# II. Information and Electronic Engineering

## 1 Engineering research fronts

### 1.1 Trends in top 10 engineering research fronts

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

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

(1) Brain-inspired intelligence

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

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

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

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

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

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

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

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

### (2) Space-terrestrial integrated network

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

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

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

### (3) Brain imaging technologies

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

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

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

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

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

### (5) Hybrid-augmented intelligence

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

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

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

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

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

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

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

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

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

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

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

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

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

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

#### (9) Quantized precise metering/measurement and related theory

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

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

#### (10) New-generation neural networks and their applications

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

## 1.2 Interpretations for three key engineering research fronts

### 1.2.1 Brain-inspired intelligence

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

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

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

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

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

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

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

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

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

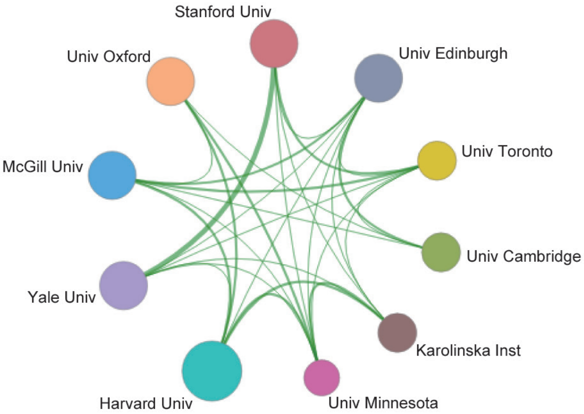

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “brain-inspired intelligence”

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

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

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

### 1.2.2 Space-terrestrial integrated network

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

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

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

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

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

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

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

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

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

### (3) Lightweight handover mechanism research for highly dynamic mobility

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

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

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

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

## 1.2.3 Brain imaging technologies

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

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

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

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

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

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

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

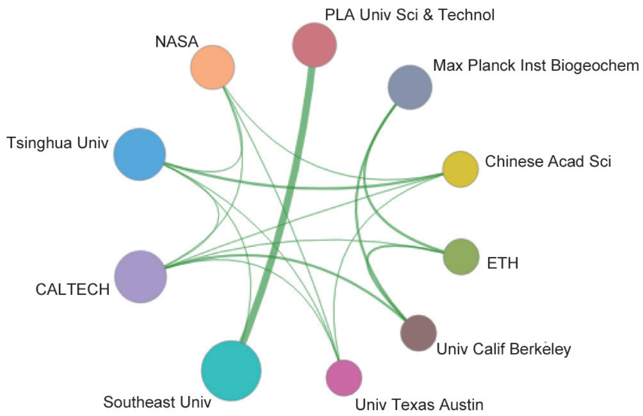

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "space-terrestrial integrated network"

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

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

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

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

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

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

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

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

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

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

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

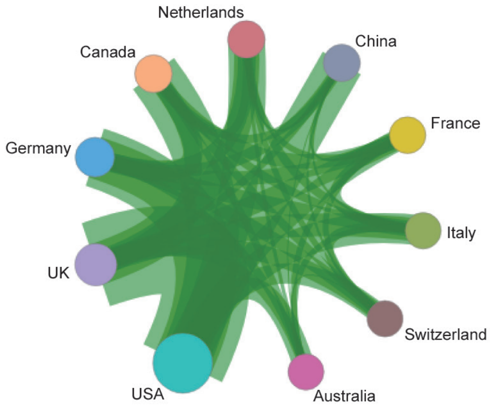

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “brain imaging technologies”

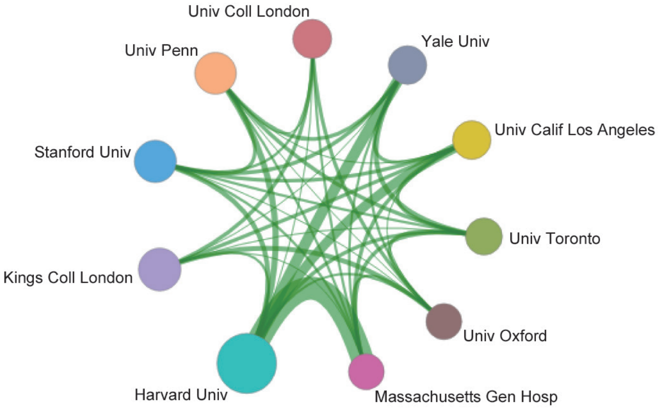

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “brain imaging technologies”

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

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

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

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

## 2 Engineering development fronts

### 2.1 Trends in top 10 engineering development fronts

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

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

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

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

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

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

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

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

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

### (2) Ultraprecision instrument technology and intelligence

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

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

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

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

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

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

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

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

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

### (5) Surgical robot technology

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

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

### (6) Energy-efficient AI chip technology

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

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

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

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

### (8) Flexible and wearable optoelectronics

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

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

### (9) Security detection technologies for IoT

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

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

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

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

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

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

## 2.2 Interpretations for three key engineering development fronts

### 2.2.1 Millimeter-wave ultra-high throughput technology

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

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

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

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

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

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

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

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

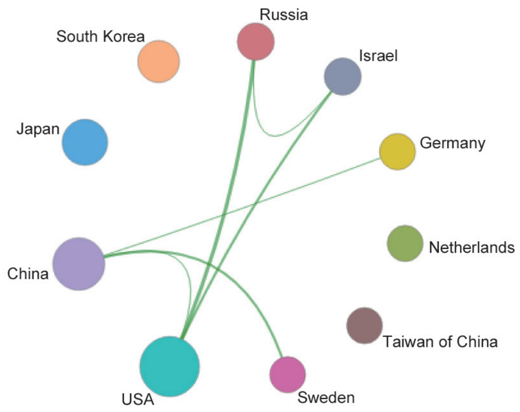

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of “millimeter-wave ultra-high throughput technology”

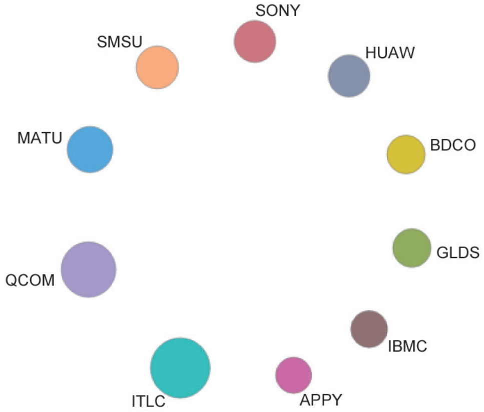

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “millimeter-wave ultra-high throughput technology”

### 2.2.2 Ultraprecision instrument technology and intelligence

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

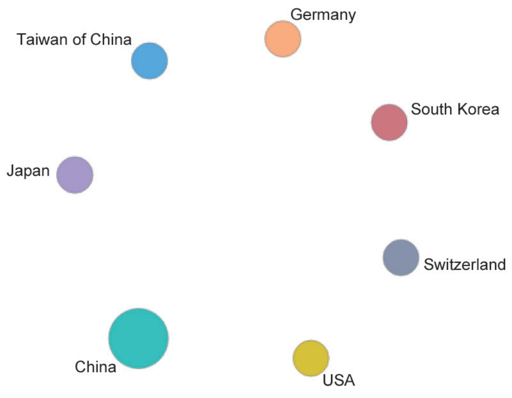

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of “ultra-precision instrument technology and intelligence”

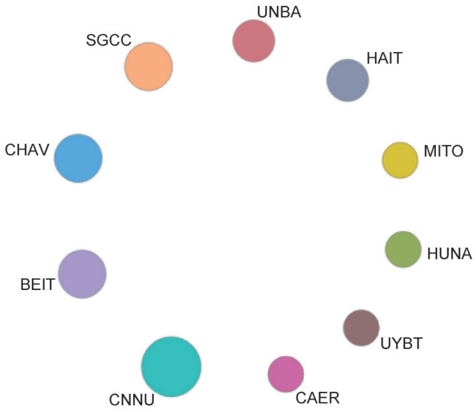

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “ultra-precision instrument technology and intelligence”

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

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

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

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

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

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

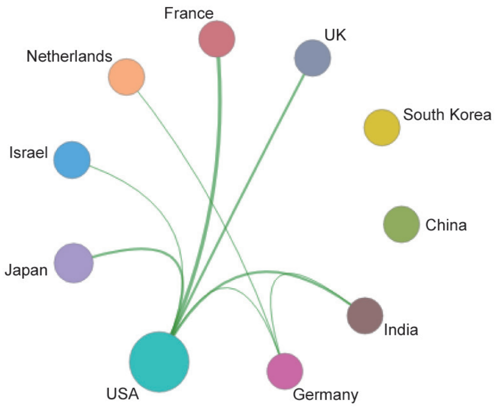

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of "systems and technologies for analysis and identification of images and videos"

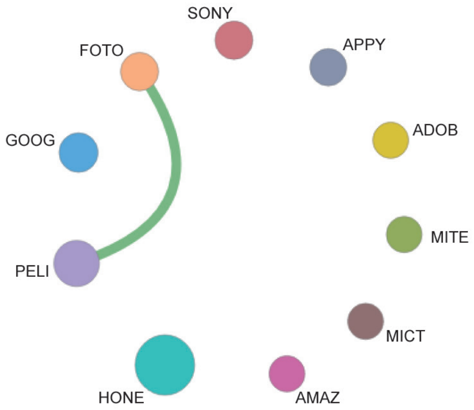

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of "systems and technologies for analysis and identification of images and videos"

## Participants of the Field Group

### Leaders

PAN Yunhe, LU Xicheng

### Co-leaders

TAN Jiubin, LYU Yueguang, CHEN Jie

### Members of the Expert Group

**Academicians**

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

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

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

**Deputy of Co-leaders**

LU Zhengang, CHE Jibin, SUN Jian

**Other Experts** (in alphabetic order of the last name)

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

### Members of the Work Group

Consultants: WU Zhaohui, LU Dongming, WU Fei

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

Liaisons: WANG Chengjun, WANG Bing, ZHANG Jia

Secretaries: ZHAI Ziyang, HU Xiaonv, YANG Weiqiang

### Report Writers (in alphabetic order of the last name)

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