patents. In the expert review stage, domain experts studied highly cited patents, and library and information experts assisted them in interpreting patent maps from multiple perspectives, such as “peaks” “blue oceans” and “islands”. Finally, domain experts merged, revised, and refined the interpreted results of the patent maps and fronts nominated by experts to obtain candidate engineering development fronts, and then selected approximately 10 engineering development fronts in each field through questionnaire surveys or multiple rounds of seminars.

In each field, three or four key development fronts were selected according to the development prospects and the significance. Authoritative experts in the front direction were invited to interpret the fronts in detail from the perspectives of national and institutional layout, cooperation networks, development trends, and R&D priorities.

3 Development roadmap

Technology roadmaps are an important tool to depict the development trend of technologies. To strengthen the academic leading role of the engineering fronts, the Global Engineering Fronts 2022 project conducted detailed analysis on the development focuses and trends of three key engineering research fronts and three key engineering development fronts for each field, and drew a development roadmap in a visual way for each front in the next five to ten years.

4 Terminologies

Publications/Papers: This includes peer-reviewed and published journal articles, reviews, and conference papers retrieved from Web of Science.

High-impact papers: Papers that are in the top 10% in terms of citation frequency are considered to be of high impact, taking into account the year of publication and journal subject category.

Clustered literature topic: A combination of topics and keywords obtained through a co-citation clustering analysis of high-impact papers.

Core papers: Depending on how the research front is obtained, core papers have two meanings. If it originates from a front that is obtained from data mining and revised by experts, the core paper is considered as a high-impact paper. If it comes from a front nominated by domain experts, the core paper is included in the top 10% of papers in terms of citation frequency obtained using the corresponding search strategy.

Percentage of core papers: The proportion of core papers in which a country or institution participates among the total number of core papers produced by all countries or institutions.

Citing papers: Collection of papers that have cited core papers.

Citation number: The number of times the paper has been cited by the Web of Science Core Collection.

Mean publication year: Average publication years for all papers among the clustered literature topics.

Consistently cited papers: Papers included in the top 10% in terms of citation velocity.

Citation velocity: An indicator used to measure the growth rate of the cumulative number of citations for a certain period. In this study, the citation velocity of each paper begins with the month of publication, and the cumulative number of citations per month was recorded.

Highly cited patents: The around top 10 000 DWPI families ranked by the average annual DPCI citations.

Core patents: According to the different ways of obtaining a development front, core patents have two meanings. If they come from the fronts of the patent map, core patents refer to highly cited patents. If they are from the fronts nominated by domain experts, core patents refer to all patents obtained by topic search.

Percentage of published patents: The proportion of core patents in which a country (priority country) or institution participates among the total number of core patents produced by all countries or institutions.

Theme Scape map: A themed landscape representing the overall outlook of a specific industry or technical field. It is a visual presentation in the form of a map obtained by analyzing the semantic similarity of value added DWPI information of patents to gather the patents of related technologies.

Technical coverage width: It is measured by the number of DWPI Classes to which each DWPI patent family covers. This indicator can reflect the breadth of the technology coverage of each patent.

Specialty division criteria system of the academic divisions of the CAE: This is specified in the Specialty Division Criteria of the Academic Divisions of the Chinese Academy of Engineering for Member Election (Trial). It refers to 53 specialized disciplines covered by the nine academic divisions of engineering science and technology, including Mechanical and Vehicle Engineering; Information and Electronic Engineering; Chemical, Metallurgical, and Materials Engineering; Energy and Mining Engineering; Civil, Hydraulic, and Architectural Engineering; Environmental and Light Textile Engineering; Agriculture; Medicine and Health; and Engineering Management.

Part B Reports in Different Fields

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The ten most-researched engineering fronts in the field of mechanical and vehicle engineering include: mechanical, transportation, ship and marine engineering; weapon science and technology; aeronautical and astronautical science and technology; and power and electrical equipment engineering and technology (as listed in Table 1.1.1). Among these, “human–robot contactless collaboration”, “underwater navigation and positioning technology”, “cooperative unmanned driving and operation optimization technologies”, “active/passive control technologies for turbulent flow around high-speed trains”, “variable stiffness technologies for robots”, and “mini and micro unmanned aerial vehicle (UAV) detection” are extensively studied traditional topics. “Autonomous ship deck landing technology for aircraft”, “triboelectric nanogenerator”, “theory and method of continuous multidimensional variable configuration flight control”, and “microrobot active drug delivery technology” are considered as emerging topics.

The annual publication of papers during the years 2016–2021 is listed in Table 1.1.2.

(1) Autonomous ship deck landing technology for aircraft

Aircraft autonomous ship deck landing refers to the processing information obtained from airborne equipment during the landing phase to obtain landing information with sufficient precision so that the aircraft can complete the autonomous landing process. It involves the cross-integration of the ship and marine engineering, aircraft design, satellite navigation, radar tracking, computer vision, artificial intelligence, and other disciplines. The technology of aircraft autonomous ship deck landing has experienced four stages, namely, full manual mode, manual-assisted semi-automatic mode, automatic mode, and unmanned aerial vehicles full autonomous mode. The related research is mainly divided into two aspects: one is the research of autonomous landing guidance technology, which is mainly used to determine the relative position of the aircraft and ship, generate the reference glide trajectory, and calculate or measure the trajectory tracking error. The second is the research of autonomous landing control technology,

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Autonomous ship deck landing technology for aircraft	8	191	23.88	2018.0
2	Human–robot contactless collaboration	3	161	53.67	2019.7
3	Triboelectric nanogenerator	21	1 157	55.10	2019.5
4	Underwater navigation and positioning technology	85	2 836	33.36	2017.6
5	Cooperative unmanned driving and operation optimization technologies	10	226	22.60	2018.0
6	Theory and method of continuous multidimensional variable configuration flight control	15	232	15.47	2017.7
7	Microrobot active drug delivery technology	41	2 564	62.54	2019.0
8	Active/passive control technologies for turbulent flow around high-speed trains	20	866	43.30	2017.7
9	Variable stiffness technologies for robots	6	344	57.33	2017.2
10	Mini and micro unmanned aerial vehicle (UAV) detection	6	175	29.17	2017.0

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

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Autonomous ship deck landing technology for aircraft	1	2	2	2	1	0
2	Human–robot contactless collaboration	0	0	1	0	1	1
3	Triboelectric nanogenerator	0	0	5	6	4	6
4	Underwater navigation and positioning technology	26	16	20	13	9	1
5	Cooperative unmanned driving and operation optimization technologies	2	3	2	0	2	1
6	Theory and method of continuous multidimensional variable configuration flight control	4	2	3	6	0	0
7	Microrobot active drug delivery technology	1	5	10	9	9	7
8	Active/passive control technologies for turbulent flow around high-speed trains	3	6	7	3	1	0
9	Variable stiffness technologies for robots	1	3	2	0	0	0
10	Mini and micro unmanned aerial vehicle (UAV) detection	2	3	0	1	0	0

which explores the landing control strategy and method with robustness to achieve the fast-tracking of the ideal glide trajectory in a complex environment and can maintain the stability of the aircraft attitude. To date, the research on aircraft autonomous ship deck landing has been developed in the direction of multi-information, all-round, and autonomy. Meanwhile, with the continuous development of satellite navigation, precision radar, visual navigation, artificial intelligence, advanced control, and other related technologies, the reliability of ship deck landing for aircraft will increase and eventually realize autonomous and intelligent landing.

(2) Human–robot contactless collaboration

Human–robot contactless collaboration means that a robot maintains a sufficiently safe distance from a human worker in the same physical space while assisting the human to complete specific tasks and reduce human labor work. Collaborative robots are featured with safety, adaptability, and comfort in the process of human–robot cooperation; specifically, the robot should not harm humans, the robot can understand the human intents accurately and adapt to human movements actively, and the robot action conforms to the cognitive habits of humans so that people can understand the action intention of the robot. The related research can be mainly categorized into three aspects, namely, the studies of prevention of collision events, prediction of human motion intention, and generation of robot anthropomorphic motions. ① To prevent collision events, exploring new sensing technologies for multi-modal information, including object distances, contact forces, and joint torques, is worthy to study the motion principles and deformation mechanism of coupled rigid-flexible-soft robots and develop collaborative robots with collision avoidance ability. ② With regard to the prediction of human motion intention, key research topics include object identification in unstructured environment, adaptive control with motion intent prediction and hand–eye coordination, and virtual reality of human–robot interaction. ③ To generate robot anthropomorphic motions, there are critical challenges to reveal the mechanisms of human-limb natural motions, identify biomechanical characteristics of human musculoskeletal systems, establish the bionic design theory, develop the generation method of robot anthropomorphic motions, and implement feedback control method that conforms to human cognitive habits. With the development of soft material science, intelligent sensing technology, ergonomics, and related disciplines, collaborative robots are expected to make breakthroughs in key technologies, such as multi-modal perception, intention recognition, environmental modeling, anthropomorphic motion, and decision optimization, and enhance the interactive experience and operation efficiency of human–robot contactless collaboration.

(3) Triboelectric nanogenerator

Triboelectric nanogenerator (TENG) is an emerging ambient energy harvesting technology used to convert mechanical energy created by the periodic contact/separation motion of two different materials (i.e., triboelectric pair) into electrical power. Based on the coupling of triboelectrification effect and electrostatic induction, the positive and the negative charges are generated at the interfaces of triboelectric pair, and then the induced charges are driven to flow in the loop to form the current that resulted from the periodic alternating of potential difference between the triboelectric pair. In general, the development of TENG has experienced three stages, namely, fundamental study and operation models, hybrid mechanisms and circuit design for integration, and self-powered smart microsystems. The related research activities can be summarized into three categories. First, the working principle of triboelectric nanogenerators, including triboelectric effect investigation, materials selection, and structural design, is studied further to enhance the electrical performance. Second, the hybrid mechanisms by the combination of triboelectric effect with other effects, including piezoelectric, electromagnetic, photovoltaic, and thermoelectric effects, are explored to design high-efficient energy generators together with power management circuit and storage devices. Third, the triboelectric nanogenerators are integrated with other functional components, especially multi-functional sensors, to construct the self-powered smart microsystems. With the advantages of high efficiency, sensitivity, and integration, the triboelectric nanogenerators show attractive potentials to address the power challenges of low-power consumption devices and microsystems, which represent the development tendency of smart self-powered electronics.

(4) Underwater navigation and positioning technology

Underwater navigation and positioning focuses on obtaining vehicle state information. This includes position, velocity, orientation, and other information concerning its motion. Traditionally, such methods rely on inertial measurements, underwater acoustics, or marine geophysics. As the demand for better navigation and positioning accuracy intensifies, techniques that rely on a single type of information fall out of favor. Moreover, subject to extended mission duration, underwater navigation and positioning technique is developing toward primary inertial guidance facilitated by underwater acoustics and marine geophysical feature matching. Currently, high accuracy instrumentation remains to be a critical topic in the area, with multiple types of information, including inertial measurement, ocean magnetic and gravitational field sensors, underwater acoustics propagation, seabed mapping, hydrologic environment, global positioning system, surface buoy, and underwater beacon. Other crucial topics focus on time synchronization, feature fusion and matching, and the state estimation problem. Meanwhile, navigation and positioning for autonomous underwater vehicles using star tracker and highly coordinating swarm is being actively researched.

(5) Cooperative unmanned driving and operation optimization technologies

Road and waterway transportation systems have lagged behind air and railway transportation in terms of unmanned due to their inherent complexity and variety. However, recently, the above two transportation systems have received substantial achievements in unmanned, flexible manned, and monomer intelligence technologies Moreover, self-driving has been applied at scale in specific scenarios in road transportation systems, such as ports, logistics parks, and open pit mines. Similar application cases for inter-island navigation and intelligent navigation of ships in ferries and closed waters emerge in waterway transportation. However, technique bottlenecks remain in unmanned vehicles in arterial transportation and urban transportation on road, and intelligent navigation of long-distance inland waterways, open seas, and ocean-going ships. Great improvements in the reliability of unmanned driving and efficient operation of transportation system can be achieved with the theoretical and methodological breakthroughs on cooperative unmanned driving and operation optimization key technologies of road and waterway transportation. The self-driving and driving optimization for a vehicle mainly concentrate on the intelligent decision making and control of a multiagent system. The key research includes multidimensional perception of a vehicle swarm, and the mechanism of vehicle dynamics under the affection of vehicle states, road conditions, and traffic environment. In addition, the decision-making optimization for multiple vehicles under strict constraints, such as time, space, and task in a specific region, and the control for a heterogeneous vehicle platooning with the time-varying communication topology are novel hotspots in this field. Ship intelligent navigation and transportation optimization mainly focus on ship collaborative remote-control technology. The main research directions include ship dynamic modeling under complex sea conditions and environments; environmental situational awareness and autonomous navigation for a single ship; cooperative motion control theory and methods for multiple ships; multi-ship formation structure; and path planning methods. Future development will focus on the transformation from single dynamics to group dynamics, individual perception to collaborative perception, and single autonomous decision making to group interactive decision making, which reflects the technology upgrade from single action planning optimization to a group level.

(6) Theory and method of continuous multidimensional variable configuration flight control

As an emerging new and high-technology weapon and equipment, continuous multi-dimensional variable configuration aircraft has become a key development direction of major military powers in the world. Given its ability to change the aerodynamic configuration on a large scale and realize multi-mission flight within a large flight envelope, this aircraft will surely play an important role in the future battlefield and is of great significance to safeguarding our country's security and development interests. The main research directions of continuous multi-dimensional variable configuration flight control include: aircraft model analysis under uncertainty and nonlinear dynamics caused by continuous deformation; flight dynamics coupling control mechanism under strong uncertainty environment; dynamic characteristics of rigid, flexible, and hydraulic coupling and control system modeling theory; smooth switching control theory under agile maneuvering at large angles of attack; integrated intelligent control method for variable configuration and aircraft; and cross-domain seamless autonomous navigation and online autonomous planning decision-making for environment-task self-matching. In the future, the control of continuous multi-dimensional variable configuration aircraft will achieve breakthroughs in the following directions: aircraft deformation control based on adaptive reinforcement learning methods; network communication characteristics of distributed deformation structures and coordinated control between distributed drives; flight control theory for nonlinear and uncertain large-scale variant aircraft with time-varying characteristics; coordinated control of a large number of actuators with communication constraints; coordinated control of large-scale distributed systems with shared channels; adaptive mechanics and control under continuous multidimensional large deformation intelligent decision making, autonomous control and trajectory planning methods under strong uncertain conditions, such as weak models, strong coupling of multiphysics, tasks and environments.

(7) Microrobot active drug delivery technology

Microrobots have a good development prospect in biomedical fields, such as active drug delivery and precision therapy, because of their small size, autonomous movement, and precise control. Compared with the traditional drug particles that passively rely on the human circulatory system, the microrobot active drug delivery technology can make microrobots accurately reach the predetermined tissue through self-driving or external environment driving to achieve accurate drug delivery. At present, the main driving modes include chemical/biochemical driving, field driving, and biological driving. The microrobot active drug delivery technology designs the drug loading, driving, and drug release modes of microrobots according to the pathological conditions to realize accurate drug delivery, improve drug efficiency, and reduce the side effects of drugs. In the future, microrobot active drug delivery technology still faces many challenges in terms of biological/human safety, driving, and navigation.

(8) Active/passive control technologies for turbulent flow around high-speed trains

The aerodynamic drag exerted on the trains increases sharply with the continuous increase in the speed of high-speed trains. Moreover, the aerodynamic drag accounts for an increasing proportion of total drag. The aerodynamic noise surpasses traction noise and wheel–rail noise as the main noise source. The above phenomena lead to considerable energy consumption and noise pollution problems. The aerodynamic drag and noise generated by the train traveling at high speed are closely related to the turbulent flow field around the train. Therefore, the active and passive control of the turbulent flow around the trains has become an increasingly prominent and urgent problem that must be solved to ensure the safe operation of the trains and meet the requirements of "energy saving, environmental friendliness, and comfortable riding". In recent years, the continuous development of active and passive flow control technologies and theories has allowed the control of the turbulent flow of high-speed trains. The research on the control of turbulent flow around high-speed trains aims to reduce drag by controlling large-scale turbulent vortex structures or near-wall turbulence characteristics. The specific research directions include drag and noise reduction based on train aerodynamic shape optimization, aerodynamic drag reduction of the high-speed trains based on bionic structure spoiler, passive drag reduction based on dimples mounted on the surfaces of aerodynamic bodies, drag reduction based on jet flow, and wall turbulent drag reduction based on plasma actuators. Future research directions include the development of new active flow control technologies with high reliability and robustness that can adapt to the harsh operating environment of trains and solve the bottleneck of current control technologies. The development of the closed-loop turbulent flow control scheme and theory based on machine learning is also included.

(9) Variable stiffness technologies for robots

The stiffness of a robot is a measure of how well it interacts with the external environment. Variable stiffness technology not only combines some of the advantages seen in compliant robots with the performance of traditional rigid robots, but it also provides physical intelligence to robots, thus it is well-recognized as enabling technology in many branches of robotics. With robots shifting from spatially isolated automatic production lines into human working and living environments, by actively changing the stiffness in real time in response to dynamic events in the interaction process, emerging applications, for example, human-robot collaboration, rehabilitation assistance, multi-fingered fine manipulation, legged bionic mobility, soft robots, can provide higher task robustness, cooperative safety, motion flexibility, operational dexterity, and energy efficiency than less sophisticated systems. Traditional variable stiffness technology passively changes the stiffness of branch chains, adding series/parallel elastic elements to the rigid structure of the robot, and offline adjusting robot elastic elements by morphing or changing the robot size, resulting in large structure size, overweight, low stiffness ratio, slow response, and difficulties in transitioning between “softness” and “rigidity”. Therefore, this kind of technology cannot meet the requirements of those emerging applications to which large stiffness ratio, high bandwidth, and fast response are critical. A current trend and hot spot in robotics is the integration of structure-actuation-transmission-perception-control by integrating materials, structure, and control of robots to achieve the active variable stiffness of robots. The main research directions of robot variable stiffness control technology include: ① integrate design and control of intelligent material-intelligent structure to achieve the unity of large deformation motion and large stiffness ratio and easily obtain a smooth transition between “softness” and “rigidity”; ② make a breakthrough in the high-power-density (quasi) direct drive technology and the integration of drive, transmission, sensing and control, to reduce the structural inertia, and to improve the speed of variable stiffness control; ③ drill into robot whole-body optimization control method to reduce the complexity of high-dimensional complex variable stiffness control and improve the real-time performance and accuracy of variable stiffness; ④ adopt machine learning to construct and enrich the stiffness profile library for typical human-robot-environment interaction application scenario to enhance the intelligent decision level of robots guided by the specific application scenario.

(10) Mini and micro unmanned aerial vehicle (UAV) detection

In recent years, mini and micro unmanned aerial vehicles (UAVs) have been misused because of their portability, simple operation, and multiple access channels. The possibility of using UAVs to create a disturbance has increased considerably. Thus, using UAVs has become a growing security threat. However, mini and micro UAVs are characterized by low flying altitude, slow speed, and small size (“low, slow, and small targets”). Thus, detecting mini and micro UAVs involves many challenges. At present, detection means mainly include radar detection, radio detection, acoustic detection, and photoelectric detection. Radar detection suffers from the interference of low-altitude complex background and clutter. At present, relevant research focuses on clutter and interference suppression technology and refined signal processing technology of echo signals. Radio detection equipment can only passively detect radio signals from airborne targets. In terms of acoustic detection, mini and micro UAVs cannot be detected easily because of the electric-motor-driven mode, which exhibits low disturbance, low noise, and slow speed. Photoelectric detection equipment can use different bands to obtain the target UAV image. However, the detection range of a visible camera is relatively limited, and the field of view and visual details are hard to reconcile. The resolution of infrared detection is limited. Distinguishing drone pixels from noise points is difficult when the UAVs are too far. The image information processing technology based on artificial intelligence has gradually attracted intensive attention. Integrating two or more sensors for joint detection based on multisource information fusion technology has become a trend to meet the requirements of mini and micro UAV detection in the actual complex environment.

1.2 Interpretations for three key engineering research fronts

1.2.1 Autonomous ship deck landing technology for aircraft

The technology of aircraft autonomous ship deck landing is an important index used to measure the safe flight of carrier-based aircraft. According to relevant statistics, aviation accidents caused by human factors during the take-off and landing phases are up to 50%. Therefore, providing a systematic guided landing solution with a high degree of automation and reliable navigation and positioning accuracy for the aircraft will help promote its application scenario and reduce the burden of personnel operation further. In this case, studying the aircraft deck landing technology is imperative and relevant. Compared with landing on a fixed platform, the successful landing on a moving ship requires overcoming more challenges, mainly the narrow landing area and the simultaneous translational and rotational movements during the landing. In addition, the landing phase will inevitably face severe external disturbances, such as atmospheric turbulence, wind over deck, and ship wake. These conditions will be further complicated when the weather and sea conditions are harsh.

With the development and application of science and technology, autonomous control of aircraft has become a research hotspot in the fields of aerospace science and technology, control science and engineering, and information and communication engineering. Thus, the aircraft autonomous ship deck landing technology is an important development trend of carrier-based aircraft autonomous landing and aircraft autonomous control. This technology has experienced four stages: full manual mode, manual-assisted semi-automatic mode, automatic mode, and unmanned aerial vehicles full autonomous mode. Due to the complex landing environment, precise guidance and control technology has become the most important tasks for the safe landing of carrier-based aircraft. The research on aircraft autonomous ship deck landing technology in China began relatively late but has been developing rapidly in recent years. The relevant research is mainly divided into two aspects, namely, studies on autonomous landing guidance and autonomous landing control. In terms of autonomous landing guidance, multi-modal information fusion landing guidance technology is explored, high-reliability wireless data links are designed, efficient real-time image processing technology is developed, and high-precision autonomous navigation and positioning are achieved. In autonomous landing control, flight control technology with strong robustness is developed, artificial intelligence methods are used to improve the estimation accuracy of the ship deck motion state, the interference of the ship wake, deck motion, air gusts and other factors are suppressed. In addition, multi-system integrated autonomous landing control technology is explored to fast-track the ideal glide trajectory in complex environments, and the stability of the aircraft attitude is maintained. The aircraft autonomous ship deck landing technology is inseparable from the development of control engineering, sensor technology, computer, artificial intelligence, and other information technologies. It has essential theoretical research value in navigation, guidance and control, instrument science, aircraft design, and other disciplines. Overall, autonomous ship deck landing technology is of great practical significance for China to achieve a strong naval force and move toward a maritime power.

The top three countries with the greatest output of core papers on “autonomous ship deck landing technology for aircraft” are China and Singapore; and the top three countries with the greatest output of citations per paper are Australia, Canada, and Tunisia, as seen in Table 1.2.1. Among the Top 6 countries with the greatest output of core papers, China has more cooperation with Singapore, and Canada has more cooperation with Tunisia, as shown in Figure 1.2.1. The top three institutions with the greatest output of core papers are Nanyang Technological University, Beihang University, and Nanjing University of Aeronautics and Astronautics. The top four institutions in the number of citations per paper are the University of New South Wales, Carthage College, University of Sfax, and University of Quebec, as shown in Table 1.2.2. As shown in Figure 1.2.2, Carthage College, University of Sfax, and University of Quebec have a lot of cooperation. Nanyang Technological University, DSO National Laboratories of Singapore, and National University of Singapore have a lot of cooperation. And Nanyang Technological University also has cooperation with Beihang University. The country with the greatest output of citing papers is China, as shown in Table 1.2.3. The main output institutions of citing papers are Beihang University and Nanjing University of Aeronautics and Astronautics, as shown in Table 1.2.4. Figure 1.2.3 shows the roadmap of this front.

Table 1.2.1 Countries with the greatest output of core papers on “autonomous ship deck landing technology for aircraft”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	4	50.00	84	21.00	2018.5
2	Singapore	2	25.00	46	23.00	2017.5
3	Australia	1	12.50	42	42.00	2017.0
4	Canada	1	12.50	33	33.00	2017.0
5	Tunisia	1	12.50	33	33.00	2017.0
6	South Korea	1	12.50	13	13.00	2020.0

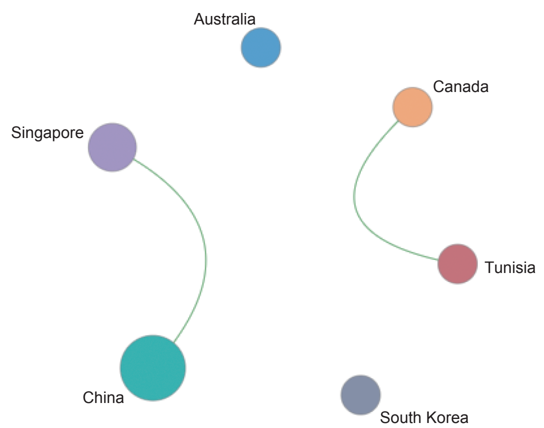

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “autonomous ship deck landing technology for aircraft”

Table 1.2.2 Institutions with the greatest output of core papers on “autonomous ship deck landing technology for aircraft”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Nanyang Technological University	2	25.00	46	23.00	2017.5
2	Beihang University	2	25.00	44	22.00	2019.0
3	Nanjing University of Aeronautics and Astronautics	2	25.00	40	20.00	2018.0
4	The University of New South Wales	1	12.50	42	42.00	2017.0
5	Carthage College	1	12.50	33	33.00	2017.0
6	University of Sfax	1	12.50	33	33.00	2017.0
7	University of Quebec	1	12.50	33	33.00	2017.0
8	DSO National Laboratories of Singapore	1	12.50	19	19.00	2016.0
9	National University of Singapore	1	12.50	19	19.00	2016.0
10	Ulsan National Institute of Science and Technology	1	12.50	13	13.00	2020.0

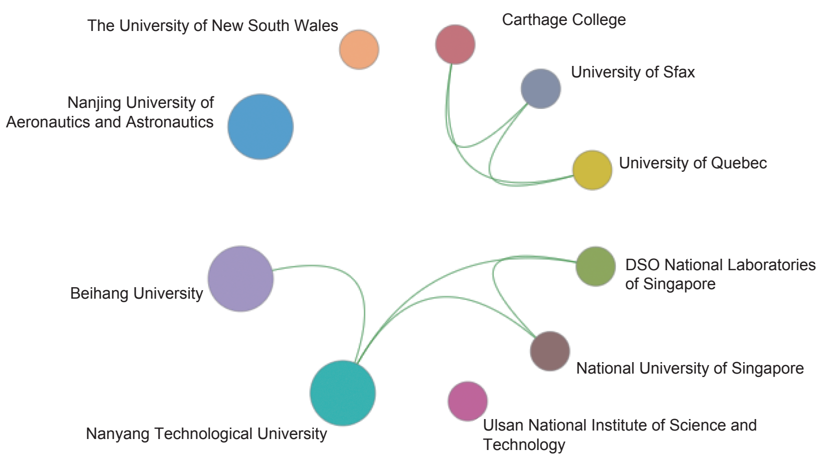

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “autonomous ship deck landing technology for aircraft”

Table 1.2.3 Countries with the greatest output of citing papers on “autonomous ship deck landing technology for aircraft”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	105	63.64	2020.0
2	USA	13	7.88	2019.1
3	South Korea	12	7.27	2019.6
4	Italy	7	4.24	2019.4
5	Singapore	6	3.64	2020.0
6	UK	5	3.03	2019.6
7	Canada	5	3.03	2020.2
8	Australia	4	2.42	2020.2
9	Romania	3	1.82	2020.3
10	India	3	1.82	2020.7

Table 1.2.4 Institutions with the greatest output of citing papers on “autonomous ship deck landing technology for aircraft”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Beihang University	18	21.95	2019.9
2	Nanjing University of Aeronautics and Astronautics	15	18.29	2020.3
3	Beijing Institute of Technology	9	10.98	2019.7
4	Tongji University	7	8.54	2019.7
5	Harbin Engineering University	7	8.54	2020.0
6	University of Science and Technology Beijing	6	7.32	2019.7
7	Nanyang Technological University	5	6.10	2020.0
8	Northwestern Polytechnical University	4	4.88	2020.0
9	Hubei University of Economics	4	4.88	2020.2
10	Chongqing University	4	4.88	2020.2

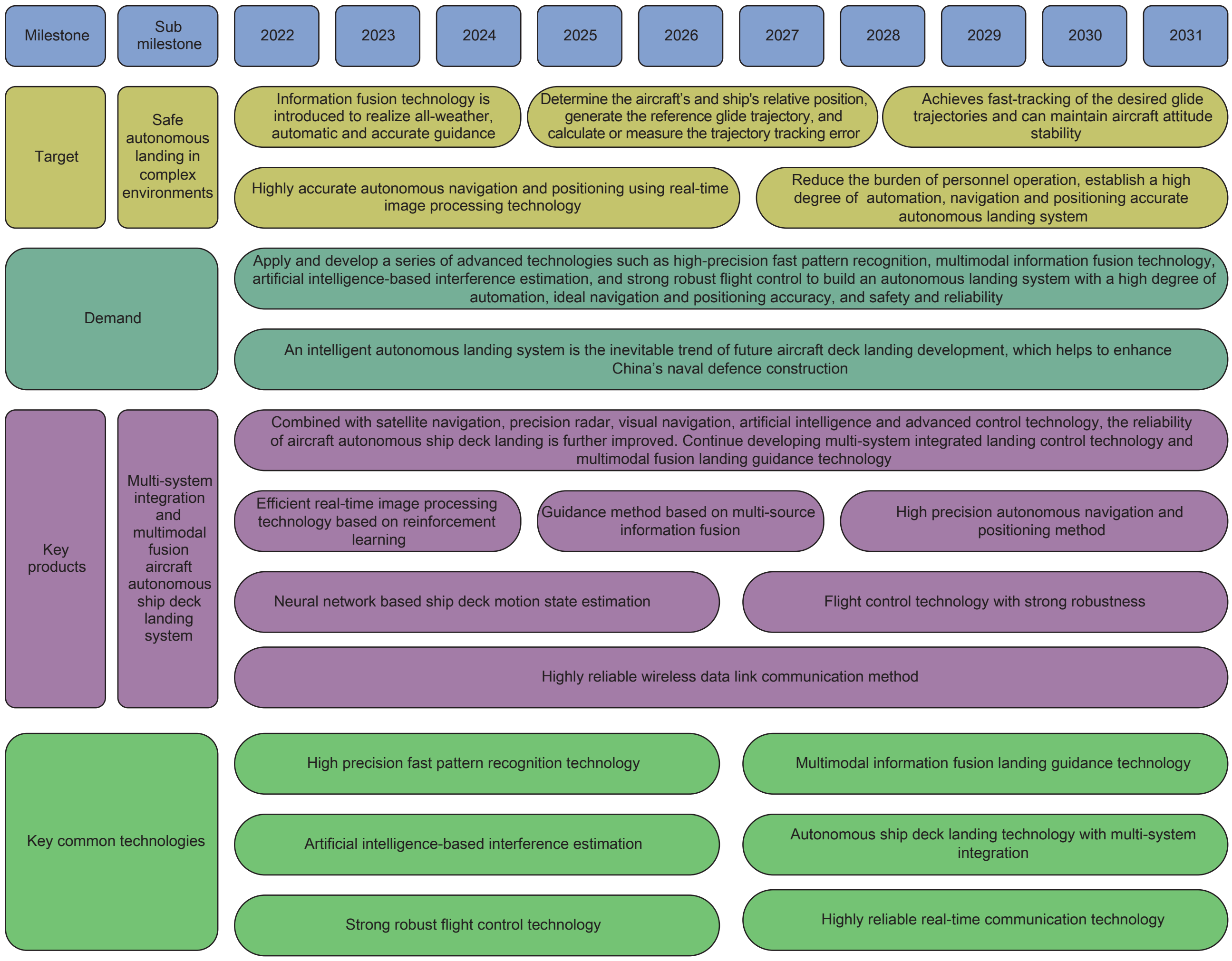

Figure 1.2.3 Roadmap of the engineering research front of "autonomous ship deck landing technology for aircraft"

1.2.2 Human–robot contactless collaboration

With the increasingly strong demand for advanced manufacturing, such as green manufacturing, intelligent manufacturing, and personalized customization, robots materialize the wisdom and experience of human experts in manufacturing activities, so that the manufacturing system can carry out intelligent activities, such as independent perception, reasoning, learning, and decision-making, share human physical labor through cooperation with people in manufacturing, expand, extend, and partially replace the mental labor of experts, and improve the flexibility adaptability and autonomy. Close cooperation between humans and robots is developing toward the direction of human–machine integration, which is the essential feature of the new-generation of robot systems. Because of the high rigidity, fast response, and large torque, traditional industrial robots can only work in the physical environment isolated from people to ensure personnel safety. As an important part of intelligent manufacturing process, collaborative robots have been widely used in electronic processing, parts grinding, paint spraying, cargo sorting, or component assembly because of their compact size, high flexibility, and master–slave teaching. Since General Motors attempted to develop a robot that worked with human workers in 1995, cooperative robots, such as UR5 of Universal Robots, LBR iiwa of KUKA, YuMi of ABB, and CR-35iA of FANUC have appeared in succession. In 2016, the International Organization for Standardization issued the latest industrial standard ISO/TS 15066 for collaborative robots.

Collaborative robots are featured with safety, adaptability, and comfort in human–robot cooperation. Specifically speaking, human–robot contactless collaboration should avoid human injury. The robot can understand the human intents accurately and adapt to human movements actively. Moreover, the robot action conforms to the cognitive habits of humans, so that people can understand the action intention of the robot. The related research can be mainly categorized into three aspects, namely, the studies of prevention of collision events, prediction of human motion intention, and generation of robot anthropomorphic motions. ① To prevent collision events, new sensing technologies for multi-modal information, including object distances, contact forces, and joint torques, are worth exploring to study the motion principles and deformation mechanism of coupled rigid-flexible-soft robots and develop collaborative robots with collision avoidance ability. ② With regard to the prediction of human motion intention, key research topics include object identification in unstructured environment, adaptive control with motion intent prediction and hand–eye coordination, and virtual reality of human–robot interaction. ③ To generate robot anthropomorphic motions, there are critical challenges to reveal the mechanisms of human-limb natural motions, identify the biomechanical characteristics of human musculoskeletal systems, establishes the bionic design theory, develop the generation method of robot anthropomorphic motions, and implement feedback control method that conforms to human cognitive habits. With the development of soft material science, intelligent sensing technology, ergonomics, and related disciplines, collaborative robots are expected to make breakthroughs in key technologies, such as multi-modal perception, intention recognition, environmental modeling, anthropomorphic motion, and decision optimization, and enhance the interactive experience and operation efficiency of human–robot contactless collaboration.

The country with the greatest output of core papers on "human–robot contactless collaboration" is Italy, as shown in Table 1.2.5. Institutions with the maximum number of core papers and the highest citations per paper are University of Modena and Reggio Emilia and Sapienza University of Rome, as shown in Table 1.2.6. Cooperation can be observed between these two Institutions (Figure 1.2.4). The top three countries with the greatest output of citing papers are Italy, China, and the USA, as shown in Table 1.2.7. The main output institutions of citing core papers are University of Modena and Reggio Emilia, Chinese Academy of Sciences, and Wuhan University of Technology, as shown in Table 1.2.8. Figure 1.2.5 shows the roadmap of this front.

1.2.3 Triboelectric nanogenerator

Prolific research toward the development of microelectronics technologies is greatly beneficial to human life since 2000s. Meanwhile, the power supply of mass number timely devices became a huge issue though it is low-power consumption. Traditional bulky and rigid battery packs could not meet its application and development demands well. As an alternative, triboelectric nanogenerators (TENGs), which convert the mechanical energy created by motion into electrical energy, offer a highly attractive energy harvesting strategy to power electronics, such as e-skin, implantable electronics, flexible

Table 1.2.5 Countries with the greatest output of core papers on "human–robot contactless collaboration"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Italy	3	100.00	161	53.67	2019.7

Table 1.2.6 Institutions with the greatest output of core papers on "human–robot contactless collaboration"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Modena and Reggio Emilia	2	66.67	158	79.00	2019.0
2	Sapienza University of Rome	2	66.67	22	11.00	2020.5

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "human–robot contactless collaboration"

Table 1.2.7 Countries with the greatest output of citing papers on "human–robot contactless collaboration"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	Italy	47	23.74	2020.5
2	China	43	21.72	2020.3
3	USA	23	11.62	2020.6
4	UK	18	9.09	2020.7
5	Germany	14	7.07	2020.3
6	Sweden	13	6.57	2020.2
7	Spain	9	4.55	2020.2
8	France	8	4.04	2020.2
9	Finland	8	4.04	2020.5
10	Portugal	8	4.04	2020.8

Table 1.2.8 Institutions with the greatest output of citing papers on "human–robot contactless collaboration"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	University of Modena and Reggio Emilia	11	17.19	2020.5
2	Chinese Academy of Sciences	9	14.06	2020.2
3	Wuhan University of Technology	7	10.94	2020.4
4	Polytechnic Institute of Turin	5	7.81	2020.4
5	Italian Institute of Technology	5	7.81	2020.4
6	Italy National Research Council	5	7.81	2020.8
7	Malardalen University	5	7.81	2020.0
8	University of Minho	5	7.81	2020.8
9	Polytechnic University of Milan	4	6.25	2020.2
10	University of Birmingham	4	6.25	2020.0

devices, and systems. Meanwhile, TENG is a robust energy source that can be applied in many fields, such as healthcare monitoring, biosensing, environmental detection, and artificial intelligence.

In the past 10 years, intensive research has been attempted and conducted in the field of triboelectric nanogenerator. The related research can be summarized into three directions, namely, fundamental study and operation models, hybrid mechanisms and circuit design for integration, and self-powered smart microsystems. First, the mechanism of triboelectric nanogenerators has been analyzed. Scientists investigated the triboelectric effect comprehensively by electromagnetic theory and physical models. Four operation models, including contact-separation (CS) mode, relative-sliding (RS) mode, single-electrode (SE) mode, and free-standing (FS) mode, were developed to build-up the theoretical domain of TENGs. In addition, the research activities on triboelectric pair selection and configuration design were carried out to strengthen the output performance of TENGs. Second, the researchers paid much attention on hybrid working principle that combined triboelectric effect with other effects, including piezoelectric effect, electromagnetic effect, photovoltaic effect, and thermoelectric effect. Furthermore, the proposed devices were integrated with suitable power management circuits and energy storage devices to form high-efficiency and stable power units. Third, the integration of triboelectric nanogenerators with sensors

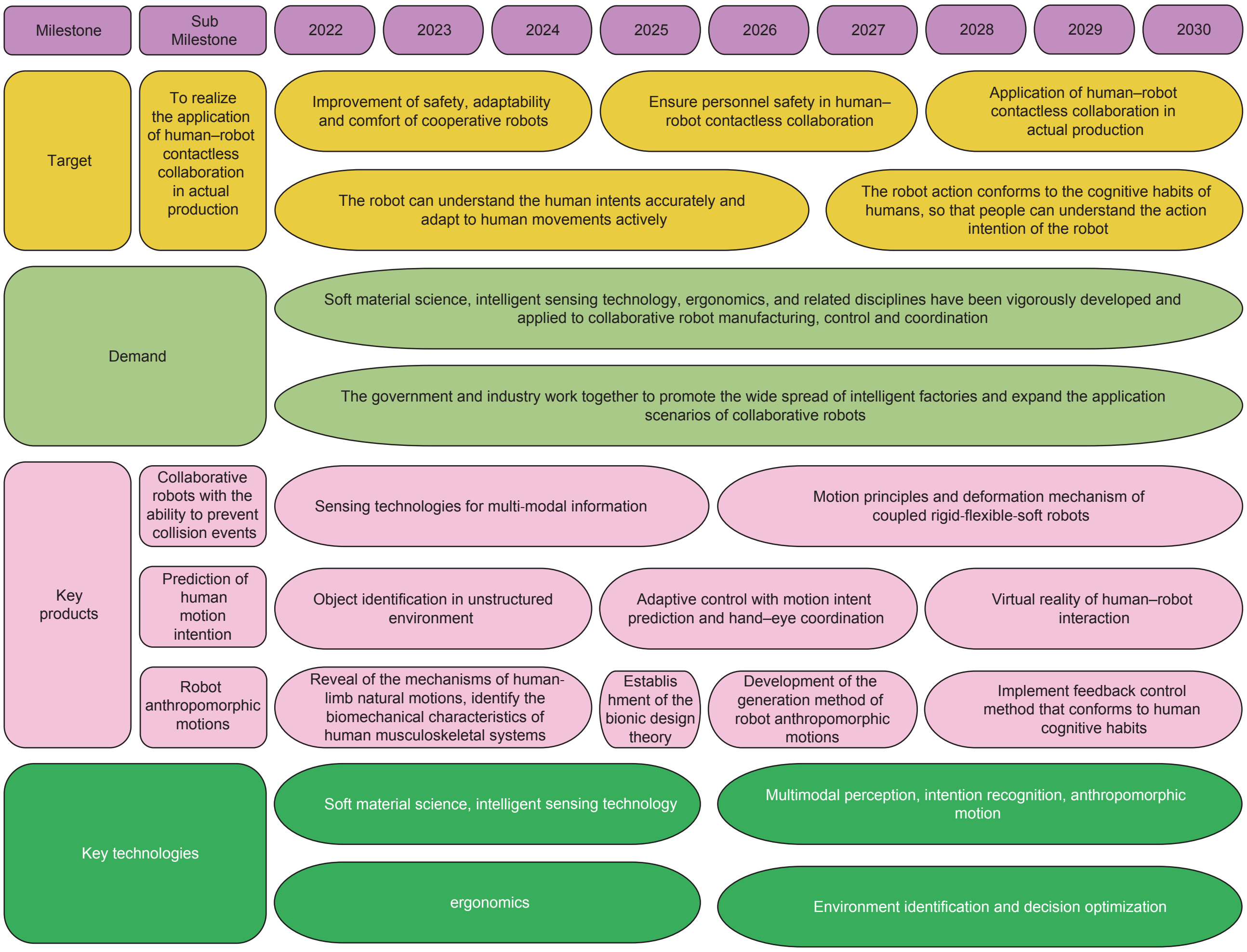

Figure 1.2.5 Roadmap of the engineering research front of "human–robot contactless collaboration"

was studied well to verify the feasibility of self-powered smart microsystems, in which TENGs serve as either a power source to supply the microsystem or an active sensor by figuring out the relation between output electric signals and external stimuli.

As the next challenging and technical acme in the field of sustainable energy, triboelectric nanogenerators offer a significant technical support to realize smart microsystems. The associated merits provide essential tools and technical approaches for exploring massive applications of electronics devices. The development of triboelectric nanogenerator can improve our country's independent technical levels in the field of sustainable energy, promote the popularization and application of microelectronics, and achieve the leading position in the international high-end smart system research and development.

The top two countries with the largest number of core papers published on "triboelectric nanogenerator" and the highest citations per paper are China and the USA, as shown in Table 1.2.9. Among the top four countries with the most published papers, more cooperation has been observed among China and the USA, as shown in Figure 1.2.6. Among the top ten institutions with the largest number of publications, institutions with the maximum number of core papers are University of California, Los Angeles and University of Electronic Science and Technology of China. The institutions with the highest citations per paper are Stanford University, Chongqing Normal University, and Chongqing University, as shown in Table 1.2.10. More cooperation can be observed between Chongqing Normal University, Chongqing University, Chinese Academy of Sciences and Stanford University, as shown in Figure 1.2.7. The top three countries with the greatest output of citing papers are China, the USA and South Korea as shown in Table 1.2.11; the top three institutions with the greatest output of citing papers are Chinese Academy of Sciences, Georgia Institute of Technology, and University of California, Los Angeles, as shown in Table 1.2.12. Figure 1.2.8 shows the roadmap of this front.

Table 1.2.9 Countries with the greatest output of core papers on “triboelectric nanogenerator”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	18	85.71	1 053	58.50	2019.3
2	USA	13	61.90	711	54.69	2020.2
3	UK	2	9.52	44	22.00	2020.0
4	Canada	1	4.76	30	30.00	2019.0

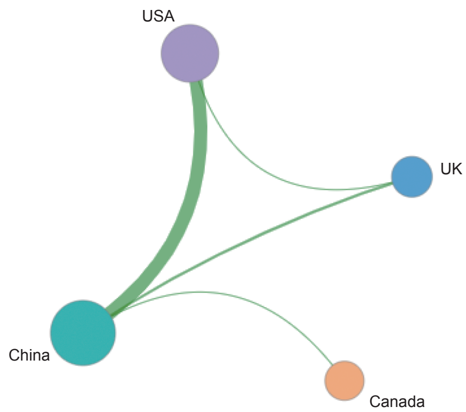

Figure 1.2.6 Collaboration network among major countries in the engineering research front of “triboelectric nanogenerator”

Table 1.2.10 Institutions with the greatest output of core papers on “triboelectric nanogenerator”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of California, Los Angeles	11	52.38	449	40.82	2020.5
2	University of Electronic Science and Technology of China	6	28.57	353	58.83	2019.2
3	Chongqing Normal University	3	14.29	347	115.67	2019.0
4	Chongqing University	3	14.29	347	115.67	2019.0
5	Chinese Academy of Sciences	3	14.29	326	108.67	2018.3
6	Stanford University	2	9.52	262	131.00	2018.5
7	Soochow University	2	9.52	90	45.00	2018.5
8	Southwest Jiaotong University	1	4.76	96	96.00	2020.0
9	Georgia Institute of Technology	1	4.76	95	95.00	2019.0
10	The Pennsylvania State University	1	4.76	71	71.00	2020.0

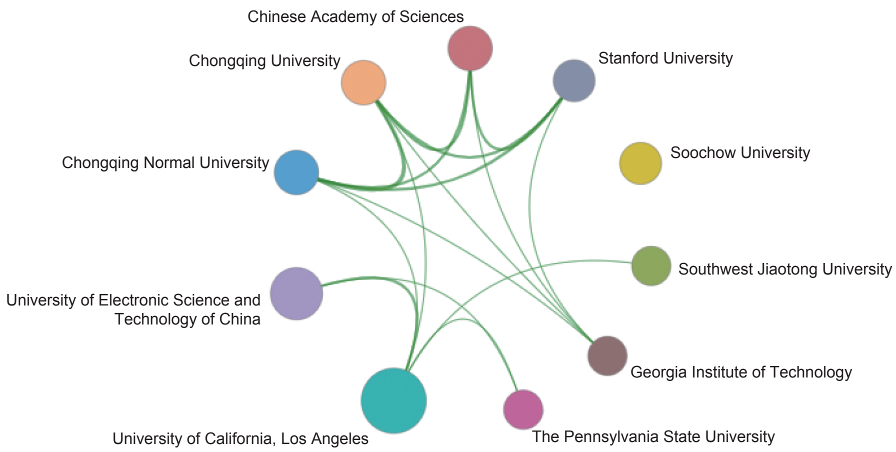

Figure 1.2.7 Collaboration network among major institutions in the engineering research front of “triboelectric nanogenerator”

Table 1.2.11 Countries with the greatest output of citing papers on “triboelectric nanogenerator”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	524	53.58	2020.3
2	USA	180	18.40	2020.3
3	South Korea	86	8.79	2020.1
4	Singapore	47	4.81	2020.3
5	India	38	3.89	2020.4
6	UK	36	3.68	2020.4
7	Australia	24	2.45	2020.6
8	Malaysia	13	1.33	2020.8
9	Iran	11	1.12	2020.7
10	Saudi Arabia	10	1.02	2020.7

Table 1.2.12 Institutions with the greatest output of citing papers on “triboelectric nanogenerator”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	115	25.50	2020.2
2	Georgia Institute of Technology	53	11.75	2019.9
3	University of California, Los Angeles	53	11.75	2020.6
4	University of Electronic Science and Technology of China	40	8.87	2020.0
5	National University of Singapore	39	8.65	2020.3
6	Chongqing University	31	6.87	2020.1
7	Guangxi University	30	6.65	2020.4
8	Soochow University	29	6.43	2019.7
9	Tsinghua University	26	5.76	2020.2
10	Southwest Jiaotong University	18	3.99	2020.3

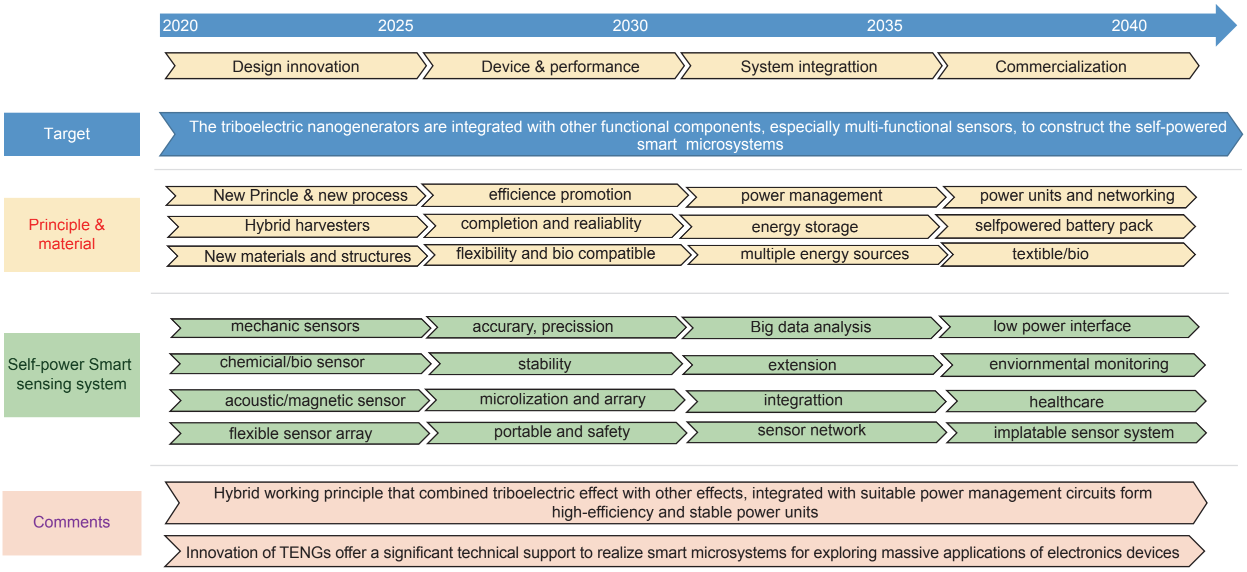

Figure 1.2.8 Roadmap of the engineering research front of "triboelectric nanogenerator"

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

Top ten development (as opposed to research) fronts in mechanical and vehicle engineering are listed in Table 2.1.1. Some of these frontiers are characterized by in-depth traditional research: "multi-sensor data fusion technique of autonomous unmanned systems", "high bypass-ratio turbofan engine", "3D printing technology of aviation carbon fiber reinforced composites", "underwater unmanned vehicle (UUV) based on acoustic-optic detection", "control and perception system of intelligent mobile robot", and "high-power-density high-efficiency electrical machine". There are also other frontiers that are newly emerging: "stealth metamaterials for ships and submarines", "hydrogen fuel

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

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Stealth metamaterials for ships and submarines	52	496	9.54	2018.7
2	Multi-sensor data fusion technique of autonomous unmanned systems	468	2 117	4.52	2019.5
3	Hydrogen fuel cell vehicle	333	1 335	4.01	2018.1
4	Reusable spacecraft	71	348	4.90	2017.9
5	High bypass-ratio turbofan engine	360	4 094	11.37	2015.8
6	Morphing flexible wing with variable curvature	359	1 965	5.47	2017.5
7	3D printing technology of aviation carbon fiber reinforced composites	67	219	3.27	2019.1
8	Underwater unmanned vehicle (UUV) based on acoustic-optic detection	93	344	3.70	2018.6
9	Control and perception system of intelligent mobile robot	146	2 359	16.16	2018.5
10	High-power-density high-efficiency electrical machine	112	303	2.71	2017.9

cell vehicle", "reusable spacecraft", and "morphing flexible wing with variable curvature". Table 2.1.2 shows the annual number of core patents published from 2016 to 2021.

(1) Stealth metamaterials for ships and submarines

These years, metamaterials, which own extraordinary physical properties in electromagnetic, acoustic, and optic, have been extensively studied. They provide a new pathway for developing superior stealth materials used in ships and submarines. Electromagnetic stealth metamaterials improve their performance by coupling multiple resonant structures and loading high-resistance metasurface. They own stronger absorbing performance but smaller thicknesses compared with the traditional radar absorbing materials, showing significant advantages in competing with radar detection. Furthermore, acoustic stealth metamaterials can achieve super low-frequency sound absorption, vibration reduction, and acoustic strength control due to their low-frequency band gap and supernormal physical characteristics. They have the best effectiveness on submarines to tremendously reduce the threat of acoustic detection. In addition, optical stealth metamaterials remarkably reduce the visual discovery distance of the target. They own good concealability to photoelectric detection but are difficult to resist radar detection. For ship designing, it mainly focuses on stealth appearances with local application of absorbing materials in the past. Nowadays, it regards stealth appearances and stealth materials as equally important. In the developing process of ships, submarines, and various navy equipment, stealth metamaterials will greatly improve their concealment performance and combat effectiveness.

(2) Multi-sensor data fusion technique of autonomous unmanned systems

The multi-sensor data fusion technique of autonomous unmanned systems refers to achieving the perception of the environment and further accomplish missions, such as understanding complex environments, object tracking, area exploration, and disaster rescue via fusion the information from different individuals and sensors. On the one hand, the unstructured operating environments are heavily obscured with strong electromagnetic interference. Furthermore, the unmanned systems are easily affected by severe weather when operating outdoors, thereby resulting in the poor accuracy and limited detection range of a single sensor. In addition, the objects in the complex environment have the characteristics of multi-type, various scales, diverse morphologies, and insignificant features, which will greatly increase difficulty in object detection and recognition. On the other hand, the multi-sensor fusion could combine the advantages of different kinds of sensors and fuse the information

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	2016	2017	2018	2019	2020	2021
1	Stealth metamaterials for ships and submarines	0	3	12	11	16	6
2	Multi-sensor data fusion technique of autonomous unmanned systems	12	38	56	80	105	169
3	Hydrogen fuel cell vehicle	48	35	45	58	49	65
4	Reusable spacecraft	3	5	10	13	16	11
5	High bypass-ratio turbofan engine	50	37	24	23	18	15
6	Morphing flexible wing with variable curvature	44	44	59	54	58	36
7	3D printing technology of aviation carbon fiber reinforced composites	3	6	8	10	14	22
8	Underwater unmanned vehicle (UUV) based on acoustic-optic detection	9	6	23	11	19	18
9	Control and perception system of intelligent mobile robot	6	21	26	22	26	32
10	High-power-density high-efficiency electrical machine	11	17	20	20	14	15

from each individual, thereby extending the perception scope of unmanned systems effectively and expanding its ability on perception in complex and harsh environment. Therefore, multi-sensor data fusion technique will be an important cornerstone to the automation and intelligence of autonomous unmanned systems. Major research topics include multi-source information preprocessing that aims to overcome the influences from severe weather and complex environment; spatiotemporal registration of heterologous, heterogeneous, and asynchronous information; and the precise association method of large-difference, low-quality, and weakly correlated information.

(3) Hydrogen fuel cell vehicle

Hydrogen fuel cell vehicles (HFCVs) are vehicles powered by electricity generated by fuel cell devices. Hydrogen energy has become an important strategic choice for accelerating the upgrade of energy transformation with the requirement of carbon neutrality. Hydrogen fuel cells offer several advantages over incumbent technologies, such as internal combustion engine and diesel engines, including higher efficiency, reduced emissions, higher torque, and no noise pollution. The core components of the HFCV system include air compressors, hydrogen circulation systems, on-board hydrogen storage systems, and fuel cell stacks. Fuel cell stack accounts for ~60% of the total cost of the vehicle. The core materials in fuel cell stacks include catalysts, proton exchange membranes, gas diffusion layers, and bipolar plates. Particularly, the cost of commercial platinum-based catalysts is still prohibitive (accounts for ~45% of the stack), and their activity/durability also needs to be improved. Therefore, investigating low- or non-platinum catalysts with high performance will be the research focus of fuel cell catalysts in the future. Proton exchange membrane is a type of solid electrolyte, and the current research focuses on the perfluoroalkyl sulfonic acid-based proton-exchange membranes and composite ones. Currently, the stability of membrane needs to be improved, and the preparation process needs to be optimized. The gas diffusion layer plays an important role in collecting current, conducting gas, and discharging reaction product water. However, the conductivity, structural stability, and mass transfer characteristics of gas diffusion layers still need to be improved. The bipolar plate is the “skeleton” of the fuel cell stacks, and the requirements for development are high electron and thermal conductivity, ultra-thin, and ultra-light. At present, the key materials of stacks, such as platinum-based catalysts and proton exchange membranes, still need to be imported. Moreover, some technologies are monopolized by foreign companies, so the domestic research should be intensively explored.

(4) Reusable spacecraft

As an important direction for future spacecraft development, reusable spacecraft is an advanced spacecraft application mode that can effectively prolong the life, reduce the operation cost, and improve the reliability and convenience of spacecraft. Reusable manned spacecrafts and cargo spacecrafts, space shuttles, and reusable orbital maneuvering vehicles are typical reusable spacecrafts. Given the increasing frequency of human space exploration and development activities, the current single-use spacecraft cannot easily meet the demand because of the high cost and long preparation cycle. Therefore, reusable spacecraft, which can adapt to more convenient and cheaper exploration, development, and utilization of space resources, has emerged as the times require. It has become a frontier hot spot in the current world space technology research field. All major space powers have taken it as the key breakthrough direction for the sustainable development of space technology in the future. The recyclable and reusable requirements of reusable spacecraft pose a major challenge to the traditional design concepts and methods of single-use spacecraft. The key research directions include reusable design theory and method, reusable spacecraft integrated design, reliable and accurate return and landing technology, long-term on-orbit precise orbit/attitude/thermal control and maintenance technology, highly reliable and reusable high-temperature and ablative resistance thermal protection technology, structure life assessment, and health management technology.

(5) High bypass-ratio turbofan engine

A high bypass-ratio turbofan engine usually means that the engine with a bypass ratio larger than 4. High bypass-ratio turbofan engines are widely applied as the engines of civil airliners and military transport aircrafts, owing to advantages of low fuel consumption ratio and noise level. The key techniques and future improvements of high bypass-ratio turbofan engines focus on the following aspects. ① High performance: this factor includes advanced thermo-aerodynamic design and manufacturing of large-scale fan, high-pressure compressor, and low-pressure turbine, such as the aerodynamic design of 3D blades and control of blade tip. ② Low pollution: NO_x emission is reduced by employing combustion control techniques, such as staged combustion, direct injection of lean oil, and rich-burn, quick-mix, lean-burn combustion. ③ Low noise level: advanced aeroacoustic design and acoustic absorption techniques are employed to reduce the noise level of turbomachines, jet, and combustion. ④ High reliability: the reliability of engine and its components could be improved in various ways, such as designing and manufacturing a long-life and high-power gear reducer.

(6) Morphing flexible wing with variable curvature

The morphing flexible wing with variable curvature can be controlled by the continuous and seamless change of wing camber and thickness through flexible deformation of the wing structure. Compared with the traditional rigid wing, the flexible wing delays the airflow separation, improves the lift–drag ratio, and reduces the aerodynamic noise. Relevant studies often focus on four aspects. The first aspect is the flexible deformable skin. This aspect includes exploring the decoupling design mechanism of in-plane elastic large deformation and out-of-plane flexural bearing capacity, studying the large deformation mechanism and forming process of periodic cellular microstructures, developing the structural technology and deformation compatibility of novel topological cellular microstructures/superelastic matrix composites. Moreover, this aspect aims to make the flexible deformable skin obtain excellent elasticity in the deformation direction and sufficient stiffness in the nondeformation direction. However, the force driving the deformation of the skin is negligible. The second aspect is the deformable support structure. This aspect includes developing a rigid–flexible coupling structure and a fully flexible structure designed by collaborative optimization, investigating the aeroelastic analytical and verification method of the flexible wing, and studying the design method of the deformable support structure with low stress and high life. The third aspect is the lightweight and efficient driving mechanism. This aspect involves developing novel lightweight and flexible driving mechanism, including piezoelectric and artificial muscle actuators with high-efficiency ratios, designing an intelligent control strategy, and obtaining high efficiency, lightweight, and high stability driving system. The fourth aspect is the integration and experiment platform. This aspect includes investigating the integration of novel structures, smart materials, advanced sensing and testing technologies, and efficient miniaturized actuators. It also involves conducting wind tunnel testing of typical samples and test flight verification of full-size wings. The technology of morphing flexible wings with variable curvature is an important direction of morphing aircraft, which is the development trend of green aviation and aircraft structural design reform in the future.

(7) 3D printing technology of aviation carbon fiber reinforced composites

Three-dimensional (3D) printing of aviation carbon-fiber-reinforced composites is a technology that manufactures aviation carbon fiber composite parts through layer-by-layer accumulation based on 3D model data. The technology can be divided into fused deposition modeling (FDM), stereo lithography apparatus (SLA), selective laser sintering (SLS) modeling, and laminated object manufacturing (LOM) according to different implementation methods. Given its mature manufacturing strategy, low cost, and strong designability, FDM is the most commonly used and widely studied method for the 3D printing of aerospace carbon fiber composite materials, particularly continuous carbon-fiber-reinforced composite materials. At present, considerable research focuses on revealing the influence law of the FDM process parameters, such as printing path, printing temperature, printing layer thickness, printing material, material stacking method, and printing scanning spacing, on the microstructure and on the porosity, interfacial property, and macroscopic mechanical properties of the composites. Therefore, the methods for printing equipment, process parameters, and material pretreatment are improved and optimized. Moreover, the mechanical property test methods and performance evaluation system for the 3D printing of aviation carbon fiber composite materials are established to print strengthened and complex carbon fiber composite structures in aviation.

(8) Underwater unmanned vehicle (UUV) based on acoustic-optic detection

Underwater unmanned vehicle (UUV) based on acousto-optic detection refers to a type of UUV equipped with acoustic and optical detection sensors for performing underwater environmental target detection tasks. At present, typical underwater acoustic and optical detection sensors include sonar, lidar, and visual cameras.

Various sensors have different effects and completeness due to different basic detection principles. The principle of underwater acoustic detection sensors refers to the detection, tracking, positioning, and identification of underwater acoustic targets within a certain range by accepting the radiated noise or scattered echoes of the target. In wide-area marine environment target detection, the acoustic detection method is the most important and most effective. The detection effect of the underwater optical sensor is easily affected by marine optical environmental conditions. It can achieve high-precision target positioning in shallow water with good visibility and calmness, which is an effective supplement to the acoustic detection method.

At present, the main research highlights in this field include underwater target localization technology based on acousto-optic sensors, underwater target detection and recognition technology based on deep learning, and autonomous detection technology based on feature learning.

Given the advantages of UUV, including good controllability, superior stealth performance, and strong maneuverability, the combined acousto-optic detection technology based on an unmanned mobile platform will be the future development trend in this field. Specifically, it mainly includes environmental background field modeling, marine environmental target feature library construction, multisource sensor information fusion, UUV structure matching optimization, and other research contents. The purpose is to achieve effective detection in high-dimensional, dynamic, complex, and changeable underwater environments.

(9) Control and perception system of intelligent mobile robot

The intelligent mobile robot is a comprehensive system integrating environment perception, dynamic decision and planning, behavior control, and execution. It generally includes land mobile robots, autonomous underwater vehicle, and flying robots represented by unmanned aerial vehicles. Most mobile robots work in unstructured environments. Their performance depends on autonomous perception, autonomous navigation, and motion control. Autonomous perception is the premise for mobile robots to move and complete their work autonomously. It involves multisensor information fusion, external parameter calibration, target detection and recognition, and scenario recognition. Autonomous navigation is the most basic and core technology, involving environment perception, autonomous localization and mapping, and motion planning. The performance of the motor control affects the stability of motion and work. Representative methods include simultaneous stabilization and tracking control based on kinematics and dynamics, and neural network adaptive control considering the dynamic nonholonomic constraint. Mobile robots have many application fields. To improve autonomous working performance, intelligent navigation systems with high self-adaptability, high real-time, high reliability, and high portability must be developed. Key technologies, such as environmental information acquisition, environmental modeling, environmental cognition, and navigation obstacle avoidance, will become the focus of intelligent mobile robot control and perception research.

(10) High-power-density high-efficiency electrical machine

High-power-density high-efficiency electrical machine is an electromagnetic electro-mechanical energy conversion device with compact structure, high power density, and effective energy conversion. It is the core power unit and key executive component in new energy and power generation, electrified transportation, high-end CNC machine tools and robots, and aerospace equipment, etc. Represented by electrification, a new round of technology revolution in energy and power systems is reshaping the global industries of vehicles, manufacturing, and many others. As the core electromechanical energy conversion equipment of electrification, high-power-density high-efficiency machine has become the technological commanding point worldwide. However, the improvement of machine power density and efficiency has encountered multiple challenges due to the limitations of materials, thermal management, and harsh environmental conditions. Recently, industries and academics have conducted extensive research in the areas of ① new high-torque-density machine topology, ② application and accurate modelling of advanced electrical materials, ③ high-frequency-loss suppression, ④ high-efficiency heat dissipation methods, ⑤ structural integration and weight reduction, and ⑥ multiphysics-based optimization and design. To further improve the power density and efficiency limit of electrical machines and broaden the application of high-power-density high-efficiency electrical machines in the new generation of emerging industries, such as electrified transportation vehicles, intelligent manufacturing, military equipment including electric fighters and tanks, researchers have concentrated efforts on promoting technological breakthrough in the following fields: ① new electromagnetic principles of flux concentration and flux modulation; ② new electrical material applications, such as supercopper wires and superconductor; ③ new cooling technologies, such as phase-transition heat transfer and direct oil cooling; ④ new intelligent simulation and optimization based on multiphysics modelling of electrical–thermal–mechanical properties.

2.2 Interpretations for three key engineering development fronts

2.2.1 Stealth metamaterials for ships and submarines

Enhancing the performance of stealth to hide from enemy detection is significantly important for ships and submarines, which directly improves their combat effectiveness. In the face of the continuous development of detection methods, traditional absorbing materials gradually expose some problems and shortcomings. In the last two decades, metamaterials have attracted much attention both in the scientific and industry communities, attributing to their extraordinary physical properties in electromagnetic, acoustic, and optic. They provide a new pathway for developing superior stealth materials used in ships and submarines.

The electromagnetic stealth metamaterials improve their performance by coupling multiple resonant structures and loading high-resistance metasurface. They own stronger absorbing performance but smaller thicknesses compared with the traditional radar absorbing materials. The US DDG1000 destroyer and Raytheon’s artificial composite skins utilize electromagnetic stealth metamaterials. Furthermore, acoustic stealth metamaterials reveal the low-frequency band gap and supernormal physical characteristics, and show the capabilities of super low-frequency sound absorption, vibration reduction, and acoustic strength control. American researchers have used hexagonal aluminum metamaterials as a coating layer for underwater equipment. Metamaterials are stealth under sonar detection and can be applied to Virginia-class submarines. The three-dimensional broadband underwater acoustic carpet cloak (by Institute of Acoustics, Chinese Academy of Sciences) and omnidirectional acoustic ground cloak (by Duke University, US) are typical acoustic stealth metamaterials. In addition, optical stealth metamaterials remarkably reduce the visual discovery distance of the target, represented by the bioinspired “chameleon metamaterials”. By employing electrochromic glasses, American and Russian researchers have developed metamaterials that can change colors and textures with the environment. They are used in equipment coatings to achieve optical stealth.

Generally, electromagnetic stealth metamaterials show significant advantages in competing with radar detection, which are the most versatile among the above three types of metamaterials. Acoustic stealth metamaterials have the best effectiveness on submarines to tremendously reduce the threat of acoustic detection. Optical stealth metamaterials have good concealability to photoelectric detection, but they are difficult to resist radar detection. For ship designing, it mainly focuses on stealth appearances with local application of absorbing materials in the past. Nowadays, it regards stealth appearances and stealth materials as equally important. In the developing process of ships, submarines, and various navy equipment, stealth metamaterials will greatly improve their concealment performance and combat effectiveness.

Currently, the country with the largest number of core patents published on “stealth metamaterials for ships and submarines” is China, and the top three countries with the highest citations per paper are Canada, the UK, and the USA, as shown in Table 2.2.1. Cooperation can be observed between Canada and the UK, and also between the USA and India, as shown in Figure 2.2.1. The top three institutions with core patent disclosures are Kuang-Chi Cutting Edge Technology Ltd., Aerospace Research Institute of Special Materials and Processing Technology, Luoyang Jianduan Equipment Technology Co., Ltd., as shown in Table 2.2.2. Cooperation has been observed between AVIC Shenyang Aircraft Design and Research Institute and National University of Defense Technology (Figure 2.2.2). Figure 2.2.3 shows the roadmap of this front.

2.2.2 Multi-sensor data fusion technique of autonomous unmanned systems

In recent years, many developed countries and economies all over the world have proposed development roadmaps of unmanned system technology, which aimed at stepping up the layout and seizing the strategic commanding height. As claimed in the 14th Five-Year Plan of China, that it is necessary to strengthen the innovation and application of advanced technology and equipment in the field of major disaster

Table 2.2.1 Countries with the greatest output of core patents on “stealth metamaterials for ships and submarines”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	38	73.08	114	22.98	3.00
2	USA	8	15.38	322	64.92	40.25
3	South Korea	2	3.85	2	0.40	1.00
4	Canada	1	1.92	44	8.87	44.00
5	UK	1	1.92	44	8.87	44.00
6	India	1	1.92	20	4.03	20.00
7	Japan	1	1.92	10	2.02	10.00
8	Netherlands	1	1.92	3	0.60	3.00
9	Spain	1	1.92	1	0.20	1.00

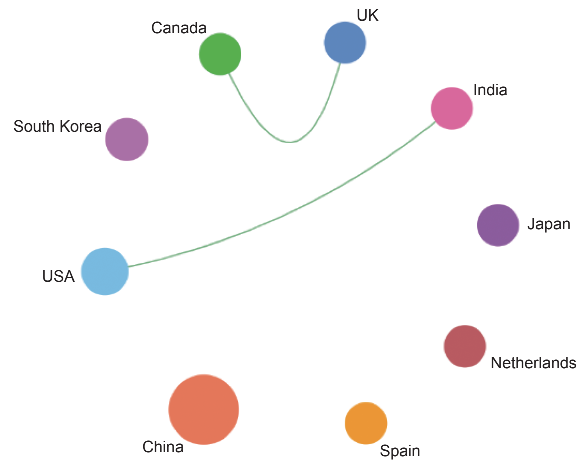

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “stealth metamaterials for ships and submarines”

Table 2.2.2 Institutions with the greatest output of core patents on “stealth metamaterials for ships and submarines”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Kuang-Chi Cutting Edge Technology Ltd.	7	13.46	8	1.61	1.25
2	Aerospace Research Institute of Special Materials and Processing Technology	5	9.62	20	4.03	4.00
3	Luoyang Jianduan Equipment Technology Co., Ltd.	3	5.77	7	1.41	2.33
4	Southeast University	2	3.85	10	2.02	5.00
5	OmniVision Technologies Inc.	1	1.92	285	57.46	285.00
6	Lambda Guard Technologies Ltd.	1	1.92	44	8.87	44.00
7	Invictus Oncology Pvt. Ltd.	1	1.92	20	4.03	20.00
8	AVIC Shenyang Aircraft Design and Research Institute	1	1.92	17	3.43	17.00
9	National University of Defense Technology	1	1.92	17	3.43	17.00
10	China State Shipbuilding Ltd.	1	1.92	13	2.62	13.00

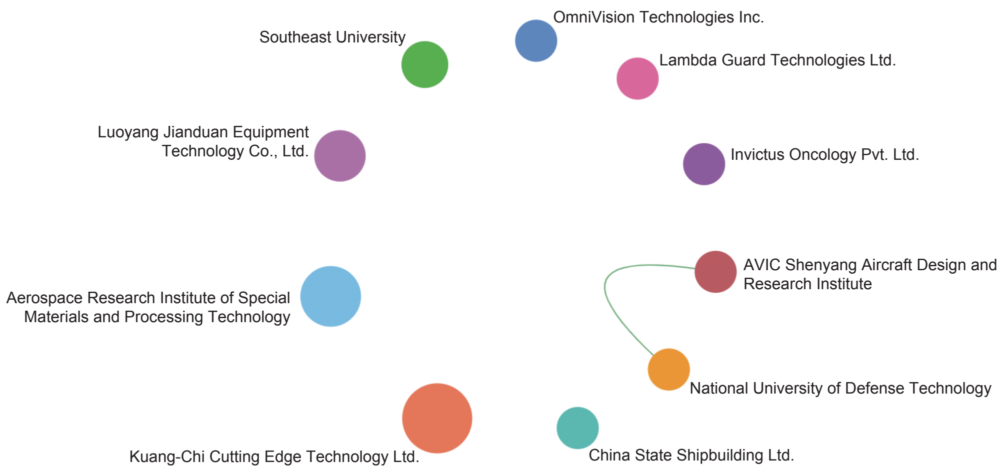

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "stealth metamaterials for ships and submarines"

prevention and rescue, which puts forward increasingly stringent requirements for the environmental perception of autonomous unmanned systems. Moreover, the China State Council clearly mentioned that "the marine unmanned system needs to cooperate with Beidou navigation, satellite, floating platform, and aircraft remote sensing to form a global service capability" in the national informatization plan, which further emphasizes the importance of multi-source information fusion. Considering the detection precision and scope to ensure that the unmanned systems can detect both clearly and comprehensively has become the focus of the studies. The multi-sensor data fusion technique, which can achieve the collaborative dynamic perception of multi-agents and multi-sensors and improve the accuracy and scope of the perception system concurrently, is essential for the perception in complex environment.

Nowadays, the studies on multi-sensor data fusion technique of autonomous unmanned systems have been conducted in China and overseas. A multi-source information registration system equipped with binocular vision, lidar, navigation radar, millimeter wave radar, side scan sonar, and other sensors and the detection system of heterogeneous unmanned systems equipped with side-scan sonar, magnetometer, and other multi-source sensors have been developed. Some achievements have also been made in the dynamic registration and synchronous transmission of sensor information at air, water surface, and underwater. For example, the School of Artificial Intelligence and Automation of Huazhong University of Science and Technology has proposed a novel method in the integration of multi-source registration, deep integration and collaborative tracking, which ensures the detection loss rate is less than 0.8%.

However, many major challenges, such as the association of low-quality information, the fusion of deep feature, and synchronous spatiotemporal registration, are still encountered in the multi-sensor data fusion of autonomous unmanned systems. Inconsistent sampling frequencies, different spatial coordinates, and diverse data forms among various sensors cause difficulties in multi-sensor data fusion. Meanwhile, the attitude difference between the agents and the insignificant features of environments further increase the difficulty of spatial registration. In addition, the potholes, muddy ground, forest, and obstacles, etc. will obstruct and attenuate the signal, thereby affecting the reliability of wireless communication and causing the continuity of the information exchange between the agents lack of guarantee, which will generate numerous heterogeneous and incomplete information that is difficult to correlate and complement reciprocally. Therefore, a fusion method designed for heterologous, heterogeneous, and asynchronous sensor information to carry out multi-sensor data fusion of autonomous unmanned systems and build wide-area perception maps that could enable the systems to possess all-weather environmental perception capabilities. The related research includes the fast calibration and registration method that solves the problem of complicated steps and long time

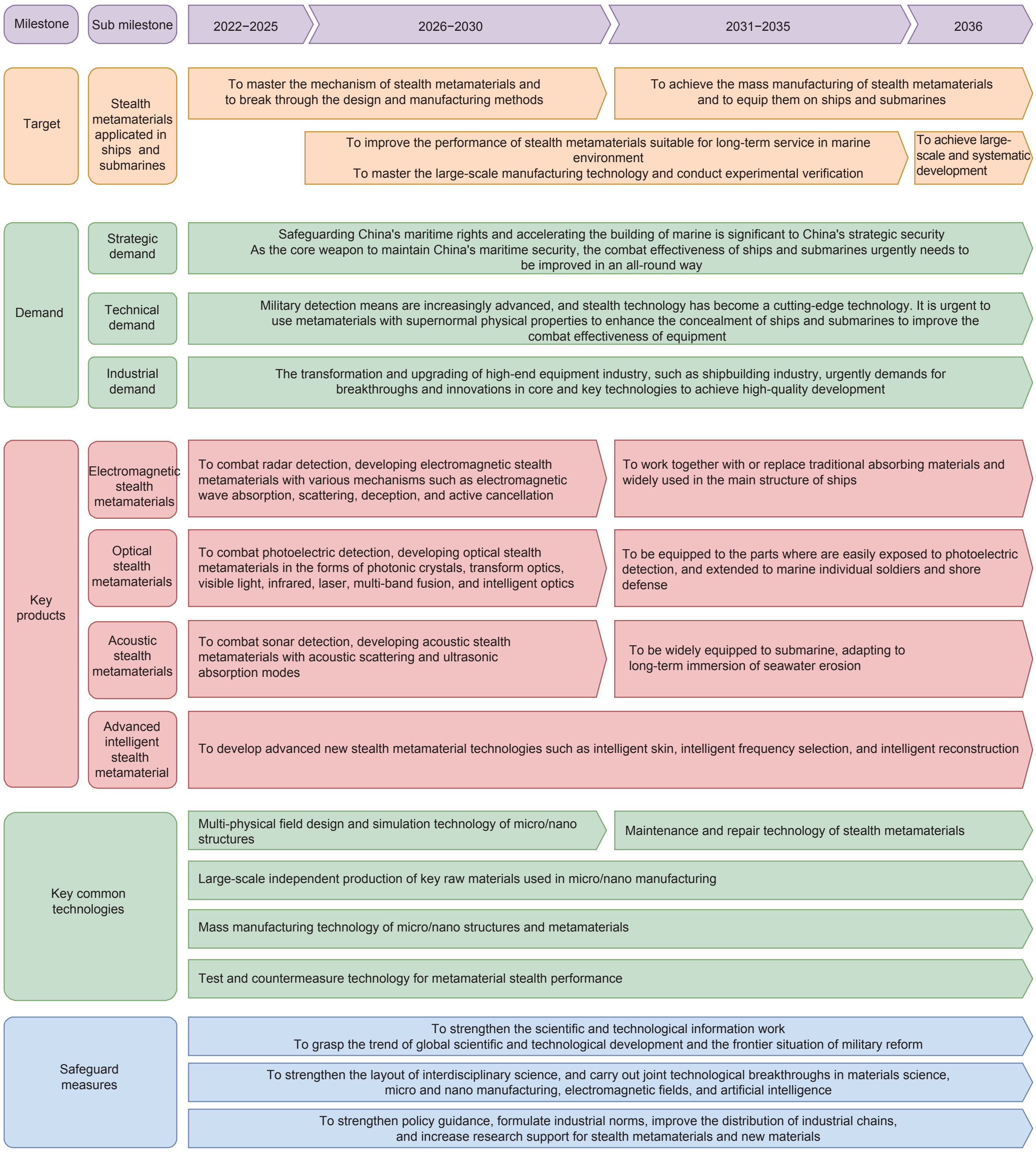

Figure 2.2.3 Roadmap of the engineering development front of “stealth metamaterials for ships and submarines”

consumption in sensor calibration; the spatiotemporal registration method and the law of fusion of the heterologous, heterogeneous, and asynchronous information; the precise association method for large-difference and weakly correlated sensor information; the method for the building of semantic maps and environment networks based on multi-sensor data fusion; and the method for the mapping of feature spaces that belong to various sensors that can achieve the fusion of information at the feature layer.

Currently, the country with the largest number of core patents published on “multi-sensor data fusion technique of autonomous unmanned systems” is China, and the top two countries with the greatest citations per paper are the USA and the UK, as shown in Table 2.2.3. No cooperation can be observed between these countries with core patents. The top three institutions with the largest number of core patents are Nanjing University of Aeronautics and Astronautics, State Grid Corporation of China, and Aerospace Research Institute of Special Materials and Processing Technology, as shown in Table 2.2.4. Cooperation has

Table 2.2.3 Countries with the greatest output of core patents on “multi-sensor data fusion technique of autonomous unmanned systems”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	458	97.86	1 940	91.64	4.24
2	USA	5	1.07	152	7.18	30.40
3	South Korea	2	0.43	1	0.05	0.50
4	Japan	2	0.43	0	0.00	0.00
5	UK	1	0.21	24	1.13	24.00

Table 2.2.4 Institutions with the greatest output of core patents on “multi-sensor data fusion technique of autonomous unmanned systems”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nanjing University of Aeronautics and Astronautics	15	3.21	138	6.52	9.20
2	State Grid Corporation of China	12	2.56	29	1.37	2.42
3	Aerospace Research Institute of Special Materials and Processing Technology	10	2.14	37	1.75	3.70
4	Harbin Engineering University	9	1.92	49	2.31	5.44
5	Beihang University	9	1.92	33	1.56	3.67
6	China Electronics Technology Group Corporation	9	1.92	27	1.28	3.00
7	Shenzhen DJ-Innovations Technology Co., Ltd.	8	1.71	109	5.15	13.62
8	Tsinghua University	8	1.71	71	3.35	8.88
9	National University of Defense Technology	8	1.71	22	1.04	2.75
10	Tianjin University	7	1.50	88	4.16	12.57

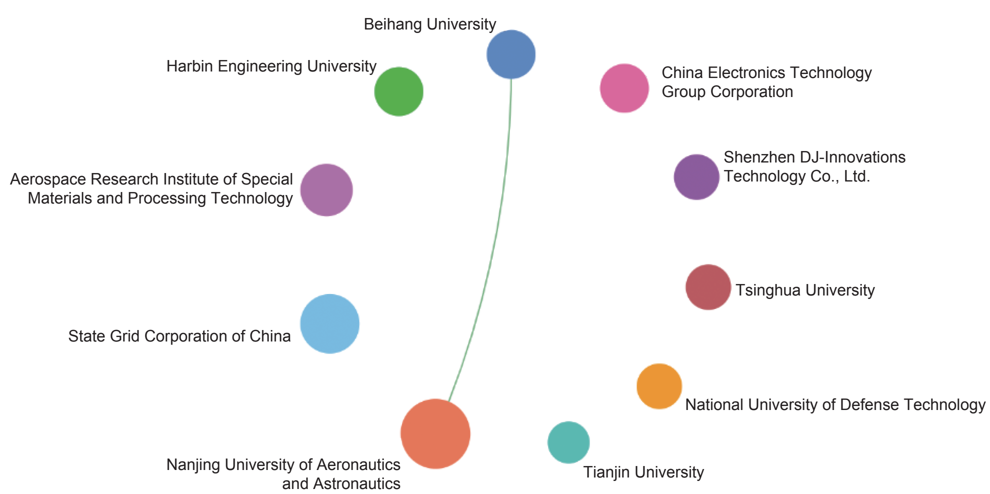

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “multi-sensor data fusion technique of autonomous unmanned systems”

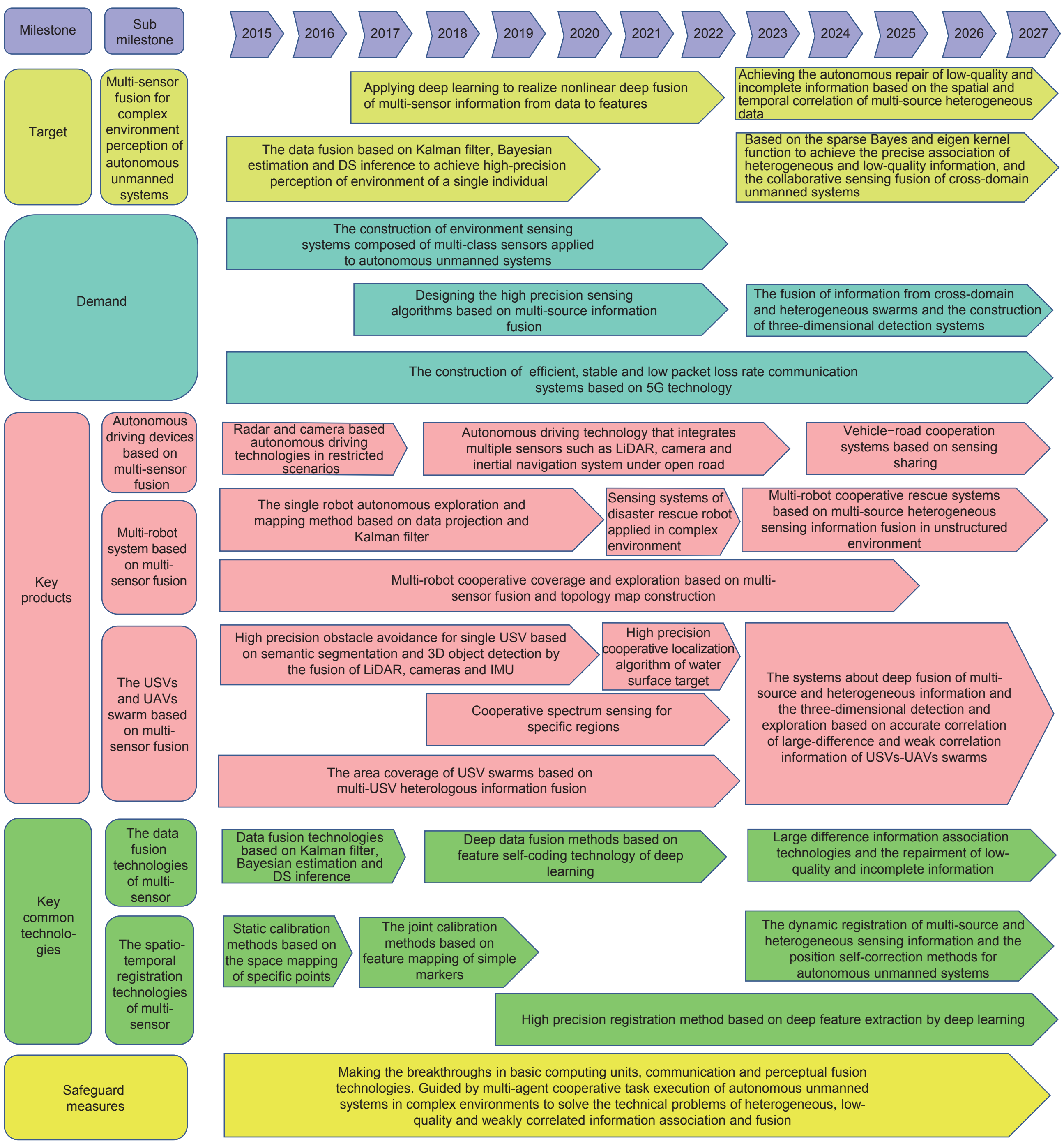

Figure 2.2.5 Roadmap of the engineering development front of "multi-sensor data fusion technique of autonomous unmanned systems"

been observed between Nanjing University of Aeronautics and Astronautics and Beihang University (Figure 2.2.4). Figure 2.2.5 shows the roadmap of this front.

2.2.3 Hydrogen fuel cell vehicle

Hydrogen fuel cells can realize the mobility, lightweight, and large-scale popularization of hydrogen energy. They can be widely applied in transportation, industry, construction, military, and other fields. In the field of transportation, hydrogen energy is known as the "ultimate form" of vehicle energy due to its advantages of non-pollution, renewable energy, fast hydrogen refueling, and sufficient life time. The first application of fuel cells was demonstrated in the NASA Gemini spacecraft in the 1960s. With the development of hydrogen energy technology in the 21st century, in December 2014, Toyota Motor Corporation of Japan took the lead in launching the world's first mass-produced hydrogen fuel cell vehicle (HFCV). In addition, the MIRAI-II model, which launched in Japan in 2020, reached a recharge mileage of 850 kilometers. On the basis of the technical characteristics of hydrogen fuel cells, the Ministry of Industry and Information Technology and the Society of Automotive Engineering confirms that the future applications of hydrogen fuel cells will focus on heavy trucks with fixed routes, medium- and long-distance trunk lines, and high load trucks. Fuel cell heavy-duty trucks will be commercialized in the next 5 to 10 years, gradually replacing the traditional fuel vehicle market.

To meet the high requirements of commercialization, the key parts of hydrogen fuel cells, such as catalysts, proton exchange membranes, gas diffusion layers, and bipolar plates, are still being optimized. For the catalyst, the mass activity of the catalyst can be significantly improved, and the amount of platinum can be reduced by platinum particle nanocrystallization and alloying. However, the stability of the catalyst under the acidic and oxidative operating conditions needs to be greatly improved. At the same time, the activity of non-platinum catalysts, such as metal–nitrogen–carbon catalysts, has been comparable to that of commercial Pt/C, whereas the stability needs to be improved under operating conditions. Commercial proton exchange membranes are perfluorinated sulfonate resins, which require material compositing to improve structural strength and reduce costs. The gas diffusion layer is composed of macroscopic porous substrate and microporous layer, which needs to meet the requirement of high resistivity, stable electrode structure, hydrophilic/hydrophobic balance, and gas transport efficiency. At present, the technology is still monopolized by foreign companies. The mass and volume of the bipolar plate account for more than 80% of the stacks, so reducing the density and thickness of the bipolar plate is an important approach to improve the power density of the stacks. In addition to stacks, in terms of hydrogen storage technology, low-temperature liquid hydrogen storage will become the best solution for long-lasting use in the future. In the management of the entire fuel cell system, the hydrogen supply and circulation system, the air supply system, the water and heat management system, the electronic control system, and the data acquisition system need to be further optimized to ensure that the fuel cell has high energy conversion efficiency and energy output power.

In summary, the development of HFCVs will focus on reducing the cost and improving the critical properties, such as stability under operating conditions, of core materials. At the same time, various technical problems of water electrolysis for hydrogen production and transportation also need to be solved.

The top three countries with the largest number of core patents published on "hydrogen fuel cell vehicle" are China, Japan, and South Korea. The top three countries with the greatest citations per paper are the Saudi Arabia, France, and Belgium, as shown in Table 2.2.5. Japan has been observed to have cooperation with the USA and Austria, and cooperation has also been observed between the USA and South Korea, as shown in Figure 2.2.6. The top three institutions with the greatest citations per paper are Hyundai Motor Company, Toyota Motor Company, and Kia Motor

Table 2.2.5 Countries with the greatest output of core patents in the engineering development front of "hydrogen fuel cell vehicle"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	123	36.94	222	16.63	1.80
2	Japan	94	28.23	484	36.25	5.15
3	South Korea	84	25.23	412	30.86	4.90
4	USA	14	4.20	93	6.97	6.64
5	Germany	14	4.20	37	2.77	2.64
6	Belgium	2	0.60	21	1.57	10.50
7	Saudi Arabia	1	0.30	52	3.90	52.00
8	France	1	0.30	11	0.82	11.00
9	Spain	1	0.30	3	0.22	3.00
10	Austria	1	0.30	0	0.00	0.00

Company, as shown in Table 2.2.6. Cooperation can been observed between Hyundai Motor Company and Kia Motor Company, as shown in Figure 2.2.7. Figure 2.2.8 shows the roadmap of this front.

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of “hydrogen fuel cell vehicle”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Hyundai Motor Company	79	23.72	408	30.56	5.16
2	Toyota Motor Company	63	18.92	272	20.37	4.32
3	Kia Motor Company	38	11.41	190	14.23	5.00
4	Wuhan Grove Hydrogen Energy Automobile Co., Ltd.	32	9.61	41	3.07	1.28
5	Honda Motor Company	9	2.70	45	3.37	5.00
6	Nissan Motor Company	5	1.50	113	8.46	22.60
7	Audi AG Company	5	1.50	30	2.25	6.00
8	State Grid Corporation of China	5	1.50	3	0.22	0.60
9	Wuhan Geological Resource Environment Industrial Technology Research Institute Co., Ltd.	4	1.20	11	0.82	2.75
10	Mitsubishi Motor Company	4	1.20	5	0.37	1.25

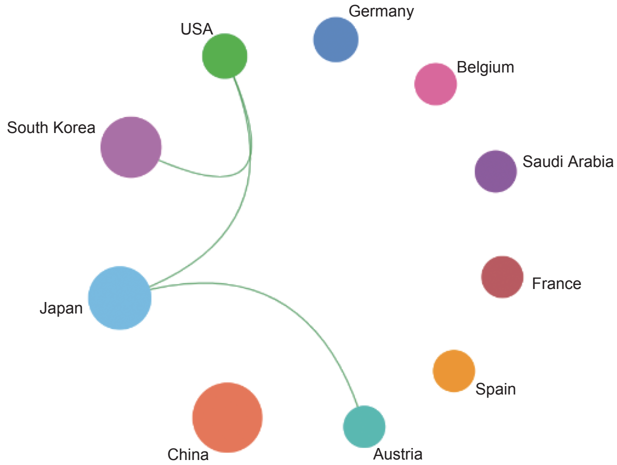

Figure 2.2.6 Collaboration network among major countries in the engineering development front of “hydrogen fuel cell vehicle”

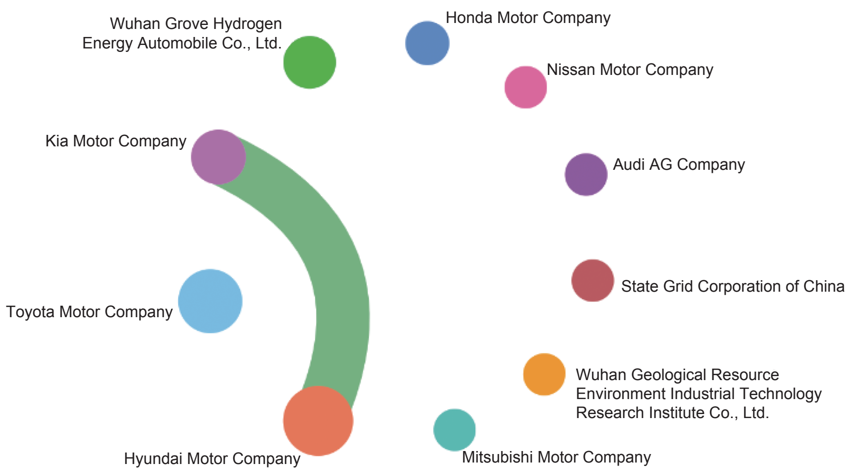

Figure 2.2.7 Collaboration network among major institutions in the engineering development front of “hydrogen fuel cell vehicle”

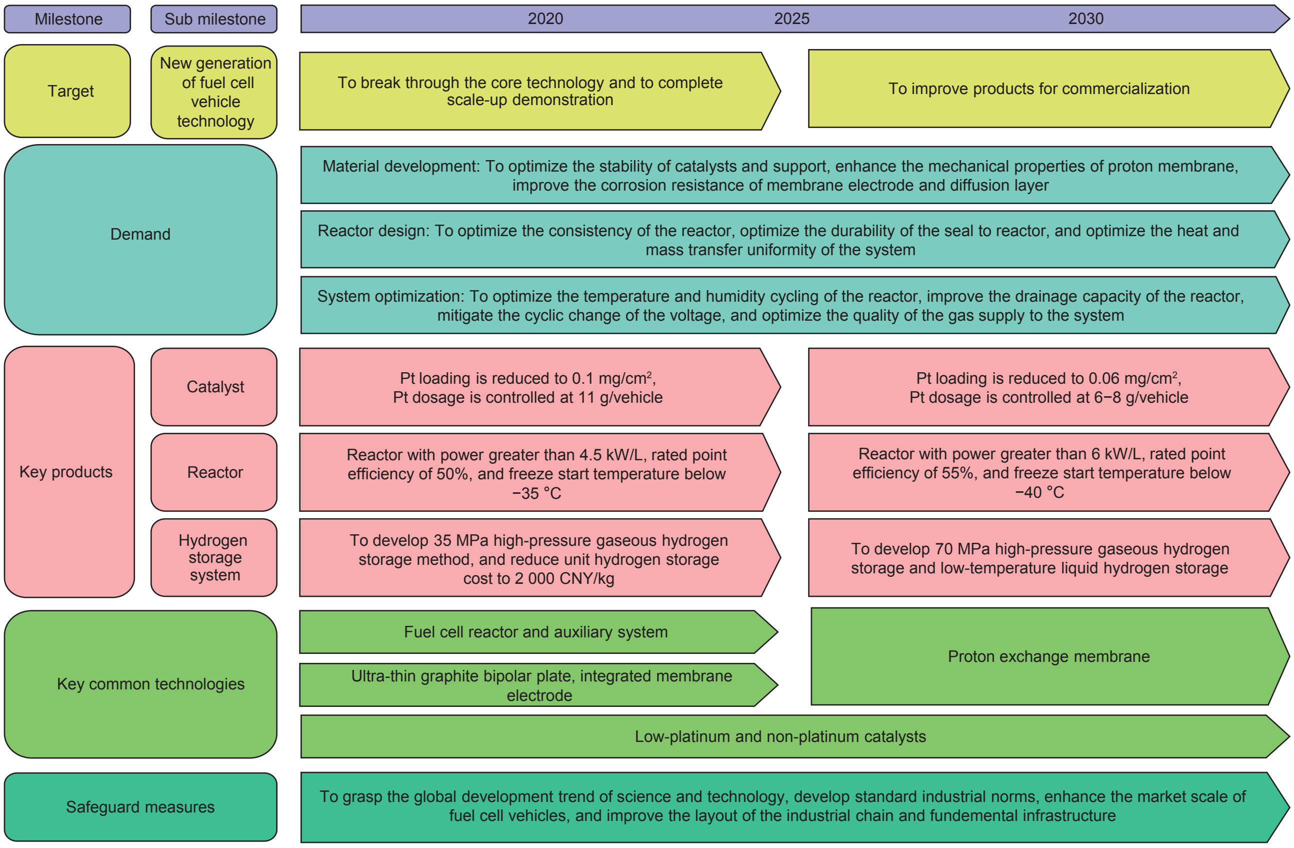

Figure 2.2.8 Roadmap of the engineering development front of “hydrogen fuel cell vehicle”

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