II. Information and Electronic Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts in the information and electronic engineering field are summarized in Table 1.1.1, encompassing the sub-fields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. “Brain-inspired intelligent chips,” “edge computing,” and “adversarial learning” are among the popular topics published by *Clarivate*, and the seven other fronts are recommended by researchers.

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

(1) Brain-inspired intelligent chips

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

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Brain-inspired intelligent chips	60	5 664	94.40	2016.1
2	Multi-scale spatial–temporal super-resolution medical imaging instruments	120	6 774	56.45	2015.5
3	Edge computing	492	32 594	66.25	2017.4
4	6G wireless transmission and network structure	22	750	34.09	2018.3
5	Carbon-based integrated circuits (ICs)	72	4 413	61.29	2015.8
6	Space–air–ground integrated navigation and positioning system	9	532	59.11	2016.2
7	Adversarial learning	216	10 725	49.65	2017.6
8	Principles and instrumentation of ultra-precision three-dimensional microscopy	83	2 909	35.05	2015.4
9	Program synthesis for cyber–physical systems (CPSs)	237	5 479	23.12	2015.7
10	Long-reach underwater wireless optical communication	55	2 875	52.27	2016.4

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

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Brain-inspired intelligent chips	10	14	12	11	8	5
2	Multi-scale spatial–temporal super-resolution medical imaging instruments	38	28	21	24	7	2
3	Edge computing	15	27	57	119	178	96
4	6G wireless transmission and network structure	0	0	1	5	3	13
5	Carbon-based ICs	16	20	14	10	9	3
6	Space–air–ground integrated navigation and positioning system	1	3	1	1	3	0
7	Adversarial learning	6	10	13	54	91	42
8	Principles and instrumentation of ultra-precision three-dimensional microscopy	27	18	19	17	2	0
9	Program synthesis for CPSs	63	53	49	37	25	10
10	Long-reach underwater wireless optical communication	2	9	17	19	7	1

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

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

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

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

(3) Edge computing

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

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

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

(4) 6G wireless transmission and network structure

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

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

(5) Carbon-based integrated ohips

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

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

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

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

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

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

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

(7) Adversarial learning

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

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

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

(9) Program synthesis for cyber–physical systems

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

(10) Long-reach underwater wireless optical communication

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

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

1.2 Interpretations for three key engineering research fronts

1.2.1 Brain-inspired intelligent chip

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

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

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

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

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

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

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

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

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

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

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

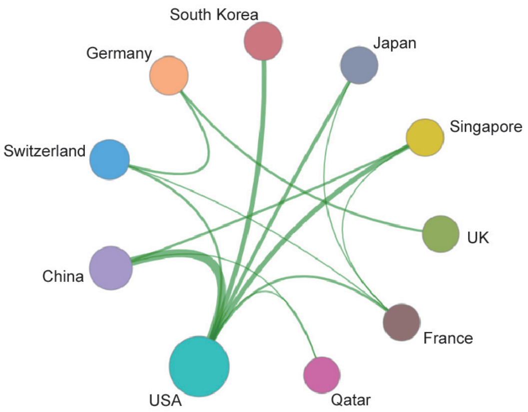

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "brain-inspired intelligent chips"

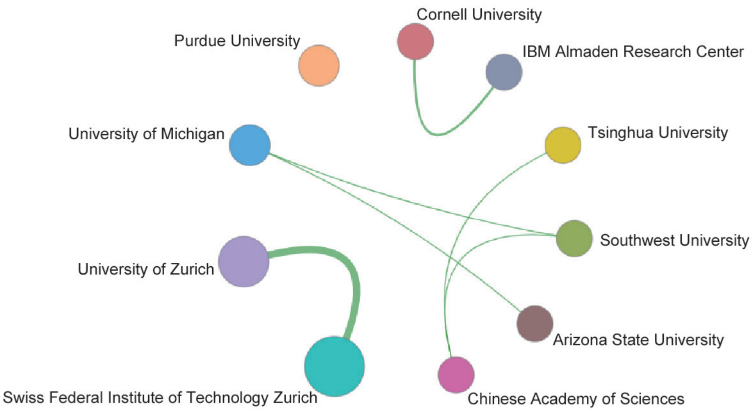

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "brain-inspired intelligent chips"

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

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

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

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

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

The development trends of medical imaging instruments are as follows:

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

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

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

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

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

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

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

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

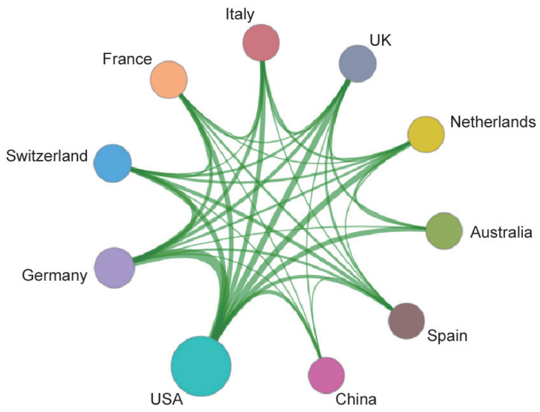

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "multi-scale spatial–temporal super-resolution medical imaging instruments"

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

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

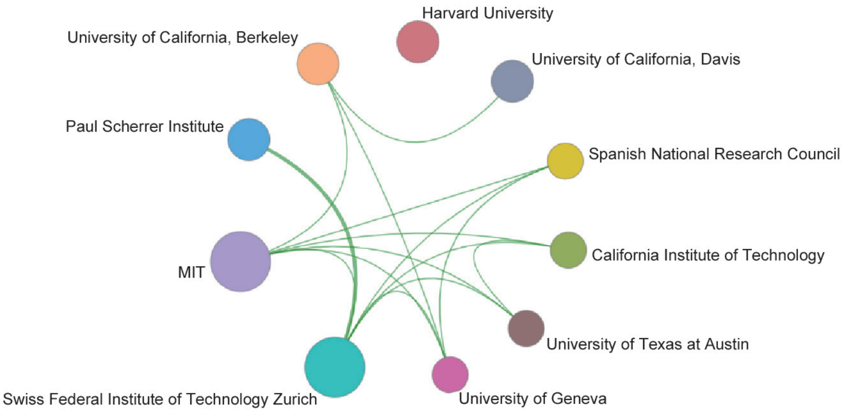

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "multi-scale spatial–temporal super-resolution medical imaging instruments"

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

1.2.3 Edge computing

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

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

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

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

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

The research on edge computing primarily includes the following aspects:

(1) Edge computing systems and platforms

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

(2) Edge–cloud collaboration and scheduling

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

(3) Algorithms for edge intelligence

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

(4) Innovative applications of edge computing

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

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

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

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

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

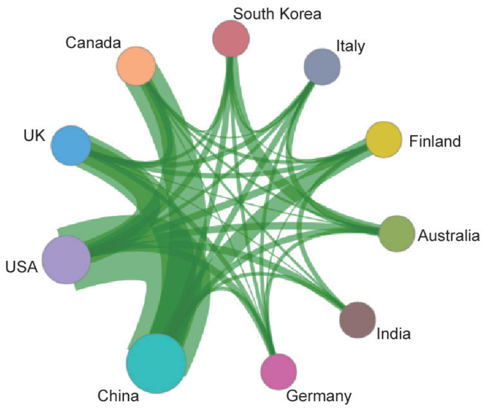

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "edge computing"

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

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

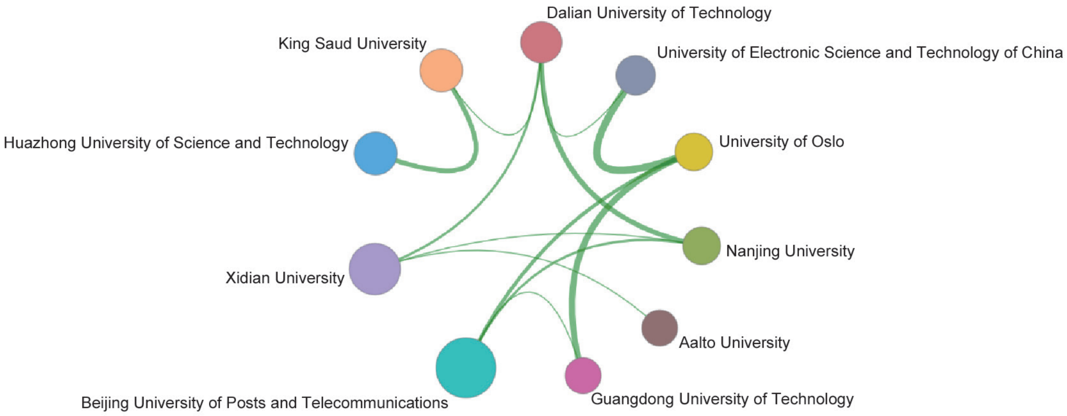

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "edge computing"

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

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

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

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

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts in the information and electronic engineering field are summarized in Table 2.1.1, encompassing the sub-fields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. Among these 10 fronts, the “development of extreme ultraviolet (EUV) light sources for IC chip nanolithography,” “integrated wireless communications and sensing technology,” “design and implementation of intelligent robot cluster cooperation systems,” and “terahertz key devices and ultra-high-speed wireless transmission applications” are recommended by researchers, and the other six fronts are published based on the analysis of *Derwent Innovation* of *Clarivate*.

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

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

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

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Development of EUV light sources for IC chip nanolithography	121	980	8.10	2014.4
2	Integrated wireless communications and sensing technology	299	1 113	3.72	2016.4
3	Design and implementation of intelligent robot cluster cooperation systems	243	1 094	4.50	2016.2
4	VR/AR near-eye display technology	156	1 869	11.98	2017.5
5	Optical frequency combs for precision measurement and time/frequency metrology	156	573	3.67	2016.2
6	Integration of the massive MIMO antenna array and radio frequency (RF)	158	843	5.34	2016.9
7	Autonomous environment perception and scene cognition technology for intelligent mobile robots	70	71	1.01	2017.5
8	Solid-state vehicle-mounted phased-array light detection and ranging (LiDAR)	47	367	7.81	2018.2
9	Terahertz key devices and ultra-high-speed wireless transmission applications	145	534	3.68	2016.3
10	Distributed network security and management based on blockchain	125	332	2.66	2018.5

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

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Development of EUV light sources for IC chip nanolithography	24	20	21	10	4	9
2	Integrated wireless communications and sensing technology	24	28	46	51	59	58
3	Design and implementation of intelligent robot cluster cooperation systems	4	9	8	26	46	66
4	VR/AR near-eye display technology	7	9	22	25	38	52
5	Optical frequency combs for precision measurement and time/frequency metrology	13	20	19	21	22	36
6	Integration of the massive MIMO antenna array and RF	18	15	24	21	36	38
7	Autonomous environment perception and scene cognition technology for intelligent mobile robots	1	7	8	9	32	13
8	Solid-state vehicle-mounted phased-array LiDAR	1	2	2	5	9	28
9	Terahertz key devices and ultra-high-speed wireless transmission applications	16	15	17	18	39	23
10	Distributed network security and management based on blockchain	0	0	1	12	33	79

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

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

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

(2) Integrated wireless communications and sensing technology

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

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

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

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

(4) VR/AR near-eye display technology

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

(10) Distributed network security and management based on blockchain

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

2.2 Interpretations for three key engineering development fronts

2.2.1 Development of EUV light sources for IC chip nanolithography

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

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

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

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

2.2.2 Integrated wireless communications and sensing technology

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

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

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

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

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

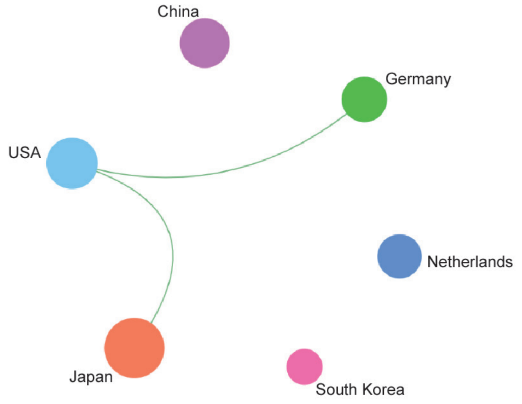

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “development of EUV light sources for IC chip nanolithography”

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

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

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

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

2.2.3 Design and implementation of intelligent robot cluster cooperation systems

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

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

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

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

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

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

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

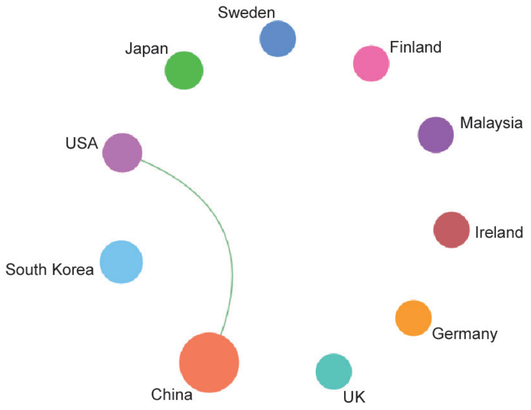

Figure 2.2.2 Collaboration network among major countries in the engineering development front of “integrated wireless communications and sensing technology”

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

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

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

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

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

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

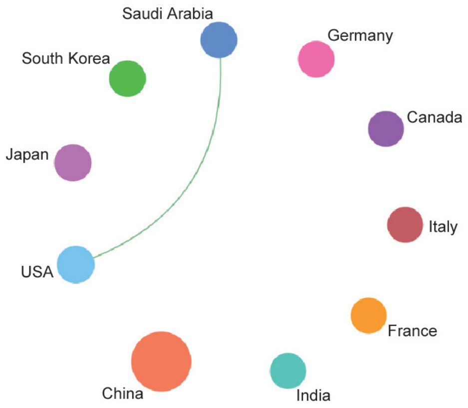

Figure 2.2.3 Collaboration network among major countries in the engineering development front of "design and implementation of intelligent robot cluster cooperation systems"

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