Part 2 Reports in Different Fields

I. Mechanical & Vehicle Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

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

(1) Self-adaptive tracking of autonomous underwater vehicles

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

Table 1.1.1 Top 10 engineering research fronts in mechanical field

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

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

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

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

(2) Consistency control of multi-agent systems

As demonstrated by clusters of birds, fish, insects, bacteria, and cells, widespread mass movement occurs in nature. The clusters formed by interconnected and constantly moving individuals are characterized complex and highly coordinated dynamic behavior. Multi-agent systems provide a means of understanding the behavior of biological and other natural clusters and have a considerable application value in such disparate fields as industrial multi-robot group coordination, unmanned aerial vehicle (UAV) formation control, human group behavior regulation and guidance, and wireless sensor network optimization. A multi-agent system is composed of a series of interacting agents, with each agent using communication, cooperation, coordination, scheduling, management, and control methods to relay the structure of the system and function, and the behavior characteristics, thereby completing many complex tasks that cannot be performed by a single agent. A multi-agent system has autonomy, distribution, and coordination functions and exhibits self-organization, learning, and inference capabilities. Therefore, the use of multi-agent systems to solve real problems offers strong robustness and reliability. As biology, computer science, artificial intelligence, automation science, physics, and other disciplines intersect with each other and develop as interdisciplinary fields, multi-agent systems are increasingly considered a focal point in engineering control. Research on the collaboration of multi-agent systems was inspired in its early stage by the clustering phenomenon, which widely exists in nature, and was explored in the fields of mathematics, computer simulation, and system science. In recent decades, much research has been conducted on multi-agent system cooperative control theory. The

primary areas of interest in multi-agent coordination control include consistency, cluster, swarm, and formation controls. Consistency control is one of the most basic challenges in multi-agent system coordination control, and its research can be promoted and applied to other cooperative control problems. Consistency control refers to the design of a consistency protocol that enables each agent to interact with local information to achieve the consistency of the target state value of all agents. Research on consistency control can be broadly separated into three key areas: the complexity of intelligent body dynamics, communication topology, and network information transmission. At present, the most important application of multi-agent systems is in the collaboration of group robots. In particular, the traditional multi-robot production line often adopts a centralized control structure in which adaptations to production are accomplished based on small task-oriented batches. In this case, dealing with many varieties is typically difficult because of the lack of agile manufacturing capacity. Given that the international manufacturing industry is moving toward a large, complex, dynamic, and open direction, the complex operation of modern manufacturing requires multi-robot cooperation. As such, a group robot system with superior compliance, consistency, and optimal performance is urgently required.

(3) Self-adaptive neural network control of manipulators

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

(4) Autonomous underwater navigation systems

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

(5) Thermal management technology of lithium-ion batteries

With the combined threat of energy crisis and environmental pollution, the development of electric vehicles has recently attracted much attention. Because of their numerous advantages, including high energy and power density, long

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

(6) Global navigation satellite system optimization

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

(7) Cognitive wireless networks

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

(8) Target recognition based on tactility

A robot can perceive the external environment or a target

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

(9) Assessment and utilization of inshore wave energy resources

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

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

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

of a nanofluid convective heat transfer mechanism enhanced by electro/magnetic field is expected to improve its industrial application.

1.2 Interpretations for three key engineering research fronts

1.2.1 Self-adaptive tracking of autonomous underwater vehicles

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

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

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

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

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

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

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

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

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

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

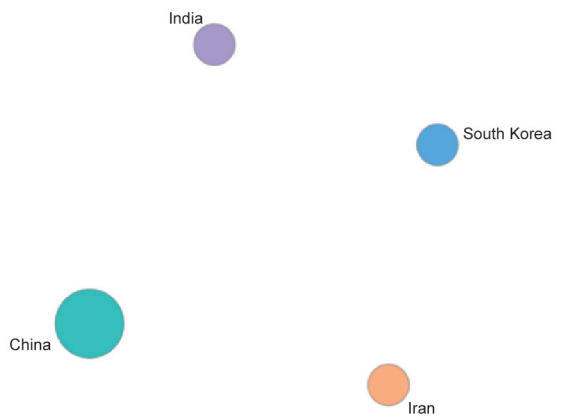

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "self-adaptive tracking of autonomous underwater vehicles"

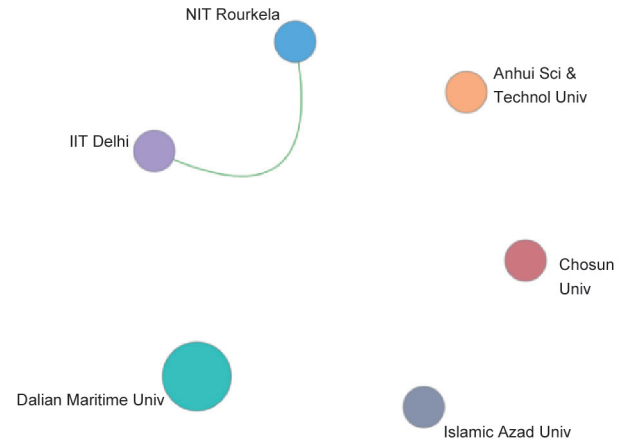

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "self-adaptive tracking of autonomous underwater vehicles"

1.2.2 Consistency control of the multi-agent systems

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

(1) Complexity of intelligent body dynamics

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

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

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

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

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

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

(2) Complexity of communication topology

Communication topology describes the interactive information relationship between intelligent bodies and can be abstracted into a figure. Therefore, algebraic graph theory knowledge is introduced to implement relevant analysis. Topology can be divided into fixed and time-varying topologies, based on whether the topology changes with time. Consistency research on multi-agent systems under fixed topology is a relatively mature field, whereas time-varying topology is still faced with numerous challenges. Based on the considerable body of research data, it is known that joint

connectivity is the weakest assumption in the case of time-varying typology. For multi-agent systems with different types of dynamics, contemporary research usually adds additional assumptions to the joint connectivity topology and achieves consistency under static or dynamic collaborative control laws. Therefore, further research is needed.

(3) Complexity of network information transmission

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

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

1.2.3 Self-adaptive neural network control of manipulators

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

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

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

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

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

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

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

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

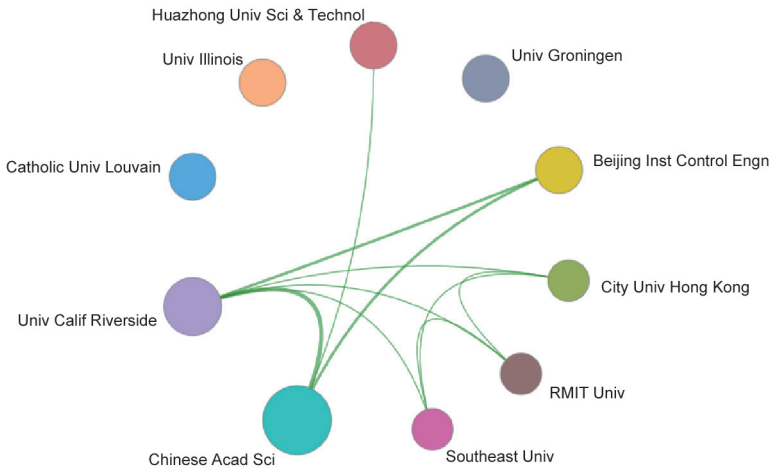

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “consistency control of multi-agent systems”

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

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

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

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

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

Although the self-adaptive neural network has accomplished significant breakthroughs and progress, and movement-tracking control of a manipulator has already been applied, it cannot completely solve the uncertain problems caused by the robot manipulator modeling error and outside interference. In recent years, intelligent control algorithms based on knowledge rules and learning inference, such as fuzzy control, learning control, expert control and genetic algorithm, and particle swarm optimization-algorithm, have been widely studied. These approaches have their own advantages in addressing system uncertainties. Nevertheless, different control theories and methods have advantages and shortcomings. As such, achieving ideal control effects using a

single method is difficult. Therefore, multiple control methods must be integrated, such that each method complements each other's limitations, and can be organically combined to form a new control method. Such a strategy is already well known in contemporary robot control research. Mixed methods with fuzzy neural network control, robust control of neural networks, fuzzy sliding mode variable structure control, and robust self-adaptive control as representatives examples, have already been developed and applied in the research on the control method of manipulators.

The country/region with the most core papers on self-adaptive neural network control of manipulators is China (3), with an average number of citations of 125.33 (Table 1.2.9).

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

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

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

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

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

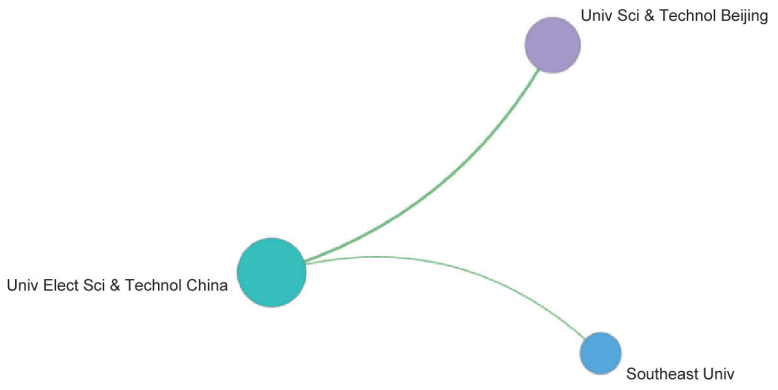

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "self-adaptive neural network control of manipulators"

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

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

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

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

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

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

(1) MEMS sensors

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

Table 2.1.1 Top 10 engineering development fronts in mechanical field

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

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

No.	Engineering development front	2012	2013	2014	2015	2016	2017
1	MEMS sensors	82	81	29	21	9	5
2	New types of ship propulsion system	22	25	33	19	24	29
3	UAVs	55	63	54	102	138	48
4	Gas turbines	76	82	46	43	10	8
5	Marine survey and positioning technology	47	46	40	31	19	8
6	Autonomous control of unmanned ground vehicles	11	11	21	14	7	6
7	Over-ocean communication, navigation, and positioning technology	39	54	33	17	15	17
8	New generation of image display technology	49	50	48	32	17	6
9	Takeoff, landing, and flying of aircraft	27	19	26	15	11	1
10	New types of engine technology	67	35	53	29	4	12

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

(2) New types of ship propulsion system

At present, “prime mover–drive system–propeller” is the most widely used propulsion mode for naval and merchant ships. This mode possesses the advantages of high power and a mature design method and manufacturing process. However, several disadvantages are also revealed in the process

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

(3) UAVs

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

(4) Gas turbines

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

traditional classical mathematics theory is difficult because of the strong nonlinearity, instability, and uncertainty. Rapidly developing intelligent algorithms, such as neural network, genetic algorithm, and expert system provide new solution concepts for these types of problems. These solutions are expected to realize localization and determination efficiently through fault detection with limited parameters.

(5) Marine survey and positioning technology

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

(6) Autonomous control of unmanned ground vehicles

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

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

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

have significantly improved over-ocean communication efficiency, quality, and distance. The long-term development direction of this marine communication technology is predicated on building a long-distance communication rate with wide transmission range, high reliability, and low price.

(8) New generation of image display technology

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

(9) Takeoff, landing, and flying of aircraft

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

(10) New types of engine technology

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

miniaturization and weight reduction have also become main trends of engine development. In addition, the integration of sensor and big data analysis technology to monitor engine health has become a frontier technology related to improving engine reliability.

2.2 Interpretations for three key engineering development fronts

2.2.1 MEMS sensors

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

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

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

frequent cooperation, as shown in Figure 2.2.2. Nineteen core patents related to engineering development devoted to MEMS sensors are public in China, and the mainland institution that is often in public is Shortcut Semiconductor Suzhou Co., Ltd.

2.2.2 New types of ship propulsion system

(1) Bionic propulsion system

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

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

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

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

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

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

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

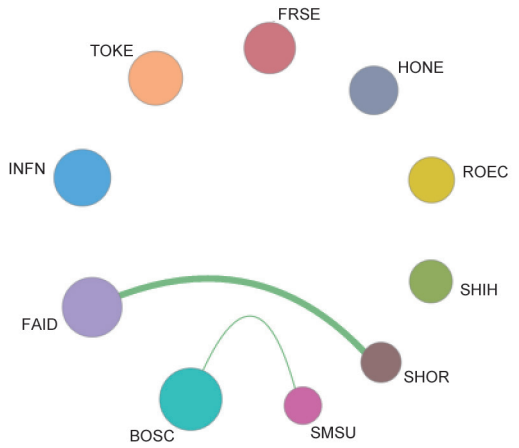

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "MEMS sensors"

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

(2) Robot fish

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

(3) Vector propulsion system

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

(4) Electric propulsion system

The main feature of the ship's electric propulsion system is the use of a ship-integrated power station to provide propulsion power, auxiliary machinery, and daily power to an entire ship, and to complete the ship maneuvering system and related tasks with the highly comprehensive economy and reliability. This process can improve the effective cabin area and operability. The technical development of the marine electric propulsion system is mainly focused on the efficiency of the propulsion device, greenization of the power source, and intelligentization of the control system. Currently, the commonly used electric propellers are the pod and full-

rotating propellers, with the former being more integrated than the latter and can coaxially convert electrical energy to mechanical energy. High-power pod propellers face several challenges, including large resistance of appendages, high bearing temperature, and sealing failure. Shaftless rim propulsion systems with integrated motor and propeller have high power density and low noise and have become a research hotspot of the new generation of electric propellers. The main sources of electrical energy are diesel generator sets, power batteries, shore-based power supplies, fuel cells, and solar energy. The new high-efficiency thermal power generation system also has a broad prospect of development.

(5) Deformable propulsion system of amphibious robot

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

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

2.2.3 UAVs

(1) Development of flight platform technology

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

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

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

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

(2) Multi-UAV cluster collaboration technology

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

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

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

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

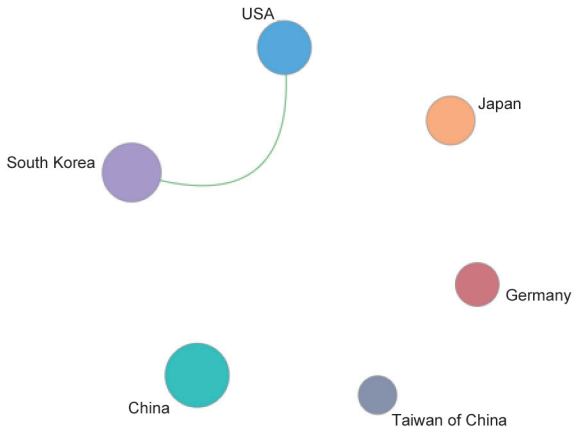

Figure 2.2.3 Collaboration network among major countries in the engineering development front of "new types of ship propulsion system"

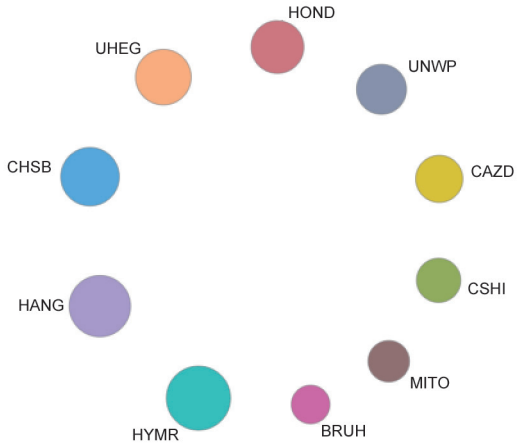

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "new types of ship propulsion system"

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

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

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

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

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

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

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

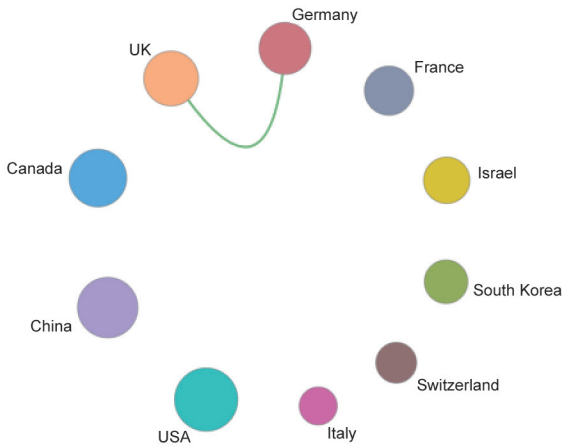

Figure 2.2.5 Collaboration network among major countries in the engineering development front of “UAVs”

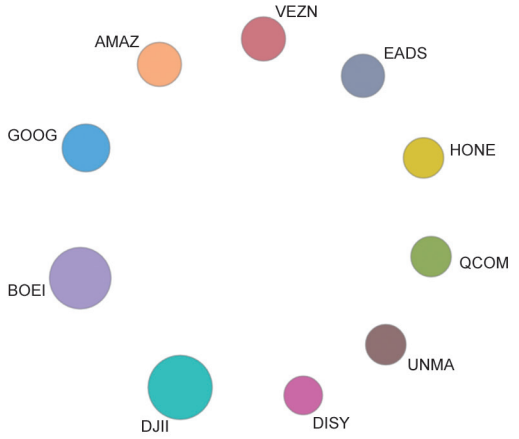

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “UAVs”

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