Part B Reports in Different Fields

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

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

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

(1) Intelligent manufacturing driven by digital twin

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

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Intelligent manufacturing driven by digital twin	9	847	94.11	2017.6
2	Hybrid additive–subtractive manufacturing method	11	625	56.82	2015.3
3	Air-breathing hypersonic vehicles	25	984	39.36	2016.6
4	Fault monitoring and diagnosis based on machine learning	41	2 986	72.83	2017.7
5	3D printing of continuous-fiber-reinforced composite	10	750	75.00	2017.2
6	Supersonic combustor technology	28	640	22.86	2016.8
7	Large space deployable antenna	11	215	19.55	2016.7
8	Vehicle-to-everything and real-time traffic management based on 5G	17	1 225	72.06	2017.1
9	Aerial manipulator	46	1 221	26.54	2015.2
10	High-power wireless power transmission	20	1 600	80.00	2016.8

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

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Intelligent manufacturing driven by digital twin	0	0	1	3	4	1
2	Hybrid additive–subtractive manufacturing method	2	4	5	0	0	0
3	Air-breathing hypersonic vehicles	1	6	4	7	4	3
4	Fault monitoring and diagnosis based on machine learning	0	1	5	10	14	11
5	3D printing of continuous-fiber-reinforced composite	0	0	2	5	2	1
6	Supersonic combustor technology	2	4	4	8	9	1
7	Large space deployable antenna	1	0	3	5	1	1
8	Vehicle-to-everything and real-time traffic management based on 5G	2	2	2	3	3	5
9	Aerial manipulator	18	14	6	5	3	0
10	High-power wireless power transmission	0	5	2	6	5	2

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

(2) Hybrid additive–subtractive manufacturing method

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

(3) Air-breathing hypersonic vehicles

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

(4) Fault monitoring and diagnosis based on machine learning

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

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

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

(6) Supersonic combustor technology

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

(7) Large space deployable antenna

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

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

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

(9) Aerial manipulator

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

(10) High-power wireless power transmission

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

1.2 Interpretations for three key engineering research fronts

1.2.1 Intelligent manufacturing driven by digital twin

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

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

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

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

1.2.2 Hybrid additive-subtractive manufacturing method

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

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

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

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

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

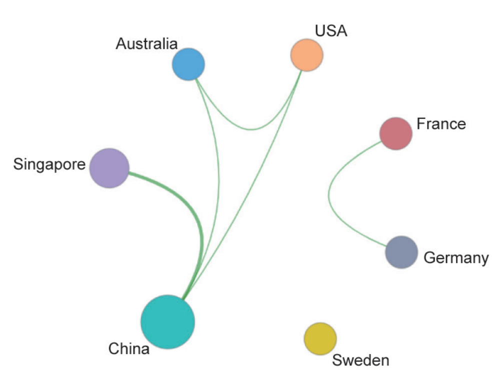

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "intelligent manufacturing driven by digital twin"

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

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

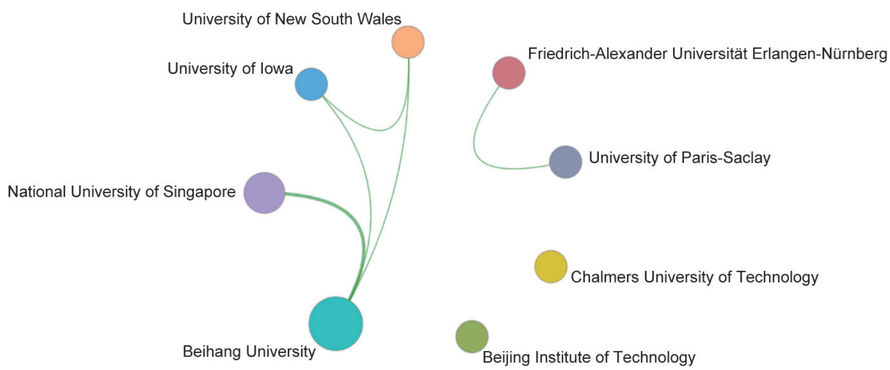

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "intelligent manufacturing driven by digital twin"

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

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

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

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

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

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

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

1.2.3 Air-breathing hypersonic vehicles

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

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

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

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

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

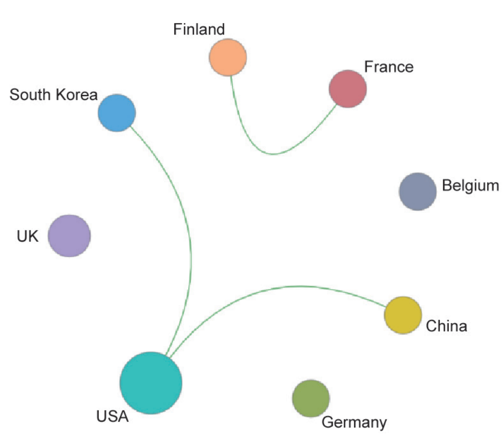

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “hybrid additive-subtractive manufacturing method”

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

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

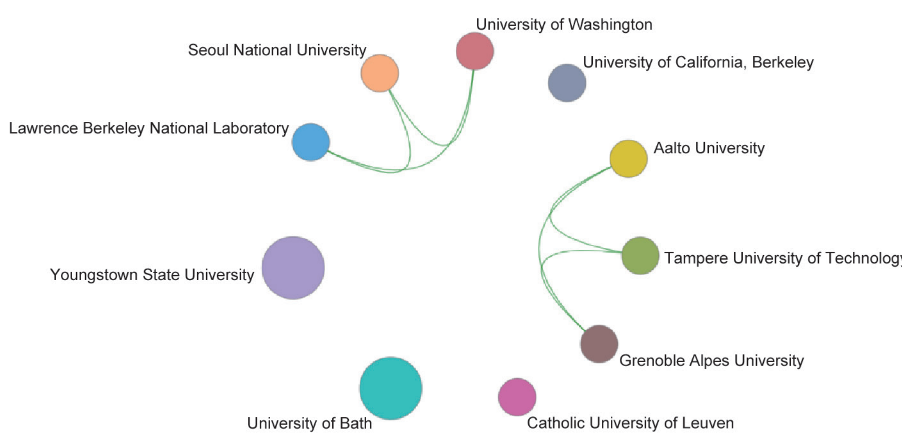

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "hybrid additive-subtractive manufacturing method"

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

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

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

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

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

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

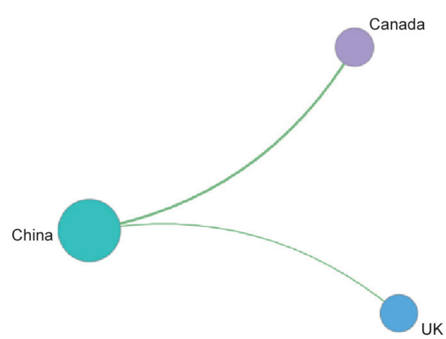

Figure 1.2.5 Collaboration network among major countries in the engineering research front of “air-breathing hypersonic vehicles”

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

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

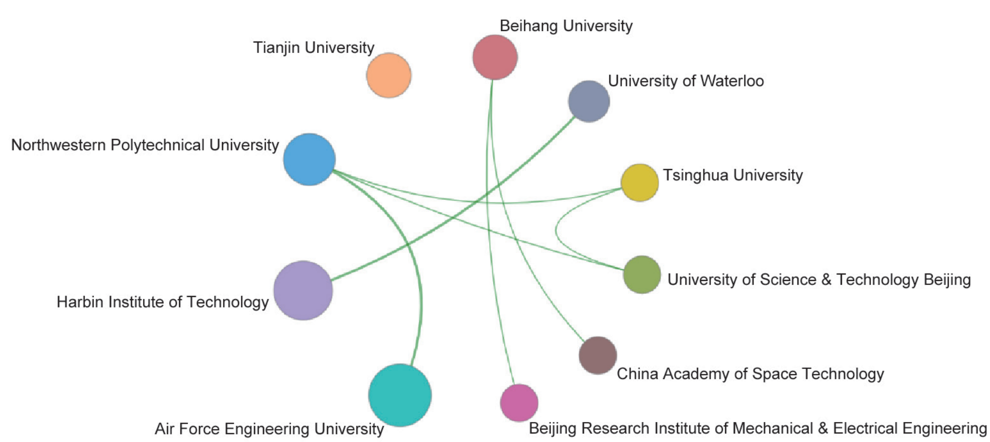

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “air-breathing hypersonic vehicles”

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

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

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

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

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

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

(1) Driverless system based on 5G technology

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

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

Compared with other types of underwater detection

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

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Driverless system based on 5G technology	137	106	0.77	2018.6
2	Underwater unmanned vehicles and their warship-load technology	536	2 413	4.50	2016.6
3	Flexible electronic manufacturing technology	671	5 047	7.52	2016.0
4	Big data driven scheduling technology for intelligent manufacturing system	26	24	0.92	2018.2
5	Ultra-precision machining technology for complex surfaces	76	259	3.41	2016.2
6	Development of fully integrated wearable multi-functional sensors	119	487	4.09	2017.1
7	Bionic soft robot	30	244	8.13	2016.4
8	Thermal protection technology for hypersonic vehicle	73	171	2.34	2017.0
9	Manned/unmanned aerial vehicle cooperative control technology	49	210	4.29	2016.7
10	Smart grid operation and dispatch technology	133	686	5.16	2016.0

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

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Driverless system based on 5G technology	1	0	3	8	30	95
2	Underwater unmanned vehicles and their warship-load technology	42	44	94	89	85	137
3	Flexible electronic manufacturing technology	60	83	84	106	121	112
4	Big data driven scheduling technology for intelligent manufacturing system	0	0	4	2	5	15
5	Ultra-precision machining technology for complex surfaces	5	14	10	14	11	14
6	Development of fully integrated wearable multi-functional sensors	6	8	18	36	34	17
7	Bionic soft robot	2	5	5	2	3	10
8	Thermal protection technology for hypersonic vehicle	2	5	6	17	16	21
9	Manned/unmanned aerial vehicle cooperative control technology	2	4	2	5	22	7
10	Smart grid operation and dispatch technology	9	29	18	22	14	22

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

(3) Flexible electronic manufacturing technology

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

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

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

(5) Ultra-precision machining technology for complex surfaces

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

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

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

(7) Bionic soft robot

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

(8) Thermal protection technology for hypersonic vehicle

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

(9) Manned/unmanned aerial vehicle cooperative control technology

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

(10) Smart grid operation and dispatch technology

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

2.2 Interpretations for three key engineering development fronts

2.2.1 Driverless system based on 5G technology

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

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

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

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

2.2.2 Underwater unmanned vehicles and their warship-load technology

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

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

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

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

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

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

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

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

2.2.3 Flexible electronic manufacturing technology

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

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

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

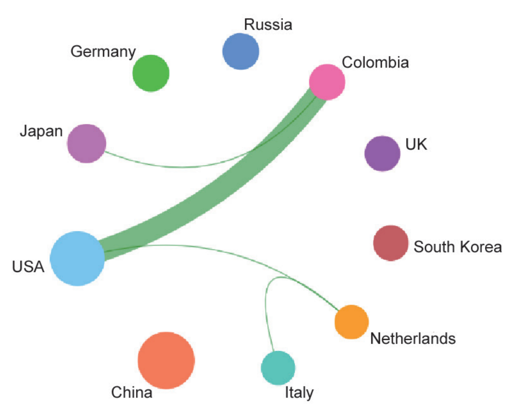

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “underwater unmanned vehicles and their warship-load technology”

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

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

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

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

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

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

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

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

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

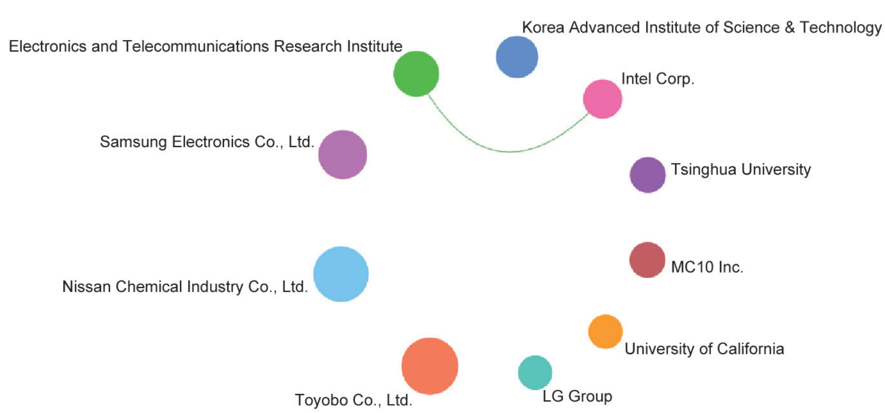

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of "flexible electronic manufacturing technology"

Participants of the Field Group

Leaders

DUAN Zhengcheng, GUO Dongming

Members

JIANG Zhuangde, HUANG Qingxue, FAN Huitao, XIANG Jinwu, LIU Yixin, DU Shanyi, XU Demin, MA Weiming, XU Qing, CHEN Yuli, SONG Aiguo, FANG Yongchun, PENG Zhike, YAO Mingfa, LIU Xin, WANG Zuankai, WANG Liping, CHEN Weiqiu, CHEN Haisheng, WANG Kaiyun, ZI Bin, XUAN Fuzhen, WANG Dong, HE Yong, ZHENG Jinyang, CHEN Xu, JIA Limin, SHI Tielin, JI Xue

Report Writers

HUANG Pei, YAN Chunze, LIU Xiaowei, XUAN Jianping, XIA Liang, LUO Feiteng, LIU Zhiyong, ZHAO Jiangbin, SUN Bo, LI Kaicheng, WEI Jiaolong, LI Baoren, HUANG Yong'an, GAO Liang, XU Jianfeng, YIN Zhouping, WU Hao, WU Zhigang, LI Yichao, ZHANG Yuanyuan, WEN Jinyu, YAO Wei, XIA Qi, CHEN Xixi