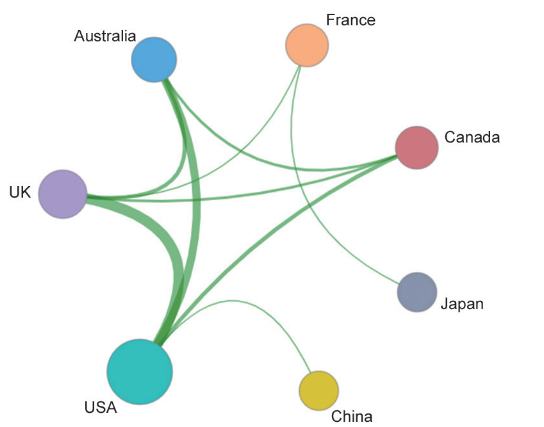

Figure 1.2.3 Collaborative network among major countries or regions in the engineering research front of "high-resolution ocean circulation models"

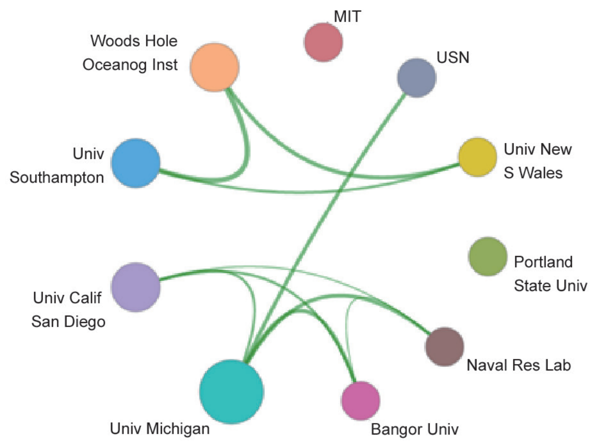

Figure 1.2.4 Collaborative network among major institutions in the engineering research front of "high-resolution ocean circulation models"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "high-resolution ocean circulation models"

No.	Country/Region	Number of cited core publications	Percentage of cited core publications	Mean year
1	USA	196	41.09%	2015.48
2	France	59	12.37%	2015.46
3	UK	55	11.53%	2015.15
4	China	41	8.60%	2015.61
5	Australia	35	7.34%	2015.26
6	Japan	28	5.87%	2015.75
7	Germany	24	5.03%	2015.04
8	Canada	24	5.03%	2015.17
9	Norway	8	1.68%	2014.63
10	Sweden	7	1.47%	2015.57

and brittle and the latter is flexible. Functional and intelligent wearable textiles sense changes in the external environment. The information processor judges the signal produced by a given change and the driver then adjusts the state of the material to adapt to the external environment and ultimately achieve self-diagnosis, self-adjustment, and self-repair, among other functions.

(1) One-dimensional flexible conductive material

One-dimensional flexible conductive material, an important component of fiber-based intelligent wearable materials, requires high-speed electronic mobility, good conductivity, practical mechanical properties, safety features, and environmental stability. Appropriate material selection and manufacture processes are key to achieving these goals. Presently, fiber-based flexible conductive materials primarily include conductive polymers, metal oxides, and carbon materials. The most promising technology in the manufacturing process is textile technology, followed by nano-coating technology.

(2) One-dimensional flexible energy storage device

In addition to exploring the function of wearable flexible textiles, researchers also pay attention to energy storage devices, such as supercapacitors and flexible batteries, especially for advanced nanotechnology, that make it feasible to directly integrate electronic devices into fibers. However, it is also a significant challenge to integrate one-dimensional fibers into three-dimensional clothing that can maintain their performance when in use. Therefore, the design of intelligent wearable components should be considered in terms of material preparation, manufacturing technology, and device structure.

(3) Intelligent wearable materials applications

The applications of intelligent wearable materials mainly include electronic components, wearable electronic devices, and other applications. Electronic components include optical fiber transistors, fabric antennas, electronic connectors, and fiber circuits. Wearable electronic devices include sensors and sensor networks, wearable energy converters, wearable energy storage, etc. Other applications include electronic intelligent protective clothing, electronic intelligent monitoring clothing, wearable computer clothing, wireless remote sensing and communication clothing, and leisure and entertainment clothing, etc.

The research front of “intelligent wearable materials” is mainly undertaken in China, the USA, and Iran (Table 1.2.9). These three countries are responsible for more than 81% of the core papers published in this field across the world, with most of this activity concentrated over the last three years. The top five research institutes relating to this front are the Institute for Color Science and Technology, Nanyang Technological University, the Chinese Academy of Sciences, Xi’an Jiaotong University, and the National University of Singapore (Table 1.2.10).

China and the USA occupy the top two positions in the research front, and China, which has cooperative relationships with many other countries, is at the forefront (Figure 1.2.5). Among

Table 1.2.8 Institutions with the greatest output of citing papers on “high-resolution ocean circulation models”

No.	Institution	Number of cited core publications	Percentage of cited core publications	Mean year
1	Univ Calif San Diego	40	17.24%	2015.60
2	Woods Hole Oceanog Inst	34	14.66%	2015.29
3	Univ Washington	23	9.91%	2015.43
4	MIT	23	9.91%	2015.74
5	Univ Southampton	22	9.48%	2014.82
6	Ocean Univ China	20	8.62%	2015.50
7	Chinese Acad Sci	19	8.19%	2015.95
8	Univ Michigan	18	7.76%	2015.22
9	Natl Oceanog Ctr	17	7.33%	2015.41
10	CALTECH	16	6.90%	2015.94

Table 1.2.9 Countries or regions with the greatest output of core papers on "intelligent wearable materials"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	82	53.95%	3 678	59.12%	44.85
2	USA	25	16.45%	925	14.87%	37.00
3	Iran	19	12.50%	465	7.47%	24.47
4	Singapore	15	9.87%	790	12.70%	52.67
5	Australia	9	5.92%	344	5.53%	38.22
6	Russia	4	2.63%	85	1.37%	21.25
7	UK	4	2.63%	63	1.01%	15.75
8	Saudi Arabia	3	1.97%	181	2.91%	60.33
9	South Korea	3	1.97%	151	2.43%	50.33
10	Japan	3	1.97%	88	1.41%	29.33

Table 1.2.10 Institutions with the greatest output of core papers on "intelligent wearable materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Inst Color Sci & Technol	16	10.53%	403	6.48%	25.19
2	Nanyang Technol Univ	9	5.92%	454	7.30%	50.44
3	Chinese Acad Sci	9	5.92%	453	7.28%	50.33
4	Xi'an Jiao Tong Univ	7	4.61%	197	3.17%	28.14
5	Natl Univ Singapore	6	3.95%	336	5.40%	56.00
6	MIT	6	3.95%	244	3.92%	40.67
7	Harbin Engn Univ	5	3.29%	114	1.83%	22.80
8	Huazhong Univ Sci & Technol	5	3.29%	605	9.73%	121.00
9	Joint Ctr Energy Storage Res	5	3.29%	216	3.47%	43.20
10	Monash Univ	4	2.63%	175	2.81%	43.75

the major institutions, MIT and Joint Ctr Energy Storage Res cooperate more than others (Figure 1.2.6).

Among major countries/regions, China ranks first in the output of citing papers on this front (Table 1.2.11). And among major institutions, Chinese Academy of Sciences ranks first in the output of citing papers on this front (Table 1.2.12).

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The top 10 engineering development fronts in this field, which are summarized in Table 2.1.1, include the subfields of environmental science, environmental engineering, meteorological science, marine science engineering, food science and engineering, textile science and engineering, and light industry technology and engineering. The number of patents issued between 2012 and 2017 related to these individual topics is summarized in Table 2.1.2.

(1) New energy and clean energy technologies

New energy and clean energy refer to solar energy, wind energy, geothermal energy, ocean energy, bioenergy, small hydropower, and nuclear energy, as opposed to conventional fossil-fuel energy and large- and medium-sized hydropower. Countries around the world are actively promoting the development and utilization of these various forms of clean energy. The main difficulties in solar and wind energy

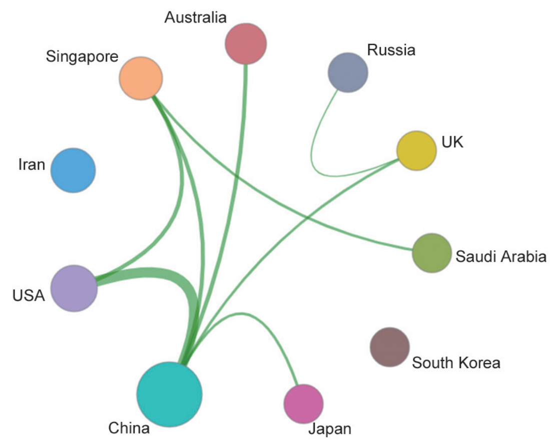

Figure 1.2.5 Collaborative network among major countries or regions in the engineering research front of "intelligent wearable materials"

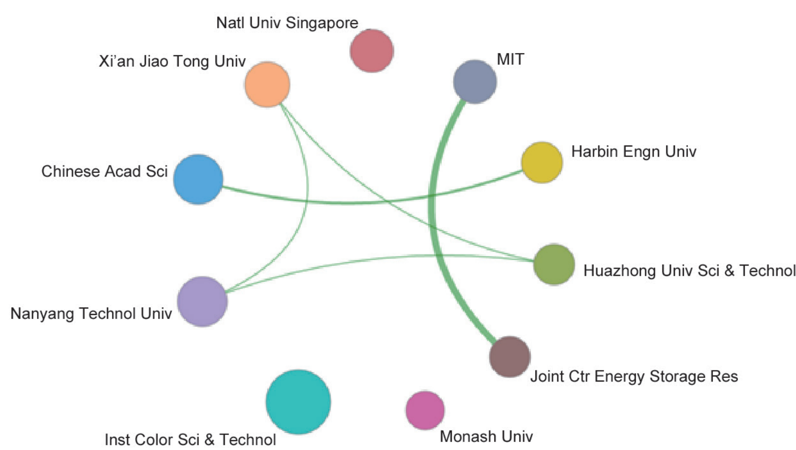

Figure 1.2.6 Collaborative network among major institutions in the engineering research front of "intelligent wearable materials"

Table 1.2.11 Countries or regions with the greatest output of citing papers on "intelligent wearable materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1 765	55.49%	2016.27
2	USA	433	13.61%	2015.95
3	South Korea	207	6.51%	2016.13
4	Iran	168	5.28%	2016.26
5	India	152	4.78%	2016.16
6	Singapore	118	3.71%	2015.38
7	Australia	110	3.46%	2015.97
8	Germany	80	2.51%	2016.19
9	UK	79	2.48%	2016.22
10	Saudi Arabia	69	2.17%	2016.03

applications are low energy conversion efficiencies, high costs, short life spans, and challenges in energy storage. The development of solar thermal conversion key materials and spectrally selective absorption coatings is a key technical

Table 1.2.12 Institutions with the greatest output of citing papers on "intelligent wearable materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	181	28.33%	2016.08
2	Nanyang Technol Univ	58	9.08%	2015.59
3	Natl Univ Singapore	54	8.45%	2015.15
4	Tsinghua Univ	53	8.29%	2016.28
5	Inst Color Sci & Technol	53	8.29%	2016.15
6	Huazhong Univ Sci & Technol	50	7.82%	2016.26
7	Tongji Univ	49	7.67%	2016.31
8	Shanghai Jiao Tong Univ	49	7.67%	2016.00
9	Cent S Univ	47	7.36%	2016.26
10	Xi'an Jiao Tong Univ	45	7.04%	2016.67

Table 2.1.1 Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	New energy and clean energy technologies	1 519	58 880	38.76	2013.07
2	Remediation technology for organic pollution in soils	780	1 116	1.43	2015.47
3	Sewage and wastewater resources energy recovery technology	47	18	0.38	2015.79
4	Air pollution control technology	252	2 848	11.30	2013.05
5	Automatic monitoring technology of remote sensing radar	149	5 083	34.11	2013.53
6	Automatic monitoring and early-warning system for disasters	302	4 931	16.33	2013.69
7	Autonomous underwater vehicles	1 000	6 517	6.52	2014.27
8	E-innovation of monitoring techniques for pesticide residues	1 000	1 100	1.10	2015.40
9	Smart wearable textiles	1 000	17 056	17.06	2014.47
10	Ecological leather	1 745	618	0.35	2015.98

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	2012	2013	2014	2015	2016	2017
1	New energy and clean energy technologies	664	404	227	149	52	23
2	Remediation technology for organic pollution in soils	43	47	88	133	192	267
3	Sewage and wastewater resources energy recovery technology	2	5	0	6	15	19
4	Air pollution control technology	23	30	34	33	27	40
5	Automatic monitoring technology of remote sensing radar	44	32	40	19	11	3
6	Automatic monitoring and early-warning system for disasters	75	77	60	53	30	7
7	Autonomous underwater vehicles	100	122	138	166	174	192
8	E-innovation of monitoring techniques for pesticide residues	37	40	156	117	107	354
9	Smart wearable textiles	79	111	190	151	181	219
10	Ecological leather	0	0	76	489	566	614

barrier to improving the utilization of solar energy. As the core of wind power generation systems, wind turbines have experienced many breakthroughs with regard to overcoming technical problems, which has had an extremely positive impact on the wind power industry. The related research, design, and manufacturing of wind turbines are the primary, future research directions. The development of renewable biomass energy has become an important resource for reducing environmental pollution and the gap between energy supply and demand. A major focus for the future is developing efficient and economical technology related to biomass gasification and liquefaction, biogas, bioethanol, and biohydrogen production, and to promote their development.

(2) Remediation technology for organic pollution in soils

China is in short supply of arable land and soils in certain regions are severely polluted with heavy metals and organic pollutants. Compared with heavy metals, organic pollution is widespread and complicated—pollutants such as PAHs affect the safety of agricultural products and the continuous utilization of land resources. Thus, it is important to develop remediation technology for organic pollution in soils.

Remediation technology for organic pollution, which includes physical, chemical, and biological remediation, was introduced in the 1970s and rapidly developed in the 1980s. Common physical remediation technologies, such as vapor extraction, thermal desorption, and incineration, were suitable for pollutants with high or semi volatility. Chemical remediation technologies oxidize the organic pollutants using Fenton's reagent or potassium permanganate, or enhance the solubility of organic pollutants in the liquid phase through surfactants that are applied to decompose non-volatile or non-degradable pollutants. Biological remediation technologies are used to degrade, absorb, or accumulate pollutants by using indigenous microorganisms and adding bacterial strains or plants. Because of the coexistence of different types of pollutants, integrated remediation techniques are required to address the soil pollution at growing industrial sites.

Although the soil remediation industry has been rapidly developing in recent years, China is still lacking advanced techniques, equipment, and innovative technology. Searching for economical, efficient, and environmentally-friendly soil remediation technology is a clear priority for the future.

(3) Sewage and wastewater resources energy recovery technology

Sewage and wastewater resources energy recovery technology enables the recycling and utilization of biological energy sources and nutrient substances. Sewage and wastewater contain valuable resources; however, current water treatment technology that focuses on removing pollutants fails to effectively harness the energy embedded in these resources. The concept of sewage treatment is currently being transformed from pollutant removal to resource energy recovery, and sewage treatment plants will also become energy recovery plants. The development of this key technology includes the following aspects. ① Advanced treatment and safe and efficient use technologies for reclaimed water. Develop new physicochemical, biochemical, and highly-efficient coupling technologies to create an advanced and super-advanced sewage treatment technology system that utilizes emerging pollutant removal technology, and highly advanced technology for treatment of high-quality reclaimed water. ② Energy self-sufficient technology for sewage treatment. Develop low carbon processes that utilizes a number of technologies: aerobic granular sludge, anaerobic membrane bioreactor, and anaerobic ammonia oxidation technology; thermal hydrolysis and gasification of sludge, anaerobic sludge digestion and related biogas recovery, and purification and technology; and combined heat and power generation, including fuel cells and micro gas turbines. ③ Sewage treatment and resource recovery technology. Study the method and potential of resource recovery in the sewage treatment process, with a focus on the recovery of phosphorus, cellulose, biodiesel, and Polyhydroxyalkanoic acids. ④ Operation management and strategy optimization technology for the next generation of sewage treatment plants. Determine the precise control factors and integrate technological advances such as the Internet of things to realize the self-perception and self-management of sewage treatment plants, realize energy-savings, reduce consumption, and optimize operation and control efficiency. Further, to achieve resource recycling, energy self-sufficiency, and environmental friendliness, recovery technology for sewage and wastewater resources will be a development focus in the water treatment field.

(4) Air pollution control technology

The onset of rapid industrialization since the middle of the last century has led to an increased discharge of pollutants that has caused air pollution to become a serious threat to human health. This has attracted significant efforts around the world to control air pollution through a series of strategies and technologies. Atmospheric pollution mainly includes harmful gases produced by industrial production, harmful substances discharged from automotive engine fuels, and naturally formed gaseous pollutants or fine particulate matter that pose a hazard to human health—with the first two items currently representing the main sources of air pollution. Air pollution control involves particle pollution control technology, gas pollutant control technology, and automobile exhaust control technology. It can be further divided into power plant boiler flue gas emission control, industrial boiler and furnace flue gas emission control, typical toxic and harmful industrial waste gas purification, vehicle exhaust emission control, typical indoor and public air pollutants purification, non-organized emission source control, monitoring and decision-making support for complex air pollution, and clean production, among others. From a clean energy perspective, foreign countries have developed and controlled automotive exhaust pollution by actively reforming fuel and combustion structures and developing efficient exhaust treatment devices. At the same time, many countries are also studying and developing specific pollutant reduction and control technologies for industrial production, such as technology to reduce mercury emissions from coal combustion. China is gradually attaching importance to the development of such technology. At present, the related development front mainly includes two parts: the separation and treatment of industrial waste gas and the treatment of exhaust gas from engines. With regard to industrial waste gas treatment, the emphasis is currently on the coordinated disposal of a variety of pollutants, integrated treatment, and deep removal. For automobiles, the development of exhaust purification technology is a key focus.

(5) Automatic monitoring technology of remote sensing radar

The application of remote sensing and radar in meteorological science mainly includes the collection, transmission, and processing of echo data, using the theory of scattering, refraction, and attenuation of radar waves in the atmosphere to study cloud and precipitation physics, detecting weather systems of various scales and clear-sky atmospheric echoes, the quantitative measurement of precipitation, and providing warnings of severe weather. The research work of radar meteorology is divided into three main areas: the study of atmospheric kinematics and dynamics under clear and cloudy conditions using Doppler measurements; the measurement of rainfall and the identification of various water condensate; and the study of precipitation and atmospheric thermal structure with a focus on kinetic-kinematics. At present, remote sensing radar data has been widely used in short-term disaster weather monitoring. However, with the increased frequency of extreme disaster weather events, the automatic monitoring technology of remote sensing radar and the level of radar and sounding intelligence must be developed further. It is necessary to improve the observation layout of weather radars while considering its widespread use for water conservancy, civil aviation, and the military, and to supplement and improve the technology by utilizing the existing, new-generation weather radar stations, with an emphasis on monitoring blank and disaster-prone areas.

(6) Automatic monitoring and early-warning system for disasters

This research, related to meteorology, is a development of traditional research fronts. In recent years, an increasing number of meteorological disasters have occurred, causing significant economic and property damage. Automatic disaster monitoring and early warning systems have become an important aspect of disaster risk mitigation. Presently, the main research focuses include making breakthroughs in the comprehensive meteorological disaster database, mechanisms of meteorological disaster, rapid assessment technology, prediction technology of disaster factors, dissemination early warning information, and the risk management of meteorological disasters. Focusing on different types of disasters, including rainstorms, floods, hurricanes, haze, droughts, and extreme high and low temperatures, will enable the establishment of a comprehensive meteorological disaster database based on large-scale data technology. It will enable researchers to better understand the characteristics, occurrence, development conditions, and disaster-causing mechanisms of meteorological disasters, and to make breakthroughs in remote sensing and rapid identification techniques. In addition, better techniques for meteorological disaster risk prevention, control, and management will be established to achieve disaster prevention and reduction by conducting automatic monitoring and providing early warnings of floods, droughts, earthquakes, surge storms, geological hazards, forest fires, and other disasters. Therefore, developing the fastest and most effective remote sensing methods and techniques, technologies for large data processing of meteorological satellite remote sensing and ground-based meteorological radar, and establishing a comprehensive, national early warning system for meteorological disasters that possesses strong visualization and high security, are the focuses for the disaster mitigation field.

(7) Autonomous underwater vehicles

Ocean underwater observations rely on measurements by sensors and probes to obtain various observation parameters. To conduct real-time or near-real-time underwater detection on a large scale, sensors need to be equipped in autonomously controllable underwater vehicles, including autonomous underwater vehicles (AUVs), autonomous or remotely controlled underwater vehicles, hybrid-driven underwater vehicles, underwater gliders, or wave gliders. The AUV is an integrated, unmanned, non-cable, underwater vehicle equipped with multiple technologies, such as artificial intelligence, detection and identification, information fusion, intelligent control, and system integration, among others. Observation of the underwater environment using AUVs is an increasingly popular area of international research and a key development trend in the field of marine engineering and technology. The main technical directions include improving the movement of AUVs, studying the action constraints of ocean currents on their autonomous behaviors, and studying the cooperative observation and integrative control of multiple vehicles.

Due to the non-cable, remote connection, AUVs can operate at great distances from the launch ship. However, AUVs are restricted by their navigation capabilities, control system, and endurance. Therefore, key breakthrough technologies will focus on developing intelligent navigation systems with strong reliability, high integration, and comprehensive compensation and correction ability, improving the shelf-adaption of control systems, and developing high-efficiency and high-density energy sources for the vehicles.

(8) E-innovation of monitoring techniques for pesticide residues

Traditional qualitative and quantitative methods for monitoring the residues of pesticide chemical pollutants are based on using the corresponding material standards as a reference. However, the world is now firmly in the information age and is increasingly transforming material standards into electronic standards. Generally speaking, by establishing a unique electronic ID for each pesticide, it is possible to realize the electronic and informationization of pesticide residues for detection technology so that traditional, physical monitoring methods can be replaced with electronic ones. A technological leap-forward has also been achieved by moving from traditional targeted detection to the non-targeted screening of pesticide residues. The effectiveness of this method is unparalleled by traditional chromatography or mass spectrometry. Coming decades will mark an epoch of progress for the detection technology of the residues of pesticide chemical pollutants, as technology currently in its infancy is expected to be widely available in 10 or 20 years.

(9) Smart wearable textiles

Smart wearable textiles are textiles that have electronics and interconnections integrated into them, providing a physical flexibility and size that cannot be achieved with other existing electronic manufacturing techniques. Components and interconnections are intrinsic to the fabric and are thus less visible. Smart wearable textiles can more easily adapt to rapid changes in the computational and sensing requirements of any specific application. Wearable systems will be characterized by their ability to automatically recognize the activity and behavioral status of their user, as well as their external environment. In this field, significant attention has been paid to materials and their manufacturing processes; various innovative technologies are emerging which aim to achieve an effective balance between flexibility, ergonomics, low power consumption, integration, and eventually, autonomy.

From an engineering perspective, smart wearable textiles require the knowledge integration of a range of subfields, including textile engineering, materials science, electricity, and control. At present, the main research focuses are one-dimensional flexible conductive yarn, one-dimensional flexible energy storage material, and smart wearable clothing such as flexible sensors, electronic and smart protective clothing, and electronic and smart monitoring clothes.

(10) Ecological leather

Manufacturing more ecologically friendly leather and fur is the most important strategic objective for the domestic and international leather industry. Chrome tanning is currently the most dominant tanning technique in the leather industry because of its excellent properties; however, there are significant environmental impacts associated with the wastewater and solid waste this technique produces. Therefore, it is vitally important to develop a chrome-free, ecological tanning technique to address the problem of chrome pollution caused by leather manufacturing. This is currently a primary research focus of the leather industry.

The main research areas and targets essential to developing chrome-free ecological leather and fur include: ① developing a series of ecological, organic tanning agents to replace conventional chrome tanning agents, and establishing the corresponding application technology with a complete understanding of the mechanisms and structure of organic tanning agents and their potential impacts; ② developing a series of amphoteric re-tanning agents and fatliquoring agents that have a high binding capability and compatibility with the organic tanning system used for ecological leather, and establishing the corresponding application technology based on a complete understanding of the influence of the molecular structure and the charge property regulation of amphoteric dyeing and finishing materials; ③ establishing ecological evaluation methods and standards for multi-component, complex systems that are capable of evaluating the impacts of tanning agents, dyeing and finishing materials, and leather and fur manufacturing processes and products; ④ establishing an integrated ecological leather industry chain by solving the balance problems in leather manufacturing and shortcomings in the industrial chain connection.

Ultimately, technological breakthroughs that will drive the future development of the leather industry will involve exploring new tanning agents, dyeing and finishing materials for manufacturing ecological leather within an integrated industry chain, and establishing ecological evaluation methods and standards for the corresponding leather products.

2.2 Interpretations of three key engineering development fronts

2.2.1 Remediation technology for organic pollution in soils

Remediation technology for organic pollution has developed significantly since the 1970s. Common remediation technologies include phytoremediation, microbial remediation, vapor extractions, thermal desorption, mixed-surfactants enhanced solubilization-washing, chemical oxidation-reduction, fixation-stabilization, electrodynamics remediation, and soil replacement. Of these technologies, physical remediation techniques have the advantage of being highly efficient but are not suitable for large-scale application due to its high cost. Additionally, the oxidant and surfactants used in chemical remediation may cause secondary pollution and further ecological risks. Therefore, bioremediation and cooperated remediation techniques have attracted more attention. The soil remediation industry in China has experienced rapid development and continuous innovation in recent years; to continue this development, it is essential to explore mobile, modularized, highly efficient, and economical soil remediation technologies and equipment that possesses proprietary intellectual property rights.

As shown in Table 2.2.1, China has issued 766 core patents related to remediation technology for organic pollution in soils over the past six years, which comprises 98% of the 780 issued patents issued in this field. As the trends in patent publication between China and the USA reveal, the soil remediation industry in China began 20 years later than in many developed countries. Soil remediation technology in the country developed rapidly as the number of related patents increased exponentially and is driven forward by world-leading R&D investment. In comparison, remediation technology has been well established in developed countries since the 1990s and the number of patents issued has gradually decreased in recent years. Meanwhile, the citation frequency of issued patents on remediation technology was 1.33—much lower than that in the USA and Canada. This statistic also reveals a lack of original techniques, innovation, and influence in the field of remediation technology for organic pollution in soils.

The top 10 patents output institutions were all from China, with 5 universities and research institutions and 5 companies represented (Table 2.2.2). The Qingdao University of

Technology has the largest number of issued patents, with 19 patents focused on the remediation of oil pollution and the combined pollution of heavy metal and organic pollutants. BCEG Environmental Remediation Co., Ltd., established in 2008, Jiangsu Suntime Environmental Remediation Co., Ltd., established in 2010, and Beijing Dingshi Environmental Engineering Co., Ltd. established in 2002, ranked second, third, and fourth respectively, and focused on equipment for ex-situ remediation. Institute of Applied Ecology at Chinese Academy of Science in Shenyang ranked fifth, specializing in the surfactant enhanced, phyto-microbial remediation of organic contaminated soils. Additionally, Zhejiang University, Institute of Soil Science at the Chinese Academy of Science, and Changzhou University ranked sixth, eighth, and tenth, respectively. As shown in Figure 2.2.1, there are no partnership among main countries/regions. As shown in Figure 2.2.2, there was no partnership between the universities, research institutions, and companies. The industry-university-research collaboration still faces significant challenges.

The issued patents over the past six years included remediation equipment for organic pollution in soils and soil additive. Microbial inoculant and composites (biomass and minerals, etc.) are main soil additives, others include biochar and nanomaterials. Remediation equipment for organic pollution in soils focuses on thermal desorption, microbial remediation, and enhanced solubilization-washing.

Table 2.2.1 Countries or regions with the greatest output of core patents on “remediation technology for organic pollution in soils”

No.	Country /Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	766	98.21%	1 015	90.95%	1.33
2	USA	4	0.51%	28	2.51%	7.00
3	Canada	3	0.38%	22	1.97%	7.33
4	South Korea	2	0.26%	1	0.09%	0.50
5	Australia	1	0.13%	47	4.21%	47.00
6	Ireland	1	0.13%	1	0.09%	1.00
7	Israel	1	0.13%	0	0.00%	0.00
8	Japan	1	0.13%	2	0.18%	2.00
9	Netherlands	1	0.13%	0	0.00%	0.00

Table 2.2.2 Institutions with the greatest output of core patents on “remediation technology for organic pollution in soils”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UNQT	19	2.44%	1	0.09%	0.05
2	BER	14	1.79%	16	1.43%	1.14
3	JSER	13	1.67%	22	1.97%	1.69
4	BDEE	11	1.41%	62	5.56%	5.64
5	CSAE	11	1.41%	22	1.97%	2.00
6	UNZH	11	1.41%	53	4.75%	4.82
7	BGET	10	1.28%	0	0.00%	0.00
8	CISS	10	1.28%	47	4.21%	4.70
9	CMEG	10	1.28%	12	1.08%	1.20
10	UNCZ	8	1.03%	3	0.27%	0.38

UNQT: Univ. Qingdao Technological; BER: BCEG Environmental Remediation Co., Ltd.; JSER: Jiangsu Suntime Environmental Remediation Co., Ltd.; BDEE: Beijing Dingshi Environmental Engineering Co., Ltd.; CSAE: Shenyang Applied Ecology Inst.; UNZH: Univ. Zhejiang; BGET: Beijing Geoenviron. Eng. & Technology Inc.; CISS: Inst. Soil Sci. Chinese Acad. Sci.; CMEG: China City Environment Protection Engineering Co., Ltd.; UNCZ: Univ. Changzhou.

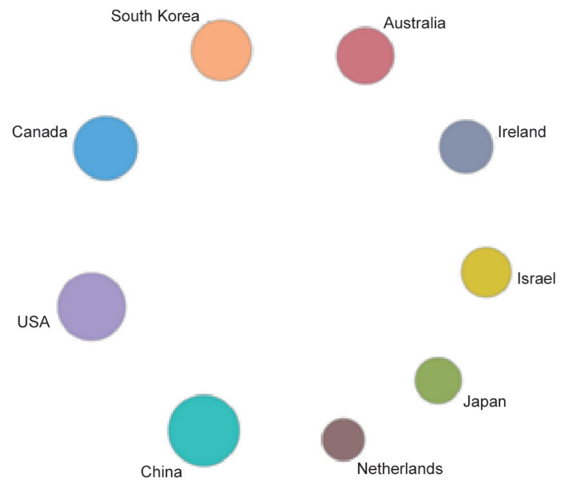

Figure 2.2.1 Collaboration network among main countries/regions on “remediation technology for organic pollution in soils”

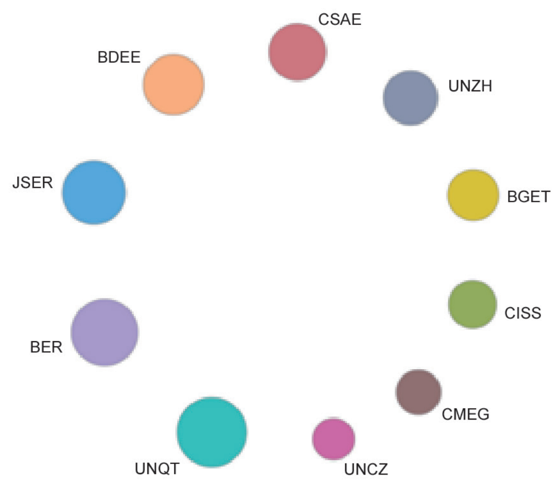

Figure 2.2.2 Collaboration network among main institutions on “remediation technology for organic pollution in soils”

Components were improved and optimized—using electricity, microwaves, solar energy, plasma or other technologies—in thermal desorption and vapor extractions to enhance the decomposition of organic pollutants; however, no mechanism innovation has been discovered. Biochar, nanomaterials, and degradable carbon sources have been used to enhance the mineralization of pollutants in microbial remediation, solubilization-washing, and phytoremediation. Furthermore, reaction conditions are optimized on the patents of chemical oxidation.

Combined remediation techniques have developed rapidly, especially since 2017. Patents for combined remediation techniques and equipment, such as the chemical oxidation-microbial degradation of organic pollutants, surfactant enhanced phyto-microbial remediation of organic pollutants, and electrochemical oxidation, have increased remarkably. These promising combined techniques would be more effective at remediating soils contaminated with a mixture of organic pollutants, and heavy metals, as well as soil-groundwater organic pollution. Developing these will be a future development trend in the field.

2.2.2 Automatic monitoring technology of remote sensing radar

In recent years, with the increasing frequency of extreme weather events, remote sensing radar data has had important applications for short-term disaster weather monitoring; however, some problems still persist. Further development is needed in the areas of the automatic monitoring technology of remote sensing radars and the level of radar and sounding intelligence. In addition, it is necessary to further improve the observation layout of weather radars by considering the diverse needs of water, civil aviation, and the military, and uniformly distributing weather radars throughout the country. Existing weather radar stations must be supplemented and improved, with particular emphasis placed on disaster-prone areas and the monitoring of new-generation weather radars in blank areas. At the same time, according to meteorological disaster prevention needs, all localities should coordinate the layout of local weather radar stations and other ground-based remote sensing observation facilities according to the unified observation methods, technical standards, and data format principles. They should also gradually unify the technical states and the use of remote control or pre-programming to achieve operation control, software upgrades, parameter modification, and online calibration to further enhance the adaptability of the devices’ observation modes. Using its automatic identification function, the equipment automatically adjusts the observation mode according to the external situation. Through these adjustments, it can alter the existing working mode, collect different observation factors from various weather phenomena, and carry out the experimental application of the intelligent observation mode. Through the development of aircraft meteorological observation capabilities and long-time patrol, high-performance, meteorological drones, airborne remote sensing can be carried out over high-altitude, unmanned areas and low-altitude substations. The construction of a special meteorological exploration aircraft with hurricane detection and meteorological satellite-borne flight functions will enable even more comprehensive observation in key areas.

The top 3 countries or regions with the highest number of patents on the engineering development front of “automatic monitoring technology of remote sensing radar” include the USA (126), China (5), and Finland (5), and the top 3 countries or regions with the highest citation frequency are the USA (4345), Finland (115), and Japan (86) (Table 2.2.3).

The top 3 institutions or enterprises with the highest number of patents include GOOG (11), MICT(7), and ITLC (6), and the top 3 institutions with the highest citations per paper are FITBIT INC (54.33), MICT (51.86), and ALARM.COM INC (44.33), which are all from the USA (Table 2.2.4).

Core patents on “automatic monitoring technology of remote sensing radar” are mostly from the USA. Although China is in second place, it is far behind the USA, which indicates that the country should increase investment in this research field and promote relevant research fields to accelerate development efforts in this area.

Figure 2.2.3 shows the collaborative network of the major

Table 2.2.3 Countries or regions with the greatest output of core patents on “automatic monitoring technology of remote sensing radar”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	126	84.56%	4 345	85.48%	34.48
2	China	5	3.36%	62	1.22%	12.40
3	Finland	5	3.36%	115	2.26%	23.00
4	Canada	4	2.68%	59	1.16%	14.75
5	UK	4	2.68%	59	1.16%	14.75
6	Germany	3	2.01%	44	0.87%	14.67
7	Japan	3	2.01%	86	1.69%	28.67
8	South Korea	2	1.34%	36	0.71%	18.00
9	Switzerland	1	0.67%	38	0.75%	38.00
10	France	1	0.67%	43	0.85%	43.00

Table 2.2.4 Institutions with the greatest output of core patents on “automatic monitoring technology of remote sensing radar”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GOOG	USA	11	7.38%	232	4.56%	21.09
2	MICT	USA	7	4.70%	363	7.14%	51.86
3	ITLC	USA	6	4.03%	149	2.93%	24.83
4	DEXM	USA	5	3.36%	171	3.36%	34.20
5	APPY	USA	4	2.68%	73	1.44%	18.25
6	OYNO	USA	4	2.68%	99	1.95%	24.75
7	ALARM.COM INC	USA	3	2.01%	133	2.62%	44.33
8	FITBIT INC	USA	3	2.01%	163	3.21%	54.33
9	FULL RECOVERY INC	USA	3	2.01%	72	1.42%	24.00
10	MEBX	USA	3	2.01%	52	1.02%	17.33

GOOG: Google Inc. or Google LLC; MICT: Microsoft Corporation; ITLC: Intel Corporation; DEXM: Dexcom Inc.; APPY: Apple Inc.; OYNO: Nokia Corporation or Nokia Technologies OY; ALARM.COM INC: Alarm.com Incorporated; FITBIT INC: Fitbit Incorporated; FULL RECOVERY INC: Full Recovery Incorporated; MEBX: State Farm Mutual Automobile Insurance or State Farm Mutual Automobile.

producing countries or regions of core patents with the engineering development focus "automatic monitoring technology of remote sensing radar". Close relationships between the USA and other countries can be found; however, there is no research and development cooperation between individual institutes or enterprises in the field (Figure 2.2.4).

2.2.3 E-innovation of monitoring techniques for pesticide residues

The informationization of pesticide multi-residue monitoring technology includes three aspects: electronic detection technology, intelligent detection data analysis, and risk traceability visualization.

The residue of pesticide chemical pollutants has become one of the most pressing food safety issues around the world. The detection of pesticides in agricultural products sold in China is still widespread, and illegal and highly toxic pesticide residues are still threatening human health. At present, there are more than 1600 kinds of chemical pollutants, including pesticides and PCBs, that are currently detectable. The EU, Japan, and the USA have set strict maximum pesticide limits for 50 000 to 160 000 items and nearly 1000 types of pesticides. Traditional detection techniques and targeted detection methods based on physical standards can no longer meet the needs of current food safety risk monitoring. However, informationization monitoring technology based on accurate quality numbers and full spectrum scanning can accurately inform qualitative analyses of "Target", "Non-Target", and "Unknown" pesticides. Therefore, it is necessary to develop reliable informatization monitoring technology to screen the high throughput of chemical pollutants in food.

In view of the high degree of digitalization, informationization, and automation of high-resolution mass spectrometry detection technology, the resulting data exhibits the 4V's of big data: large volume, variety, high generation velocity, and low-value density characteristics. This presents a significant challenge for the collection, processing, storage, and analysis of pesticide residue data. Therefore, to carry out fast and intelligent analyses of massive amounts of data, a detection technology platform that can be used for the collection, transmission, and statistical and intelligent analysis of pesticide residue data must be developed urgently.

In the context of the current big data era, it is important for the field of pesticide residue analysis to conduct research on the most effective methods for obtaining mass pesticide residue detection data and displaying them directly on a map in real time. Web-GIS technology combined with the application of data statistical analysis methods can innovatively use visual expression methods such as maps, statistical charts, and thematic maps to present the current situation of pesticide residues in China across multiple forms, perspectives, and levels. Using this program, a pesticide residue map can be created to provide an effective tool for tracking pesticide residue risk.

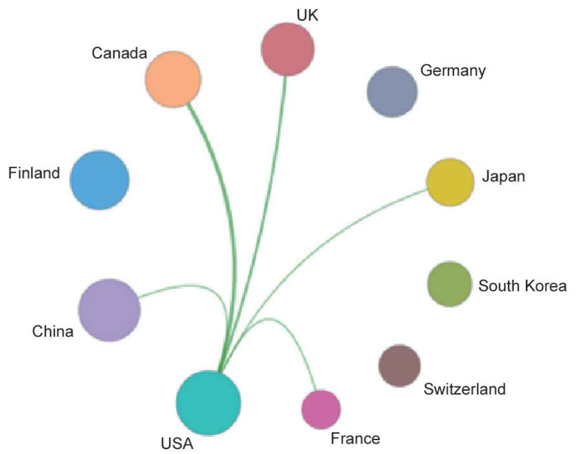

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "automatic monitoring technology of remote sensing radar"

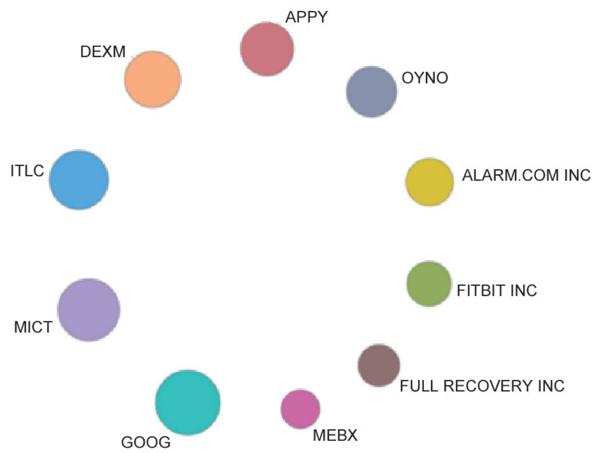

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "automatic monitoring technology of remote sensing radar"

(1) Electronic detection technology refers to the replacement of physical standards with electronic standards (retention time, first-order additive ion accurate mass, isotope distribution and abundance, and secondary fragment accurate mass and spectrum) to qualitatively determine “Target”, “Non-Target”, and “Unknown” pesticides. This will enable a shift from targeted detection to a non-targeted screening of pesticide residues.

A number of key technologies must be developed in this field. ① To establish a theoretical foundation for the high-throughput screening method, researchers must evaluate the mass spectrometric characteristics of 1200 pesticide chemical contaminants worldwide, establish the TOFMS, QE, and NMR accurate mass database, the fragment ion spectrum library, and the NMR library. ② Rapid pretreatment techniques for hundreds of pesticide chemical contaminants in plants, fruits, and vegetables must be established. ③ High-throughput screening methods capable of meeting the requirements of maximum residue limits (MRLs) in the EU, Japan, and the USA must be established to achieve a comprehensive screening of more than 1000 pesticide residues in the sample through one sample preparation and one sample injection—the method performance is unparalleled compared with traditional chromatography and mass spectrometry.

(2) Intelligent detection of test data: a pesticide residue data acquisition system and intelligent analysis system must be created to realize online data collection, result determination, statistical analysis and the automation of a “one-click download” report production.

A number of key technologies to be developed include: ① a basic database to provide the standard and scientific basis for analysis of the pesticide residue detection data and to determine pollution levels; ② the establishment of a data acquisition system to perform automatic uploading of test results, data preprocessing, and pollution level determination, and to build a database of pesticide residue detection results; ③ and the establishment of a data analysis system to correlate pesticide residue detection results database and the basic database, to achieve the automation of single-item and comprehensive statistical analysis of multi-dimensional pesticide residue data, and automation of the report generation of graphical results.

(3) Visualization of risk traceability: Pesticide residue electronic detection technology should be combined with Web-GIS technology to construct a visualization system for pesticide residue risk monitoring.

A number of key technologies to be developed include: ① the research and development of online mapping systems: Web-GIS technology combined with the application of data statistical analysis methods that can innovatively use visual expression methods such as maps, statistical charts, and thematic maps to present the current situation of pesticide residues in China across multiple forms, perspectives, and levels; and ② research and compile paper maps: systematic ideas should be used to integrate spatial information such as the spatial distribution of pesticide residues, types of pesticides, types of agricultural products, residues, toxicity, and conditions over the standards.

Presently, the detection technology of pesticide residues typically combines gas chromatography or liquid chromatography with a selective detector, and low-resolution primary mass spectrometry and secondary mass spectrometry. The common characteristic shared by these methods is that the qualitative identification cannot be separated from the reference of the standard sample. Besides, because of the limitations of the slow scanning speed and dwell time, about 100 compounds can be scanned each time; thus, it takes more than 6 iterations to finish the scanning of 500 compounds. Moreover, it is tedious to compile the data theory method for each collection method.

Statistical analyses of pesticide residues over the past 20 years show that the detection technology has developed from traditional chromatography and mass spectrometry to high-resolution mass spectrometry (HRMS). HRMS uses accurate mass measurements, combined with information on compound retention times and isotope abundance and distribution, to improve the qualitative identification of compounds and reduce the rate of false positives. In full scan mode, the qualitative points are higher than 10 and the sensitivity is high (≤10 μg/kg); it can be used for the rapid qualitative identification of compounds in a complex matrix and the detection of unknown compounds. A high scanning speed of four times per second allows for the simultaneous high-throughput screening of pesticides without being limited by the number of compounds. The identification of isomeric compounds is achieved through the determination of the differences in the species and the abundance of compound fragments. Thus, a clear trend in the field of pesticide multi-residue is to conduct detection based on the accurate mass number of HRMS without the qualitative control of standard samples.

Since 2009, Guofang Pang's research team at the Chinese Academy of Inspection and Quarantine has conducted HRMS in pesticide multi-residue analysis. ① GC/LC-Q-TOFMS has been developed to replace the traditional pesticide multi-residue method based on physical standards with a precise mass number, realizing a significant advancement in the development of pesticide residue detection technology from targeted detection to non-targeted screening. ② A platform for pesticide residue detection technology based on high-resolution mass spectrometry, internet, and data science ternary fusion technology was established. The real-time detection, data collection, management, and intelligent analysis of pesticide residues in edible agricultural products were realized, and the automatic generation of pesticide residue detection reports was achieved. ③ HRMS and GIS fusion technology were established, and a map for visualizing pesticide residue results was created. ④ Big data fusion technology was established to evaluate the risk and warning signs of dietary exposure to pesticide residues, and a special software for the automatic calculation of risk value and multi-dimensional information collection and analysis was developed. Furthermore, the comprehensive and rapid diagnosis of pesticide residue risk was realized. These achievements have initially solved the four major problems facing the field of pesticide residue research in China and provided technical support for the construction of a sound pesticide residue monitoring system.

As shown in Table 2.2.5, China (964), South Korea (20), and the USA (6) are the top three countries with the greatest output of core patents in the front of e-innovation of monitoring techniques for pesticide residues. As shown in Table 2.2.6, the three institutions with the greatest output of core patents are CAIQ (28), CNTA (19), and CAGS (15).

As shown in the collaboration network among major countries/regions in the development front of e-innovation of monitoring techniques for pesticide residues (Figure 2.2.5), cooperation exists between China and the Netherlands as well as Spain and the UK. As shown in the collaboration network among main institutions in this front (Figure 2.2.6), cooperation among the institutions or enterprises is weak or even barely exits.

Table 2.2.5 Countries or regions with the greatest output of core patents on “e-innovation of monitoring techniques for pesticide residues”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	964	96.40%	1 010	91.82%	1.05
2	South Korea	20	2.00%	36	3.27%	1.80
3	USA	6	0.60%	31	2.82%	5.17
4	Taiwan of China	3	0.30%	0	0.00%	0.00
5	Spain	2	0.20%	13	1.18%	6.50
6	Japan	2	0.20%	8	0.73%	4.00
7	Germany	1	0.10%	2	0.18%	2.00
8	UK	1	0.10%	0	0.00%	0.00
9	India	1	0.10%	0	0.00%	0.00
10	Netherlands	1	0.10%	4	0.36%	4.00

Table 2.2.6 Institutions with the greatest output of core patents on “e-innovation of monitoring techniques for pesticide residues”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CAIQ	China	28	2.80%	5	0.45%	0.18
2	CNTA	China	19	1.90%	44	4.00%	2.32
3	CAGS	China	15	1.50%	50	4.55%	3.33
4	Beosen Jiangsu Food Safety Technology Co	China	14	1.40%	0	0.00%	0.00
5	Guangzhou Jindian Jingfang Pharm Co Ltd	China	12	1.20%	0	0.00%	0.00
6	XRES	China	11	1.10%	1	0.09%	0.09
7	Runtivo Biological Technology Beijing Co	China	9	0.90%	14	1.27%	1.56
8	UYJS	China	9	0.90%	5	0.45%	0.56
9	Qingdao Baolikang New Materials Co Ltd	China	8	0.80%	8	0.73%	1.00
10	UCAG	China	8	0.80%	17	1.55%	2.13

CAIQ: Chinese Academy of Inspection and Quarantine; CNTA: China National Tobacco of Chinese Academy of Agricultural Sciences; CAGS: Chinese Academy of Geological Sciences; XRES: Wuxi X Research Product Design & Research Co., Ltd.; UYJS: Jiangsu University; UCAG: China Agricultural University.

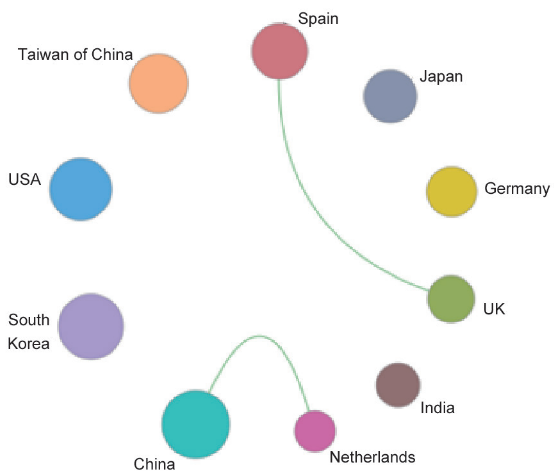

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “e-innovation of monitoring techniques for pesticide residues”

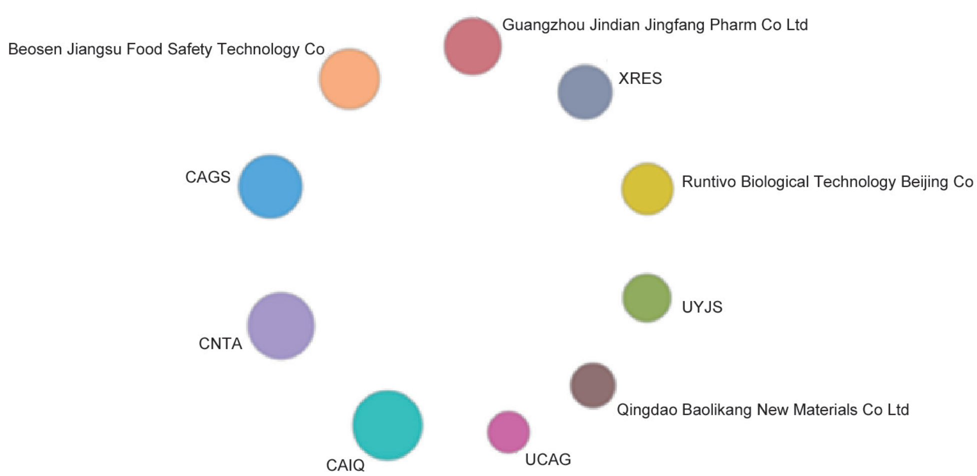

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “e-innovation of monitoring techniques for pesticide residues”

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VII. Agriculture

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts assessed by the field of agricultural engineering research are classified into the following three categories.

In-depth established research fronts: “impact of climate change on crop production” of agricultural resource science, “soil microbial diversity and biological nitrogen fixation” of applied ecology, “plant diversity and global biosecurity” of applied ecology, “plant diversity and global biosecurity” of agricultural resource science, “heavy-metal pollution in soil and stress on crops” of agricultural resource science, “crop nutrition supply and agricultural sustainable development” of crop science, and “impact of forest structure on forest carbon cycle” of forestry engineering.

Newly emerging research fronts: “crop breeding by molecular design” of crop science, “intelligent agricultural equipment” of agricultural engineering, and “mechanism of plant response to biotic and abiotic stress” of agricultural resource science.

Ground breaking research front: “CRISPR/Cas9 genome editing in agricultural biotechnology” of agricultural bioengineering.

Important research fronts are established by a number of core papers, with an average of 123 papers per front. The highest number of papers (491) was written in the area of the “intelligent agricultural equipment” and the lowest number of papers (18) was in the area of “response mechanisms of plants to biotic and abiotic stress.” the majority of the surveyed papers were published in August 2014 (Table 1.1.1) with the average number of citations per papers 82 times greater. During 2012–2017, there were no obvious changes in the number of papers published for eight of the 10 research fronts. However, the number of published papers in the area of the “CRISPR/Cas9 genome editing in agricultural biotechnology” and the “intelligent agricultural equipment” showed a clear increasing trend (Table 1.1.2).

Table 1.1.1 Top 10 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Crop breeding by molecular design	70	5 829	83.27	2014.23	–	–
2	CRISPR/Cas9 genome editing in agricultural biotechnology	157	17 299	110.18	2015.20	–	–
3	Intelligent agricultural equipment	491	2 213	4.51	2015.37	–	–
4	Impact of climate change on crop production	63	6 457	102.49	2014.51	–	–
5	Soil microbial diversity and biological nitrogen fixation	215	18 377	85.47	2014.54	–	–
6	Plant diversity and global biosecurity	70	6 190	88.43	2014.74	–	–
7	Heavy metal pollution in soil and stress on crops	26	2 639	101.50	2015.12	–	–
8	Crop nutrition supply and agricultural sustainable development	60	4 028	67.13	2014.65	–	–
9	Mechanism of plant response to biotic and abiotic stress	18	1 330	73.89	2014.61	55.60%	0
10	Impact of forest structure on forest carbon cycle	56	5 695	101.70	2014.34	–	–

Table 1.1.2 Annual number of core papers published for each of the top 10 engineering research fronts in agriculture

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Crop breeding by molecular design	15	11	14	10	13	7
2	CRISPR/Cas9 genome editing in agricultural biotechnology	7	17	26	32	38	37
3	Intelligent agricultural equipment	26	44	71	73	133	144
4	Impact of climate change on crop production	8	13	11	12	8	11
5	Soil microbial diversity and biological nitrogen fixation	38	34	34	31	38	40
6	Plant diversity and global biosecurity	11	9	10	12	13	15
7	Heavy metal pollution in soil and stress on crops	1	5	3	5	5	7
8	Crop nutrition supply and agricultural sustainable development	10	6	9	15	10	10
9	Mechanism of plant response to biotic and abiotic stress	1	3	4	4	6	0
10	Impact of forest structure on forest carbon cycle	9	12	6	13	12	4

The top 10 engineering research fronts are summarized below based on the number of publications.

(1) Crop breeding by molecular design

Molecular-design breeding of major crops belongs to the field of crop science, and is a newly emerging research front. Generally, molecular-design breeding can be divided into directed, systematic and designed molecular breeding. More precisely, molecular breeding integrates the physiological, biochemical, biostatistical and genetic information of the crop-breeding process using bioinformatics as the platform, and the genomic and proteomics databases are used as its foundation. First, the optimal breeding program for a specific crop is designed based on the breeding target and the growth environment. Next, molecular breeding experiments are conducted. Molecular breeding is a technique that integrates multiple scientific and technological areas to simulate and optimize various factors during the breeding process. It identifies the optimal genotypes that are required to meet the breeding objectives, and provides parent- and progeny-selection strategies for achieving the desired genotypes. Molecular breeding significantly improves the predictability and effectiveness of crop breeding, thus transforming the conventional “experimental breeding” into a highly effective “precision breeding.”

(2) CRISPR/Cas9 genome editing in agricultural biotechnology

The clustered regularly interspaced short palindromic repeats/CRISPR-associated protein (CRISPR/Cas9) genome editing belongs to the field of agricultural bioengineering. This disruptive technology is a ground breaking research front. Genome editing technology involves the use of endonucleases to cleave deoxyribonucleic acid (DNA) at specific sites, producing double-strand DNA breaks, thus inducing DNA-damage repair. The result is a targeted gene modification. CRISPR/Cas9 is an accurate, highly efficient, and versatile genome-editing tool. CRISPR is a repetitive sequence of regular, clustered, short palindromes that are present in bacteria and archaea. This naturally occurring, ancient defense mechanism relies on a ribonucleic acid (RNA)-guided Cas9 protein to recognize and cut the target sequence, creating a double-strand DNA break. This is a highly specialized immune response mechanism that allows an organism to resist the invasion of foreign genetic material, such as plasmids and viruses. CRISPR/Cas9 technology speeds up the breeding process, solving the problem of the long generation-time encountered in standard breeding.

(3) Intelligent agricultural equipment

This is a newly emerging research front in the field of agricultural engineering. The development of intelligent control technology for agricultural equipment focuses on the development and expansion of information technology for use in sensors, communication systems, computer vision and image-processing. Examples for sensors include those used for vehicle steering, lowering and raising of surface implements, hydraulic systems for position and pressure-depth. Examples for image monitoring systems include those used for maturity determination based on crop characteristics, seedling thinning and weeding devices that utilize integrated image processing with a visual-sensing function (automatic visual inspection systems), and computer vision and image-processing technology (stereoscopic vision systems) used during the coordinated multi-machine operation of combine harvester-grain cart systems (consisting of the radio load-control of harvester-granary and grain-conveyor speed controllers) to improve the threshing mechanism and the grain-collection performance of combine harvesters.

(4) Impact of global climate change on crop production

This is an in-depth established research front in the field of agricultural resources science. Global climate change or global warming refers primarily to the rise in the average temperature of the global climate system owing to the excessive emission of greenhouse gases, such as carbon dioxide, due to human activity. Global climate change is expected to ① change the growth environment, seriously affect crop production and sustainable agricultural development, ② impact crop cultivation areas and change cropping systems, and ③ affect the cost and management methods of agricultural production. To cope with the impact of climate change, new strategies, theories, methods and technologies are required to establish new scientific, technological and production systems for crop cultivation.

(5) Soil microbial diversity and biological nitrogen fixation

This is an in-depth established research front in the field of applied ecology. The nitrogen cycle is closely related to agricultural production and the ecological environment. The application of nitrogen fertilizers increases crop yield. At the same time, fertilizer runoff disrupts the natural balance of nitrogen leading to global environmental problems. Numerous studies have shown that the natural nitrogen cycle is facilitated by microorganisms. Some bacteria can convert atmospheric nitrogen into ammonia by employing a process referred to as nitrogen fixation. Abundant in nature, nitrogen-fixing bacteria can be categorized as free-living, symbiotic and associative. Nitrification is a biological process in which ammonium nitrogen is used directly as a substrate, and it is a key step in the nitrogen cycle. Nitrification is caused by bacteria and archaea, and it is generally performed symbiotically by ammonia and nitrite oxidizers. Theoretical studies of biological nitrogen fixation have focused on the optimal conditions responsible for inducing the nodulation of non-legume crops and improving the efficiency of symbiotic nitrogen fixation. Some of the research areas include effective methods for inducing the formation of symbiotic nodules in key crops using rhizobium invasion, improving the efficiency of the symbiotic nodules of non-legume crops, and the path, the induction site, and the symbiotic mechanism of *Rhizobium* induced into non-legume host cells. The basic and applied research has focused primarily on developing new nitrogen-fixing plants, for example, by using biotechnology to transform nitrogen-fixing bacteria and existing crops to facilitate the formation of the symbiotic relationship between the new bacteria and the new crops, thus improving their nitrogen-fixing efficiency.

(6) Plant diversity and global biosecurity

This is an in-depth established research front in the field of applied ecology. Plant diversity includes species, genetic and ecological diversity. The analysis of the mechanisms behind biodiversity generation and the use of various scales to explain the factors that contribute to plant diversity patterns enable us to have a better understanding of the neutral and niche processes that are responsible for the coexistence of species, and helps to recognize potential threats to global biodiversity.

(7) Heavy-metal pollution in soil and stress on crops

This is an in-depth established research front in the field of agricultural resources science. Heavy-metal pollution refers to environmental pollution caused by heavy metals or their compounds, and is primarily due to human factors such as mining, exhaust emissions, sewage irrigation and products with excessive heavy-metal content. Heavy metals are defined as metallic elements with a density exceeding 4.5 g/cm^3. The most common heavy metals include lead, cadmium, mercury, chromium, and the metalloid arsenic. Heavy-metal pollution directly affects agricultural production and food safety, thus endangering the human habitat, and it is one of the most serious ecological and environmental problems currently being faced globally. There are few visible signs of heavy-metal pollution in farming. However, heavy metals are highly toxic, and their chemical behavior and ecological effects are complex. They remain in soil for a long time, and are absorbed by crops and are transferred into the food chain, or migrate into water bodies and the atmosphere. Thus, heavy-metal pollution poses a significant threat to human survival and sustainable development. Given its damaging effect on the environment, food safety and agricultural development, heavy-metal pollution of farmlands has become an important research front in the areas of environmental science and other related fields. The effects of heavy metals on crops are mainly reflected in the crop growth and development process, the physiological and biochemical indices, as well as crop yield and quality. At present, there are two types of remediation techniques for heavy-metal contaminated soil. One is to directly remove the heavy-metal contaminated soil, while the other involves changing the form of the heavy metals in soil to reduce their activity, mobility, and bioavailability. Remediation methods can be categorized as physical, chemical, electrical and biological methods.

(8) Crop nutrition supply and agricultural sustainable development

This is an in-depth established research front in the field of crop science. In agriculture, soil is the basic means of production, and is the foundation of crop growth. The support of fertilizers is required to improve soil fertility. Therefore, ensuring a stable supply of soil fertilizers and improving the efficiency of their use is the key to realizing sustainable agricultural development. In addition, improving the distribution of soil fertilizers, preventing environmental pollution and arable land degradation, and meeting the nutritional requirements of crops through rational fertilization are essential for achieving green agricultural development. The composition of soil should be thoroughly tested before applying a specific fertilization treatment. For highly fertile soils, ensuring high productivity and the efficient recycling of nutrients are important areas of research.

(9) Mechanism of plant response to biotic and abiotic stress

This is a newly emerging research front in the field of agricultural resources science. The important research front diagram reveals two major areas of research: biotic and abiotic stress. Of these types, biotic stressors include insects (herbivory) and gray mold (fungus). The main research directions include defense-response, immune response, systemic acquired resistance, induced resistance and signal transduction. In the area of abiotic stress, the most commonly researched factors and fronts include drought, reactive oxygen species, high temperature, salt, oxidative stress and osmotic stress. The research involves content such as the role of abscisic, salicylic, and jasmonic acids in hormone signaling. It also includes major areas such as photosynthesis, stomatal conductance, and antioxidant enzyme systems. With respect to the methods employed, gene expression, transcription factors and transcriptional regulation remain the focus of this research. At the same time, modern “omics” fields, including transcriptomics and proteomics, are also important areas of research.

(10) Impact of forest structure on forest carbon cycle

This is an in-depth established research front in the field of forestry engineering. The carbon cycle has significant impacts at a global scale, especially climate warming. As forest ecosystems are a principal component of the terrestrial biosphere, changes in the carbon cycle of forest ecosystems have become an important research area in the field of global change. Research into the carbon cycle of forest ecosystem involves experimental methods such as biomass inventory, micrometeorology, the carbon-isotope technique, and geo-information science methods and modeling. Carbon sequestration and carbon-density distribution show large regional and spatiotemporal differences in forest vegetation and soil. In addition, the effect of environmental factors changes in different seasons. Therefore, research into carbon-cycle dynamics in forest ecosystems generally adopts a regional-scale transect carbon source/sink structure as the basis for the development of mainstream methodologies, including spatiotemporal quantification, acquisition of geo-information and modeling. Its goal is to quantitatively analyze the effect of human activity on the carbon budget of forest ecosystems, and to investigate the changes in the carbon cycle in these systems under global climate change. These unique carbon-cycle models for forest ecosystems have helped to broaden the application of modern science and technology, in areas such as computer technology and remote sensing, in the field of forest ecology.

1.2 Interpretations for three key engineering research fronts

1.2.1 Crop breeding by molecular design

The concept of molecular breeding was first proposed in 2003 by the Dutch scientists Peleman and van der Voort. The rapid development of the whole-genome sequencing technology and the significant progress in research on plant functional genomics have made it possible to conduct molecular design and breeding of crop cultivars at the whole-genome level, thus setting the direction of future development of crop-breeding technology. At the core of molecular breeding is the understanding of key genes, which control important agronomic traits, and their regulatory networks. Biotechnology and other methods are used to acquire or develop elite germplasm resources for use as components of molecular design. The appropriate design components are selected based on the breeding objectives, and are assembled using system-biology methods to cultivate new crop varieties. Compared with standard breeding, molecular-design breeding allows for the precise regulation of agronomic traits at the genetic level, and solves the problem of linkage drag. In addition, it shortens the breeding cycle, thus greatly increasing the breeding efficiency. Compared with molecular marker-assisted breeding, molecular-design breeding is more precise and offers more control. At present, a new generation of genomic-selection breeding technologies, such as zinc-finger nucleases, transcription activator-like effector nucleases (TALENs), CRISPR/Cas9, and oligonucleotide-directed mutagenesis, are being refined. These technologies are expected to be the core of future molecular-design breeding. Molecular-design breeding consists of the following three main steps. (1) Researching the target-trait genes and the relationship between genes, including the genetic population structure, polymorphic marker screening, genetic linkage map construction, and phenotypic and genetic analysis of quantitative traits. (2) Designing the target genotype based on the breeding objectives, under various ecological environment conditions. This step involves using the genetic information of important breeding traits (such as chromosome location and genetic effects of genes, gene-to-trait expression pathways and biochemical networks, gene-gene interaction, the interaction between the genes, and the genetic background and the environment) that have already been identified to simulate the phenotypes of various possible genotypes, so that the genotypes that satisfy specific breeding objectives can be selected. (3) Formulation of specific breeding programs. At present, many obstacles need to be overcome to achieve the full benefits of molecular-design breeding. For example, there is a need for a more accurate analysis of the highly intricate genetic pathways. In addition, a high throughput and accurate identification of crop phenotypic traits are required.

An analysis of relevant academic papers is presented below. According to the table of distribution by country (Table 1.2.1), the USA contributed the majority of core papers, accounting for about 39% of a total of 27 papers, with the citation rate exceeding 50%. In addition, Australia, Germany and France also had a relatively high number of core papers. In terms of research institutions (Table 1.2.2), Cornell University (USA) and ICRISAT were the main contributors. It is evident from the collaboration diagram (Figure 1.2.1) that there was close collaboration between the USA and France. Also, ICRISAT in India and CIMMYT in Mexico also cooperated frequently (Figure 1.2.2). With only five papers published, the Chinese Academy of Sciences had a relatively small number of core papers and frequently cited papers (Figure 1.2.2). The USA, China and Australia had the highest number of cited core papers (Table 1.2.3). In addition, the Agricultural Research Service, US Department of Agriculture had the highest output, accounting for about 22% of the total (Table 1.2.4).

Table 1.2.1 Countries or regions with the greatest output of core papers on the “crop breeding by molecular design”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	27	38.57%	2 897	49.70%	107.30
2	Australia	15	21.43%	1 233	21.15%	82.20
3	Germany	12	17.14%	1 159	19.88%	96.58
4	France	12	17.14%	706	12.11%	58.83
5	China	10	14.29%	1 067	18.31%	106.70
6	India	10	14.29%	1 055	18.10%	105.50
7	Mexico	10	14.29%	1 178	20.21%	117.80
8	Japan	7	10.00%	333	5.71%	47.57
9	Spain	5	7.14%	857	14.70%	171.40
10	Canada	4	5.71%	624	10.71%	156.00

An in-depth analysis of supporting data revealed that the highly cited representative paper entitled “A high-density SNP genotyping array for rice biology and molecular breeding” published in 2014 in *Molecular Plant* was cited 68

Table 1.2.2 Institutions with the greatest output of core papers on the “crop breeding by molecular design”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Cornell Univ	10	14.29%	1 422	24.40%	142.20
2	Int Crops Res Inst Semi Arid Trop	9	12.86%	1 001	17.17%	111.22
3	Int Maize & Wheat Improvement Ctr	9	12.86%	1 077	18.48%	119.67
4	USDA Agr Res Service	7	10.00%	977	16.76%	139.57
5	Univ Western Australia	6	8.57%	628	10.77%	104.67
6	Chinese Acad Agr Sci	5	7.14%	317	5.44%	63.40
7	Kansas State Univ	3	4.29%	365	6.26%	121.67
8	Donald Danforth Plant Sci Ctr	3	4.29%	261	4.48%	87.00
9	Leibniz Inst Plant Genet & Crop Plant Res	3	4.29%	221	3.79%	73.67
10	Limagrain Europe	3	4.29%	170	2.92%	56.67

Table 1.2.3 Countries or regions with the greatest output of citing papers on the “crop breeding by molecular design”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	1 393	28.72%	2015.81
2	China	838	17.28%	2016.18
3	Australia	543	11.20%	2015.71
4	India	444	9.15%	2015.78
5	Germany	429	8.85%	2015.60
6	France	324	6.68%	2015.65
7	Canada	258	5.32%	2015.67
8	UK	252	5.20%	2015.97
9	Brazil	200	4.12%	2015.84
10	Mexico	169	3.48%	2015.66

Table 1.2.4 Institutions with the greatest output of citing papers on the “crop breeding by molecular design”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	USDA Agr Res Service	313	20.85%	2015.89
2	Int Crops Res Inst Semi Arid Trop	164	10.93%	2015.56
3	Cornell Univ	155	10.33%	2015.45
4	Int Maize & Wheat Improvement Ctr	143	9.53%	2015.73
5	Chinese Acad Sci	137	9.13%	2016.20
6	Ins Nat Rec Agr	134	8.93%	2015.44
7	Chinese Acad Agr Sci	127	8.46%	2016.19
8	Univ Western Australia	113	7.53%	2016.04
9	Univ Queensland	109	7.26%	2015.67
10	Kansas State Univ	106	7.06%	2015.75

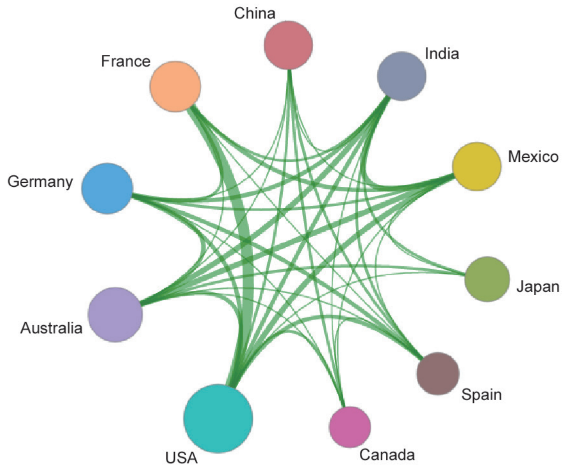

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "crop breeding by molecular design"

times. One of the most important papers was "crop breeding chips and genotyping platforms: progress, challenges, and perspectives" published in 2017 in *Molecular Plant*. The most important research institutions included the Chinese Academy of Agricultural Sciences, ICRISAT and Cornell University. A high-frequency keyword analysis revealed that genomic selection, SNP and QTL were the main focuses of scientific research.

1.2.2 CRISPR/Cas9 genome editing in agricultural biotechnology

The emergence of genome-editing technology has led to a new global-scale trend in research. In 2012, it was listed as one of the top 10 scientific breakthroughs in the *Science*, and in 2014, it was selected by *Nature Methods* as one of the top

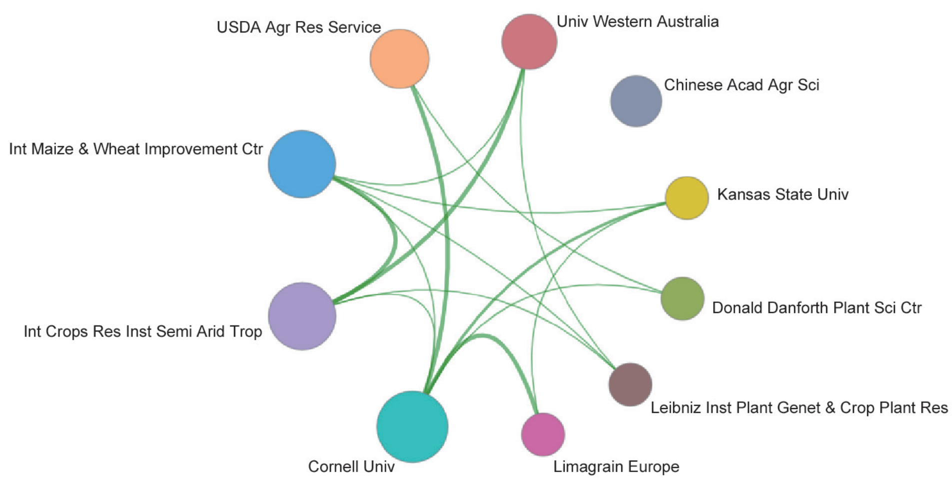

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "crop breeding by molecular design"

10 most influential methods in biological research over the previous decade. Genome-editing technology involves the use of endonucleases to cleave DNA at specific sites, producing double-strand DNA breaks and thereby inducing DNA-damage repair. The result is a targeted gene modification. The use of this technology speeds up the breeding process, solving the problem of long generation-time encountered in standard crossbreeding. At the same time, because the artificial mutation efficiency increase changed the natural evolution of crops, the environmental and food-safety risks of the genome-edited plans also increased. Four generations of gene-editing tools have already been developed and improved: the ZFNs, TALENs, MGN (meganucleases) and CRISPR/Cas9 systems.

CRISPR/Cas9 is an accurate, highly efficient and versatile genome-editing tool. The basic principle of this editing tool is that the single-guide RNA (sgRNA) recognizes the three conserved nucleotides NGG (N being any nucleotide), called the protospacer adjacent motif (PAM) sequence, in the foreign genome. The sgRNA then guides the Cas9 protein to cleave the DNA strands upstream of the PAM. The double-stranded break in the DNA is repaired through non-homologous end joining, sometimes leading to insertions and deletions of base pairs. As a result, a frameshift mutation of the gene occurs, thus achieving a knockout of that gene. The CRISPR sgRNA requires a sequence of only 20 nucleotides to recognize the target PAM sequence, allowing the Cas9 monomeric protein to function. Compared with other types of gene-editing tools, the CRISPR/Cas9 system is easier to use. In addition, it has a higher knockout efficiency, allowing for more precise gene-editing and significantly reducing the off-target activity. The CRISPR/Cas9 has been widely used to edit important genes of animals and plants.

An analysis of relevant academic papers revealed the following. In terms of distribution by country (Table 1.2.5), the USA, China and Germany contributed the majority of core papers. The USA, China and Germany also had the highest number of citations. In terms of research institutions (Table 1.2.6), the Chinese Academy of Sciences ranked first with 11 core papers, but it had the third largest number of total citations, and was fifth in the average number of citations per paper. It is evident from the country collaboration diagram (Figure 1.2.3) that the USA cooperated most closely with China and Germany, having a leading role in research. The collaboration diagram of main research institutions (Figure 1.2.4) shows that the Chinese Academy of Sciences cooperated closely with the University of the Chinese Academy of Sciences, and had a degree of collaboration with the University of Minnesota (USA). The USA and China had the highest number of cited core papers. In addition, the proportions of cited core papers of these two countries far exceeded those of other countries or regions (Table 1.2.7). The combined number of cited core papers of the Chinese Academy of Sciences and the University of the Chinese

Table 1.2.5 Countries or regions with the greatest output of core papers on the “CRISPR/Cas9 genome editing in agricultural biotechnology”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	74	47.13%	10 028	57.97%	135.51
2	China	30	19.11%	2514	14.53%	83.80
3	Germany	21	13.38%	2297	13.28%	109.38
4	UK	17	10.83%	930	5.38%	54.71
5	Japan	12	7.64%	872	5.04%	72.67
6	South Korea	11	7.01%	1351	7.81%	122.82
7	Netherlands	8	5.10%	1255	7.25%	156.88
8	Australia	8	5.10%	857	4.95%	107.13
9	Italy	8	5.10%	686	3.97%	85.75
10	France	8	5.10%	407	2.35%	50.88

Table 1.2.6 Institutions with the greatest output of core papers on the “CRISPR/Cas9 genome editing in agricultural biotechnology”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Chinese Acad Sci	11	7.01%	1706	9.86%	155.09
2	Univ Minnesota	7	4.46%	395	2.28%	56.43
3	Iowa State Univ	6	3.82%	458	2.65%	76.33
4	Massachusetts Ins Tech	5	3.18%	2274	13.15%	454.80
5	Univ Calif Berkeley	5	3.18%	1895	10.95%	379.00
6	Seoul Natl Univ	5	3.18%	1103	6.38%	220.60
7	Univ Calif Davis	5	3.18%	533	3.08%	106.60
8	Harvard Med Sch	5	3.18%	179	1.03%	35.80
9	Vanderbilt Univ	4	2.55%	634	3.67%	158.50
10	Univ Chinese Acad Sci	4	2.55%	408	2.36%	102.00

Academy of Sciences approached 900, whereas the citation rate of the core papers exceeded 40% (Table 1.2.8).

An in-depth analysis of supporting data revealed that 40 papers were cited more than 200 times, of which eight papers were cited more than 500 times. The article "Genome engineering using the CRISPR/Cas9 system" published in 2013 in *Nature Protocols* was cited more than 1900 times. Also, the paper entitled "Development and applications of CRISPR/Cas9 for genome engineering" published in 2014 in *Cell* was cited nearly 1600 times. These two articles laid the foundation for the CRISPR/Cas9 system to become the leading gene-editing technology. At present, the CRISPR/Cas9 technology is widely applied in genomes of organisms such as humans, *Arabidopsis*, yeast, mice and fruit flies. Also, it has been

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "CRISPR/Cas9 genome editing in agricultural biotechnology"

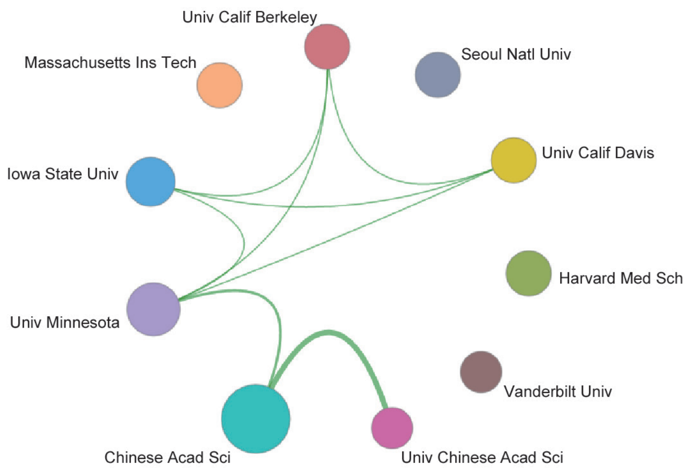

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "CRISPR/Cas9 genome editing in agricultural biotechnology"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "CRISPR/Cas9 genome editing in agricultural biotechnology"

No.	Country/Region	Citing core papers	Percentage of citing papers	Mean year
1	USA	4 318	36.55%	2016.22
2	China	2 291	19.39%	2016.45
3	Germany	1 050	8.89%	2016.33
4	UK	878	7.43%	2016.25
5	Japan	690	5.84%	2016.10
6	France	621	5.26%	2016.33
7	Australia	553	4.68%	2016.26
8	Netherlands	506	4.28%	2016.22
9	Canada	499	4.22%	2016.41
10	Italy	408	3.45%	2016.29

Table 1.2.8 Institutions with the greatest output of citing papers on the “CRISPR/Cas9 genome editing in agricultural biotechnology”

No.	Institution	Citing core papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	625	29.69%	2016.20
2	Univ Chinese Acad Sci	251	11.92%	2016.42
3	Harvard Univ	213	10.12%	2015.58
4	Univ Calif Berkeley	173	8.22%	2016.01
5	Harvard Med Sch	166	7.89%	2016.90
6	Massachusetts Ins Tech	154	7.32%	2015.98
7	Chinese Acad Agr Sci	149	7.08%	2016.71
8	Univ Calif San Diego	125	5.94%	2016.40
9	Stanford Univ	125	5.94%	2016.34
10	Univ Calif Davis	124	5.89%	2016.15

successfully used in the genomes of economically important animals, including cattle, pigs and sheep as well as important crops, such as wheat, sorghum, rice and maize, thus achieving targeted genome editing. The analysis of high-frequency words revealed that CRISPR/Cas9, TALENs, and microbial population were the front areas of scientific research.

1.2.3 Intelligent agricultural equipment

The development of intelligent agricultural equipment control technology focuses on the development and expansion of various information technologies, including sensors, communication systems, image-processing systems and computer vision. For this research front there are four major research areas. (1) Specialized sensors: research on new principles, methods, and technology for agricultural sensors; the theory and technology of multi-sensor information fusion and measurement; and agricultural sensor networks. (2) Agricultural bioinstruments: research and development of animal and plant bioinformation monitoring sensors and devices; precision breeding equipment and information technology products; and animal and plant microphysiological-information testing equipment. (3) Intelligent agricultural machinery: research on precise variable-rate control, navigation, and real-time operation-monitoring technologies. The development of agricultural intelligent equipment that supports precise farming operations. (4) Agricultural robots: research on bionic principles; design of fundamental components; optimization paths; intelligent control; and decision-support algorithms. The development of model robotic-systems for farming operations. Research on developments in 2017 revealed that most of the patents that are related to the present study came from China and the USA. China accounted for about 75% of all patents, while the USA accounted for less than 25%. However, the ratio of patent citations is just the opposite, indicating that despite having fewer patents, the USA had a significant influence in this area. In terms of contributing institutions, Hunter Industries (USA) and China Agricultural University were the major contributors to patents. Also, USA and Canadian institutions collaborated significantly. At present, while the existing equipment meets the agricultural needs at various levels, further research and development are required. Future research directions are expected to include digital design, simulation systems and testing platforms of intelligent equipment; agricultural sensors, agricultural robots and navigation control technology with microelectromechanical systems; and the integration of advanced information technology (such as the Internet of Things, big data, cloud computing and cloud services) into the design of intelligent agricultural equipment.

An analysis of relevant academic papers revealed the following. In terms of distribution by country (Table 1.2.9), the majority of core articles was contributed by China and the USA. Although the contribution of core papers from Spain was less than half that from China, it ranked first with respect to the number of cited papers. In terms of research institutions (Table 1.2.10), the distribution of core papers was relatively randomly distributed, with no particularly strong contributors.

The country collaboration diagram (Figure 1.2.5) reveals that there was frequent collaboration between the USA and China as well as the USA and India. In addition, Spain and Italy also collaborated closely. The institution collaboration diagram (Figure 1.2.6) shows that only the University of Sydney (Australia) and the University of São Paulo (Brazil) collaborated closely. China ranked first in terms of the number of core papers contributed in this research direction. However, it ranked only fifth in terms of the number of cited papers and its average citation rates also lagged behind those of other countries (Table 1.2.11). The Chinese Academy of Sciences was the largest contributor of cited core papers (Table 1.2.12).

An in-depth analysis of supporting data revealed that Chinese scientists produced more research papers on intelligent agricultural equipment than in other areas. In addition, the number of conference papers was also relatively high. A high-frequency keyword analysis revealed that unmanned aerial vehicle, system integration and precision farming were the fronts on interest by the scientific community in this field.

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The top 10 engineering development fronts assessed by the field of agricultural engineering research are classified into the following three categories.

Ground breaking development front: “utilization technology

Table 1.2.9 Countries or regions with the greatest output of core papers on the “intelligent agricultural equipment”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	85	17.31%	185	8.36%	2.18
2	USA	64	13.03%	274	12.38%	4.28
3	Spain	43	8.76%	386	17.44%	8.98
4	India	40	8.15%	26	1.17%	0.65
5	Germany	35	7.13%	188	8.50%	5.37
6	Japan	24	4.89%	22	0.99%	0.92
7	Italy	23	4.68%	293	13.24%	12.74
8	Australia	21	4.28%	136	6.15%	6.48
9	Israel	18	3.67%	163	7.37%	9.06
10	Netherlands	15	3.06%	223	10.08%	14.87

Table 1.2.10 Institutions with the greatest output of core papers on the “intelligent agricultural equipment”

No.	Institution	Number of core papers	Fraction of core papers	Total citation	Fraction of citations	Citations/paper
1	Ben Gurion Univ Negev	9	1.83%	96	4.34%	10.67
2	Univ Florida	9	1.83%	49	2.21%	5.44
3	Univ Tecn Federico Santa Maria	8	1.63%	36	1.63%	4.50
4	Univ Sydney	8	1.63%	29	1.31%	3.63
5	Consejo Superior Invest Cient	7	1.43%	158	7.14%	22.57
6	Nanjing Agr Univ	7	1.43%	42	1.90%	6.00
7	Agr Res Org	7	1.43%	41	1.85%	5.86
8	Hokkaido Univ	7	1.43%	10	0.45%	1.43
9	Univ Sao Paulo	7	1.43%	12	0.54%	1.71
10	Wageningen Univ	6	1.22%	87	3.93%	14.50

Table 1.2.11 Countries or regions with the greatest output of citing papers on the "intelligent agricultural equipment"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	309	24.72%	2016.59
2	USA	252	20.16%	2016.53
3	Spain	143	11.44%	2016.33
4	Australia	117	9.36%	2016.65
5	Germany	110	8.80%	2016.28
6	Italy	84	6.72%	2016.12
7	UK	66	5.28%	2016.64
8	France	65	5.20%	2016.46
9	Canada	52	4.16%	2016.42
10	Japan	52	4.16%	2016.50

Table 1.2.12 Institutes with the greatest output of citing papers on the "intelligent agricultural equipment"

No.	Institutions	Citing papers	Percentage of citing papers	Mean year
1	Chinese Acad Sci	29	14.87%	2016.14
2	Consejo Superior Invest Cient	24	12.31%	2016.29
3	USDA Agr Res Service	22	11.28%	2016.45
4	China Agr Univ	22	11.28%	2016.27
5	Univ Florida	18	9.23%	2016.33
6	Mendel Univ Brno	17	8.72%	2014.18
7	Univ Tecn Federico Santa Maria	17	8.72%	2016.29
8	Wageningen Univ	16	8.21%	2016.50
9	Northwest A&F Univ	15	7.69%	2016.53
10	Univ Sydney	15	7.69%	2016.53

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "intelligent agricultural equipment"

of animal stem cell" of veterinary science, "crop transgenic technology" of crop science, and "animal models and animal genome editing" of veterinary science.

Newly emerging development fronts: "agricultural waste and biomass energy conversion" of agricultural engineering, "efficient utilization of solar energy in agricultural facilities" of agricultural engineering, and "development and utilization of intelligent agricultural machinery" of agricultural engineering.

In-depth established development fronts: "development of high-efficiency, low-toxicity disease control compounds for agricultural use" of plant protection science, "introduction of disease-resistant genes and utilization of new disease-resistant varieties" plant protection science, "forestry information database and ecosystem construction" of

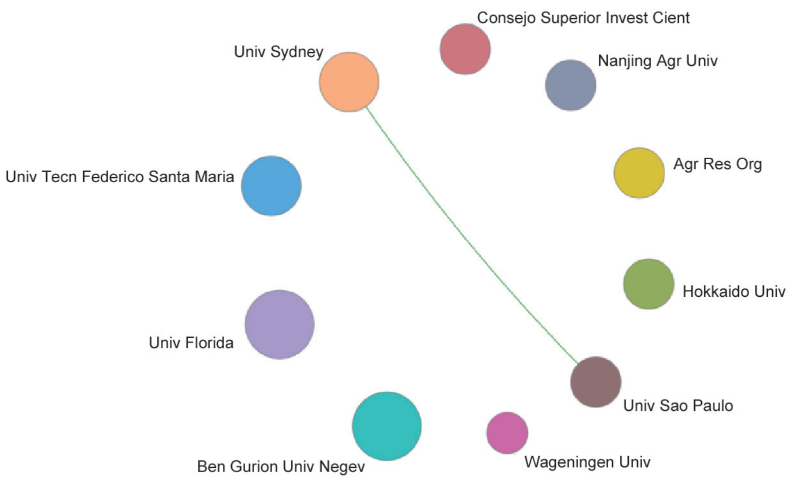

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "intelligent agricultural equipment"

forestry science, and "breeding of inbred lines and new hybrid varieties of crops" of crop science.

"Crop transgenic technology" had the highest number of patents, reaching 738. The average number of patents was around 310 patents. The article "animal models and animal genome editing" had the highest average number of patent citations, reaching about 33. Important research-area patents averaged 17 citations. A list of the highest average number of patents was published in May 2013 (Table 2.1.1). The average number of patents for all important research fronts showed a steadily decreasing trend year after year (Table 2.1.2).

Top 10 engineering development fronts are summarized below.

(1) Utilization technology of animal stem cell

This technology is a ground breaking development front in the field of veterinary medical science. Animal stem cells are a type of self-renewing pluripotent cells. Under certain conditions, stem cells can be separated into different types of functional cells. Based on their developmental stage, stem cells can be divided into embryonic stem cells and somatic stem cells. Based on their differentiation potential, stem cells can be divided into three types: totipotent stem cells, pluripotent stem cells, and unipotent stem cells. Stem cells are a type of immature, undifferentiated cells that have the potential to regenerate various tissues and organs of the human body. In the medical field, these cells are known as all-

Table 2.1.1 Top 10 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Utilization technology of animal stem cell	281	4 232	15.06	2013.91
2	Agricultural waste and biomass energy conversion	209	4 017	19.22	2012.86
3	Crop transgenic technology	738	14 216	19.26	2013.62
4	Development of high-efficiency and low-toxic pesticide	170	1 813	10.66	2013.29
5	Animal model and animal genome editing	135	4 549	33.70	2013.46
6	Introduction of disease resistance gene and its utilization	308	4 639	15.06	2013.40
7	Efficient use of solar energy in agricultural facilities	157	3 299	21.01	2012.78
8	Development and utilization of intelligent agricultural machinery	595	12 540	21.08	2013.64
9	Forestry information database construction and ecosystem construction	210	765	3.64	2013.89
10	Crop inbred lines breeding and new hybrid varieties	301	4 005	13.31	2013.45

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

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Utilization technology of animal stem cell	74	49	58	37	53	10
2	Agricultural waste and biomass energy conversion	102	56	35	12	3	1
3	Crop transgenic technology	187	185	173	115	73	5
4	Development of high-efficiency and low-toxic pesticide	58	46	32	27	7	0
5	Animal model and animal genome editing	37	33	40	19	3	3
6	Introduction of disease resistance gene and its utilization	108	77	55	39	18	11
7	Efficient use of solar energy in agricultural facilities	82	40	23	11	1	0
8	Development and utilization of intelligent agricultural machinery	155	140	124	124	45	7
9	Forestry information database construction and ecosystem construction	40	43	56	47	19	5
10	Crop inbred lines breeding and new hybrid varieties	84	90	66	34	23	4

purpose cells. Stem cells are widely used in the basic research of animal medicine and the animal disease treatment.

(2) Agricultural waste and biomass energy conversion

This is a newly emerging development front in the field of agricultural engineering. High consumption and high production have been the long-term pattern of agricultural development. As a result, while the supply of agricultural products has been increasing, the quantity of agricultural byproducts and waste, such as crop straw and animal manure, has also increased rapidly. In addition, the improper use of agricultural waste has led to serious natural-resource and environmental problems. At present, the development of biomass energy is focused on five technologies: gasification, compressed fuel, combustion power-generation, ethanol production and biodiesel production. Among these, biomass gasification fuel and biomass compression molding are already mature technologies. In terms of biomass combustion power-generation, high-efficiency direct-fired power-generation is considered to be the most viable method of biomass utilization, and it is an important future direction of technological development.

(3) Crop transgenic technology

This technology is a ground breaking development front in the field of crop science. Transgenic technology utilizes modern biotechnology to introduce and integrate the desired target genes, after their artificial separation and recombination, into the genome of an organism, thereby improving its original traits or introducing new traits. In addition to introducing foreign genes, transgenic technology can be used to alter the genetic characteristics of organisms in order to obtain desired traits, using such techniques as gene processing, knockout and shielding. The main processes of transgenic technology include the cloning of foreign genes, the construction of expression vectors, the establishment of genetic transformation systems, the selection of genetic transformants, the analysis of genetic stability and backcrossing.

(4) Development of high-efficiency and low-toxic pesticide

This is an in-depth established development front in the field of plant protection science. With the removal of some of the highly toxic organophosphorus pesticides from the international market, the demand for environmentally-friendly pesticides has increased significantly. This has presented more opportunities for the development of new types of pesticides, and has generated more public interest as well as research and development investments. High-efficiency, low-risk pesticides have the following main characteristics: ① high activity against target organisms, low dosage per unit area; ② low toxicity to humans and animals; ③ safety for crops, no phytotoxicity; ④ environmentally friendly and biosafe (for example, low toxicity to fish, hummingbirds and silkworm); and ⑤ easy to degrade to nontoxic substances. Chemical pesticides kill natural pests, pollute the environment, and are harmful to humans. In addition, plant pests and diseases may develop resistance to chemical pesticides.

(5) Animal models and animal genome editing

This technology is a ground breaking development front in the field of veterinary medical science. Animal disease models are used in experimental physiology, experimental pathology and experimental therapeutics (including screening of new drugs). Animal models of human diseases are animals and materials that are used to simulate human disease in biomedical science experiments. Genome-editing technologies can be used to precisely modify the targeted endogenous genes of organisms, thereby providing valuable tools in the field of biomedical research. With the rapid development of genomics and genome-editing technology as well as the wide application of microinjection technology and somatic cell cloning technology, strategies and methods of breeding by molecular writing have also been gradually developed. Molecular writing can be used to efficiently create and verify new genetic markers. It also allows for the directional breeding of new varieties through precise, molecular-level genome editing, not only removing the reproductive barriers that separate various taxa and allowing cross-species genetic transfers, but also enabling the insertion, deletion, and substitution of single nucleotides into individual genomes. As a result, more animal models can be developed.

(6) Introduction of disease resistance gene and its utilization

This is an in-depth established development front in the field of plant protection science. Based on the conserved structure of their encoding protein, plant disease-resistance genes are divided into five or more classes: including NBS-LRR, eLRR-TM, eLRR-TM-pkinase and STK. Although the distribution of different genes varies at the cellular level, and the structures of the NBS, kinase and LRR domains vary between different types of genes, they are able to participate in the cell-defense against invading pathogens through various mechanisms. In addition, the pyramiding of multiple effective disease-resistance genes not only improves crop resistance, but also increases crop yield and quality. In particular, from the perspective of disease resistance, the prolonged repeated use of a single gene makes it prone to the loss of its disease resistance. Therefore, gene pyramiding can expand the resistance spectrum of genes, thus improving crop resistance.

(7) Efficient use of solar energy in agricultural facilities

This is a newly emerging development front in the field of agricultural engineering. The photovoltaic (PV) solar energy greenhouse is a newly emerging type of agricultural facility that combines modern agricultural greenhouses with thin-film PV power-generation technology and LED lighting technology. This technology enables the utilization of farmlands for direct low-cost power-generation without affecting the growth of greenhouse crops. Solar-powered sprinkler irrigation units combine the PV solar power-generation technology with a sprinkler machine to transform current irrigation methods into mobile sprinkler irrigation. In addition to the highly uniform distribution of water and its associated energy savings, this technology also has a significant water-saving potential. In order to achieve the on-site consumption of PV energy, an intelligent micro-energy network based on time-shiftable agricultural load can be constructed for the solar greenhouse. The development of this low-carbon footprint agricultural technology will result in both economic and ecological benefits.

(8) Development and utilization of intelligent agricultural machinery

This is a newly emerging development front in the field of agricultural engineering. Research in the area of intelligent agricultural machinery involves the use of precise variable-rate control technology, navigation technology and real-time operation-monitoring technology to develop intelligent agricultural equipment that supports precise farming operations. Intelligent agricultural machinery integrates advanced technologies, such as information and communication technology, computer network technology, and control and detection technology, which are essential for the rapid development of modern agriculture. Some of the development trends in this field include intelligent agricultural big-data platform establishment, connected agricultural-equipment operations, and agricultural robot and original farming-equipment technology development.

(9) Forestry information database construction and ecosystem construction

This is an in-depth established development front in the field of forestry. Forest reserves form the constantly changing material base of forestry. To optimize forest structure and distribution, and to continuously improve the quality and quantity of forest resources, it is essential to improve the management of forest reserves and to use computer technology to manage the storage of quantitative forest resources data. Such a storage system comprises the forestry information database. The forestry information database includes existing forest information technologies such as the forestry resources survey-management system, the forest land-management system, the forest tenure-management system, and the comprehensive decision-support system. Integrating the existing forestry resources data and transforming current forestry management methods can strengthen resource supervision and work management, and can also improve forestry-related social services. Finally, with the associated scientific and technological advancements, the forestry information database should also be connected to geographic information systems, the remote-sensing information system and the forecasting model system to contribute in a more prominent way to the scientific management of forest resources and the construction of forest ecosystems.

(10) Crop inbred lines breeding and new hybrid varieties

This is an in-depth established development front in the field of crop science. The crop inbred line refers to the nearly identical offspring of a single plant after successive selfings. Crop inbreeding allows for the utilization of the effects of heterosis, which is an important approach that is employed to significantly increase crop yield, quality, stress resistance and adaptability. Basic research on heterosis includes: ① the use of germplasm resources to maximize the development and utilization of heterosis, ② an in-depth study of heterotic groups and their identification at the molecular level, ③ the screening of quantitative trait loci (QTL) for yield-related heterosis formation, and ④ suitable genetic populations for studying heterosis. Gene-expression profiling studies contribute to the understanding of the molecular mechanisms behind heterosis formation.

2.2 Interpretations for three key engineering development fronts

2.2.1 Utilization technology of animal stem cell

Of the many types of adult stem cells, hematopoietic stem cells (HSCs) are a type of stem cell that has been the subject of early studies on genetics, and are recognized to be effective in clinical applications. HSCs are self-renewing and pluripotent adult stem cells that have the potential to differentiate into various blood cells. Being the most primitive type of cells in the hematopoietic system, they are the source of all red blood cells, platelets and white blood cells (including granulocytes, monocytes and lymphocytes), sustaining the lifelong hematopoiesis of organisms. HSCs are found in microenvironments within the bone marrow. Therefore, the HSC functions are regulated by various internal and external factors. HSC transplantation is used not only to treat hematopoietic malignancies, but also to treat other diseases such as autoimmune and metabolic diseases. In addition, they are important in animal regenerative medicine.

For this development front, the majority of published patents are from the USA and China (Table 2.2.1). The USA accounted for two-thirds, occupying the leading position. In terms of core patent distribution by contributing institutions (Table 2.2.2), DuPont USA had the highest number of patents, whereas the China Agricultural University had a higher number of core patent citations. The country and region collaboration diagrams (Figure 2.2.1) indicate that the USA, Denmark and Switzerland cooperated extensively. The institution collaboration network diagram (Figure 2.2.2) indicates that BROD (Broad Inst. Inc.), MASI (Massachusetts Inst. Tech.), and HARD (Harvard College) had the closest collaboration.

2.2.2 Agricultural waste and biomass energy conversion

Biomass energy refers to a form of energy that comes from the conversion of solar energy into chemical energy by plants, and is stored in biomass. This type of energy comes directly or indirectly from the photosynthesis of green plants, and can be converted into conventional solid, liquid, or gaseous fuels. Biomass is an inexhaustible and renewable energy source, and is the only renewable source of carbon. At present, the development of biomass energy is focused on five technologies, namely gasification, compressed fuel, combustion power-generation, ethanol production, and biodiesel production. Among them, biomass gasification fuel and biomass compression molding are already mature technologies. In terms of biomass combustion power-generation, high-efficiency direct-fired power-generation is considered to be the most viable method of biomass utilization, which is an important future direction for potential technological development. However, the efficiency of forest-waste conversion into fuel ethanol is still low, remaining in the experimental stage. The development of ethanol production technology based on lignocellulose will be the front of future

Table 2.2.1 Countries or regions with the greatest output of core patents on the "utilization technology of animal stem cell"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	178	63.35%	2 876	67.96%	16.16
2	China	54	19.22%	606	14.32%	11.22
3	Denmark	13	4.63%	223	5.27%	17.15
4	Netherlands	11	3.91%	180	4.25%	16.36
5	France	9	3.20%	188	4.44%	20.89
6	Japan	9	3.20%	98	2.32%	10.89
7	Canada	5	1.78%	69	1.63%	13.80
8	Germany	5	1.78%	121	2.86%	24.20
9	UK	5	1.78%	56	1.32%	11.20
10	Switzerland	4	1.42%	59	1.39%	14.75

Table 2.2.2 Institutions with the greatest output of core patents on the "utilization technology of animal stem cell"

No.	Institutions	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	DUPO	USA	20	7.12%	331	7.82%	16.55
2	MASI	USA	16	5.69%	421	9.95%	26.31
3	Broad Inst Inc	USA	15	5.34%	412	9.74%	27.47
4	HARD	USA	12	4.27%	268	6.33%	22.33
5	REGN	USA	12	4.27%	169	3.99%	14.08
6	STAM	Netherlands	7	2.49%	103	2.43%	14.71
7	CECT	France	6	2.14%	145	3.43%	24.17
8	Recombinetics Inc	USA	6	2.14%	99	2.34%	16.50
9	REGC	USA	5	1.78%	85	2.01%	17.00
10	STRD	USA	5	1.78%	88	2.08%	17.60

DUPO: Dupont Nutrition Biosciences Aps; MASI: Massachusetts Inst. Technology; HARD: Harvard College; REGN: Regeneron Pharm Inc.; STAM: Dsm Intellectual Property Assets Manage; CECT: Cellectis; REGC: Univ. California; STRD: Univ. Leland Stanford Junior.

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "utilization technology of animal stem cell"

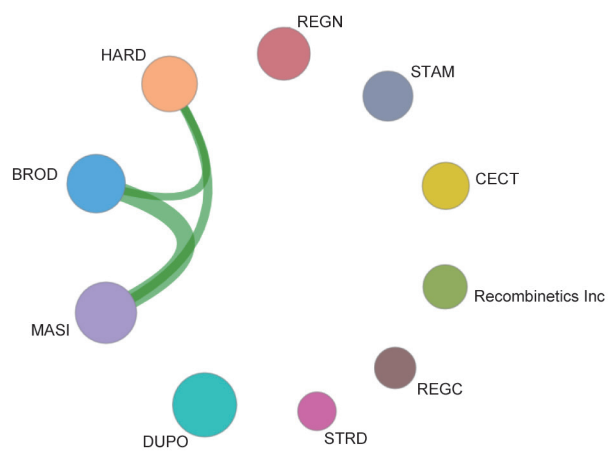

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "utilization technology of animal stem cell"

research and development. The technology for extracting biodiesel from tree seeds with high oil content remains in the exploration stage, and is still a long way from industrialization. This technology will become the front of future research and development.

The overwhelming majority of published patents in this development area came from the USA (Table 2.2.3), followed by China. The differences in the average number of citations between various countries were not significant. In terms of core patent distribution by contributing institutions (Table 2.2.4), the Butamax Advanced Biofuels LLC had the highest number of patents. The country and region collaboration diagram (Figure 2.2.3) indicates that the USA, the Netherlands, and the UK collaborated closely. It is evident from the institution collaboration diagram (Figure 2.2.4) that two companies in Suzhou, China had significant collaboration.

Table 2.2.3 Countries or regions with the greatest output of core patents on the "agricultural waste and biomass energy conversion"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	141	67.46%	2816	70.10%	19.97
2	China	32	15.31%	531	13.22%	16.59
3	Netherlands	9	4.31%	166	4.13%	18.44
4	Canada	8	3.83%	167	4.16%	20.88
5	Germany	5	2.39%	99	2.46%	19.80
6	Denmark	4	1.91%	80	1.99%	20.00
7	UK	4	1.91%	116	2.89%	29.00
8	Australia	3	1.44%	77	1.92%	25.67
9	France	3	1.44%	37	0.92%	12.33
10	Japan	3	1.44%	52	1.29%	17.33

Table 2.2.4 Institutions with the greatest output of core patents on the "agricultural waste and biomass energy conversion"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	BUTA	USA	14	6.70%	350	8.71%	25.00
2	SHEL	USA	8	3.83%	216	5.38%	27.00
3	DUPO	USA	7	3.35%	141	3.51%	20.14
4	Suzhou Mingyue Pharm Technology Co Ltd	China	7	3.35%	109	2.71%	15.57
5	UNVO	USA	6	2.87%	114	2.84%	19.00
6	XYLE	USA	6	2.87%	116	2.89%	19.33
7	DOWC	USA	5	2.39%	75	1.87%	15.00
8	Suzhou Miracpharma Technology Co Ltd	China	5	2.39%	79	1.97%	15.80
9	ANGC	USA	4	1.91%	62	1.54%	15.50
10	Api Intellectual Property Holdings LLC	USA	4	1.91%	55	1.37%	13.75

BUTA: Butamax Advanced Biofuels LLC; SHEL: Shell Int. Res. Mij Bv; DUPO: Dupont Nutrition Biosciences APS; UNVO: UOP LLC; XYLE: Xyleco Inc.; DOWC: Dow Global Technologies LLC; ANGC: Angus Chemical Company.

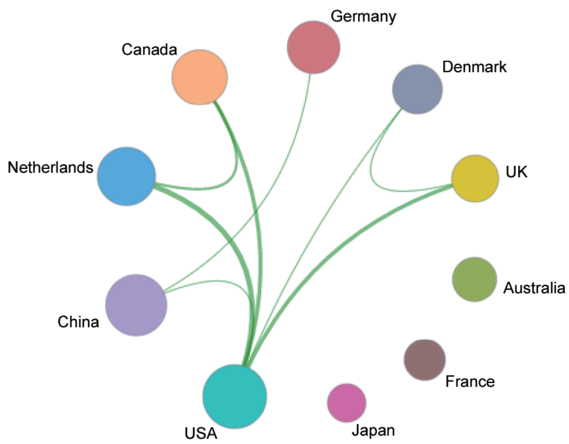

Figure 2.2.3 Collaboration network among major countries in the engineering development front of "agricultural waste and biomass energy conversion"

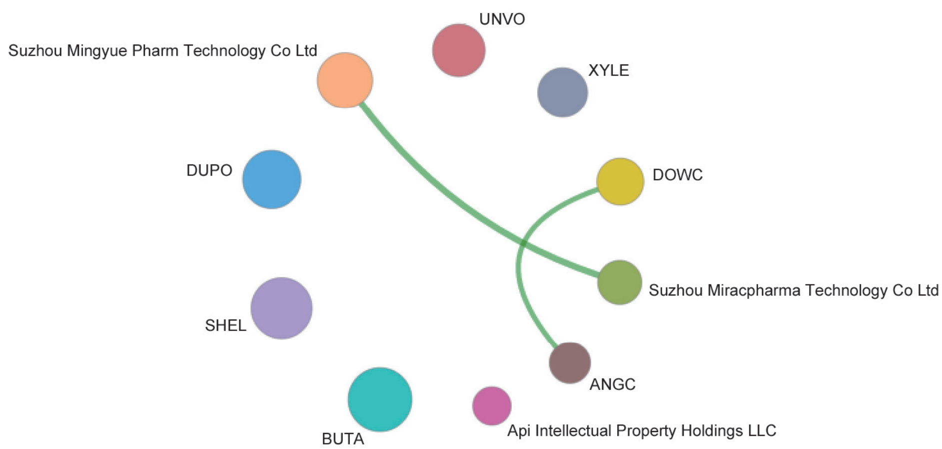

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "agricultural waste and biomass energy conversion"

2.2.3 Crop transgenic technology

Transgenic technology utilizes modern biotechnology to introduce and integrate the desired target genes, after their artificial separation and recombination, into the genome of an organism, thereby improving its original traits or introducing new traits. In addition to introducing foreign genes, transgenic technology can be used to alter the genetic characteristics of organisms in order to obtain desired traits, using techniques such as gene processing, knockout and shielding. The main processes of transgenic technology include the cloning of foreign genes, the construction of expression vectors, the establishment of genetic transformation systems, the selection of genetic transformants, the analysis of genetic stability and backcrossing.

The majority of published patents in this front area are from the USA and China. The USA had the highest proportion of published patents and a large number of average citations (Table 2.2.5). In terms of research institutions, the differences in the number of published core patents between various institutions decreased gradually (Table 2.2.6). The country and region collaboration diagram shows that the USA, Denmark, and Switzerland collaborated closely (Figure 2.2.5). The institution collaboration network diagram indicates that MASI, BROD, and HARD had the closest collaboration (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents on the “crop transgenic technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	462	62.60%	9959	70.05%	21.56
2	China	114	15.45%	1285	9.04%	11.27
3	Denmark	35	4.74%	717	5.04%	20.49
4	Germany	31	4.20%	721	5.07%	23.26
5	Switzerland	24	3.25%	592	4.16%	24.67
6	UK	24	3.25%	334	2.35%	13.92
7	Netherlands	24	3.25%	456	3.21%	19.00
8	Japan	19	2.57%	307	2.16%	16.16
9	France	17	2.30%	325	2.29%	19.12
10	Canada	16	2.17%	202	1.42%	12.63

Table 2.2.6 Institutions with the greatest output of core patents on the “crop transgenic technology”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	HARD	USA	35	4.74%	940	6.61%	26.86
2	NOVO	Denmark	34	4.61%	736	5.18%	21.65
3	DUPO	USA	32	4.34%	500	3.52%	15.63
4	BROD	USA	27	3.66%	954	6.71%	35.33
5	MASI	USA	27	3.66%	959	6.75%	35.52
6	BUTA	USA	26	3.52%	688	4.84%	26.46
7	Moderna Therapeutics	USA	14	1.90%	599	4.21%	42.79
8	HOFF	Switzerland	13	1.76%	287	2.02%	22.08
9	STAM	Netherlands	13	1.76%	180	1.27%	13.85
10	CAGS	China	12	1.63%	149	1.05%	12.42

HARD: Harvard College; NOVO: Novozymes AS; DUPO: Dupont Nutrition Biosciences APS; MASI: Massachusetts Inst Technol; BUTA: Butamax Advanced Biofuels LLC; BROD: Broad Inst. Inc.; HOFF: Hoffmann La Roche & Co Ag F; STAM: Dsm Intellectual Property Assets Manage; CAGS: Inst Crop Sci Chinese Acad Agric Sci.

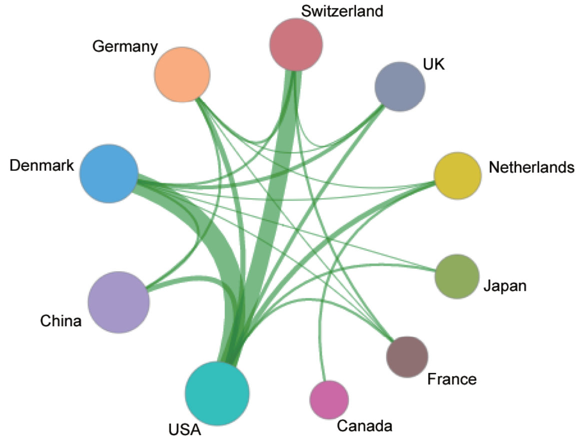

Figure 2.2.5 Collaboration network among major countries in the engineering development front of “crop transgenic technology”

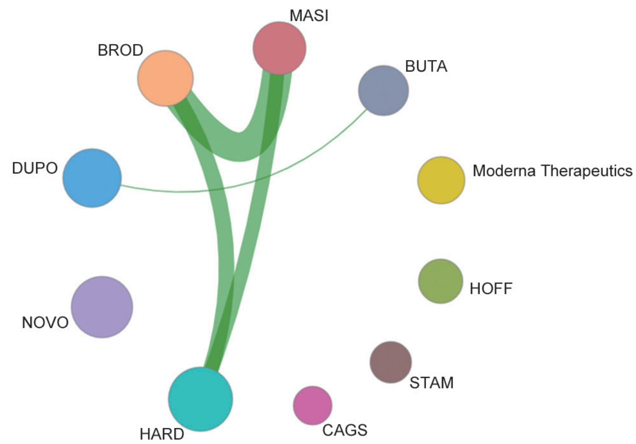

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "crop transgenic technology"

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VIII. Medicine & Health

1 Engineering research fronts

1.1 Development trends in the top 9 engineering research fronts

The top 9 engineering research fronts related to the Field of Medicine & Health are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including basic medicine, clinical medicine, medical informatics and biomedical engineering, pharmacy, public health and preventive medicine. These 9 research fronts also involve "new taxonomy based on aberrant molecules and targeted therapy," "stem cell and cell therapies," "precision medicine research based on biomedical big data," "prevention and intervention of aging," "safety evaluation, risk control, and quality standards of traditional Chinese medicine," "regenerative medicine and regeneration microenvironment," "discovery of emerging highly pathogenic viruses and their epidemic warning and control," "neurodegenerative disorders," and "gut microbiota and development of tumor." All core papers on these fronts published between the years 2012–2017 are listed in Table 1.1.2.

(1) New taxonomy based on aberrant molecules and targeted therapy

New taxonomy based on aberrant molecule is the cornerstone of precision medicine. It is a new classification method of cancer based on the molecular variation of cells that could drive occurrence and development of tumor, and can be used as a target for effective treatment. The first step in creating new taxonomy of tumors is information sharing. Data from a large number of cancer patients are available for extensive research, and the internal connections between these data are explored. These data are combined with the continuously developing new knowledge on basic biological process—form new knowledge network to serve all stakeholders. Further, the subclassification of particular diseases into those with different molecular mechanisms, prognoses, and/or treatments could be predicted by such hypotheses. Finally, all these ideas could be tested in an attempt to establish their validity, reproducibility, and robustness. Targeted therapy is a drug treatment approach based on molecular taxonomy of cancer, which aims at the specific molecular abnormality. It designs specific targeted drugs and selects the appropriate population for specific treatment so as to improve the efficacy and reduce side effects. Molecular taxonomy and targeted therapy are indivisibly whole. Molecular typing is the basis of targeted therapy, which, in turn, is the key to the establishment and validation of molecular taxonomy. In 2001, Imatinib was the first Food and Drug Administration (FDA)-approved targeted therapy drug for chronic myeloid leukemia

Table 1.1.1 Top 9 engineering research fronts in medicine and health

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	New taxonomy based on aberrant molecules and targeted therapy	847	189 790	224.07	2014.69
2	Stem cell and cell therapies	189	31 559	166.98	2014.40
3	Precision medical research based on biomedical big data	768	165 076	214.94	2014.50
4	Prevention and intervention of aging	13	2 054	158.00	2014.31
5	Safety evaluation, risk control, and quality standards of traditional Chinese medicine	131	790	6.03	2014.88
6	Regenerative medicine and regeneration microenvironment	11	1 492	135.64	2015.00
7	Discovery of emerging highly pathogenic viruses and their epidemic warning and control	34	6 277	184.62	2014.32
8	Neurodegenerative disorders	68	9 590	141.03	2014.56
9	Gut microbiota and development of tumor	55	9 241	168.02	2014.76

Table 1.1.2 Annual number of core papers published for each of the top 9 engineering research fronts in medicine and health

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	New taxonomy based on aberrant molecules and targeted therapy	108	138	134	143	178	146
2	Stem cell and cell therapies	28	42	29	36	25	29
3	Precision medical research based on biomedical big data	127	121	131	146	116	127
4	Prevention and intervention of aging	1	4	3	1	3	1
5	Safety evaluation, risk control, and quality standards of traditional Chinese medicine	15	13	22	25	35	21
6	Regenerative medicine and regeneration microenvironment	1	1	3	1	2	3
7	Discovery of emerging highly pathogenic viruses and their epidemic warning and control	4	9	7	4	6	4
8	Neurodegenerative disorders	11	12	11	10	10	14
9	Gut microbiota and development of tumor	3	13	8	11	10	10

patients harboring the BCR-ABL fusion. Following this, the research based on targeted therapies for lung and associated cancers having molecular aberrations rapidly expanded: Gefitinib, an epidermal growth factor (EGF) receptor tyrosine kinase inhibitor (EGFR TKIs) is used to treat lung cancer with EGFR mutation; Crizotinib, an anaplastic lymphoma kinase (ALK) and c-ros oncogene 1(ROS1) inhibitor is applied in the treatment of patients harboring ALK/ROS1 fusion. Soon after, the ALK fusion gene was found to be associated with a series of cancers with specific clinical characteristics, and a new word, ALKoma, was coined to describe a new subtype of cancer. Targeted therapy has prolonged the median overall survival (OS) from 10 months to 50 months for advanced lung cancer with mutated ALK in past 10 years. The fields involved in cancer molecular taxonomy and targeted therapy encompass molecular biology research, bioinformatics, and gene analysis of the characteristics of cancer, discovery of drug targets and development of corresponding drugs, establishment of convenient molecular diagnostic methods, and design and implementation of innovative clinical trials. All these fields are at the forefront of current life sciences, guiding the research direction of medical science. By the next 20 years, research on targeted drugs will be a constant area of work.

(2) Stem cell and cell therapies

A stem cell possesses the potential for self-renewal and multi-directional differentiation. It is capable of differentiating into multiple functional cells depending upon different conditions. Stem cells can be roughly classified into embryonic stem cells (ESCs) and adult stem cells (ASCs) according to their developmental stages. The ESCs derived from the reprogramming of differentiated cells are called induced pluripotent stem cells (iPSCs). ESCs and iPSCs are highly proliferative and able to differentiate into any cell type in the body. ASCs are a type of undifferentiated cells existing in different body tissues, having limited proliferative ability, and can only differentiate into specific types of tissues. Stem cells are often referred to as “seed cells” in the medical community because of their potential for regenerating various tissues and organs within the human body. The stem cell technology utilizes this potential to repair, replace, or otherwise interfere with damaged tissues and organs. Therapeutic stem cell research has made meaningful attempts towards the treatment of a number of severe systemic diseases, such as nervous system diseases, and cardiovascular, cerebrovascular, hepatic, and renal diseases. It has brought new hopes for effective treatment, thus becoming a highly important field of investment for various national governments. Some developed countries and regions such as Europe, the USA, and Japan have prioritized stem cell research as a strategy for national science and technological development, and made enormous efforts to promote its clinical applications. A number of pre-clinical and clinical trials have been carried out around the world, including the treatment of Parkinson’s disease with dopaminergic neurons differentiated from neural stem cells, the treatment of chronic spinal cord injury with spinal cord neural stem cells, and the application of autologous interstitial precursor cells for the repair and regeneration of damaged tissues. These trials and findings have helped the development and emergence of several stem cell products into the market. Being the main supporters of the stem cell research industry, many major pharmaceutical companies have made huge investments and even adjusted the core of their businesses to seize the opportunities brought about by stem cell development and translational medicine. Globally, more than 700 companies are conducting research in this emerging field, and the competition is becoming increasingly fierce. In recent years, the stem cell industry has made rapid progress, and according to the latest prediction, the global stem cell research market will reach 400 billion USD by 2020.

(3) Precision medical research based on biomedical big data

Precision medicine is a new medical model based on personalized medicine, generated with the rapid development of genome sequencing technology and the cross-application of bioinformatics and big data science. In 2011, a long-form report by the American Academy of Sciences entitled "Towards Precision Medicine: Building a Knowledge Network for Biomedical Research and a New Taxonomy of Disease" first proposed precision medicine. Its main content/role is to form a knowledge network revealing the molecular mechanism and genetic susceptibility of an individual's disease by interactively analyzing the clinical information and omics data at one- or multi-dimensional levels in large-scale populations. The knowledge network generates disease taxonomy and provides disease prevention and treatments for patients based on their genome and other individual characteristics. The aim of precision medicine is to provide accurate and timely warning and treatment based on an individual's genomic information and the molecular mechanisms of disease. This in turn can reduce the incidence of the disease, solve treatment inefficiencies, and reduce medical costs. As the future medical model and national health protection measure, precision medicine will bring about implementation of personalized medical services in many aspects. The disease risk of healthy or sub-healthy individuals will be predicted, especially for major chronic diseases, thereby reducing the incidence rate due to prior warnings. For the patient population, early diagnosis and precise treatment, like selection of the most appropriate drug, its dosage or duration of treatment for a given patient's genotype, could be provided to further improve the efficacy and cure rate. For infants with various birth defects, pre-implantation genetic screening or diagnosis could be performed to reduce the disease risk in newborns. After the Precision Medicine Initiative was launched by President Obama, several precision medicine projects have been developed around the world, including the 100 000 Genomes Projects in the United Kingdom (UK), the Genomic Medicine Plan 2025 in France, the Genome South Korea in Ulsan, and the Zero Childhood Cancer Program in Australia. In 2016, China also released a special project focused on precision medicine research. The project aimed at common dangerous diseases with high prevalence, as well as rare diseases with relatively high prevalence in China, and conducting research from the perspective of cohort, platform, technology, system, and demonstration application. The ultimate mission is to improve population health and make precision medicine the new rise point in economic growth and social development.

(4) Prevention and intervention of aging

Aging is related to a progressive decline of physical, psychological, and social functions and a great risk of many disabilities, diseases, and even death. The pursuit of longevity is the common aspiration of human beings. Human bodies age at different rates, which are determined by both genetic and environmental factors. The omics analyses (genomics, metabolomics, metagenomics, epigenetics, etc.) and multi-dimensional/time point big data information of large sample sizes or multi-center cohort data can be used to build highly accurate methods to assess aging and its feasible intervention schemes. This would definitely provide strong scientific evidence to clarify the mechanisms of aging, in addition to providing the technical means and prevention strategies for aging intervention. This research front contributes to food, lifestyle, medical, and pharmaceutical development, in addition to precise health management, personalization and utility evaluation of public health policies, and improvement of the human aging processes, associated with geriatric and neurodegenerative diseases. The accurate diagnosis and medical guidance based on cancer genetic testing has begun to show its effectiveness. However, the assessment and prevention of aging based on the individual's health status is still lacking evidence and feasible measures. Aging-related diseases and rates require more research and investments in order to improve people's yearning for a better life and enhance the industrial structure, including ecological civilization. The integration of multi-omics, environment, high throughput data, and validation with prospective cohorts will enable finding precise and simpler aging assessment methods apart from more effective and feasible control of aging. Food, medicine, lifestyle, and psychological interventions, combined with machine learning application, artificial intelligence, and deep biostatistical inference are the trend and hotspot of aging prevention and intervention research.

(5) Safety evaluation, risk control, and quality standards of traditional Chinese medicine

The uncertain safety of traditional Chinese medicine (TCM) has been a key factor restricting the development of the TCM industry and public health. However, the complexity of TCM ingredients and the unpredictability of their nonlinear interactions with the human body; the integrity of multiple components, pathways, and target points; and the role reversal and inter-restriction of TCM effective substances; have become the main challenges for TCM safety evaluation. In view of the above hurdles, TCM safety evaluation should focus on elucidating the toxic characteristics, especially the "toxic" TCMs with curative effects, on the basis of the good laboratory practice (GLP) evaluation system. It should strengthen studies on toxicity control and detoxification instead of disabling TCM; it should enhance the risk control management of TCM research and pay more attention on its correlation and systematization. This is mainly performed by identification, processing, compatibility, and syndrome/symptom differentiation. With the new changes brought about by the intensified risk consciousness, quality improvement, and progress in science, TCM risk control has gradually extended to the early prediction and real-time dynamic monitoring of toxicity, adverse reaction reports, and lifelong follow-through. TCM theories are fusions of traditional and modern medicine enabling us to study its toxicity and prescription of toxicity. Further, TCM helps to effectively characterize the material basis of formula for individual drugs and their ingredients in order to provide sufficient guarantee of the safety and efficacy of TCM. The relationships between toxicity, effectiveness, compatibility, and pattern of toxic TCM needs to be elucidated. Moreover, much clarity is needed to see the toxic characteristics, like its occurrence, mechanism of toxic reactions, and its *in vivo* metabolism. In order to promote scientific and rational use of drugs in clinical practice, better understand the risk of "toxic TCMs," and effectively establish quality control standards, we need to establish toxicity control methods, scientific assessment pattern, and technical system for the early prediction of toxicity associated risk of "toxic TCMs."

(6) Regenerative medicine and regeneration microenvironment

Regenerative medicine refers to the recovery of impaired tissues and organs to rescue normal functions, using biological engineering principles. The key barrier for regenerative medicine is how to establish the best regeneration microenvironment, i.e., the local microenvironment required for regeneration, to promote tissue regeneration process. Since the last century, studies indicate a very intricate relationship between regeneration microenvironment and regenerative medicine. The mechanism of regeneration involves the participation of cells having regeneration potential, and the microenvironment containing soluble factors and extracellular matrix. Amongst other physical or chemical factors secreted by the cells in the regeneration microenvironment, the trophic factors, adhesion molecules, and extracellular matrix molecules play important roles in regeneration. Studies on the regeneration microenvironment have provided key theories and technical guidance for regenerative medicine. The establishment of new theories, technology, and products based on these investigations will create new areas for the development of regenerative medicine and benefit mankind.

(7) Discovery of emerging highly pathogenic viruses and their epidemic warning and control

Identifying emerging highly pathogenic (HP) viruses is a measure for their isolation through real-time monitoring and control of their epidemics. This aids to achieve timely detection of the epidemic causing pathogens, their effective prevention, and treatment of the viral infection (conceptual elaboration). The key scientific issues include pathogen identification, studying their transmission routes, epidemic monitoring, and development of control strategies such as vaccines and therapeutics. Owing to their potential threat to human health and socio-economic stability, the discovery of emerging HP viruses, early epidemic warning, and corresponding epidemic control will pave the way for combating emerging infectious disease worldwide. At present, the well-established gene sequencing technologies and bioinformatics can be applied to quickly identify the species and genetic information of the emerging highly pathogenic viruses in order to monitor their epidemics. Moreover, through the isolation of viruses, the related viral strains can be timely obtained and their transmission and pathogenicity can be promptly studied. In recent years, great progress has been made in the development of protein-based therapeutics (e.g., antibodies), and vaccines can be developed in a short period of time for urgent treatment of infected patients and prevention of epidemics Recently, the international community has once again joined hands to launch the "Global Virus Group Project." With the advancing development of novel technologies, discovery and characterization of pathogens, the monitoring and early indications of epidemics, and development of prevention and treatment strategies can be completed more precisely, promptly, securely and effectively. At present, China has established advanced comprehensive systems for virus identification and public health surveillance, providing international early warning programs and setting up platforms to swiftly develop prophylactic and therapeutic programs.

(8) Neurodegenerative disorders

Neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis are characterized by chronic and progressive neuronal loss, which is accompanied by neuroinflammation in the selected central nervous system (CNS) region. Aging is the most significant risk factor for induction of neurodegeneration. However, despite many years of research, early diagnosis and treatment of these diseases remain highly challenging. Studies on the molecular foundation underlying these diseases will ultimately provide some solutions for resolving the dilemma. The key scientific questions in this field relate to the elucidation of pathogenic factors, as well as the critical molecular mechanisms of pathogenesis that would facilitate early diagnosis and interventions. In the past decades, various disease-causing genes coding for familiar neurodegenerative disorders have been identified. Research in this field has transitioned from the description of pathological changes in the past to the functional studying a specific disease-causing gene. It is worth noting that current research has undergone significant changes at various levels: ① At the molecular level, studies have now extended from gene regulation to epigenetic regulation. ② At the cellular level, the interactions between the neuronal and non-neuronal cells (e.g., neuroglia) have received increasing attention in the past several years. ③ At the neural circuitry level, the hidden roles of the interactions between the diseased CNS regions and remote connecting CNS regions are being explored. ④ At the system level, the cross-talks between the CNS and peripheral tissue and organs (e.g. brain-gut axis and immune system) and their influence on the pathogenesis of neurodegenerative diseases have recently received much attention. ⑤ Technically, sequence-based techniques are used to redefine the categorization of various sub-types of neural cells. Innovative animal models are urgently needed to deeply promote neurodegenerative disease research. Brain imaging techniques with higher spatiotemporal resolutions are under development. Taken together, studies on the molecular basis of neurodegenerative disorders will lay a foundation for further understanding the neurodegenerative disease pathogenesis while simultaneously promoting the development of a new approach for the early diagnosis and treatment of these diseases.

(9) Gut microbiota and development of tumor

The human gut microbiota has become an extremely complex community after long-term co-evolution. The bacteria and their hosts have a close symbiosis, and maintaining a well-balanced intestinal flora is vitally important to human health. The imbalance in gut microbiota may influence the occurrence and development of tumors. The key scientific problems include the mechanisms of gut microbiota in influencing the occurrence and development of tumors, and drug resistance of tumors and the detailed microbiota involved. Since the USA first proposed the Human Microbiome Project in 2007, the study of intestinal flora has become a hot topic. The gut microbiota can not only regulate the innate immunity of the body, but can also stimulate the immune response either through the bacteria themselves, or through their metabolites. The imbalance of gut microbiota may lead to abnormal immune mechanisms, leading to tumor formation, especially colorectal cancer. Specific bacteria can also exert chemotherapeutic effect on tumors and even confer drug resistance. However, there are still many problems that remain unsolved. Therefore, we need to systematically clarify the mechanism of intestinal flora imbalance involved in the tumor development and put forward novel ideas and directions for the early stage prevention and control of tumorigenesis.

1.2 Interpretations for three key engineering research fronts

1.2.1 New taxonomy based on aberrant molecules and targeted therapy

New taxonomy based on aberrant molecule is the cornerstone of precision medicine. It is a new classification method of cancer based on the molecular variation of cells that could drive occurrence and development of tumor, and can be used as a target for effective treatment. The first step in creating new taxonomy of tumors is information sharing. Data from a large number of cancer patients are available for extensive research, and the internal connections between these data are explored. These data are combined with the continuously developing new knowledge on basic biological process—form new knowledge network to serve all stakeholders. Further, the subclassification of particular diseases into those with different molecular mechanisms, prognoses, and/or treatments could be predicted by such hypotheses. Finally, all these ideas could be tested in an attempt to establish their validity, reproducibility, and robustness. Targeted therapy is a drug treatment approach based on molecular taxonomy of cancer, which aims at the specific molecular abnormality. It designs specific targeted drugs and selects the appropriate population for specific treatment so as to improve the efficacy and reduce side effects. Molecular taxonomy and targeted therapy are indivisibly whole. Molecular typing is the basis of targeted therapy, which, in turn, is the key to the establishment and validation of molecular taxonomy. In 2001, Imatinib was the first Food and Drug Administration (FDA)-approved targeted therapy drug for chronic myeloid leukemia patients harboring the BCR-ABL fusion. Following this, the research based on targeted therapies for lung and associated cancers having molecular aberrations rapidly expanded: Gefitinib, an epidermal growth factor (EGF) receptor tyrosine kinase inhibitor (EGFR TKIs) is used to treat lung cancer with EGFR mutation; Crizotinib¬, an anaplastic lymphoma kinase (ALK) and c-ros oncogene 1(ROS1) inhibitor is applied in the treatment of patients harboring ALK/ROS1 fusion. Soon after, the ALK fusion gene was found to be associated with a series of cancers with specific clinical characteristics, and a new word, ALKoma, was coined to describe a new subtype of cancer. Targeted therapy has prolonged the median overall survival (OS) from 10 months to 50 months for advanced lung cancer with mutated ALK in past 10 years. The fields involved in cancer molecular taxonomy and targeted therapy encompass molecular biology research, bioinformatics, and gene analysis of the characteristics of cancer, discovery of drug targets and development of corresponding drugs, establishment of convenient molecular diagnostic methods, and design and implementation of innovative clinical trials. All these fields are at the forefront of current life sciences, guiding the research direction of medical science. By the next 20 years, research on targeted drugs will be a constant area of work.

At present, some key scientific issues in research on cancer molecular taxonomy and targeted therapy are as follows: development of new detection technologies and simultaneous innovation and application of bioinformatics methods to capture the molecular variation of cancer cells in the microenvironment; construction of the holographic map at the molecular level of cancer and visualization of the molecular tumor typing; integration and sharing of large-scale data of cancer patients and the rapidly expanding knowledge of tumor molecular evolution to build a new and shareable network of cancer knowledge; identification of key active targets and drug-susceptible compounds; and innovative clinical trials and companion diagnostic methods. Overall development trend in this field is the extension by cancer molecular variation research to the microenvironment of molecular information research, including targeted therapy and immunotherapy, comprehensive integration to build a new cancer molecular taxonomy, seamless connection with the drug development process simultaneously, the speed of targeted drugs reaching the market, and earlier clinical benefits to the patients.

The research fronts include: (1) new techniques used for cancer molecular taxonomy, such as single-cell sequencing, multi-dimensional tissue mass spectrometry, second- and even third-generation sequencing, liquid biopsy, etc.; (2) location of new targeted aberrant genes and determining their functions; (3) optimized design and screening of compounds for drug production; (4) discovering biomarkers for immune checkpoints application; (5) big data analysis for real-world clinical molecular evolution data calculation and deep learning technology; (6) organization and implementation of innovative clinical trials, such as basket tests, umbrella tests for seamless development, etc.

Papers concerning fronts of "new taxonomy based on aberrant molecules and targeted therapy" are mostly published by researchers from the USA, accounting for 77.59% of all studies and ranking first within 15 countries. France and Germany rank second and third, respectively. Among the three Asian countries, i.e., South Korea, Japan, and China, papers published in this area from China ranked 14th. Citations per paper on this research front "new taxonomy based on aberrant molecules and targeted therapy" are high, ranging from 225.05 to 294.63 (Table 1.2.1).

Among the top 10 organizations with the greatest output of core papers on the "new taxonomy based on aberrant molecules and targeted therapy," nine are from the United States, and the remaining one is from the Institute Gustave Roussy in France. The top three organizations are the UT MD Anderson Cancer Center, Memorial Sloan-Kettering Cancer Center, and Dana-Farber Cancer Institute (Table 1.2.2). More importantly, the newly listed targeted drugs, discovery of original targets, and global research and development (R&D) of drugs in recent years are almost monopolized by Unite States, Europe, and Japan, indicating that these countries have extremely strong innovation capacity and are leading the development direction of the global front, leaving China far behind. At the same time, the collaboration network among the top 10 countries or regions and among institutions are close in the engineering research front of "new taxonomy based on aberrant molecules and targeted therapy" (Figure 1.2.1 and Figure 1.2.2). It further demonstrates that cooperation and collaborations between institutes are very important and urgent.

From the perspective of technology and development trend, almost all of the most important core papers from China are based on large-scale clinical trials, and most of the top-ranking research institutions are good for clinical trials. This is precisely because of the huge patient resources in China. This advantage would not exist even if Western countries combined with global resources for clinical trials. This trend needs more attention by our policy makers.

Suggestions for the development of "Cancer molecular taxonomy and targeted therapy": (1) strengthening the research and transformation of key technologies of tumor molecular typing and targeted therapy, such as single-cell sequencing, multi-mass spectrometry and new knowledge framework, especially the substantive cooperation between

Table1.2.1 Countries or regions with the greatest output of core papers on the "new taxonomy based on aberrant molecules and targeted therapy"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	658	77.59%	159 929	84.24%	243.05
2	France	298	35.14%	83 149	43.80%	279.02
3	Germany	286	33.73%	73 802	38.88%	258.05
4	UK	261	30.78%	65 664	34.59%	251.59
5	Italy	239	28.18%	64 624	34.04%	270.39
6	Spain	203	23.94%	55 926	29.46%	275.50
7	Canada	184	21.70%	49 067	25.85%	266.67
8	Australia	176	20.75%	51 855	27.31%	294.63
9	Belgium	144	16.98%	32 407	17.07%	225.05
10	South Korea	135	15.92%	35 398	18.65%	262.21
11	Switzerland	115	13.56%	23 635	12.45%	205.52
12	Japan	109	12.85%	26 706	14.07%	245.01
13	Poland	103	12.15%	30 047	15.83%	291.72
14	China	102	12.03%	21 767	11.47%	213.40
15	Netherlands	93	10.97%	23 672	12.47%	254.54

Table 1.2.2 Institutions with the greatest output of core papers on the "new taxonomy based on aberrant molecules and targeted therapy"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Texas MD Anderson Cancer Center	167	19.69%	44 188	23.28%	264.60
2	Mem Sloan Kettering Cancer Center	161	18.99%	50 392	26.54%	312.99
3	Dana Farber Canc Inst	153	18.04%	42 927	22.61%	280.57
4	Massachusetts Gen Hosp	91	10.73%	29 236	15.40%	321.27
5	Univ Calif Los Angeles	80	9.43%	26 751	14.09%	334.39
6	Mayo Clin	77	9.08%	22 088	11.63%	286.86
7	Univ Calif San Francisco	64	7.55%	16 326	8.60%	255.09
8	Inst Gustave Roussy	61	7.19%	21 581	11.37%	353.79
9	Univ Penn	59	6.96%	17 214	9.07%	291.76
10	Weill Cornell Med Coll	55	6.49%	16 523	8.70%	300.42

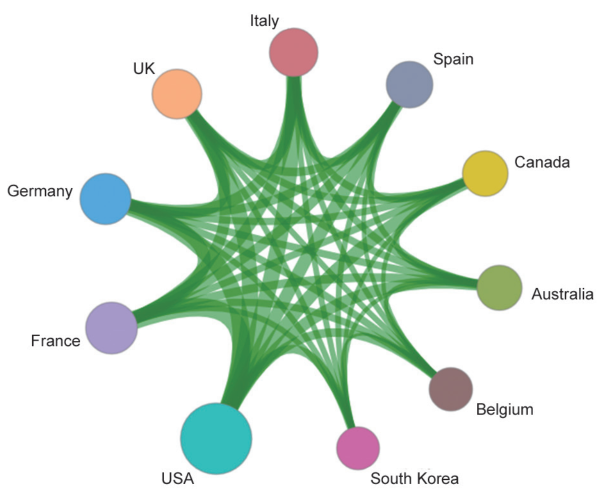

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "new taxonomy based on aberrant molecules and targeted therapy"

research institutions and clinical centers; (2) strengthening the cultivation of bioinformatics skills, which may be the biggest bottleneck restricting the development of this field in future; (3) accelerating the development of new drugs, especially the originally targeted drugs, and interconnecting the diagnosis and new drug development together to remove all the institutional obstacles hindering the development of new drugs; (4) incentive implementation of information sharing and global cooperation; (5) selection of 1–2 projects to explore new research system (these projects should be mandatorily conducted by the highly skilled researchers in leading institutes and guided by clinical outcomes).

1.2.2 Stem cell and cell therapies

A stem cell is a type of cell with the potential for self-renewal and multi-directional differentiation. It is capable of differentiating into multiple functional cells under certain conditions. Stem cells can be roughly classified into embryonic stem cells (ESCs) and ASCs according to their developmental stages. The ESCs derived from the reprogramming of differentiated cells are called induced pluripotent stem cells (iPSCs). ESCs and iPSCs are highly proliferative and are able to differentiate themselves into any cell type of the body; ASC, a type of undifferentiated cell existing in different tissues of the body, has limited proliferative ability and can only differentiate into specific types of tissue in the body.

Stem cells are often referred to as "seed cells" in the medical community because of their potential for regenerating various tissues and organs within the human body. The stem cell technology utilizes this potential to repair, replace, or otherwise interfere with damaged tissues and organs. Therapeutic stem cell research has made meaningful attempts towards the treatment of a number of severe systemic diseases, such as nervous system diseases, and cardiovascular, cerebrovascular, hepatic, and renal diseases. It has brought new hopes for effective treatment, thus becoming a highly important field of investment for various national governments. Some developed countries and regions such as Europe, the USA, and Japan have prioritized stem cell research as a strategy for national science and technological development, and made enormous efforts to promote its

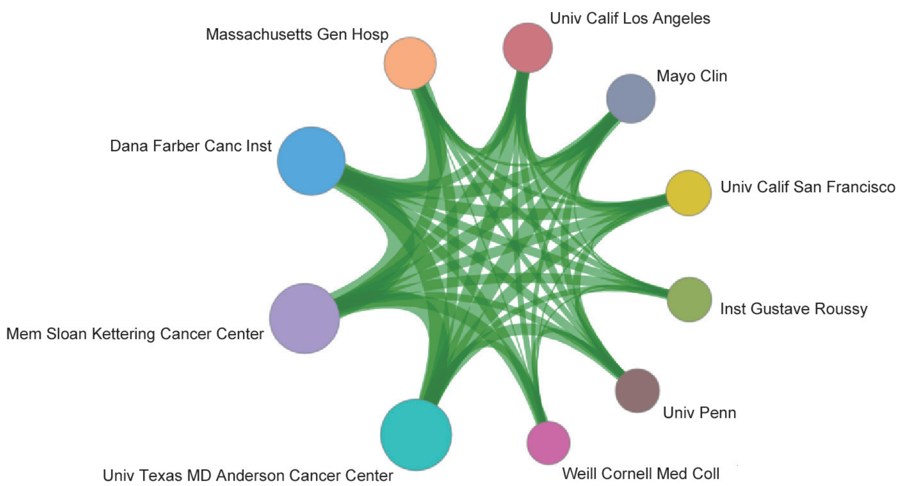

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "new taxonomy based on aberrant molecules and targeted therapy"

clinical applications. A number of pre-clinical and clinical trials have been carried out around the world, including the treatment of Parkinson's disease with dopaminergic neurons differentiated from neural stem cells, the treatment of chronic spinal cord injury with spinal cord neural stem cells, and the application of autologous interstitial precursor cells for the repair and regeneration of damaged tissues. These trials and findings have helped the development and emergence of several stem cell products into the market. Being the main supporters of the stem cell research industry, many major pharmaceutical companies have made huge investments and even adjusted the core of their businesses to seize the opportunities brought about by stem cell development and translational medicine. Globally, more than 700 companies are conducting research in this emerging field, and the competition is becoming increasingly fierce. In recent years, the stem cell industry has made rapid progress, and according to the latest prediction, the global stem cell research market will reach 400 billion USD by 2020.

Throughout developments at home and abroad, the key technical problems to be solved in stem cell research and development include: (1) Establishment and culturing of pluripotent stem cells at the clinical level: Maintenance mechanisms of the pluripotency of pluripotent stem cells, especially the ground state; optimization of *in vitro* reprogramming methods; characterizing the surface molecular antigens and transcription factors of pluripotent stem cells; and revealing pluripotency withdrawal, lineage differentiation mechanisms, and tumorigenicity of pluripotent stem cells. (2) Isolation and culturing methods of tissue stem cells at the clinical level: The heterogeneity of tissue stem cells and the unidentified surface markers are impeding the maintenance of long-term growth and expansion of stem cells cultured by current *in vitro* methods. (3) Directional differentiation of pluripotent stem cells: Using multi-lineage differentiation potential of pluripotent stem cells, as well as growth factors and drug interventions *in vitro*, and establishing methods for pluripotent stem cells to directionally differentiate into specific tissues or cells, such as islet β cells, endothelial cells, and hematopoietic stem cells. (4) Trans-differentiation: transforming into a new cell from the body's own mature somatic cells as a starting cell by expressing some specific genes or by drug induction. Recently, it has been reported to be useful in *in situ* trans-differentiation by allowing other cells from the damaged tissue to transform into the cells of interest for therapeutic purposes. (5) Forming complex structures *in vitro*: Stem cells can be spontaneously formed into micro-organs *in vitro* using 3-dimensional (3D) culture technology with the support of some special materials. They have certain functions and structures similar to normal body tissues and organs, laying the foundation of artificial tissue and organ transplantation in the future. (6) Stem cell genetic and epigenetic manipulation techniques: Given the special biological characteristics of stem cells, it is important to know how to use the emerging genome editing technology to manipulate stem cells and realize gene therapy potential for patient treatment.

These key questions are also the focus of the current academia. In the field of "stem cell and cell therapy," the top three core research publishing countries were the USA, China, and UK. The core papers of the "stem cell and cell therapy" research are all cited frequently (122.71–253.82), indicating that many countries attach great value to the research in this field. Also, the top three cited countries/regions are Italy, Australia, and the Netherlands (Table 1.2.3). As far as cooperation goes, there are collaborations between the top 10 core research papers-publishing countries (Figure 1.2.3). Among the 10 organizations that have published the highest number of core papers on stem cell and cell therapy, the top three are from the USA and China: Harvard University, Stanford University, and Shanghai Jiao Tong University (Table 1.2.4). As shown in the collaboration network of the top 10 core paper producing/yielding agencies, there is cooperation between different parts of the agencies (Figure 1.2.4).

Based on the statistical analysis results, China is currently at a level similar to that for foreign developed countries regarding the front of "stem cell and cell therapy" research. During the 12th Five-Year Plan and 13th Five-Year Plan periods, the state further increased its investment in stem cell research and specifically established major scientific research

Table 1.2.3 Countries or regions with the greatest output of core papers on the "stem cell and cell therapies"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	115	60.53%	19 537	61.88%	169.89
2	China	28	14.74%	3 436	10.88%	122.71
3	UK	23	12.11%	3 855	12.21%	167.61
4	Germany	22	11.58%	3 282	10.40%	149.18
5	Japan	22	11.58%	3 920	12.42%	178.18
6	Italy	17	8.95%	4 315	13.67%	253.82
7	Netherlands	16	8.42%	2 986	9.46%	186.63
8	France	15	7.89%	2 382	7.54%	158.80
9	Canada	14	7.37%	1 831	5.80%	130.79
10	Australia	13	6.84%	2 521	7.98%	193.92

Table 1.2.4 Institutions with the greatest output of core papers on the "stem cell and cell therapies"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	23	12.11%	4 010	12.70%	174.35
2	Stanford Univ	14	7.37%	2 252	7.13%	160.86
3	Shanghai Jiao Tong Univ	8	4.21%	801	2.54%	100.13
4	Howard Hughes Med Inst	7	3.68%	1 094	3.47%	156.29
5	Univ Hlth Network	7	3.68%	604	1.91%	86.29
6	Univ Toronto	7	3.68%	708	2.24%	101.14
7	Johns Hopkins Univ	6	3.16%	1 578	5.00%	263.00
8	Univ Med Ctr Utrecht	6	3.16%	1 512	4.79%	252.00
9	Univ Miami	6	3.16%	1 084	3.43%	180.67
10	Boston Childrens Hosp	6	3.16%	956	3.03%	159.33

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "stem cell and cell therapies"

projects, such as the "Scientific Research Program for Stem Cell Research" and "Strategic Science and Technology Pilot Project for Stem Cell and Regenerative Medicine," enabling some progress in basic stem cell research, key technologies, and resource platform construction. However, compared with developed countries such as the USA, Europe, and Japan, there still remains a large gap. To be more specific, China's R&D investment is lower than that of other countries. As such, the basic research output is lagging behind, and the core technologies and original results of stem cell translational research are insufficient. Most of the domestic stem cell transformation applications and the industrial layout are concentrated in the field of tissue stem cell storage, relying on resource collection and expansion in

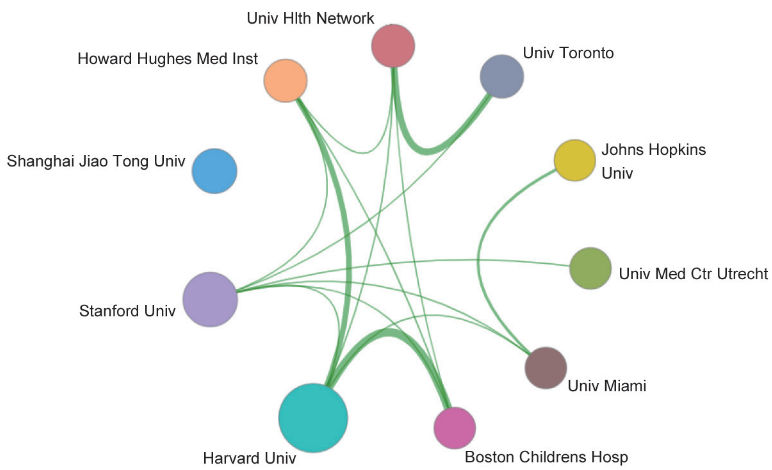

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "stem cell and cell therapies"

scale for profitability. However, no standardized stem cell transformation application or products are coming into the market. Registered stem cell-related clinical trials in China are mainly based on mature ASCs, notably lacking in pluripotent stem cell transformation applications that are quite highly trending in stem cell and regenerative medicine. In addition, the technical specifications, standards, and ethics related to stem cell therapy in China are relatively backward with respect to other countries. The lack of research groups and academic institutions specializing in stem cell quality control and standard research has resulted in some stem cell related products illegitimately evading government supervision and lacking preclinical research data. This has provoked severe international criticism and negatively affected the development of stem cell research and translational medicine in China.

For the past few years, the stem cell industry has maintained a momentum of rapid development. Developed countries such as the USA occupy the main market of the stem cell industry. China's stem cell biotechnology industry is mainly an upstream industry until now, with stem cell storage as the mainstay. To accelerate the process of turning stem cell basic research results into clinical applications, China has introduced a series of creative regulations and policies. Nevertheless, the pace of clinical transition of stem cells needs to be further expedited. One of the main issues is the lack of strict industrial and national standards for various stem cell products, which can be resolved by advocating the research on quality control standards for stem cell products and strengthening the training of relevant professionals.

1.2.3 Precision medical research based on biomedical big data

Precision medicine is a new medical model based on personalized medicine, generated with the rapid development of genome sequencing technology and the cross-application of bioinformatics and big data science. In 2011, a long-form report by the American Academy of Sciences entitled "Towards Precision Medicine: Building a Knowledge Network for Biomedical Research and a New Taxonomy of Disease" first proposed precision medicine. Its main content/role is to form a knowledge network revealing the molecular mechanism and genetic susceptibility of an individual's disease by interactively analyzing the clinical information and omics data at one- or multi-dimensional levels in large-scale populations. The knowledge network generates disease taxonomy and provides disease prevention and treatments for patients based on their genome and other individual characteristics. The aim of precision medicine is to provide accurate and timely warning and treatment based on an individual's genomic information and the molecular mechanisms of disease. This in turn can reduce the incidence of the disease, solve treatment inefficiencies, and reduce medical costs. As the future medical model and national health protection measure, precision medicine will bring about implementation of personalized medical services in many aspects. The disease risk of healthy or sub-healthy individuals will be predicted, especially for major chronic diseases, thereby reducing the incidence rate due to prior warnings. For the patient population, early diagnosis and precise treatment, like selection of the most appropriate drug, its dosage or duration of treatment for a given patient's genotype, could be provided to further improve the efficacy and cure rate. For infants with various birth defects, pre-implantation genetic screening or diagnosis could be performed to reduce the disease risk in newborns. After the Precision Medicine Initiative was launched by President Obama, several precision medicine projects have been developed around the world, including the 100 000 Genomes Projects in the United Kingdom (UK), the Genomic Medicine Plan 2025 in France, the Genome South Korea in Ulsan, and the Zero Childhood Cancer Program in Australia. In 2016, China also released a special project focused on precision medicine research. The project aimed at common dangerous diseases with high prevalence, as well as rare diseases with relatively high prevalence in China, and conducting research from the perspective of cohort, platform, technology, system, and demonstration application. The ultimate mission is to improve population health and make precision medicine the new rise point in economic growth and social development.

At present, the biomedical big data resources are maintained at different organizations and lack standardization. They are shared and utilized at low efficiency, and the omic data are not integrated with medical information, leading to the underutilization and non-processing of big biomedical data. The annual data generation capability in the life sciences has jumped by nine orders of magnitude from the gigabyte (GB) to the exabyte (EB) level in just over a decade (1 EB = 1 billion GBs). Therefore, big data centers that collect, manage, integrate, and utilize medical data have become indispensable basic support platforms for various precision medical programs. In the field of biological data collection and sharing, the USA, Europe, and Japan have established three major biological data centers (NCBI, EBI, and DDBJ) since the 1980s. These centers control most of the world's biological data. In the field of clinical medical data collection and sharing, the National Institute of Health (NIH) funded the establishment of the clinical data warehouse i2b2 as early as 2004 to manage health information coming from various sources (https://i2b2.cchmc.org/). At present, the extended framework developed by i2b2 can integrate genomic data to assist in personalized treatment. In addition, the European Union (EU) is currently actively building a biomedical big data center named BioMedBridges. In the field of bioscience data integration with medical information, the Health Level-7 (HL-7) Version 3 standard is expanding from the medical field to the health and omics fields. Mainstream medical information integration engines such as Ensemble are developing semantics-based integrated configuration technology. The "Big Data to Knowledge" (BD2K) plan of the USA involves studying relevant methods and software tools for data integration, management, analysis, and sharing. In 2014, the UK Medical Research Council established the "Medical Bioinformatics Program" to study the integration of omics data and health records. Currently, China has established several data centers for different research purposes, including: the Big Data Center of the Beijing Institute of Genomics, Chinese Academy of Sciences (CAS); the NONCODE database of the Institute of Biophysics, CAS; the Bioinformatics Center of Peking University; the Shanghai Center for Bioinformatics Technology; and the Bioinformatics Comprehensive Analysis Platform and the Basic Medical Science Data Center of the Beijing Institute of Genomics in Shenzhen. China promotes the standardization and sharing of medical data through a series of standards such as the Metadata Specification of Health Information Dataset, the Classification and Coding Rules of Health Information Dataset, the Rules for Data Element Standardization of Health Information, and the Basic Structure and Data Standards for the Electronic Medical Record. An integration engine based on interface technologies such as HL-7 and Digital Imaging and Communications in Medicine (DICOM) was also created to integrate disparate medical data. There are several important tasks that need to be performed in the field of precision medicine based on biomedical big data: (1) the basis is the accumulation of large-scale phenotype and omics data, including a large number of clinical population and prospective cohorts of natural populations; (2) the premise is the establishment of a big data platform with the management and sharing service or communication interfaces between the existing data centers; (3) the critical process is the establishment of a standardization technology system that can manage, analyze, and integrate the biomedical information efficiently based on heterogeneous computing, cloud computing, artificial intelligence, and blockchain technologies is the critical process; and (4) the establishment of a disease-centered medical knowledge base and a clinical decision support system is the starting point and ultimate goal of rapid translation from basic research to clinical application. The storage and integration, deep mining, and transformation applications of biomedical big data will play huge roles in future health science research and in achieving the goal of national health.

Papers regarding the fronts of “precision medicine research based on biomedical big data” are mostly published by researchers from USA, accounting for 74.74% of all studies and ranking first within 10 countries. the UK and Canada rank second and third, respectively. China ranks fourth in terms of papers published in this front, indicating that China is catching up fast. Citations per paper in this topic are high, and range between 122.52 and 285.03 (Table 1.2.5). The top three organization are Harvard University, Dana-Farber Cancer Institute, and Memorial Sloan-Kettering Cancer Center (Table 1.2.6). In parallel, the cooperation among the top 10 countries or regions and among institutions are closely promoted regarding “precision medicine research based on biomedical big data” (Figures 1.2.5 and 1.2.6). It further demonstrates that mutual cooperation between institutes is very essential and urgent.

Table 1.2.5 Countries or regions with the greatest output of core papers on the “precision medicine research based on biomedical big data”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	577	74.74%	136 758	82.84%	237.02
2	UK	158	20.47%	44 160	26.75%	279.49
3	Canada	116	15.03%	31 964	19.36%	275.55
4	China	107	13.86%	13 110	7.94%	122.52
5	Germany	104	13.47%	25 253	15.30%	242.82
6	Italy	81	10.49%	22 652	13.72%	279.65
7	Australia	70	9.07%	17 717	10.73%	253.10
8	Netherlands	68	8.81%	19 007	11.51%	279.51
9	France	68	8.81%	18 494	11.20%	271.97
10	Spain	63	8.16%	17 957	10.88%	285.03

Table 1.2.6 Institutions with the greatest output of core papers on the "precision medicine research based on biomedical big data"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Harvard Univ	142	18.39%	50 610	30.66%	356.41
2	Dana Farber Canc Inst	123	15.93%	38 814	23.51%	315.56
3	Mem Sloan Kettering Canc Ctr	96	12.44%	28 722	17.40%	299.19
4	Univ Texas MD Anderson Canc Ctr	93	12.05%	22 483	13.62%	241.75
5	Massachusetts Gen Hosp	71	9.20%	20 971	12.70%	295.37
6	Brigham & Womens Hosp	66	8.55%	20 917	12.67%	316.92
7	Univ Calif San Francisco	59	7.64%	16 021	9.70%	271.54
8	NCI	52	6.74%	14 251	8.63%	274.06
9	Univ Cambridge	52	6.74%	16 478	9.98%	316.88
10	MIT	51	6.61%	20 359	12.33%	399.20

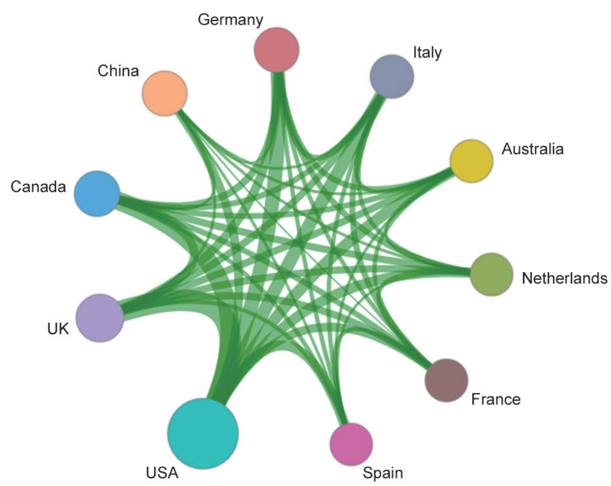

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "precision medicine research based on biomedical big data"

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The top 10 engineering development fronts related to the field of Medicine & Health are summarized in Table 2.1.1. These fronts cover a variety of disciples, including basic medicine, clinical medicine, pharmacy, medical informatics and biomedical engineering, public health and preventive medicine. Artificial intelligence (AI) and disease diagnosis, and AI health management are emerging fronts. Traditional research has focused on stem cell technologies, biomedical materials, tumor immunotherapy, genome editing, robotic surgery system, telemedicine, personalized therapeutic cancer vaccine, and medical 3D printing technology. All patents involved in these fronts published between the years 2012–2017 are listed in Table 2.1.2.

(1) Stem cell technologies

Stem cell technology refers to the repair, improvement, or regeneration of human tissues and organs and treatment of diseases based on the study of separation, subculturing, induction, and differentiation of stem cells. Stem cells, defined

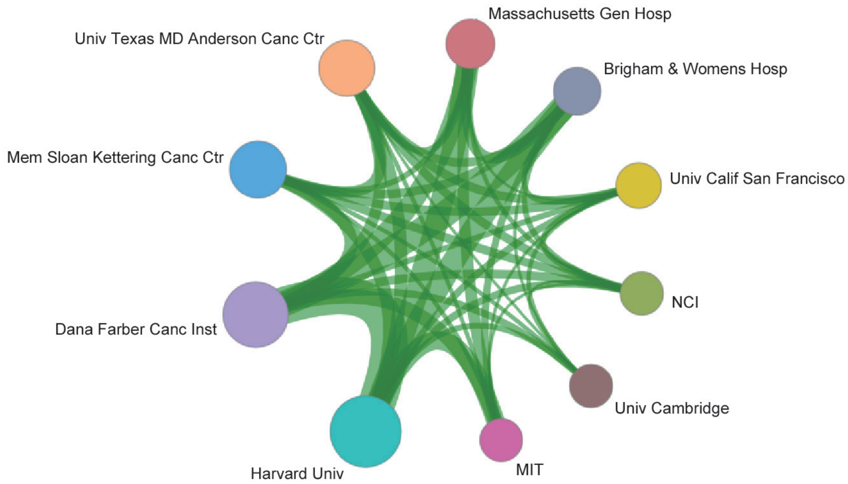

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "precision medicine research based on biomedical big data"

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	Stem cell technologies	8 458	8 943	1.06	2014.88
2	AI and disease diagnosis	747	2 064	2.76	2015.48
3	Biomedical materials	2 326	2 696	1.16	2015.19
4	Tumor immunotherapy	8 508	23 004	2.70	2014.89
5	AI health management	745	2 053	2.76	2015.48
6	Genome editing	2 529	12 042	4.76	2015.89
7	Robotic surgery system	2 976	35 337	11.87	2014.96
8	Telemedicine	2 195	5 102	2.32	2014.91
9	Personalized therapeutic cancer vaccine	460	844	1.83	2015.06
10	Medical 3D printing technology	1 896	2 121	1.12	2016.05

Table 2.1.2 Annual number of patents published for the top 10 engineering development fronts in medicine and health

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	Stem cell technologies	1 145	1 117	1 122	1 433	1 537	2 104
2	AI and disease diagnosis	58	69	68	95	175	282
3	Biomedical materials	208	266	276	398	481	697
4	Tumor immunotherapy	1 088	1 108	1 239	1 353	1 630	2 090
5	AI health management	58	68	68	94	175	282
6	Genome editing	55	90	227	400	679	1 078
7	Robotic surgery system	298	374	507	483	593	721
8	Telemedicine	229	285	307	432	522	420
9	Personalized therapeutic cancer vaccine	50	51	73	59	101	126
10	Medical 3D printing technology	22	50	109	289	591	835

by the features of self-renewal and differentiation potential, can differentiate into all cell types and tissues of the body. Their unique features have offered great opportunities for treating devastating diseases such as blood system diseases (e.g., leukemia), nervous system diseases (e.g., Parkinson's disease), cardiovascular diseases (e.g., myocardial infarction), and endocrine diseases (e.g., diabetes). In addition to cell therapy, stem cells have broad applications in the field of tissue and organ repair, disease modeling, drug screening, and precision medicine. With the continuous improvement of stem cell technology, its related treatment is expected to become the third choice for disease treatment, after drug treatment and surgery, leading to profound changes in the existing clinical treatment model. The huge potential of stem cell research in medicine has gathered support from all countries in the world, which promote the development of stem cell technology. Significant advances have been made in many key stem cell technologies, such as stem cell isolation, mechanism of cell fate conversion, and functional cell acquisition. Great achievements of basic research have accelerated the use of stem cells in clinical trials. Hematopoietic stem cell transplantation has become a mature and widely used treatment. A series of stem cell clinical trials have shown good therapeutic effects. Stem cell therapy was reported to halt a female patient's macular degeneration and brightened her vision. In addition, the number of stem cell-related drugs has reached 350.

(2) AI and disease diagnosis

AI and disease diagnosis refers to the use of AI technology to carry out drug screening and early tumor warning predictions, pathological detection and analysis, along with disease diagnosis, classification, surgery planning, and treatment. AI also encompasses postoperative evaluation and rehabilitation in order to achieve accurate and intelligent disease diagnosis. The application of AI technology in the medical field has significantly improved physician efficiency. It is expected to alleviate the shortage of physicians, improve the accuracy of diagnosis and treatment, promote the optimal allocation of quality medical resources, and the entry of medical treatment into new heights of quantitative analysis.

(3) Biomedical materials

Biomedical materials are used to diagnose, treat, repair, or replace damaged tissues, organs, or functions of living organisms. The concept of biomedical materials originated in the mid-1940s, and the industry was formed in the 1980s. The application of biomedical materials not only saves the lives of a large number of critically ill patients but also significantly reduces the mortality of major diseases such as cardiovascular disease, cancer, and trauma. It also substantially improves the health and quality of human life. In parallel, reforms in the health care system play a guiding role in considerably reducing medical costs. They are an important material basis for solving current issues of difficult and expensive medical treatments so as to build a stable unified society. The development of biomedical materials has experienced the following stages: the use of partially oxide ceramics, medical carbon materials, medical metal and polymer materials, generally bio-inert materials stage, mainly with highly biologically active and controllable degradable bioactive glass, bioceramics, and composites thereof. Until now, research and development on biomaterials has focused on improving and developing traditional biomedical materials in addition to producing third-generation biomedical materials based on cellular and molecular level requirements.

(4) Tumor immunotherapy

Tumor immunotherapy is one of the most effective treatments based on the application of immunological theories and techniques to improve the immunogenicity of tumor cells, the killing sensitivity of effector cells, and the enhancement of the body's immune response. The infusion of immune cells or effector molecules into the patient's body could kill the tumor cells, thus inhibiting the growth of the tumor. Tumor immunotherapy includes the applications of monoclonal antibodies against immune checkpoints, therapeutic antibodies, immunological cell therapy, tumor vaccines, and small molecule inhibitors. It has attracted much attention in recent years due to its remarkable clinical efficacy, and has become a front in both the scientific and pharmaceutical enterprises. In December 2013, the *Science* journal ranked tumor immunotherapy as the first of 10 scientific breakthroughs of the year. In April 2016, cancer immunotherapy was put up on the cover of *American Weekly* magazine. So far, three programmed death-1 (PD-1) inhibitor types, blinatumomab and talimogene laherparepvec (T-VEC) oncolytic viral therapy have been approved by the American Food and Drug Administration or the European Medicines Agency. Identifying new immune checkpoints, chimeric antigen receptor therapy, and small molecule inhibitor screening are the focus of competition in this field. Compared with the traditional cancer treatment, tumor immunotherapy has the advantages of quick reaction, fewer side effects, and durable curative effects. However, there are also some drawbacks in tumor immunotherapy, such as the excessive immune response of the body, immunosuppressive microenvironment of tumor tissue, and heterogeneity of tumor cells. Future topics of research in this field include the improvement of the efficacy and specificity of treatment, control of adverse reactions, and expansion of indications. Specifically, we should focus on the engineering of precise immune cell therapies, screening of more biomarkers, and combining traditional tumor therapy, immunotherapy, or different immunotherapies. In conclusion, tumor immunotherapy is considered to be the “fourth treatment” after surgery, chemotherapy, and radiotherapy. In the future, radical treatment of patients with advanced, recurrent, and refractory tumors can be achieved using tumor immunotherapy.

(5) AI health management

AI health management refers to the process of comprehensively managing individual or population health risk factors in a digital and intelligent way using AI, big data, and similarly advanced technologies. With the continuous development of computer technologies, health management has experienced the era of health management v1.0 based on the Internet technology, the era of health management v2.0 based on mobile internet, and finally, the new era of health management v3.0 based on AI and big data. With further development of technologies such as big data, AI, and blockchain, AI health management is being placed into the market by laboratory research and is gradually being applied to sub-health groups, elderly groups, and chronic disease and high-risk groups, effectively reducing the risk of an individual's illness and medical expenses at the same time. It is estimated that by 2020, the health service industry will reach a market scale of 8 trillion CNY, an average annual growth rate of 26%. In particular, third-party medical examination organizations, which have healthy big data resources, are accelerating their layout and exploration. With the development of information technology such as AI, the improvement of modern medical disease spectrum, and the emergence of new ideas in medical management is in rapid progress. The future of AI health management will be vigorously developed while significantly reducing medical costs and improving the health quality of individuals. This will eventually achieve the primary goal of disease prevention, thus achieving great health.

(6) Genome editing

Genome engineering is a type of genetic engineering in which deoxyribonucleic acid (DNA) is inserted, deleted, and replaced in the genome of a living organism. From meganucleases that emerged in 1994 to the recently developed CRISPR-Cas9 technology in 2012, genetic engineering is progressing at a rapid pace. The CRISPR-Cas9 technology can easily and efficiently induce mutations at single or multiple loci in living cells. Beyond genome editing, many CRISPR-Cas9-based technologies have been developed, including gene activation, gene silencing, RNA editing, epigenetic modification, and base editing, which all provide powerful tools to unlock the mysteries of life, uncover disease mechanisms, and cure genetic diseases. The technology is already widely used in research and development to engineer better suited and clinically relevant disease models, screen for new therapeutic targets, and generate CRISPR-engineered plants resistant against diseases or neutralizing the effects of climate change in agriculture. The CRISPR-Cas9 technology also seems very promising for clinical application when it comes to human papillomavirus (HPV) infection, hemoglobinopathies, and chimeric antigen receptor (CAR) T-cell therapy on treatment of cancers. The first therapeutic application of the CRISPR technology will likely target cells with established delivery systems, such as *ex vivo* genome editing, to modify and return cells of an individual patient to treat thalassemia or cancer. For *in vivo* applications, high efficiency of precise editing, high fidelity of genetic tools, and robust delivery systems are persistent challenges in the field. These improvements will facilitate *in vivo* therapy on opthalmic diseases, hearing loss, spinal muscular atrophy, and Duchenne muscular dystrophy. The clinical application of genome editing will be undoubtedly accelerated by appropriate safety and efficacy measures for any potential therapy involving patients, new genome editing tools with independent property rights, and good manufacturing practice (GMP) workshop for drug delivery with genome editing elements.

(7) Robotic surgery system

Robotic surgery system is a smart surgical system used to assist a surgeon in performing complex minimally invasive surgeries. Since the first robot-assisted surgery in 1984, robotic surgery systems have undergone multiple generations of innovations in different technological companies. It can now participate in cardiac surgery, cardiac electrophysiology, colorectal and gastrointestinal surgery, breast surgery, gynecology, pediatrics, plastic surgery, spine surgery, transplantation, and urology. The technology has currently advanced to such an extent that doctors can now precisely control the operation stick even while being physically away from the patient. The *in-situ* master-slave control mode of operation increases its accuracy and smoothness to enhance the field of surgery with 3D high-definition cameras. The technology helps reduce the complexity of traditional minimally invasive surgery and shorten the doctors' surgical learning curve. Since the advent of robotic surgery systems, the confinement created by traditional, minimally invasive surgeries have now been diminished. Surgeons are capable of performing fine operations in a small surgical space in a manner similar to open surgery, implying that high-risk surgeries are no longer a great challenge and there is a greater possibility for carrying out complicated minimally invasive surgeries. Innovations of the robotic surgical system are continually happening. For example, the structure of the mechanical arm has been improved to decrease in size and weight, and the sensing system will now provide tactile feedback to surgeons. At the same time, with remote surgery consultation and professional teaching of the robotic surgery system, medical efficiency would be further improved so that the limited medical resources of the country can be rationally distributed.

(8) Telemedicine

Telemedicine refers to the use of telecommunication and information technology to interactively deliver information for long-distance medical services. It is a new type of medical service that integrates modern medicine, computer technology, and communication closely together. A series of advanced technologies needs to be specifically developed to ensure the high quality and efficiency of telemedicine, such as the Internet, wireless communication, Internet of Things, virtual reality, electronic medical records, cloud computing, medical big data, and AI. In addition, intelligent terminals (e.g., computers, mobile phones, personal digital assistants, virtual reality equipment) and smart medical devices (e.g., remote blood pressure monitors, electrocardiograph, fetal heart rate monitors) are also important to solidify the intelligent medical interactions between patients and healthcare providers, medical institutions, and medical equipment. Telemedicine has a wide range of applications, including diagnostic systems, consultation systems for discussions on treatment plans, tele-surgery systems for treatment, education systems for teaching and training, and remote bed monitoring systems for home care patients. The purpose of telemedicine is to optimize the allocation of medical resources and provide remote or low-resource areas with smart and high-quality healthcare services. It is believed that telemedicine started relatively late in China, around 1986. Nowadays, as various technologies are gradually maturing, the telemedicine sector is also developing quickly. China has made significant progresses in remote diagnosis and consultation, diagnostic imaging, AI-assisted diagnosis, registration, distance education, and information sharing. The future development of telemedicine has taken another leap by advancing from just the treatment to disease prevention too, thereby providing personalized and intelligent healthcare services to individuals and enabling daily preventative health care and medical monitoring services.

(9) Personalized therapeutic cancer vaccine

Personalized therapeutic cancer vaccine is tailored to a single patient. These custom-tailored vaccines are designed based on each patient's particular tumor mutations (neoantigens), with the goal of inducing high-affinity immune T-cell response against cancer. In July 2017, Nature magazine reported that the new tumor antigen vaccine based on peptide and mRNA respectively, successfully reduced or delayed the recurrence or metastasis of melanoma surgery in a small number of patients, marking individualized cancer treatment vaccines have been clinically successful for the first time (Nature: 2017, 547: 217-21; Nature, 2017, 547: 222-6). As a brand new cancer therapy, this technology can theoretically be applied to any cancer, and has great potential in preventing recurrence and metastasis, which remain major problems in the current treatment of cancer. This technology is also expected to overcome the shortcomings of existing tumor immunotherapy, such as the complex mechanism of action of immune checkpoint inhibitors and the genetic engineering of

CAR-T cell therapy. Personalized therapeutic cancer vaccines are becoming a new research front in tumor immunotherapy and reflect the future direction of precision medicine. Nonetheless, research in this field still faces many challenges, such as longer vaccine customization cycle, which takes three months on an average, thus limiting its application to slow-growing cancers. In addition, it is still necessary to determine which types of tumors can benefit from immunotherapy. The vaccines are most commonly used on tumors with several mutations, such as melanoma. The development of this technology still requires intensive research, including the rapid detection of individual tumor-specific T-cell epitopes, an efficient T-cell epitope delivery pathway, and the rapid detection of single-cell expression profiles of tumor cells. It also requires quick and efficient technology for analysis of individual T-cell epitopes combined with cloud computing and AI, as well as a highly efficient intracellular introduction pathway of T-cell epitope vaccine. Finally, our purpose is to accelerate the development and clinical transformation of personalized therapeutic cancer vaccines.

(10) Medical 3D printing technology

Medical 3D printing technology is defined as the material forming or processing technology aimed at making applicable, personalized 3D medical products based on the patients' medical imaging data. The research front of medical 3D printing focuses on of 3D printer optimization, development of new printable materials and precise modeling software, and the multicellular precise 3D printing technology. With the progress in precision medicine and personalized medicine, as well as novel 3D-printable biomaterials and printers, this technology has become a leading manufacturing process in healthcare and medicine for a wide range of applications, including anatomical models, medical devices, surgical guides, 3D-printed implants, artificial tissues/organs, and drug screening. The 3D-printed products, such as orthopedic metal implants, ceramic dentures, and dural patches, have obtained FDA or China Food and Drug Administration (CFDA) certification, whereas 3D bioprinted tissues/organs are still in the experimental stage. Compared with foreign countries, the current 3D printing industry in China has shown high enthusiasm in the research and development of equipment as well as the application related services. Until now, the performance scale of these equipment is close to the advanced international level. However, several problems still need to be solved, such as the shortage and poor quality of printable materials, insufficient competition due to small scale of enterprises and meager investments, incompatibility between payment system and medical insurance, and lack of corresponding standards for 3D printing products. With the development of 3D printing technology, personalized medical products can not only achieve "adjustable scale and size" but also satisfy diverse needs such as anatomical structures, mechanical properties, and biological functions. Thus, it is evident that the process has evolved from medical models to bioprinted artificial organs. These technological advancements are of great significance for the development of regenerative medicine, which may be revolutionized fundamentally in the next 20 years.

2.2 Interpretations for three key engineering development fronts

2.2.1 Stem cell technologies

Stem cell technology refers to the repair, improvement, or regeneration of human tissues and organs and treatment of diseases based on the study of separation, subculturing, induction, and differentiation of stem cells. Stem cells, defined by the features of self-renewal and differentiation potential, can differentiate into all cell types and tissues of the body. Their unique features have offered great opportunities for treating devastating diseases such as blood system diseases (e.g., leukemia), nervous system diseases (e.g., Parkinson's disease), cardiovascular diseases (e.g., myocardial infarction), and endocrine diseases (e.g., diabetes). In addition to cell therapy, stem cells have broad applications in the field of tissue and organ repair, disease modeling, drug screening, and precision medicine. With the continuous improvement of stem cell technology, its related treatment is expected to become the third choice for disease treatment, after drug treatment and surgery, leading to profound changes in the existing clinical treatment model. The huge potential of stem cell research in medicine has gathered support from all countries in the world, which promote the development of stem cell technology. Significant advances have been made in many key stem cell technologies, such as stem cell isolation, mechanism of cell fate conversion, and functional cell acquisition. Great achievements of basic research have accelerated the use of stem cells in clinical trials. Hematopoietic stem cell transplantation has become a mature and widely used treatment. A series of stem cell clinical trials have shown good therapeutic effects. Stem cell therapy was reported to halt a female patient's macular degeneration and brightened her vision. In addition, the number of stem cell-related drugs has reached 350.

Presently, the development of stem cell technology must solve the following key technical problems: improvement and optimization of methods for stem cell isolation and pluripotency maintenance; understanding the mechanism of stem cell differentiation and regulation, acquisition, and functional studies on ASC; investigation of the machinery of tissue and organ formation; construction of artificial tissue and organs; establishment and regulation of *in vivo* functions after stem cell transplantation; and creation of evaluation standards for safety and effectiveness.

The current hot spots in the field of international stem cell technology include: (1) Pluripotent stem cell induction method that optimizes the reprogramming recipe using transcription factors, chemicals, and CRISPR-based methods for efficiently inducing a somatic cell to pluripotent stem cell. This will ensure a safe method of human pluripotent stem cell induction for clinical application. (2) Maintenance of pluripotency through the identification of additional transcription factors and epigenetic enzymes necessary for stem cell self-renewal (e.g., mesenchymal, hematopoietic, and neural stem cell acquisition, maintenance, and large-scale expansion in adult stem cells). (3) Committed differentiation, wherein, the stem cells can be differentiated into specific lineages and functional cells by improving culture methods or optimizing induction strategies. This involves proliferation of differentiated cells by the optimization of the physical and biological conditions for large-scale stem cell expansion to gradually yield quick differentiation and functional cell acquisition. (4) Establishment and regulation of *in vivo* functions after stem cell transplantation, i.e., establishment of cell tracking techniques to evaluate the therapeutic effect of specific cells types on diseases. (5) Stem cell-based therapy for tissue and organ repair, which uses micro-organ culturing or biological materials to construct functional brain, pancreas, liver, and teeth. There is a huge potential market of stem cell research in medicine due to its rapid development in the past 10 years. It has gradually moved from the laboratory to clinic and toward industrialization. The global stem cell industry has had a potential market of approximately 80 billion USD over the past two years, estimated to reach 400 billion USD by 2020. In China, the stem cell industry is also quite promising. According to a research report, the Chinese stem cell industry has formed a complete upstream to downstream industrial chain covering all its clinical applications. The income of the stem cell industry is expected to increase from 2 billion CNY to 30 billion CNY in the next five years, with an annual growth rate of 170%.

In total, the stem cell technology has been applied on 8458 patents in the past six years. China, the USA, and South Korea are ranked among top three countries with the highest number of patents in force (Table 2.2.1). The patents filed by Chinese authors/researchers account for 41.55% of the total global patents. China has become one of the key countries conducting research on this aspect of engineering development, with an average cited frequency of 0.63 (Table 2.2.1). This finding provides evidence that the quality of patents needs improvement. As shown in the cooperation network of patent-producing countries (Figure 2.2.1), the USA, Japan, Switzerland, and South Korea cooperate more closely than other countries. The top three institutions with the maximum proportion of core patent inventors are the Guangzhou Salia Stem Cell Technology Co., Kyoto University (KYOU), and University of Southern California (REGC) (Table 2.2.2). In addition, the collaboration network among international institutions shows the cooperation of Seoul National University Industry Foundation (USEO) and Konkuk University Industrial Cooperation Corp (UKUK) (Figure 2.2.2).

2.2.2 AI and disease diagnosis

AI and disease diagnosis refers to the use of AI technology to carry out drug screening and early tumor warning predictions, pathological detection and analysis, along with disease diagnosis, classification, surgery planning, and treatment. AI also encompasses postoperative evaluation and rehabilitation in order to achieve accurate and intelligent disease diagnosis. The application of AI technology in the medical field has significantly improved physician efficiency. It is expected to alleviate the shortage of physicians, improve the accuracy of diagnosis and treatment, promote the optimal allocation of quality medical resources, and the entry of medical treatment into new heights of quantitative analysis.

Table 2.2.1 Countries or regions with the greatest output of patents on the "stem cell technology"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	3 514	41.55%	2 203	24.63%	0.63
2	USA	1 694	20.03%	3 123	34.92%	1.84
3	South Korea	1 181	13.96%	824	9.21%	0.70
4	Japan	863	10.20%	1 094	12.23%	1.27
5	Taiwan of China	169	2.00%	179	2.00%	1.06
6	Germany	111	1.31%	176	1.97%	1.59
7	France	90	1.06%	118	1.32%	1.31
8	UK	85	1.00%	110	1.23%	1.29
9	Russia	82	0.97%	15	0.17%	0.18
10	Switzerland	70	0.83%	156	1.74%	2.23

Table 2.2.2 Institutions with the greatest output of patents on the "stem cell technology"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Guangzhou Saliai Stemcell Science and Technology Co Ltd	209	2.47%	72	0.81%	0.34
2	Kyoto University	103	1.22%	247	2.76%	2.40
3	University of Southern California	87	1.03%	156	1.74%	1.79
4	Seoul National University Industry Foundation	81	0.96%	29	0.32%	0.36
5	LG Chem Co Ltd	66	0.78%	76	0.85%	1.15
6	The Catholic University of Korea Industry-Academic Cooperation Foundation	55	0.65%	4	0.04%	0.07
7	Industry-Academic Cooperation Foundation Yonsei University	52	0.61%	20	0.22%	0.38
8	Konkuk University Industrial Cooperation Corp	49	0.58%	1	0.01%	0.02
9	Zhejiang University	47	0.56%	22	0.25%	0.47
10	Agency for Science Technology and Research, Singapore	44	0.52%	100	1.12%	2.27

The key technical problems to be solved in AI and disease diagnosis research include accuracy and related problems of medical data annotation, machine learning problems of limited or incomplete medical data, and mixed learning problems of multi-source medical data. Additional areas of technical hurdles include use of AI in different feature selection cases in disease applications, privacy protection in medical data, and application of AI in surgical intervention and rehabilitation. At present, the fronts of AI research include: (1) Eye diseases: Deep network learning techniques are used to study retinal fundus images, which can be used for the diagnosis of glaucoma, macular degeneration, and diabetic retinopathy. (2) Tumor treatment: Individualized and authoritative treatment programs are developed for cancer patients by integrating pathological sample feature extraction and genome sequencing data combined with clinical guidelines and evidence-based medicine. They have been used in lung and esophageal cancer. (3) Pathological diagnosis: The feature extraction and deep learning have been used for quantitative diagnosis and disease prognosis assessment. They have been used for treatment of cancers of lung, cervix, breast, stomach, and intestines. (4) Medical

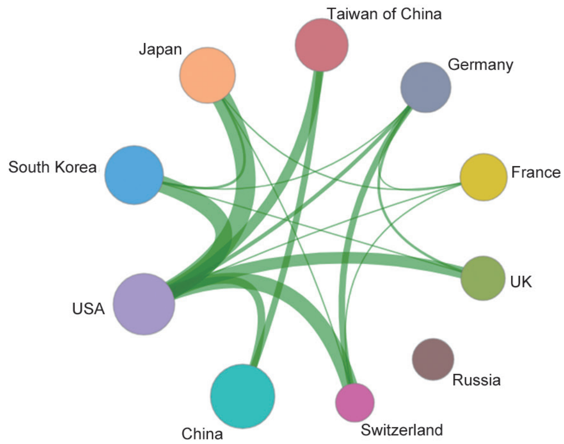

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “stem cell technology”

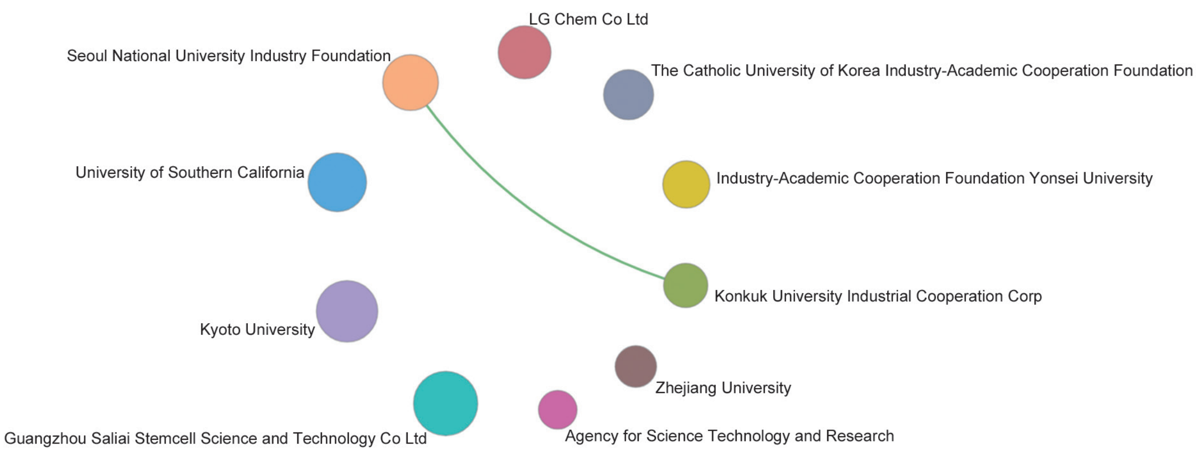

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “stem cell technology”

imaging: Through large databases and deep learning, many AI algorithms have been successfully used in a variety of medical imaging applications. For example, Alzheimer’s disease classification accuracy using brain MRI has reached 91.67% by using AI techniques and AI-assisted heart MRI imaging system (American Aeterys) has been certified by the FDA. (5) Skin diseases: AI technology carries out migration learning through the corresponding model and can diagnose skin cancer and melanoma with an accuracy rate of over 90%, greatly reducing the cost of medical testing. (6) Surgical robot: A series of surgical robots has been applied in urology, cardiology, orthopedics, and extra-sacral surgery. A typical example is the Da Vinci surgical robot system, which was developed by Intuitive Surgical Inc., USA. By using these surgical robots, the operation becomes more efficient and safe. The medical market demand for AI is very large and has been growing at a rate of 40% annually. However, the high-end market is still dominated by the USA and other western countries.

AI and disease diagnosis has been applied on 747 patents in the past six years. China, USA, and South Korea are ranked as the top three countries with the most patents in force. The patents applied by Chinese and US authors account for 41.37% and 33.07% of the total patents, respectively. The USA and China have become key countries researching on this aspect of engineering development. However the average cited frequency of China is only 1.66 (ranked ninth among the top 10 countries), which was significantly lower than the index in the Israel (13), USA (4.73), and Switzerland (4.2) (Table 2.2.3). As shown in the cooperation network of patent-producing countries (Figure 2.2.3), the USA is cooperating closely with Germany and India.

The top three institutions with maximum number of patent inventors are Siemens Healthcare Gmbh (SIEI), State Grid Corporation, China (SGCC), and International Business Machines Corporation, US (IBMC) (Table 2.2.4). Moreover, the collaboration networks among international institutions show low cooperation with regard to AI and disease diagnosis (Figure 2.2.4).

2.2.3 Biomedical materials

Biomedical materials are used to diagnose, treat, repair, or replace damaged tissues, organs, or functions of living organisms. The concept of biomedical materials originated in the mid-1940s, and the industry was formed in the 1980s. The application of biomedical materials not only saves the lives of a large number of critically ill patients but also significantly reduces the mortality of major diseases such as cardiovascular disease, cancer, and trauma. It also substantially improves the health and quality of human life. In parallel, reforms in the health care system play a guiding role in considerably reducing medical costs. They are an important material basis for solving current issues of difficult and expensive medical treatments

Table 2.2.3 Countries or regions with the greatest output of patents on the “AI and disease diagnosis”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	309	41.37%	513	24.85%	1.66
2	USA	247	33.07%	1 168	56.59%	4.73
3	South Korea	46	6.16%	33	1.60%	0.72
4	Germany	32	4.28%	95	4.60%	2.97
5	Japan	22	2.95%	58	2.81%	2.64
6	India	21	2.81%	48	2.33%	2.29
7	Canada	16	2.14%	51	2.47%	3.19
8	Israel	7	0.94%	91	4.41%	13.00
9	Switzerland	5	0.67%	21	1.02%	4.20
10	France	5	0.67%	16	0.78%	3.20

Table 2.2.4 Institutions with the greatest output of patents on the “AI and disease diagnosis”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Siemens Healthcare GmbH	33	4.42%	81	3.92%	2.45
2	State Grid Corporation	19	2.54%	11	0.53%	0.58
3	International Business Machines Corporation	15	2.01%	34	1.65%	2.27
4	HeartFlow Inc	11	1.47%	57	2.76%	5.18
5	Iteris Inc	10	1.34%	19	0.92%	1.90
6	General Electric Co	7	0.94%	33	1.60%	4.71
7	Merge Healthcare Inc	7	0.94%	3	0.15%	0.43
8	Beihang University	7	0.94%	8	0.39%	1.14
9	Microsoft Corporation	6	0.80%	26	1.26%	4.33
10	Jilin Agriculture Science & Technology College	5	0.67%	0	0.00%	0.00

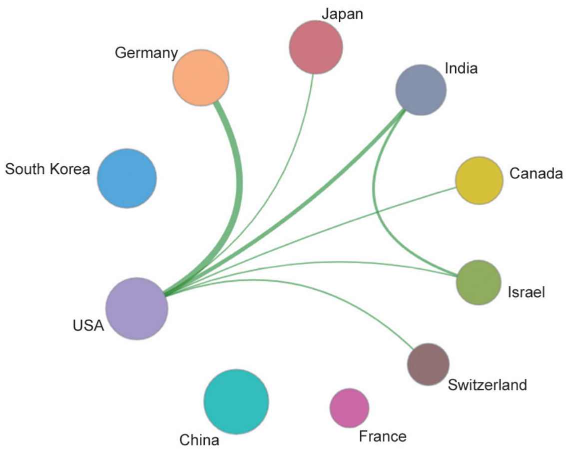

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “AI and disease diagnosis”

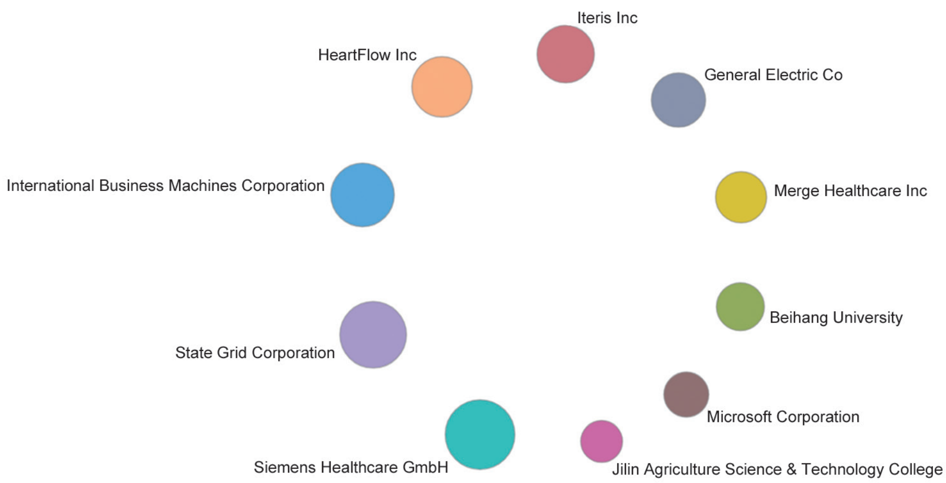

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “AI and disease diagnosis”

needs to solve the following key technical problems: (1) improvement and development of methods for evaluating the biocompatibility of biomedical materials; (2) design and synthesis of novel biodegradable materials; (3) development of artificial organs and tissue materials with comprehensive physiological function; (4) development of new drug delivery systems and drug carrier materials; (5) surface modification of materials; and (6) development of nanomedical materials.

The global medical device market is growing rapidly. As a new industry with low raw material and energy consumption and high technology added value, the biomedical material industry has shown a good development trend in recent years, and the market demand is very huge. In the past decade, the industry has been growing at an annual rate of 8%. It has

so as to build a stable unified society. The development of biomedical materials has experienced the following stages: the use of partially oxide ceramics, medical carbon materials, medical metal and polymer materials, generally bio-inert materials stage, mainly with highly biologically active and controllable degradable bioactive glass, bioceramics, and composites thereof. Until now, research and development on biomaterials has focused on improving and developing traditional biomedical materials in addition to producing third-generation biomedical materials based on cellular and molecular level requirements.

Presently, the development of biomedical materials

reached 130 billion and 220 billion USD in 2013 and 2016, respectively. Western countries such as the USA occupy the high-end market of biomedical materials, and share of China in the domestic market of biomedical materials in is only 3%, mainly in the low-end market of products. However, in terms of R&D, China has the highest number of patent applications in the forefront of biomedical material development in 2012–2017, and the proportion of patents applied has reached 69.91%. However, the quality of patents still needs to be further improved. Moreover, the total number of patents cited and average number of citations of the patents are still far from those of the USA.

The current fronts in the field of international medical material research include: (1) Biodegradable materials that can be gradually degraded or metabolized with time after being implanted in the human body. The foreign body implanted will automatically degrade into non-toxic, harmless substances that can be expelled from the body soon after they are used. (2) Tissue engineering materials and artificial organs to construct biological devices by using engineering principles and methods. These would replace the damaged tissues or organs, involving the use of biological scaffolds, seed cells, and growth factors to establish complex 3D biological structures composed of cells and biological materials. It is imperative to develop biological materials with good biocompatibility and ability to gradually degrade and be assimilated in the human body. These materials are used mainly to develop artificial blood, liver, heart, kidney, pancreas, blood vessel, cornea, and cerebrovascular stents. (3) Materials like bones and cartilages to repair defective bones and joints using tissue engineering principles. Electrospinning technology is used on bones, cartilages, and adipose tissue stem cells to develop artificial bones, cartilage knee joints, hip joints, meniscus, ligament, and muscles. (4) Dental restorative materials for developing biomaterials for the restoration of maxillofacial, mandibular, and tooth defects. (5) Controlled-release materials for the delivery of drugs at a constant rate over a certain period of time. These are divided into natural and synthetic polymers. (6) Bionic intelligent materials; these materials are designed on the principle of synergistic interaction among biological macromolecules to produce intelligent/smart materials with the desired host response. They imitate the cooperative behavior of biomedical materials. (7) Antibacterial membrane biomaterials; a biofilm is often formed on the surface of implant materials to protect bacterial growth and results in postoperative infections. As postoperative clinical bacterial film infections occur in 2%–3% of the total cases, therefore, there is a huge market for developing antibacterial materials to solve postoperative bacterial film infection. (8) Nano-biomedical materials is a new interdisciplinary field regarding the structure and function of genes and proteins, including their identification, integration, transformation, special factor release, bioelectrochemical signal generation and conduction, and biomechanical and thermodynamic properties. They also involve the development of new technical tools using multidisciplinary research.

With the improved economic development and severe forms of population aging, the demand for the medical market worldwide is increasing. In China, the demand for the development of biomedical materials has dramatically increased, and China has now become the second largest biomedical material market in the world. The development of this industry is important to improve the quality of life and delay the social problems brought about by aging. At the same time, biomedical materials, as a high-tech industry with low energy consumption and high added value, also have a great development potential and economic value. China has made a series of advances in the development of traditional biomedical materials. In some high-end areas, localization has also been replaced by imports, but there is still a big gap when compared with the actual needs of clinical applications. However, with the development of new technologies such as material science and molecular biology, especially stem cell engineering and 3D printing, numerous scientific attempts are being made towards success of biomedical materials especially in China. There are also new challenges and opportunities for the promotion of biomedical materials in China.

In total, 2326 patents on biomedical materials have been applied within the past six years. China, USA, and Japan are ranked as the top three countries with the most patents in force. The patents applied by Chinese authors account for 69.91% (Table 2.2.5). The average cited frequency of China is 0.78 (Table 2.2.5). The number of patents granted in the USA is fewer than that in China, but the average cited frequency in USA is 3.27. This suggests that the patent quality of our country needs improvement. As shown in the cooperation network of patent-producing countries (Figure 2.2.5), USA, Japan, and China are closely cooperating with each other.

The top three institutions with the maximum number of inventors of patents in force are West China Hospital Sichuan University (USCU), Tokuyama Dental Corporation (TDNT), and Hefei Chuangwo Technology Co., Ltd. (Table 2.2.6). In addition, the collaboration network among international institutions shows the cooperation of Shanghai Institute of Ceramics Chinese Academy of Sciences (CAGU) and Shanghai Jiao Tong University (USJT) (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of patents on the "biomedical materials"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	1 626	69.91%	1 273	47.22%	0.78
2	USA	223	9.59%	730	27.08%	3.27
3	Japan	169	7.27%	196	7.27%	1.16
4	South Korea	107	4.60%	51	1.89%	0.48
5	Taiwan of China	28	1.20%	45	1.67%	1.61
6	Germany	25	1.07%	54	2.00%	2.16
7	UK	25	1.07%	88	3.26%	3.52
8	Switzerland	19	0.82%	30	1.11%	1.58
9	France	17	0.73%	14	0.52%	0.82
10	India	16	0.69%	1	0.04%	0.06

Table 2.2.6 Institutions with the greatest output of patents on the "biomedical materials"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	West China Hospital Sichuan University	39	1.68%	48	1.78%	1.23
2	Tokuyama Dental Corporation	36	1.55%	36	1.34%	1.00
3	Hefei Chuangwo Technology Co Ltd	30	1.29%	0	0.00%	0.00
4	South China University of Technology	25	1.07%	32	1.19%	1.28
5	Donghua University	23	0.99%	40	1.48%	1.74
6	Wuhu Yangzhan New Material Technology	21	0.90%	0	0.00%	0.00
7	Zhejiang University	20	0.86%	1	0.04%	0.05
8	Soochow University	18	0.77%	28	1.04%	1.56
9	Shanghai Institute of Ceramics Chinese Academy of Sciences	17	0.73%	4	0.15%	0.24
10	Shanghai Jiao Tong University	17	0.73%	15	0.56%	0.88

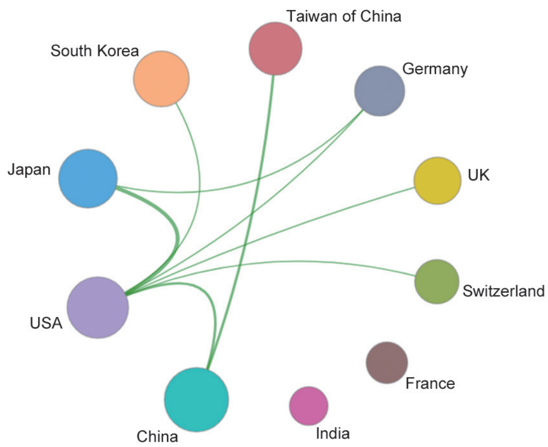

Figure 2.2.5 Collaboration network among major countries in the engineering development front of “biomedical materials”

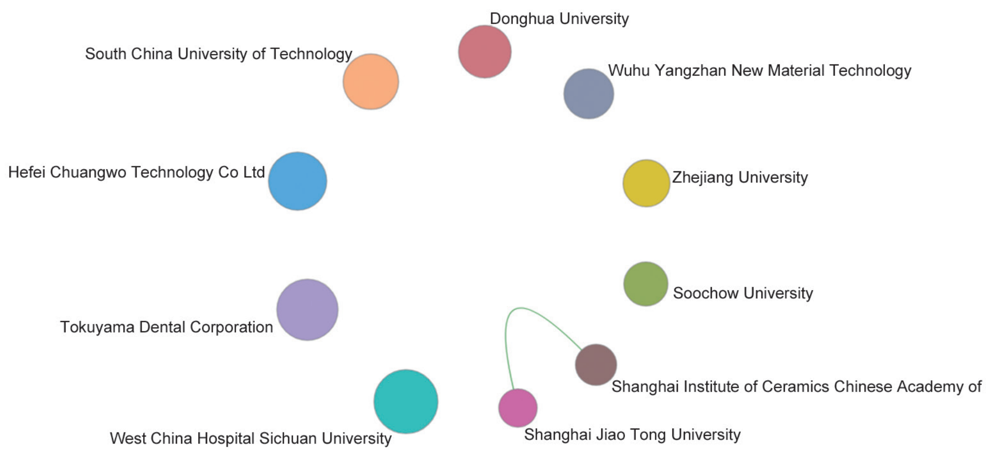

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “biomedical materials”

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IX. Engineering Management

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The fronts of global engineering management research focus on 10 topics: "service-oriented strategies of manufacturing enterprises," "charging strategies for electric vehicles," "utilization of land resources under the Shared Socioeconomic Pathway," "impact of climate change on water resources in arid regions," "diagnosis of mental diseases by using mobile-device sensors," "strategic plans for regional environmental management," "energy management based on distributed microgrid technology," "water–energy–food nexus," "application of ecosystem services in ecological risk assessment," and "influence of the built environment on commuting." The core papers on these topics are summarized in Tables 1.1.1 and 1.1.2. Front studies on these topics have been published in the fields of mechanical engineering, electrical engineering, energy, environment, medical science, construction, agriculture, and other disciplines, while key interpretations for the topics of "service-oriented strategies of manufacturing enterprises," "charging strategies for electric vehicles," and "utilization of land resources under the Shared Socioeconomic Pathway" have been obtained. The current and future development trends of these studies are discussed further in the later sections of this work.

(1) Service-oriented strategies of manufacturing enterprises

With the development of the economy, most customers are no longer satisfied with merely purchasing goods and have started demanding services to accompany these goods. Therefore, enterprises have begun to offer their customers goods–services packages to meet their expectations and satisfy their needs, while an increasing number of traditional enterprises have begun shifting their focus from goods to services. By providing more value-added

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Service-oriented strategies of manufacturing enterprises	13	288	22.15	2015.92	23.1%	0.00
2	Charging strategies for electric vehicles	18	406	22.56	2015.50	0.0%	0.00
3	Utilization of land resources under the Shared Socioeconomic Pathway	13	381	29.31	2015.54	7.7%	0.00
4	Impact of climate change on water resources in arid regions	4	206	51.50	2016.25	25.0%	0.00
5	Diagnosis of mental diseases by using mobile-device sensors	5	172	34.40	2015.40	20.0%	0.00
6	Strategic plans for regional environmental management	4	51	12.75	2016.75	0.0%	0.00
7	Energy management based on distributed microgrid technology	4	42	10.50	2016.75	50.0%	0.00
8	Water–energy–food nexus	5	57	11.40	2016.40	0.0%	0.00
9	Application of ecosystem services in ecological risk assessment	4	38	9.50	2016.75	0.0%	0.00
10	Impact of built environment on commuting	4	64	16.00	2016.25	0.0%	0.00

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

No.	Engineering research front	2012	2013	2014	2015	2016	2017
1	Service-oriented strategies of manufacturing enterprises	0	1	1	3	1	7
2	Charging strategies for electric vehicles	0	0	2	8	5	3
3	Utilization of land resources under the Shared Socioeconomic Pathway	2	0	3	0	0	8
4	Impact of climate change on water resources in arid regions	0	0	0	0	3	1
5	Diagnosis of mental diseases by using mobile-device sensors	0	0	0	3	2	0
6	Strategic plans for regional environmental management	0	0	0	0	1	3
7	Energy management based on distributed microgrid technology	0	0	0	0	1	3
8	Water–energy–food nexus	0	0	0	0	3	2
9	Application of ecosystem services in ecological risk assessment	0	0	0	0	1	3
10	Impact of built environment on commuting	0	0	1	0	0	3

services, manufacturing enterprises have switched from product homogenization to service differentiation and from selling a single product to providing overall solutions to the needs of their customers. Manufacturing servitization is an advanced manufacturing mode that combines manufacturing with service and ensures a coordinated development of manufacturing services and service-oriented manufacturing. The key issues in manufacturing service research include the influence mechanism of the manufacturing servitization business model, product and service optimization matching and design, manufacturing- and service-integrated optimization decision control, collaborative management of the product servitization supply chain, and the role of new information technologies in servitization transformation.

(2) Charging strategies for electric vehicles

With the tight supply-and-demand relationship of petroleum resources around the world and the increasingly strict regulations on vehicle emissions, new energy vehicles, typified by electric vehicles, represent an important development trend in the automobile industry. To reduce the energy consumption of charging vehicles and to improve the security of power grids, several countries have adopted the electric-vehicle charging strategy as a strategic research direction. Electric vehicles are electric loads for which practical use is being hindered by two key problems. First, the current energy supply methods for electric vehicles include slow charging, fast charging, and battery replacement, while their power consumption during driving is affected by various factors, including unit mileage power consumption, load capacity, and road conditions. Therefore, a reasonable charging method must be determined to minimize the costs of charging and to promote the development of electric vehicles while taking their charging requirements into account. Second, the disorderly charging of electric vehicles can produce harmful effects, such as increasing the peak–valley difference in power systems and voltage drops in local areas. The orderly charging of electric vehicles is among the most convenient and feasible ways to realize the peak load shifting of power systems and improve the economic operation of electric vehicles.

(3) Utilization of land resources under the Shared Socioeconomic Pathway

Shared Socioeconomic Pathway (SSP) is a new framework in land utilization, ecological environment, and climate change research. SSP predicts future development trends, reveals the logic of causal relationships, and shows historical trends that cannot be easily captured by using models. This framework also supplements the predictions of quantitative models, which quantify the basis and meaning of SSP predictions (e.g., future changes in population, human development, economy, lifestyle, policies, institutions, technologies, environments, and natural resources) based on several key qualitative description factors. SSP has been divided into five paths—sustainable development, regional competition, inequality, fossil fuel development, and intermediate development—all of which aim to address the challenges related to climate change alleviation and adaptation, ensure future social and economic development, and facilitate climate change research and policy analysis. The utilization of land resources under SSP fully covers all potential development situations, satisfies the demands of agricultural and industrial development, provides guidance for various laws and regulations, and requires improvements in the position, productivity, environmental influence, trade, and globalization of future markets. By using data on land utilization changes and classifying aerial scenario images, this research front focuses on developing energy, agricultural, and production systems, reducing greenhouse gas (GHG) emissions and environmental influences, alleviating the harmful effects of climate change and urbanization, providing solutions to climate policy and other social objectives, and improving biodiversity conservation, ecosystem service value, and land utilization sustainability.

(4) Impact of climate change on water resources in arid regions

Climate change can transform the spatial distribution and temporal variation characteristics of atmospheric precipitation, thereby altering water circulation systems and influencing the spatiotemporal pattern of water resources. Under the joint influence of social economy development and global climate change, the demand for water resources in arid regions is gradually increasing along with the increasingly harmful effects of drought. Studies on the influence of climate change on water resources in arid regions have mainly focused on the ocean–atmosphere–land interface, water resources and ecological impacts in arid regions, the simulation and evaluation of the effects of global and regional climate modes on the climate in arid regions, the prediction of the spatiotemporal patterns of water resources in arid regions across various climate change situations by using hydrological models, the uncertainty of the influences and predictions of the climate mode and assessment models, and the use of technologies to monitor and forecast drought hazards and issue alerts. Conducting quantitative research on the spatiotemporal response features of water resources in arid regions, especially the frequency, cycle, strength, duration, and influence of extreme hydrological processes, under the background of climate change is of great importance in preventing and mitigating extreme hydrological disasters, maintaining social stability, and ensuring sustainable economic development.

(5) Diagnosis of mental diseases by using mobile-device sensors

Sensors receive relevant signals or stimuli and produce the necessary responses. These devices can also send physical or chemical quantities to be measured to another device in a specific time and space to meet the requirements of information transmission, storage, and processing. Mobile devices, such as smartphones, computers, and wearable sensors, can continuously monitor behavioral components (e.g., decreased activity, delayed mental activity, and changes in sleeping patterns) and motivational states (e.g., loss of pleasure) associated with mental diseases as well as the physiological states (e.g., heart rate, body temperature, and skin electrical reactions) of people with mental diseases. These data can help psychiatrists conduct real-time monitoring, provide their patients with behavioral intervention, and control their conditions. Mobile-device sensors are widely used as advanced technologies for diagnosing mental diseases. However, some challenges hinder their application, particularly their inability to connect the vast amount of data to the feelings of patients. Moreover, one cannot guarantee that patients will strictly follow their treatment process. As an application prospect, mobile-device sensors can encourage healthy behaviors of individuals by using the Internet of things and subsequently improve their mental health. However, the use of mobile-device sensors for mental disease diagnosis and intervention is still in its infancy. Nevertheless, a new generation of technologies is expected to bring revolutionary changes in digital psychiatry practice and support the global population.

(6) Strategic plans for regional environmental management

As economic development is gradually regionalized, the regionalization of environment problems is becoming increasingly apparent. Unlike the traditional environmental treatment mode that focuses on the companies or projects of the point source, the regional environmental treatment mode that uses the entire natural region as its treatment object has become increasingly important. Regional environmental treatment plans must regard those ecological regions that are divided by natural boundaries as their treatment objects, and environmental actors in ecological regions (especially local governments) must serve the overall environmental interests of their respective regions. Area division and cooperative treatment are basic features of regional environmental treatment plans. The special nature of environmental problems requires the implementation of unique treatments in different areas based on the characteristics of their natural regions. All administrative regions in a natural ecological area must cooperate in implementing environmental treatments to achieve their environmental objectives. Extant studies on regional environmental treatment plans have mainly focused on ecological civilization, air pollution, and haze treatment. The key issues in this front include the legal protection and accountability mechanism of regional environmental treatment and the roles of local government cooperation and composite incentive mechanism construction in cross-regional environmental treatment. Investigating the multiple collaborative management mode, division of responsibilities, and legal protection of local governments in natural regions under the background of regional environmental treatment are of great importance in enhancing cooperation among local governments and preventing and mitigating environmental pollution problems in a region.

(7) Energy management based on distributed microgrid technology

A distributed microgrid is a small power distribution system with distributed power sources, energy storage and conversion devices, related loads and monitoring tools, and protection devices. The most prominent difference between a microgrid and a conventional distribution and power supply network is that the former can operate independently while ensuring power quality. A microgrid also combines modern technologies, such as energy conversion tools, power electronics, power grids, and automatic controls, and presents an important direction for the future development of energy technologies. The development of energy management technologies based on distributed microgrid technology can motivate further studies on control strategies; lead to the formulation of punitive solutions for the abandonment of excess heat generation; and increase the flexibility, accessibility, reliability, and cost-effectiveness of grids. Instead of merely selling electricity, enterprises can integrate the four functions of power generation, power distribution, power management, and electricity sales and realize flexible microgrid control through efficient distributed energy integration, which in turn can support the development of new supply modes. Hot research topics in this area include using a distributed microgrid to integrate renewable energy, energy storage systems, and local loads into the grid optimization configuration; using a microgrid to exceed the new energy penetration power limit; paralleling multiple microgrids; stabilizing microgrids in grid-connected and island operations; using microgrids to improve power quality; applying stochastic energy management to solve issues related to uncertain random supply and demand and to improve the balance of supply and demand in the whole system; improving power quality, energy utilization, autonomy, and adaptability; using a multi-micro network coordinated control strategy to improve the stability of the multi-micro network; developing an energy management system with prominent interaction functions; solving the optimization strategy based on the time–demand response; developing new power electronic equipment (e.g., grid-connected inverters, static switches, and power control devices) as supporting equipment; and developing superconductor energy storage technologies for microgrids and super capacitors.

(8) Water–energy–food nexus

The water–energy–food nexus implies a close relationship among water safety, energy safety, and food safety. The operation, decision, and movement of any of these resource systems are related to changes in the other two systems. However, the coping strategies of a resource system always lead to the transfer of problems from one resource system to another, thereby creating a dilemma in resource treatment. This nexus necessitates a shift from pursuing the efficiency of a single department to exploring cohesive and comprehensive solutions to resource problems from cross-departmental perspectives. However, this shift can introduce fundamental changes in resource governance concepts and challenge the current structure, policy, and procedure at the global, regional, and (sub)state levels. The water–energy–food nexus has three core aspects: the interactional core nexus of water, energy, and food in production, consumption, and waste treatment processes; the internal influential relationships formed by population, trade, and climate change elements; and the external influential relationships formed by the impact of nexus changes on the social–economic–ecological system. The number of studies on this nexus is rapidly increasing at the global, domain, and family levels, while data are being collected at the urban and regional levels to develop the necessary research tools. Along with the standardization of criteria for data calculation—the integration of the WEF-Nexus model in all spatiotemporal dimensions, the monitoring of data, the supply and demand of multiple resources, the development of integrated models for the toughness and sustainability of the infrastructure (green, gray, and blue) system, and the creation of an intelligent decision system—the WEF-Nexus paradigm is expected to become an important tool for ensuring the sustainable development of human society.

(9) Application of ecosystem services in ecological risk assessment

Ecosystem services (ESs) refer to life support products and services that are directly or indirectly obtained by humans through the structure, processes, and functions of ecosystems. These services include supply, regulatory, cultural, and support services, the sustainable supply of which provides a foundation for ensuring sustainable economic and social development and directly benefits humans. ESs clarify the link between human well-being and ecosystem structures and processes. They have been applied in ecological risk assessment to define the environmental value that must be maintained; to analyze the risks in the structure, process, and function of an ecosystem subjected to external pressures; to examine the complex processes of an ecosystem; to consider the integrality and complexity of an ecosystem in the risk analysis process; to assess the impact of service output based on a holistic characterization of ecological risk; to examine how highly comprehensive environmental protection, environmental policymaking, and other policy and implementation actions can be promoted; to investigate the comprehensive action policy of environmental quality standards; and to assess the risks to human health and ecology. In the ecosystem process and service discipline, ESs mainly focus on the classification and tradeoff of ecosystem services; the formation and provision of mechanisms, quantitative analysis, and evaluation methods; the scale effect and regional integration; and the optimal regulation of ecosystem services. The key issues in the application of ESs in ecological risk assessment include comprehensively evaluating the direct or indirect interactions among various risk sources and receptors in ecosystems, establishing a system for simulating and evaluating ecological risk in ecosystems, using the ecological production function to assess the influence of an external pressure disturbance on the ecosystem service output and to measure the resulting risk of applying external pressure on the system material energy flow and circulation rate, examining the causal relationship between the ecological system process and the social economy, establishing a nonlinear risk assessment model for subsystems, improving the docking between the evaluation process and the social ecological management process, promoting research on ecosystem services in the follow-up stage of ecological risk assessment, and integrating the game strategies of various stakeholders into the evaluation process.

(10) Impact of built environment on commuting

Aside from traffic congestion charges, odd–even traffic schemes, fuel taxes, and other travel-demand-management strategies, emphasizing the positive effect of the built environment on traffic and reducing the dependence of people on vehicles are essential in solving traffic problems. The formation of a built environment has a deep-rooted influence on the daily travel behavior of commuters, which in turn determines the spatial distribution of urban residents' activities at the macroscopic level. This distribution cannot be easily changed after the formation of an urban built environment and may produce a long "lock-in effect" on traffic. Given that commuting is an important daily activity, how to optimize the urban built environment to affect the commuting demand, reduce car ownership and use, and encourage people to engage in green travel to alleviate traffic problems have become hot research topics in urban traffic planning and related disciplines. The development of big data and spatiotemporal behavioral science in recent years provides a feasible means of collecting data on the relationship between the built environment and commuting. The key issues in this area include examining the micro-mechanism of the influence of the multi-scale built environment on commuting, testing the synergistic effect of the built environment and traffic demand management on commuting, investigating the influence mechanism of the built environment on multidimensional traffic behavior, and studying the correlation mechanism between the built environment and rail commuting. In the context of China's urban development, examining how the built environment of typical Chinese cities affects commuting can provide a theoretical basis and decision-making support for the formulation of land use, traffic planning, and traffic-demand-management strategies in China.

1.2 Interpretations for three key engineering research fronts

1.2.1 Service-oriented strategies of manufacturing enterprises

The concept of manufacturing servitization was introduced by Vandermerwe and Rada in 1988, and it was later defined by Needly from Cambridge University, as the innovation of organizational capabilities and processes that create value for customers and businesses from the sale of products to the provision of products and related services. In other words, manufacturing servitization is essentially a process of transforming product service systems. Strategically, this process can enhance the relationships of enterprises with their customers and contribute to their sustainable development. Economically, services have a high profit margin as well as a long-lasting and stable revenue stream. Environmentally, the full life-cycle management of products implemented by manufacturing enterprises under servitization can reduce the consumption of resources. The "Made in China 2025" initiative highlights a productive service industry as an important source of support for transforming and upgrading the manufacturing industry and presents the only way to upgrade the industrial value chain.

Manufacturing servitization can be divided into three main modes. Take the case of Philips as an example. The company sells nuclear magnetic resonance equipment to medical institutions in the mode of manufacturing servitization and provides maintenance and repair services in the mode of equipment use. In the use-oriented mode, when renting out equipment to medical institutions, Philips charges a rental fee depending on the time of use. Meanwhile, in the results-oriented mode, Philips directly provides inspection services and conducts a final inspection of the diagnostic results.

Early studies on manufacturing servitization are mainly concentrated in Europe, and this topic was not examined in China until around 2008. Service-oriented manufacturing is a service transformation business model adopted by manufacturing enterprises. Chinese scholars specializing in manufacturing servitization mainly come from Shanghai Jiao Tong University and Xi'an Jiao Tong University, of which the former has recently completed a National Natural Science Foundation project on China's service-oriented manufacturing in 2013. Despite the large number of studies that guide the practice of enterprises, all of them are placed at the forefront of the world.

Four hotspots in manufacturing servitization research, namely, competitiveness of manufacturing service business models, configuration of the product service system, control and collaboration in manufacturing and services, and manufacturing servitization based on new information technology, are discussed in detail in the following sections.

(1) Competitiveness of manufacturing servitization business models. The advantages of the manufacturing service business model have been widely recognized in academic and business circles. Although many well-known manufacturers, such as IBM, Royce, and Shaanxi Drum, have successfully transformed their business models, other enterprises, such as Intel, have lost profits during their transition and have even completely abandoned their adoption of this model. This situation has been referred to by academic circles as the "paradox of servitization." Research on the competitiveness of the manufacturing service business model has theoretical significance for enterprises and guides their selection of suitable service modes. Hot topics in this area include the choice of service type, the choice of breadth of service, the configuration of products, and the influence of service investments, the market competition environment, and product and industry characteristics on service performance.

(2) Product service system configuration. A product service system refers to the product service package provided by manufacturing servitization enterprises that emphasizes the integration of products and services, even the whole solution, to achieve a 1 + 1 > 2 integration effect. The configuration of a product service system begins from understanding the requirements of consumers, translating such requirements to product and service feature requirements, and optimizing the configuration via knowledge engineering or by using an optimization model. Given the continuous development of new information technologies, the product service configuration must focus on the whole product or service life cycle; fuse and seamlessly integrate products, services, and information based on the demand of users; and integrate products, services, and information into business models. Meanwhile, the hot topics in the product service system and product and service optimal configuration include the choice of product service system mode, the optimized configuration of the product service system, and the personalized customization of the product service system.

(3) Control and collaboration in manufacturing and services. By integrating manufacturing and services, service-oriented manufacturing must also integrate and optimize various manufacturing and service processes, combine manufacturing and service capabilities, and develop a complete system

function to achieve an overall system optimization. However, given the involvement of customers in the process, manufacturing and service integration control must also consider the behavior of these customers. The product and service flows can also affect and interact with each other and must be managed collaboratively. The rapid development of information technology can help manufacturing companies achieve integrated control and collaborative management of manufacturing and services. Hot topics related to this area include joint forecast of product and service demand, optimal configuration and real-time allocation of manufacturing and service hybrid system resources, optimization of the manufacturing and service integration control system under new information technology, and development of a coordinating mechanism for product manufacturers and service providers.

(4) Manufacturing servitization based on new information technology. A new generation of information technology, represented by big data, cloud computing, and the Internet of things, has not only enhanced the function and effectiveness of product services but also created added value by providing services based on new information technology and introducing a new mode of service operation. Therefore, examining the service mode and its selection under the background of new information technology is important in promoting the shift of enterprises to intellectualization and servitization, enhancing the integration of products and services, and increasing the competitiveness of the enterprise market. Hot topics related to this area include using new information and communication technology to realize the fusion of products and services, launching a new service form under the background of information and communication technology, examining the value creation mode of manufacturing enterprises, and investigating the service transformation of manufacturing enterprises under the background of information and communication technology.

Given its rapid development, the impact of new information technology on the services of manufacturing enterprises has become a research hotspot. Extant studies have mainly examined the mechanism of new information technology in promoting servitization and the role of such technology in servitization transformation. These studies also have emphasized the need to consider the behavior and demand of customers to improve product design, manufacturing processes, and service integration optimization theory. The product servitization supply chain must coordinate the manufacturing, maintenance, spare parts supply, and logistics systems, and achieve supply chain coordination under a use/results-oriented product service system. Interdisciplinary studies in computer science, operational research, management science, engineering, and other disciplines must be strengthened in the future. From the application perspective, China has demonstrated promising performance in promoting service-oriented manufacturing in the large aircraft, high-speed rail, shipbuilding, nuclear power, and other high-end equipment manufacturing industries.

Finland, UK, and the USA are the top three countries that have published the largest number of core papers related to the service-oriented strategy of manufacturing enterprises (Table 1.2.1), while New Zealand, Canada, and Switzerland are the top three countries with the largest average number of citations (Table 1.2.1). Among the top 10 countries/regions that have published the largest number of core papers, UK, Spain, Finland, Sweden, and Switzerland have demonstrated the largest degree of cooperation (Figure 1.2.1).

Linkoping University, Aalto University, and the University of Cambridge are the top three institutions that have published the largest number of core papers (Table 1.2.2). Meanwhile, Boston University, Dartmouth College, and MIT have shown the largest degree of cooperation among the top 10 universities that have published the largest number of core papers (Figure 1.2.2).

Table 1.2.3 shows that the number of citing papers of China has not yet entered the ranks of the top ten. So it means that China is in a non-following position on service-oriented strategy research of manufacturing enterprises.

1.2.2 Charging strategies for electric vehicles

With a tight supply–demand relationship for fossil fuels globally, new energy vehicles, such as electric vehicles, represent an important development trend in the automobile industry. Electric vehicles have unique advantages over traditional fuel vehicles, including no pollution, low noise, high energy efficiency, and easy maintenance, all of which have prompted many countries to increase their production of electric vehicles. For instance, in 2017, China sold approximately 777 000 electric vehicles, which was 53.3%

Table 1.2.1 Countries or regions with the greatest output of core papers on the "service-oriented strategies of manufacturing enterprises"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Finland	5	38.46%	100	34.72%	20.00
2	UK	5	38.46%	59	20.49%	11.80
3	USA	4	30.77%	116	40.28%	29.00
4	Switzerland	3	23.08%	110	38.19%	36.67
5	Sweden	3	23.08%	70	24.31%	23.33
6	Spain	3	23.08%	32	11.11%	10.67
7	Italy	2	15.38%	12	4.17%	6.00
8	Canada	1	7.69%	45	15.63%	45.00
9	New Zealand	1	7.69%	55	19.10%	55.00
10	Ireland	1	7.69%	20	6.94%	20.00

Table 1.2.2 Institutions with the greatest output of core papers on the "service-oriented strategies of manufacturing enterprises"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Linkoping University	3	23.08%	70	24.31%	23.33
2	Aalto University	3	23.08%	35	12.15%	11.67
3	University of Cambridge	3	23.08%	47	16.32%	15.67
4	Boston University	2	15.38%	102	35.42%	51.00
5	Dartmouth College	2	15.38%	102	35.42%	51.00
6	MIT	2	15.38%	102	35.42%	51.00
7	Hanken School of Economics	2	15.38%	65	22.57%	32.50
8	University of Granada	2	15.38%	12	4.17%	6.00
9	HEC Montreal	1	7.69%	45	15.63%	45.00
10	IMD International	1	7.69%	45	15.63%	45.00

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "service-oriented strategies of manufacturing enterprises"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	UK	39	20.31%	2016.59
2	USA	28	14.58%	2016.04
3	Finland	27	14.06%	2016.52
4	Sweden	21	10.94%	2016.57
5	Germany	20	10.42%	2016.70
6	Italy	19	9.90%	2016.63
7	Spain	14	7.29%	2016.50
8	Switzerland	10	5.21%	2016.30
9	Denmark	7	3.65%	2016.86
10	Australia	7	3.65%	2016.86

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “service-oriented strategies of manufacturing enterprises”

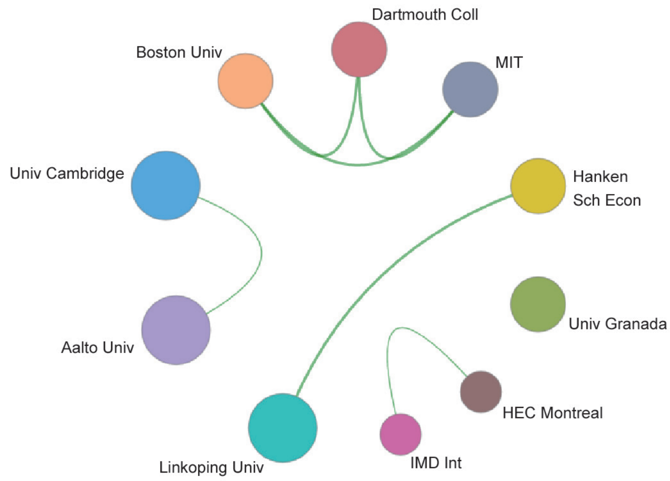

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “service-oriented strategies of manufacturing enterprises”

higher than the electrical vehicle sales in the previous year. However, given the restricted amount of electricity stored in their batteries, electric vehicles have limited mileage, which prevents the market share of electric-vehicle manufacturers from increasing further. Moreover, the charging demand of electric vehicles shows great randomness as reflected in their diverse charging methods and complex charging site selection. Therefore, a scientific electric-vehicle charging strategy must be developed to promote the large-scale production of electric vehicles.

(1) Optimal selection of charging mode. Electric vehicles have three charging modes. First, the slow-charging mode can effectively extend the service life of batteries. This involves charging electric vehicles during off-peak hours and discharging them during peak hours, thereby reducing their charging cost and increasing their discharge revenue. However, this mode requires a long charging time and cannot meet the charging demand of vehicles during driving. Second, the fast-charging mode requires a short charging time and can charge or discharge vehicles in large capacities. However, apart from the low charging efficiency and high charging cost of this mode, the large current generated during the charging process can reduce the battery life and affect the quality of the power system. Third, the battery replacement mode has a short changing time, thereby providing convenience to users of electric vehicles. However, the battery shape of these vehicles and their other parameters cannot be easily standardized within a short period, and the high cost of supporting infrastructure restricts the promotion and application of this mode. Therefore, to minimize charging costs and determine the shortest driving route, a charging-mode selection model for electric vehicles was built while taking the constraints of battery capacity, charging time, power distribution system node voltage, power system trends, and user satisfaction into account. The fast-charging, slow-charging, or battery replacement modes were optimized for various scenarios according to the goals and preferences of users.

(2) Electric-vehicle path selection and charging navigation optimization arrangement. When the traffic condition information is determined in advance, a multi-objective decision model with the shortest travel time and lowest charging cost under various electricity price mechanisms was constructed while considering the constraints of path selection and battery capacity as well as the mutual exclusion of charge and discharge states. Different electricity prices were set according to the operating conditions of the grid load at peak to achieve an orderly charge, shift the peak load, and improve the security of the power grid.

(3) Electric-vehicle path optimization and charging navigation based on crowd sensing. When the traffic condition information is known to be uncertain in advance, the user can actively upload the perceived real-time traffic condition and charging reservation information to the decision center (cloud platform) by using mobile smart devices, such as GPS-

equipped mobile phones, during their travel. The use of infrared sensors installed in charging stations and chargers enables the number of electric vehicles waiting to be charged and being charged to be confirmed, and real-time information on traffic rate and charging stations can be obtained. A path optimization and charging navigation decision model with the optimal path, charging station waiting time, electric-vehicle battery loss, and charging costs was constructed while considering the constraints of path selection, driving time, battery capacity, and power distribution system node voltage. Guiding the user to orderly charge and discharge can alleviate the harmful effects of the access to a large number of electric vehicles on the operation of the power system.

Many scholars have recently aimed to improve the charging strategies for electric vehicles. For instance, in 2016, Turkish scholars Bunyamin Yagcitekina and Mehmet Uzunoglu proposed a two-layer intelligent charging strategy for electric vehicles that uses the electric-vehicle smart charging management algorithm to achieve two-level control and to determine the optimal charging path of electric vehicles, thereby reducing the charging cost. The transformer capacity, state of the charging station, and shortest route to the charging station were all considered before using the first level of control to charge the vehicles. The second level of control was used in the process of charging electric vehicles to ensure stable and safe charging, to reduce the negative impact of the charging process on the power grid, and to prevent the transformer from overloading. In 2017, South Korean scholars Sang Keun Moon and Jin Kim proposed a charging demand management method for electric vehicles. By constructing a curve for the influence of electricity price fluctuations on fluctuations in charging demand, they aimed to find the balance point between user charging cost and electric load to reach the ideal state and successfully reduced the number of charging operations. In 2016, American scholars Mostafa Majidpour, Charlie Qiu, and others conducted predictive research on electric-vehicle charging load by conducting site measurements or collecting customer charging and site record data from the charging station exit port. By using four different prediction algorithms, including the weighting algorithm based on adjacent time points, time series prediction algorithm, support vector regression algorithm, and random forest algorithm, they found that using electric-vehicle user data can effectively improve the accuracy of charging load forecasting; however, it increases the risk of leaking the private information of electric-vehicle users. The number of studies on charging strategies for electric vehicles is continuing to increase along with the number of these vehicles, their types of users, and their driving coverage. For example, some studies have begun to examine the optimization of electric-vehicle driving paths, the selection of charging modes, and the planning of charging infrastructure to coordinate the operations of power and transportation systems and improve their operation efficiency.

China, the USA, and Germany are the three countries that have published the largest number of core papers related to charging strategies for electric vehicles (Table 1.2.4). Meanwhile, Belgium, Germany, and the USA are the three countries that have published the most frequently cited papers on this topic (Table 1.2.4). Figure 1.2.3 shows a high degree of cooperation between China and the USA among those countries that have produced core papers on this topic.

Cardiff University, the University of Hong Kong, and the University of Würzburg are ranked as the three institutions that have published the largest number of core papers related to charging strategies for electric vehicles (Table 1.2.5). Figure 1.2.4 shows strong cooperation between Cardiff University and Tianjin University.

From 2012 to 2017, China published six core papers on charging strategies for electric vehicles (Table 1.2.4). These papers were mainly written by researchers from the University of Hong Kong, Tianjin University, and Hunan University (Table 1.2.5).

1.2.3 Utilization of land resources under SSP

The land system faces many challenges from all aspects, such as satisfying the demand of human beings for food, protecting landscape functions, maintaining and improving the ecosystem service value, and alleviating climate change. Given that the driving factors of land utilization (e.g. population, economy, technology, policy, and soil) have great associated uncertainties, the dynamic change trends of land utilization cannot be easily imitated by using the traditional mode. Under SSP, studies on land resource utilization can analyze the dynamic changes of land under various paths by considering several influential factors. Some research achievements have been realized in the areas of energy utilization, environmental protection, and urbanization, but further research must be

Table 1.2.4 Countries or regions with the greatest output of core papers on the "charging strategies for electric vehicles"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	6	33.33%	153	37.68%	25.50
2	USA	4	22.22%	109	26.85%	27.25
3	Germany	4	22.22%	115	28.33%	28.75
4	UK	4	22.22%	62	15.27%	15.50
5	Croatia	1	5.56%	27	6.65%	27.00
6	Switzerland	1	5.56%	27	6.65%	27.00
7	Belgium	1	5.56%	31	7.64%	31.00
8	Italy	1	5.56%	24	5.91%	24.00
9	Australia	1	5.56%	13	3.20%	13.00
10	Bosnia & Herceg	1	5.56%	16	3.94%	16.00

Table 1.2.5 Institutions with the greatest output of core papers on the "charging strategies for electric vehicles"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Cardiff University	3	16.67%	39	9.61%	13.00
2	University of Hong Kong	2	11.11%	73	17.98%	36.50
3	University of Würzburg	2	11.11%	61	15.02%	30.50
4	Tianjin University	2	11.11%	24	5.91%	12.00
5	Argonne National Laboratory	1	5.56%	40	9.85%	40.00
6	Hunan University	1	5.56%	40	9.85%	40.00
7	FZI Research Center for Information Technology	1	5.56%	34	8.37%	34.00
8	University of Zagreb	1	5.56%	27	6.65%	27.00
9	China Electric Power Research Institute	1	5.56%	18	4.43%	18.00
10	Tianjin Electric Power Research Institute	1	5.56%	6	1.48%	6.00

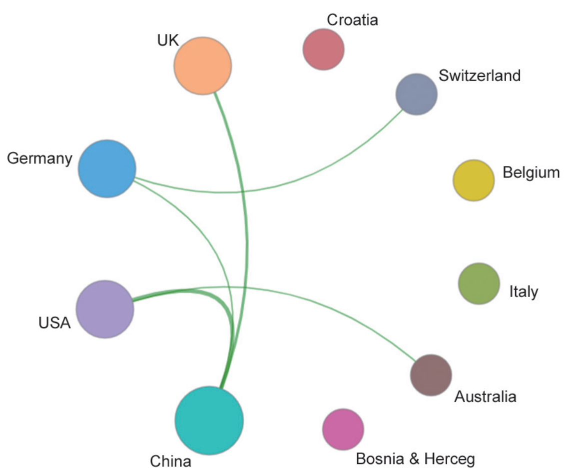

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "charging strategies for electric vehicles"

conducted on the theoretical and actual application of SSP as soon as possible. Specifically, future studies on SSP must focus on the following.

(1) Influence of land resource utilization on environmental protection. Land utilization and the related changes directly affect biodiversity conservation, GHG emission, soil quality, and food production. The carbon emissions generated by the transformation of agricultural land to forest land have been identified as an important driver of global warming. Problems in improving agricultural productivity must be solved as soon as possible to facilitate the expansion of agricultural land. The global land utilization mode, MAgPIE (regarding the influence of agricultural production mode on the environment), is an important tool for evaluating the economic

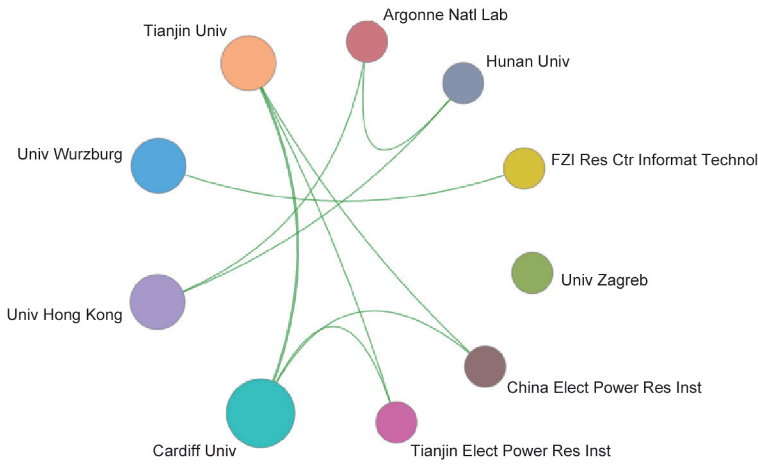

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "charging strategies for electric vehicles"

and environmental influences of land utilization. Under different SSP conditions, waste and GHG emissions produce different effects on landscape changes and ecosystem service value, thereby proving that laws and regulations, protection of natural forests, development and improvement of the carbon sink, and utilization of low-carbon technology are essential measures for environmental protection.

(2) Influence of land resource utilization on energy utilization. Energy plays an important role in satisfying the basic demands for human development and well-being. Future changes in the demand of humans for energy reserves and the demand characteristics are fundamentally influenced by social and economic conditions, availability of energy and resources, energy supply, transformation technology, and ultimate usage of energy. Meanwhile, GHG emissions and other environmental and external social factors can influence energy supply and demand. Therefore, the development of an energy system is influenced by the changes in social demands and the choice of strategic policy. Global land utilization and global energy–economy–climate models are important tools in energy utilization research.

(3) Influence of land resources utilization on urbanization. A study on metropolitan suburbs revealed that nonagricultural land expansion is mainly characterized by an increase in industrial land, which subsequently leads to an increase in farmland and a reduction in woodland. A country-initiated increase in farmland leads the expansion of nonagricultural land, while all the other developments from lower levels are of little significance. This observation may be partially explained by the fact that, while adapting to the increasing demands of the population and the effects of economic growth, the plan plays a key role in improving spatial growth and attracting external investments. Rapid urbanization in China is occurring along with farmer immigration and changes in farmland utilization strength. The relationship between farmer immigration and farmland utilization strength remains unclear, although previous studies have shown that farmer immigration has an opposite P relationship with farmland utilization strength. The positive influence of productivity increase caused by the household responsibility system is identified as the primary driver of the increase in farmland utilization strength. Meanwhile, the labor shortage resulting from the excessive loss of agricultural labor has been identified as the primary driver of the reduction in farmland utilization strength. However, increases in fertilizer and pesticide investments or changes in crop types can cover the negative influences of labor shortages and improve farmland utilization strength. In addition, the excessive and intensive use of farmland has a negative influence on the ecological environment and national food safety.

Remote-sensing images provide a basis for land resource utilization research. Given the rapid development of satellite sensor technology, high-spatial-resolution (HSR) remote-sensing data have received great attention in the military and civil disciplines. Scene classification has also become an important task for full utilization of HSR image data. The unsupervised learning method examines deconvolutional networks by classifying sensing images from a large-scale dataset. First, the diagram and filter of each image are measured based on the reconstruction error between the minimized input images and the convolution results by applying the deconvolutional networks with light weight. This diagram can capture large amounts of edge and pattern information related to the HSR image. Second, those features with different sizes are aggregated by using the spatial pyramid model (SPM) to maintain the spatial pattern of the HSR image scenes. A differentiated expression of HSR images is obtained by combining initiated weighted deconvolutional models with SPM. Third, the expression vector quantity is included in the support vector machine model to complete the classification. Some researchers have also used a large-scale aerial image dataset for the scene classification of remote-sensing images. The performance of the deep-learning method is then evaluated by using more than 10 000 remote-sensing images and scenes.

The automatic semantic mark problems of HR optical satellite images cannot be easily solved, and the complex and obscure parts of satellite images are difficult to distinguish. Moreover, an annotation method with complete supervision requires a large amount of training samples with HR labels. To address such challenges, researchers have developed a unified annotation framework by conducting an advanced study of features and feature transfer with weak supervision.

The land utilization and land cover changes (LUCC) imitation model analyzes landscape dynamics under various conditions; however, some of its defects remain unaddressed. The future land utilization imitation model clearly imitates the spatial and long-term LUCC, and it is applied through the top-down system dynamics model and the bottom-up cellular automata (CA) model. Adaptive inertia and competition mechanisms are adopted in the CA model to deal with the complex competition and interaction among various land utilization types and to increase the capability of this model to imitate the land utilization mode accurately. Climate change, soil conditions, and other influential factors are also gradually included in this model. Enhancing the identification capability of land utilization optimization in various spaces is expected to become a development trend in future research.

Germany, the USA, and Australia are the three countries that have published the largest number of core papers related to the utilization of land resources under SSP (Table 1.2.6). Meanwhile, Germany, the USA, and Ukraine are the top three countries with the highest average number of citations (Table 1.2.6). Figure 1.2.5 shows that all 10 countries that have published the largest number of core papers on this topic have demonstrated close cooperation.

The Potsdam Institute for Climate Impact Research, Humboldt University of Berlin, and Australia Commonwealth Scientific and Industrial Research Organization have been ranked as the three institutions that have published the largest number of papers on the utilization of land under SSP (Table 1.2.7). Figure 1.2.6 reveals close cooperation among the 10 institutions that have published the largest number of core papers.

As shown in Table 1.2.8, China has published 24 cited core papers and ranked ninth among the 10 countries that have published the largest number of core papers on the utilization of land under SSP.

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

The global development fronts in the field of engineering management focus on 10 aspects, namely, “electric-vehicle charging management methods and systems,” “intelligent health management methods and systems,” “intelligent connected vehicle technology,” “risk management methods and systems,” “building information modeling (BIM)-based construction management systems,” “monitoring-system development based on positioning technology,” “energy management control methods and systems,” “logistics management methods and systems,” “medical service management methods and systems,” and “intelligent medical management methods and systems”, as listed in Tables 2.1.1 and 2.1.2. These fronts cover a wide range of disciplines, including mechanics, transportation, energy, medicine, construction, and electronics. The fronts of key interpretations include “electric-vehicle charging management methods and systems,” “intelligent health management methods and systems,” “and intelligent connected vehicle technology”, for which current developing states and future trends are discussed in detail in this section.

Table 1.2.6 Countries or regions with the greatest output of core papers on the "utilization of land resources under SSP"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Germany	10	76.92%	328	86.09%	32.80
2	USA	7	53.85%	172	45.14%	24.57
3	Australia	5	38.46%	115	30.18%	23.00
4	Japan	5	38.46%	104	27.30%	20.80
5	Netherlands	4	30.77%	83	21.78%	20.75
6	Austria	4	30.77%	82	21.52%	20.50
7	Italy	3	23.08%	54	14.17%	18.00
8	Ukraine	2	15.38%	47	12.34%	23.50
9	South Korea	2	15.38%	26	6.82%	13.00
10	Norway	2	15.38%	42	11.02%	21.00

Table 1.2.7 Institutions with the greatest output of core papers on the "utilization of land resources under SSP"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Potsdam Institute for Climate Impact Research	10	76.92%	328	86.09%	32.80
2	Humboldt University of Berlin	4	30.77%	159	41.73%	39.75
3	Commonwealth Scientific and Industrial Research Organisation	4	30.77%	97	25.46%	24.25
4	Utrecht University	4	30.77%	83	21.78%	20.75
5	PBL Netherlands Environmental Assessment Agency	3	23.08%	71	18.64%	23.67
6	Graz University of Technology	3	23.08%	70	18.37%	23.33
7	International Institute for Applied Systems Analysis (IIASA)	3	23.08%	59	15.49%	19.67
8	National Institute for Environmental Studies	3	23.08%	63	16.54%	21.00
9	Pacific Northwest National Laboratory	3	23.08%	56	14.70%	18.67
10	Mercator Research Institute on Global Commons and Climate Change	3	23.08%	54	14.17%	18.00

Table 1.2.8 Countries or regions with the greatest output of citing papers on the "utilization of land resources under SSP"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Germany	89	20.46%	2015.87
2	USA	75	17.24%	2016.07
3	Netherlands	45	10.34%	2016.16
4	Austria	43	9.89%	2016.02
5	UK	41	9.43%	2016.17
6	Australia	34	7.82%	2016.12
7	France	31	7.13%	2015.87
8	Japan	31	7.13%	2016.42
9	China	24	5.52%	2016.42
10	Italy	22	5.06%	2016.18

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "utilization of land resources under SSP"

(1) Electric vehicles charging management methods and systems

With the tight supply and demand for petroleum resources in the world and the increasingly strict regulations on GHG emissions, new-energy vehicles, as represented by electric vehicles, represent an important development trend in the automobile industry. Electric vehicles are driven by motor wheels, equipped with a vehicular power supply, and recharged by either charging or replacing their batteries. However, these vehicles only have a limited amount of electricity stored in their batteries, which restricts their mileage and their large-scale promotion and application. Facilitating the orderly charging of these vehicles is an important research direction for improving the driving stability and reliability of new-energy vehicles, reducing their

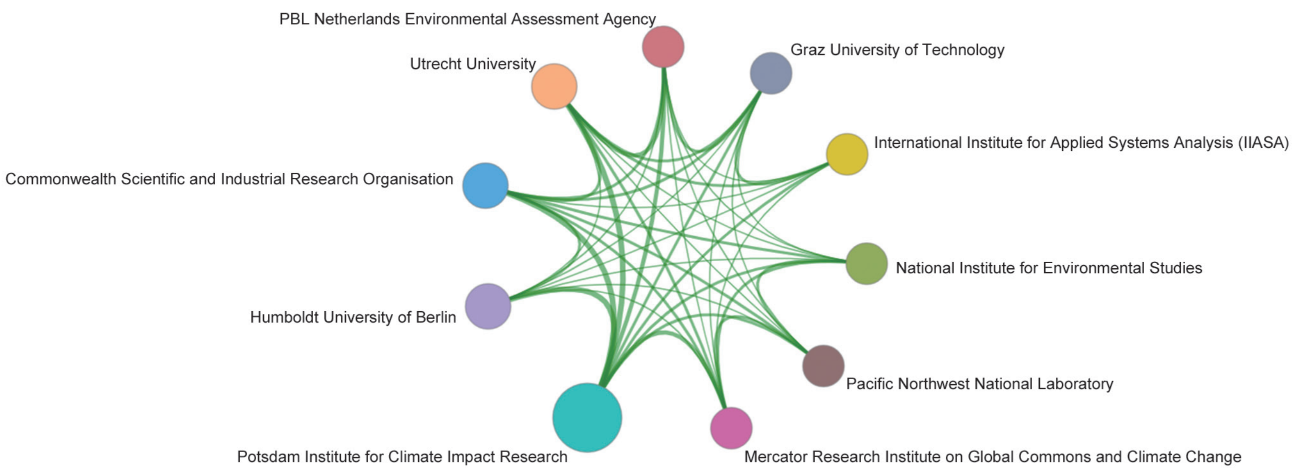

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "utilization of land resources under SSP"

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	Electric-vehicle charging management methods and systems	17	104	6.12	2013.24
2	Intelligent health management methods and systems	20	98	4.90	2014.35
3	Intelligent connected vehicle technology	13	30	2.31	2013.77
4	Risk management methods and systems	14	148	10.57	2013.57
5	BIM-based construction management systems	8	58	7.25	2013.88
6	Monitoring-system development based on positioning technology	13	59	4.54	2013.23
7	Energy management control methods and systems	55	279	5.07	2013.40
8	Logistics management methods and systems	42	195	4.64	2013.83
9	Medical service management methods and systems	17	81	4.76	2013.76
10	Intelligent medical management methods and systems	25	177	7.08	2013.84

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

No.	Engineering development front	2012	2013	2014	2016	2016	2017
1	Electric-vehicle charging management methods and systems	6	5	4	0	2	0
2	Intelligent health management methods and systems	1	2	7	9	1	0
3	Intelligent connected vehicle technology	3	4	2	2	1	1
4	Risk management methods and systems	4	3	3	3	1	0
5	BIM-based construction management systems	1	2	3	1	1	0
6	Monitoring-system development based on positioning technology	5	4	0	4	0	0
7	Energy management control methods and systems	14	17	13	10	1	0
8	Logistics management methods and systems	5	15	8	11	2	1
9	Medical service management methods and systems	4	1	8	3	1	0
10	Intelligent medical management methods and systems	5	6	4	8	2	0

charging costs, and devising various charging management methods for these vehicles.

(2) Intelligent health management methods and systems

Intelligent health management simultaneously focuses on health promotion and disease prevention. With the rapid development of health management devices and mobile information technologies, a circulatory system that integrates self-health management, health monitoring, health risk assessment, and telemedicine functions is being developed to monitor individual health and to improve the national health level. China has designed various intelligent health management systems, including a personal intelligent health management system based on cloud computing; a multifunction information database health management system based on information integration, the Internet of things, and cloud technology; a multidimensional intelligent health management platform based on Hadoop and virtualized storage technology; and an intelligent health report prompt system based on online-to-offline health management. However, despite its important role in the construction of an intelligent city, the intelligent health management system faces some problems related to quality, information integrity, and information security. The future development of an intelligent health management system requires technological breakthroughs and improvements in the use this system in hospitals, communities, and households all over the country. Integrating big data can also support medical, drug use, nursing, and recovery functions so that such technology can be used in disease prediction, monitoring, and management.

(3) Intelligent connected vehicle technology

Intelligent connected vehicles (ICVs) are equipped with advanced in-vehicle sensors, controllers, and actuators that integrate modern communication and network technologies to realize intelligent information exchange between vehicles and people, roads, cloud platforms, and other vehicles. Given their complex environment awareness, intelligent decision making, and collaborative control and execution, ICVs are considered safe, comfortable, and energy and driving efficient. They are ready to become the next generation of vehicles that will ultimately replace manually operated vehicles. The ICV technology system comprises three levels (environment awareness, intelligent decision-making, and control execution systems), covers three fields (automobile, information interaction, and basic support), and focuses on several key technologies (environment awareness, navigation and positioning, intelligent decision control, and Internet of vehicles). ICV is not only a future development direction of automobile technology but also a development direction of integrating intelligent (automatic driving) and networked (Internet of vehicles) automobiles. In their emerging technology life cycle predictions in the field of intelligent machines, Gartner regards ICV as one of the most promising emerging technologies. Accordingly, countries all over the world have included the development of the ICV industry as part of their national strategies.

(4) Risk management methods and systems

Risk management involves identifying, estimating, and assessing risks, the results of which are used to select and optimize various risk management technologies, effectively control risks, and properly handle the consequences of risk-induced losses to achieve maximum security at a minimum cost. Scholars have adopted various analytical methods in risk management research, including Monte Carlo simulation, analytic hierarchy process, artificial neural network, fuzzy mathematics, genetic algorithms, and Bayesian networks. A fuzzy evaluation method is introduced to reduce the impact of subjective factors on risk assessment results in the process of using expert scoring, the Delphi method, and an analytic hierarchy process. The relationship between individual characteristics (e.g., risk preference, risk attitude, and risk perception) and assessment results must also be examined further to develop relevant psychological research theories and to accurately determine the impact of subjective factors on the risk assessment results. Risk assessment models can also be improved by considering the correlation, dynamics, and transmission path among various risk factors in risk management systems and by considering the manageability, predictability, and other characteristics of risks based on risk occurrence probability and the impact. With the rapid development of management ideas, methods, and modern computer technologies, highly integrated and sophisticated risk management methods have begun to emerge to deal with increasingly complex risk management systems.

(5) BIM-based construction management systems

BIM is used to create building models based on relevant information regarding construction projects and simulates the real information of buildings through digital information simulation. BIM is an integrated process based on design, construction, operational coordination, and project information with the five characteristics of visualization, coordination, simulation, optimization, and graphics. With its continuous application in industry, BIM technology has shifted from a single BIM software application to a multi-software integrated application, from a desktop application to a cloud and mobile client, and from a single application to a comprehensive application. This technology has also started to demonstrate the new features of BIM+ and can be used to realize information sharing among BIM models and build integrated delivery platforms, device information management modules, maintenance management modules, operation and maintenance knowledge base modules, and emergency plan management modules for a variety of purposes. These include improving the efficiency of multi-collaboration; helping construction, supervision, and even property employees identify the physical location of specific equipment; effectively maintaining a large amount of construction equipment information; and managing emergency plans. Web-based BIM systems, which connect progress and cost to a web 3D model during project management, can be used to simulate a web 3D model, create 2D or 3D drawings, generate engineering progress and cost information to portable devices, and improve information liquidity. The construction information is input into the BIM system to generate construction plans automatically and produce construction performance and other information that can help in effectively planning and managing building construction projects and in maximizing the value of such information.

(6) Monitoring system development based on positioning technology

A monitoring system uses various positioning technologies to achieve integrated monitoring of the location, status, and other information related to a monitored object. The main components of such systems include an identification subsystem, a data transmission subsystem, a data storage subsystem, and the integrated display and control subsystem of a monitored object. This system is widely used in cargo transportation, garbage collection, transportation monitoring, public-transport operation, and school bus and student safety monitoring. Positioning technology is divided into indoor and outdoor positioning, of which the former includes infrared, ultrasonic, RFID, Bluetooth, Wi-Fi, ZigBee, and ultra-wideband technologies, while the latter includes GPS and Beidou civil positioning technologies. Monitoring systems based on positioning technology are expected to attract wide applications in engineering management, especially in on-site construction safety management. The safety monitoring of personnel and equipment on construction sites has several primary considerations, such as positioning accuracy and cost. GPS has a positioning accuracy of 10 m, while Beidou civil positioning has an accuracy that can reach within 10 m of a plane and 10 m of the elevation without base stations. When a base station is deployed, the sharp rise in costs cannot meet the needs of the project. In this case, adopting Bluetooth plus phased-array technology with a decimeter positioning accuracy is highly feasible. By deploying secondary base stations and positioning tags, position monitoring can be used to track the movements of personnel and identify the specific location of equipment at a reasonable cost.

(7) Energy management control methods and systems

Energy management is a process of developing strategies for national energy and economic development and of monitoring the implementation of such strategies at various stages. On the one hand, a sufficient energy supply must be ensured to provide energy support for national economic development. On the other hand, energy must be effectively and reasonably used to promote healthy development and to improve the quality of the living environment and social economy. The major development directions in energy management are mainly concerned with energy performance contracting (EPC), information energy management systems, and distributed energy management systems. EPC, also known as EMC in China, is a new energy-saving mechanism that was developed based on the demands of the market. In this mechanism, a professional energy-saving service company signs a contract with an energy-using company and provides the diagnostic design and necessary financing for conducting energy-saving projects; upgrading, installing, procuring, and commissioning construction equipment; training operations management personnel; measuring and verifying energy savings; and ensuring a high energy saving rate. Meanwhile, the energy-using company aims to achieve high energy-saving efficiency to finance its project investments and to ensure the profitability of the energy-saving mechanism adopted in the market. Supported by the Internet and logistics information technologies (e.g., computer networking and database technologies), information energy management systems have several functions, including data maintenance, query, statistics, and analysis, as well as energy-saving management. Based on the power generated from distributed renewable energy, the distributed energy management system constructs an energy Internet system that can read real-time, high-speed, and bidirectional power data and provide renewable energy access. This energy Internet system comprises an intelligent energy management system, distributed renewable energy, energy-storing devices, converter devices, and smart terminals. Utilizing such technologies can ensure low carbon emissions and effective energy consumption. A comprehensive and efficient overseas energy supply auxiliary system must also be developed to improve energy supply management in China.

(8) Logistics management methods and systems

Logistics refers to the physical flow of goods from their origins to their intended recipients. Basic functions in logistics include transportation, storage, loading, unloading, handling, packaging, circulation, processing, distribution, recycling, and information processing. Given the increasingly important role of logistics in modern socioeconomic development, advanced logistics management methods and systems have attracted wide application prospects. The deepening application of the Internet of things and mobile Internet along with Internet-driven transformations in business and management have created several challenges that hinder the application of logistics management methods and systems. From the perspective of enterprise logistics, upstream and downstream logistics resources must be integrated with service cooperation under the supply chain structure to build a supply chain logistics integration control platform that can serve as the basis of enterprise operations. From the perspective of living logistics, broad logistics resource sharing and service cooperation are feasible future directions. From the perspective of regional logistics management, the effective organization of regional logistics resources and the optimization of multi-modal transport organization based on big data and modern information technology not only guarantee efficient logistics services and high energy savings but also require consideration of the effective utilization of regional space resources. The organic integration of surface air with the underground intelligent logistics system presents an important future direction in this area. Piecemeal and single-link management methods for logistics technologies have reached maturity, while the wide-area logistics service model, which is supported by the block chain technology and the comprehensive optimization decision-making method, must be developed further. Applying logistics dynamic risk analysis and control methods in a big-data environment is expected to improve the real-time quality of logistics services.

(9) Medical service management methods and systems

Medical service is an umbrella term for various clinical services, such as diagnosis, treatment, rehabilitation, and nursing, which are provided by qualified medical institutions and their medical staff. Medical service management methods and systems aim to improve the quality and efficiency of medical services by using science and technology and advanced medical management modes. The development of medical service management methods and systems is currently focused on informatization, intellectualization, integralization, and precision. These methods highlight the use of the Internet and technologies for constructing a regional medical service big-data and cloud-computing platform as well as an integrated and intelligent medical service delivery system. To provide remote and accurate medical services, these methods must balance the standardization, precision, and complexity of medical problems. Guided by medical best practices and the requirements of evidence-based medicine and cost control, standardized clinical pathway management has been implemented to reduce the space for flexible treatment. The application of big data and the Internet is further improving the intelligence and precision of hospital diagnosis and treatment systems, reducing service delays and resource wastage, and improving the service experience and satisfaction of patients. However, given the complexity, uncertainty, and differences in their occurrence and development, chronic diseases are difficult to predict. Rising medical costs and other issues related to protecting the rights and interests of patients present additional challenges to the improvement of medical service management methods and systems.

(10) Intelligent medical management methods and systems

Intelligent medical management realizes information interaction among medical service elements by using advanced artificial intelligence, the Internet of things, and data fusion technologies and realizes the intellectualization and automation of clinical services through digital means. Although the development of intelligent medical management methods and systems is still in the exploratory stage, the in-depth application of artificial intelligence and big-data technology in the medical field is overwhelming. Given the lack of high-quality human resources, the inefficiency of human services, and the wastage of health resources, the emergence of intelligent medical management systems is expected to further enhance the efficiency and quality of medical services, optimize the allocation and sharing of health resources, and reduce social medical costs. Intelligent medical management systems have produced promising results in intelligent diagnosis, intelligent treatment, intelligent nursing, and intelligent healthcare and have been successfully used to launch intelligent service projects, such as intelligent medicine and intelligent wearing. Such systems also enhance the efficiency and precision of clinical decisions and medical practices by empowering and providing assistance to medical personnel. However, the development of intelligent medical management systems is affected by the complexity of the medical environment and certain health problems, as well as the ever-changing degree of cooperation among various medical service elements. Given these problems, intelligent management systems cannot adapt well to complex medical practices. The application of artificial intelligence in the field of medical services remains weak, unable to conduct multitask learning, and dependent on big-data learning. However, with the development of precision medicine, small-data learning is expected to become a future development trend.

2.2 Interpretations for three key engineering development fronts

2.2.1 Electric-vehicle charging management methods and systems

Electric vehicles have unique advantages over traditional fuel vehicles, such as their low pollution, low noise, high energy efficiency, and easy maintenance. These vehicles meet the travel needs of people while complying with traffic network flow control. A large number of these vehicles are connected to the power system. When charging the batteries of these vehicles, the power is taken as a load from the power grid and then fed back as a power source during discharge. The orderly charging and discharging of electric vehicles can reduce the peak–valley difference of power systems and eliminate the intermittent generation of renewable energy. Therefore, studies on charging management methods for electric vehicles can significantly improve the operational efficiency of power and transportation systems and promote the coordinated development of energy, economy, and environment.

Given the differences in the number, users, and driving coverage of electric vehicles, their charging methods also demonstrate various characteristics, while their charging demand shows great uncertainty. The current power supply modes for electric vehicles include slow charging, fast charging, and battery replacement. These vehicles show clear differences in their charging time, charging cost, and battery life under different supply modes. The electric-vehicle charging management method aims to minimize the charging cost and facilitate the optimization of charging facility pricing decisions, site selection, and volume. The safety constraints of the power system must also be considered to meet the driving demand of electric vehicles, realize their economic operation, and enhance the economic efficiency of their charging and replacing stations.

(1) Orderly charge and discharge optimization decision for electric vehicles to meet driving demand. A charging and discharging decision-making method was proposed to minimize the charging cost and power peak–valley difference, to reduce the negative impact of the power system peak–valley difference resulting from disordered charging and voltage drop in local areas, to improve the operating efficiency of the power system, and to meet the driving path demand of electric vehicles while considering their battery capacity and the mutual exclusion of their charge and discharge states.

(2) Charging station pricing decision considering the demand response of electric-vehicle users. A combination package for charging station parking, charging, and discharging was designed while considering the differences in the demands of electric-vehicle users, while a pricing decision model with the minimum operating cost of the charging station was devised to guide the orderly charging and discharging of electric vehicles. This model is expected to increase the economic benefits of charging stations and reduce the charging costs for users.

(3) Charging and replacing power station planning while considering the characteristics of electric-vehicle energy replenishment. By acting as the node service facility of a traffic network and the load/power node of the power network, the battery charging and replacing power station can improve the charging efficiency of electric vehicles via reasonable location planning. Based on the charging demand characteristics of electric vehicles and by considering the constraints of traffic network flow and power network operation, a site selection and volume decision model for the multi-objective charging and replacement of power stations was established while considering the construction and operating costs of new road networks and power grids. This model can determine the charging method that satisfies the charging requirements of different electric vehicles, reduce the electricity purchase costs of electric-vehicle users, and provide technical support for the planning and construction of electric-vehicle charging and battery-replacing service facilities.

The USA, Japan, and various European countries are actively developing electric-vehicle charging management methods and investigating their application. Studies in the USA have primarily focused on improving electric-vehicle battery systems. In 2012, Elwha LLC developed a battery management system for electric vehicles that can be remotely manipulated. By loading data packets on the battery system and recording battery running data, this system can evaluate the usage state of the battery and provide users with charging strategy recommendations. Studies in Germany mainly focused on optimal charging path planning for electric vehicles to reduce their charging time and cost. This strategy relies on the advantages of the automobile and power industries to promote the development of the electric-vehicle industry. By 2013, Germany built 4,454 charging stations to provide electric vehicles with several options. Robert Bosch GmbH developed an optimal charging path device based on battery charging state and navigation data. This device comprises a battery state output and a continuously updated navigation data output system. Based on information regarding the remaining battery power and navigation of the electric vehicle, this device can determine the optimal charging path to the destination of the users, thereby saving charging time and cost. Studies in Japan have focused on the scientific management of electric-vehicle battery parts. In 2012, Toyota Motor Corporation developed an electric-vehicle battery parts management system that comprises a vehicle management device, a data storage device, and a controller. This device can record the usage state of various battery parts and prompt users to repair and replace worn or damaged parts as soon as possible. Scholars are currently examining ways to improve the battery performance and charging facilities for electric vehicles. However, studies on the sharing, pricing, and planning of electric-vehicle charging infrastructure are still in their infancy. Therefore, a pricing and planning decision theory system that can guide electric-vehicle users in the sharing and orderly charging or discharging of vehicles and charging facilities is yet to be developed. Thus, research on the sharing, pricing, and planning of electric-vehicle charging infrastructure is currently in demand and is expected to provide important scientific and economic value in the future.

Japan, South Korea, and the USA are the top three countries/regions that have published the largest number of core studies on electric-vehicle charging management methods and systems, with China ranking fourth (Table 2.2.1). Figure 2.2.1 shows a low level of cooperation among those countries that have published core papers on this topic. However, a close cooperation is observed between Israel and Switzerland.

2.2.2 Intelligent health management methods and systems

Since the 1960s and 1970s, management scholars in Europe and the USA have examined management problems in the field of healthcare. The health demands and medical expenditures of individuals continue to increase as they age, thereby imposing an unprecedented pressure on each country. During the past decade, many scholars have begun to examine the management problems in the field of healthcare, including the auxiliary optimization of medical decision making, the optimization of public health policies for management, and the optimization of key medical resources. The rapid development of mobile Internet, cloud platform, and smart wearable device technologies has enabled real-time access to individual health information and the analysis of massive medical information, based on which intelligent health management methods and systems have been developed. The intelligent health management method and systems can provide comprehensive services, such as collecting, storing, and analyzing health data; providing health consultation services to residents; and supporting the intelligent management of chronic diseases and key hospital resources. The following sections discuss the four aspects of individual health intelligent management systems, intelligent hospital systems, intelligent management systems in community hospitals, and intelligent pension systems.

(1) Individual health intelligent management system. Intelligent health management methods and systems have focused on the intelligent management of individual health during the past five years. These methods primarily collect personal health information and physiological indicators, such as blood glucose, blood pressure, pulse, blood oxygen, BMI, and waist-to-hip ratio, in real time by using intelligent wearable devices, and then these data are sent to a health management platform or terminal equipment via Wi-Fi or Bluetooth technology. These data are then collected and analyzed, and users can search for personal health data, dietary recommendations and recipes, fitness advice, and health tendency diagrams by visiting a website or using mobile applications. When they begin showing abnormal symptoms, such as a physical signs index that exceeds the usual limit, users receive an SMS message reminding them to pay attention to their health. Afterward, they can respond to these health threats in a timely manner by adjusting their sleeping and eating habits.

(2) Intelligent hospital system. Intelligent health devices can be linked to an intelligent cloud hospital to give their users access to a database that covers their entire diagnosis and treatment processes. These patients can then register and receive diagnosis and treatment in an intelligent hospital system, while doctors can perform telemedicine and other functions through this system. In this way, the working efficiency of medical professionals can be improved, and the urgent nature of medical resources can be eased. The intelligent hospital system can also store the personal health records of each patient in a cloud platform, and users can upload additional information to these records by using portable devices. This functionality not only allows doctors to re-examine and adjust the treatment and medication for their

Table 2.2.1 Countries or regions with the greatest output of core patents on the “electric-vehicle charging management methods and systems”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	7	41.18%	23	22.12%	3.29
2	South Korea	3	17.65%	33	31.73%	11.00
3	USA	3	17.65%	6	5.77%	2.00
4	China	2	11.76%	7	6.73%	3.50
5	Switzerland	1	5.88%	31	29.81%	31.00
6	Germany	1	5.88%	4	3.85%	4.00
7	Israel	1	5.88%	31	29.81%	31.00

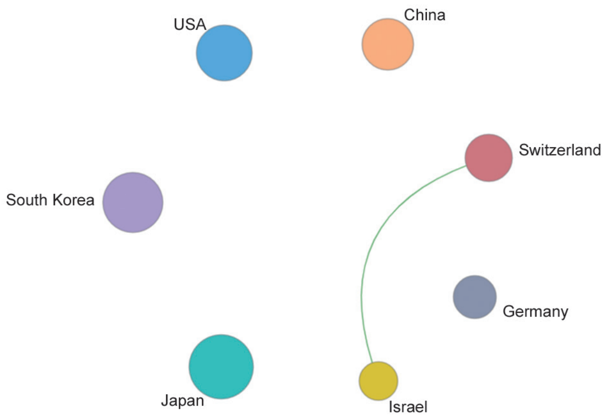

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "electric-vehicle charging management methods and systems"

patients but also helps patients understand changes in their health and take appropriate actions.

(3) Intelligent management system in community hospitals. Community hospitals are called "gatekeepers" in Europe and the USA. These institutions provide basic medical and healthcare services, such as prevention, recovery, and health education. The intelligent management system in community hospitals collects health or medical information from patients either online or offline, constructs and stores their health records, monitors their health throughout their whole life cycle, and allows them to check on their health records and seek medical treatment online at any time. The medical staff can also learn about the personal and group health status of community residents by using this system. For instance, when the residents in communities under their jurisdiction begin to show abnormal physical conditions, these medical staff can call on doctors to examine and provide health recommendations to these respondents relating to their diet, medication, or treatment. Moreover, when an epidemic is predicted to affect a community, these medical professionals can immediately implement the necessary intervention measures through this system. China has no traditional family healthcare system, and only few families in the country periodically undergo physical examination. By storing health records in a cloud platform, the intelligent management system can be used as a complete family healthcare and prevention system by commercial health insurance agencies, family doctors, and community hospitals. Doctors can also arrange appointments, periodically diagnose each family member, and regularly provide long-term services. Community hospitals can offer offline clinical services for certain procedures that need to be administrated personally, such as blood sampling. Community hospitals establish a closed loop among online diagnosis, offline guidance, and insurance payment, thereby providing one-stop medical treatment solutions to residents.

(4) Intelligent pension system. Smart health equipment also has a crucial function in pension enterprises. An intelligent health management system can collect basic health information from the elderly to establish a comprehensive information database to monitor the health status of this vulnerable population and to conduct regular tests to ensure their well-being. By using wearable intelligent health portable devices, the elderly can immediately ask for urgent assistance, household care, housekeeping, mental care, and health management services. In this way, communities can effectively integrate their social service resources and establish a comprehensive pension service system.

Given the advances in artificial intelligence, intelligent health management methods have recently become a hot research topic in the area of medical services. However, these methods are still in their infancy. Further explorations on health management may be extended to personal health information collection and management; remote health consultation; medical, clinical appointment, and registration services; and health management services for the elderly. These methods also provide many benefits, such as early illness prediction, smart diagnosis, medicine use management, and epidemic prevention. Therefore, future research and developments in this area must focus on smart medical systems and integrate intelligent health management systems into intelligent medical systems. By using intelligent health management systems, hospital managers can collect and store large amounts of medical data (including clinical and management data) that provide a foundation for intelligent medical treatment (including intelligent medical decision making and intelligent medical management). The condition of patients can be predicted, the decisions of medical professionals can be optimized, the misdiagnosis rate can be reduced, and the efficiency of medical services can be improved by conducting a machine-learning and intelligent analysis of personal health data and examination results.

China and South Korea are the top two countries/regions that have published the largest number of public patents related to intelligent health management methods and systems. Specifically, China has published 19 core patents in this area (Table 2.2.2). Among those institutions that have published such patents, Anycheck Information Technologies Co., Ltd. has published six, of which two have been cited (Table 2.2.3).

2.2.3 Intelligent connected vehicle technology

ICVs have been in operation for nearly 80 years since the emergence of the world's first automatic driving concept car. After going through the phases of concept launch, basic research and development, and running tests, ICVs entered the phase of the market economy. With the rapid advancement of Internet technologies and the continuous development of other technologies, such as communication and perception, ICV technology has embarked on the development path of “smart plus connected” unmanned vehicles.

The development of ICV technology has two major aspects. On the one hand, intelligence (i.e., automatic driving) is expected to be realized gradually. The International Society of Automotive Engineers (SAE) divides automatic-driving technology into five development stages from driving support to fully automatic driving, with “unmanned driving” being the highest stage (Level 5). On the other hand, network connection (Internet of vehicles) aims to realize an intelligent information exchange among vehicles and between vehicles and roads.

The development of unmanned driving is driven by two technical factions, namely, ADAS, an independent intelligent technology represented by traditional automobile companies, such as General Motors, Volkswagen, and Mercedes-Benz, and artificial intelligence and network technology, which is represented by Internet companies, such as Google, Apple, and Baidu. ADAS is gradually realizing intelligent unmanned driving based on existing automobile technologies, sensing, and machine decision making, while artificial intelligence and network technology controls and transforms traditional vehicles through computers and the Internet. Although these technologies have different starting points, they are eventually merging to achieve completely unmanned driving.

ICV technology integrates technologies in the fields of automotive engineering, artificial intelligence, computers, microelectronics, automatic control, communication, and data platforms. This technical complex also integrates environment awareness, planning decision making, control execution, and information interaction with an interdependent technology chain and an industrial chain system.

The ICV technology system comprises three levels, namely, the environment awareness system, intelligent decision-making system, and control execution system, and it is divided into three directions, namely, connected vehicle, autonomous vehicle, and ICV, depending on its technology development path. ICV combines the technical advantages of autonomous and connected vehicles and utilizes technologies in the fields of automobile, information interaction, and basic support. Implementing these functions greatly depends on key

Table 2.2.2 Countries or regions with the greatest output of core patents on the “intelligent health management methods and systems”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	19	95%	97	98.98%	5.11
2	South Korea	1	5%	1	1.02%	1.00

Table 2.2.3 Institutions with the greatest output of core patents on the “intelligent health management methods and systems”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Anycheck Information Technologies Co., Ltd.	China	4	20%	8	12.25%	2
2	Hangzhou Yinjiang Intelligence Medical	China	2	10%	5	5.10%	2.5
3	Jiaxing Zhiheng Precision Instruments Co., Ltd.	China	2	10%	7	7.14%	3.5

technologies, including environment awareness, navigation and positioning, intelligent decision making, control execution, information fusion, and Internet of vehicles.

(1) Environment awareness and navigation and positioning technology. This technology is mainly used for the real-time navigation and positioning of intelligent connected vehicles in motion. The environment awareness system combines advanced communication, information sensing, and computer control technologies; uses the main vehicle sensors (e.g., cameras, millimeter-wave radars, laser radars, and ultrasonic) and the "V2X" communication system to sense the surrounding environment; and provides a decision-making basis for intelligent connected vehicles by extracting road condition information and detecting obstacles. In auxiliary and driverless systems, the Beidou navigation system is combined with electronic maps, radio communication networks, and computer vehicle management information systems. Given its highly accurate positioning, the Beidou system provides high-precision positioning solutions with low cost and wide coverage that allow automatic-driving vehicles to implement certain functions, such as vehicle tracking and traffic management.

(2) Intelligent decision-making technology. The ICV decision-making control technology offers decision guidance control over driving behaviors by processing and collecting information. Its technical system involves key technologies, such as information fusion, path programming, and vehicle control technologies, and it is treated as a core part of the whole system of ICVs.

(3) Control execution technology. Integrated vehicle control can be realized by controlling the execution actions of vehicle power, chassis, and electronic appliances.

(4) Information fusion technology. Big data are a premise of ICV decision making. Information fusion technology improves the reliability and security of the system and the accuracy and credibility of the information by integrating data from various sources.

(5) Internet of vehicles technology (i.e., networked). The Internet of vehicles is based on in-vehicle networks, inter-vehicle networks, and vehicle-mounted mobile Internet. It facilitates wireless communication and information exchange between vehicles and people, vehicles and roads, and vehicles and cloud platforms, as well as among vehicles, based on agreed communication protocols and data interaction standards. This technology also creates an integrated network of intelligent traffic management, intelligent dynamic information service, and vehicle intelligent control. The Internet of vehicles adopts several key technologies, such as sensors and sensor information integration technologies, open and intelligent vehicle terminal system platforms, speech recognition technology, server computing and service integration technologies, communication and application technologies, and Internet technology.

Several countries, including the USA, Japan, and European Union countries, have included the development of the ICV industry in their national strategies. *The US Intelligent Transportation System Strategic Plan (2015–2019)*, which was released in the USA in 2015, identifies the Internet of vehicles and vehicle automation as two strategic priorities. In 2011, the European Union promulgated the *White Paper on EU Integrated Transportation*, which focuses on the development of vehicle intelligent safety, informatization, and traffic safety management. It takes information security, information reliability, and large-scale demonstration application verification as key technology research areas. Launched in 2013, the *Horizon 2020 Research Plan* promotes the development of ICV technology from the aspects of standard systems, infrastructure, and network security. Japan began studying ICVs and intelligent transportation systems in the 1990s. In 2013, its strategy for establishing a state-of-the-art IT country included some elements and targets for ICVs. In 2020, Japanese automatic-driving cars are expected to appear on highways. In the ICV technosphere, Europe, the USA, and Japan have formed a tripartite confrontation. Specifically, the USA is focusing on networking and has rapidly developed its V2X-based networked automotive industrialization capability given the strong R&D system of its government. Europe has established some world-class suppliers of automotive electronic components and created vehicle companies with relatively advanced autonomous self-driving technologies. Japan has actively promoted and improved automatic-driving technology with the help of its excellent transportation infrastructure.

Compared with these developed countries, China started relatively late in ICV technology research and development. In its *Made in China 2025* plan launched in 2015, China lists ICVs, energy-saving vehicles, and new energy vehicles as important strategic directions for the development of its automobile industry. The plan clearly states three objectives: (1) mastering the overall and key technologies of intelligent-assisted driving by 2020; (2) establishing a relatively complete ICV independent research and development system, production supporting system, and industrial cluster; and (3) transforming and upgrading the automotive industry of the country.

From the technological perspective, the transition from manual mechanical operation to electronic information system control is accelerated by the wide application of artificial intelligence, information communication, positioning and navigation, big data, cloud computing, and other technologies in the automotive field. This trend is inevitable in the development of ICV technology. The traditional automobile industry conforms to the general trend and accelerates its cross-border cooperation with information communication, intelligent transportation, and other fields along with the rapid development of Internet technology and the continuous development of other technologies, such as communication and perception. The automobile industry chain faces reconstruction; the value chain continues to expand; and the industrial development is driven by intelligence, platforms, and networks. The ICV industry is a new type of industry that is deeply integrated in the fields of automobiles, electronics, information, transportation, positioning and navigation, network communication, and Internet applications. Accordingly, ICVs have become a key topic in global innovation and future development.

China, South Korea, and Japan are the three countries/regions that have published the largest number of core patents related to ICV technology, among which China takes the lead with nine patents (Table 2.2.4). Each organization listed in Table 2.2.5 has produced only one patent. Among these organizations, Tianjin Anlian Chengtong Information Technology Co., Ltd., JGJT, and Shanghai Zheshan Electronic Technology all received five citations (Table 2.2.5). A limited degree of cooperation is observed among these organizations, as shown in Figure 2.2.2.

Table 2.2.4 Countries or regions with the greatest output of core patents on the “ICV technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	9	69.23%	24	80.00%	2.67
2	South Korea	3	23.08%	4	13.33%	1.33
3	Japan	1	7.69%	2	6.67%	2.00

Table 2.2.5 Institutions with the greatest output of core patents on the “ICV technology”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	JGJT	China	1	7.69%	5	16.67%	5
2	Shanghai Zheshan Electronic Technology	China	1	7.69%	5	16.67%	5
3	Tianjin Anlian Chengtong Information Technology Co., Ltd.	China	1	7.69%	5	16.67%	5
4	Hunan Chuanxin Electronic Technology Co., Ltd.	China	1	7.69%	3	10.00%	3
5	WSGC	China	1	7.69%	3	10.00%	3

JGJT: Jinan Iron & Steel Group Co., Ltd.; WSGC: Wuhan Iron and Steel (Group) Kunming Iron and Steel Co., Ltd.

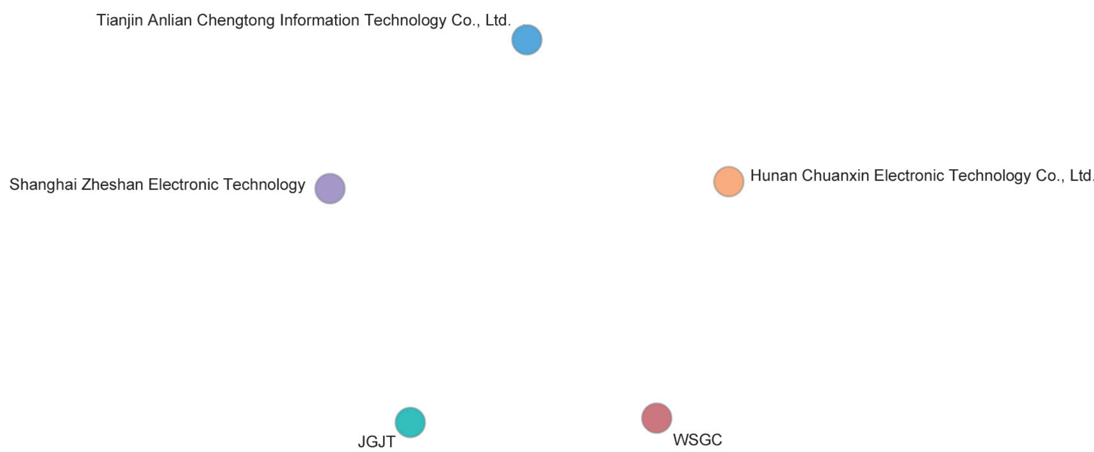

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “ICV technology”

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Engineering Fronts

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