I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The ten most-researched engineering topics in the field of mechanical and vehicle engineering (hereafter referred to as mechanical field) 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, "high-energy density solid-state lithium batteries," "drag/heat reduction in supersonic flow," "high-performance nano-biosensors," "information security and privacy protection in the Internet of Vehicles (IoV)," "self-adaptive target capture by tethered space robots," and "hybrid power systems with renewable energy and fuel cells" are extensively studied traditional topics. "Intelligent manufacturing based on the industrial Internet of Things (IIoT)," "cooperative control of multirobot systems," "integration of design and manufacturing based on topology optimization and additive manufacturing," and "resource scheduling and risk assessment of smart grids" are considered as emerging topics. The annual publication of papers during the years 2013–2018 is listed in Table 1.1.2. "Hybrid power systems with renewable energy and fuel cells" and "cooperative control of multirobot systems" are the most rapidly growing topics in terms of paper publications in recent years.

(1) Intelligent manufacturing based on the industrial IIoT

The IIoT can achieve rational allocation of manufacturing resources, on-demand execution and continuous optimization of manufacturing processes, and rapid adaptation of manufacturing environments through network interconnections, data exchange, and system interoperation of manufacturing systems. As a result, intelligent manufacturing systems driven by innovative manufacturing services are developed. Relevant studies are currently categorized in three main areas: 1) intellisense (i.e., intelligent perception) and iterative optimization of smart products in their entire life cycle that includes the perception and handling of large amounts of data in the industrial value chains of design, production, logistics, sales, and services; 2) universal interconnection and accurate control of manufacturing systems that include sensing devices, distributed control systems, manufacturing execution systems, enterprise resource planning systems, and supply chain management systems at the equipment, control, shop floor, enterprise, and enterprise collaboration layers; 3) modeling, simulation, and real-time analysis of intelligent functions of manufacturing systems including entity coordination, system

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Intelligent manufacturing based on the IIoT	21	460	21.90	2017.1
2	High-energy density solid-state lithium batteries	26	828	31.85	2015.4
3	Drag/heat reduction in supersonic flow	48	983	20.48	2016.3
4	Cooperative control of multirobot systems	23	764	33.22	2017.1
5	High-performance nano-biosensors	45	1478	32.84	2016.6
6	Information security and privacy protection in the IoV	17	617	36.29	2015.6
7	Integration of design and manufacturing based on topology optimization and additive manufacturing	5	86	17.20	2017.0
8	Self-adaptive target capture by tethered space robots	34	779	22.91	2015.5
9	Hybrid power systems with renewable energy and fuel cells	47	1179	25.09	2016.7
10	Resource scheduling and risk assessment for smart grids	18	689	38.28	2016.5

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	2013	2014	2015	2016	2017	2018
1	Intelligent manufacturing based on the IIoT	0	0	0	3	13	5
2	High-energy density solid-state lithium batteries	3	7	2	8	4	2
3	Drag/heat reduction in supersonic flow	3	5	5	10	14	11
4	Cooperative control of multirobot systems	0	2	1	0	10	10
5	High-performance nano-biosensors	2	2	5	4	23	9
6	Information security and privacy protection in the IoV	2	2	2	6	5	0
7	Integration of design and manufacturing based on topology optimization and additive manufacturing	0	0	1	0	2	2
8	Self-adaptive target capture by tethered space robots	2	6	5	14	7	0
9	Hybrid power systems with renewable energy and fuel cells	0	1	3	16	17	10
10	Resource scheduling and risk assessment for smart grids	0	0	3	5	8	2

integration, information fusion, and new business patterns such as customization and predictive maintenance of smart products. Research in these areas faces the challenges of the complexity and diversity of interconnection technologies and protocols, a wide range of applications, numerous hidden issues of cyber security and data safety. Therefore, new 5G mobile networks, human–cyber–physical systems (HCPSs), software-defined networks, edge computing, digital twins, and so on have emerged as frontiers in the research and development trends of intelligent manufacturing based on the industrial Internet of Things.

(2) High-energy density solid-state lithium batteries

Liquid-state lithium batteries are in widespread use, but they have already reached their theoretical or engineering limits in the key metrics of energy density and safety. Therefore, new methods of energy storage must be developed to satisfy future needs. Solid-state batteries use solid instead of liquid electrolytes containing small organic molecules. Thus, these batteries possess advantages over liquid batteries in terms of energy density, safety, and life cycle and are believed to be the next-generation electrochemical power sources. Surface/interface mass transfer, key materials compatibility, low interfacial impedance technology, evolution mechanism during the entire life cycle, and other frontier science challenges are mainly addressed in the emerging technology of solid-state batteries. In future, in situ analysis and characterization techniques will be developed for interface impedance problems such as the following. 1) Matching of key materials with high specific energy include cathode materials with high capacity/high voltage, high-performance solid electrolytes, and high capacity lithium anodes with high capacity metals. These challenges require considerable attention at present. 2) Preparation techniques for low impedance micro-interfaces that include design and material matching are vital for mass production. 3) The attenuation in the battery performance and the evolutionary route of the materials in the system during the entire life cycle are key factors in the assessment and prediction of health status of solid-state batteries. Further development of solid-state metal–air batteries based on solid electrolytes with long lifetimes will become the ultimate goal of research on electrochemical power components.

(3) Drag/heat reduction in supersonic flow

Drag/heat reduction in supersonic flow studies the flow of gas or plasma on solid surfaces with a relative speed above Mach 3. Such a supersonic flow occurs in nozzles on hypersonic vehicles, around spacecrafts re-entering the atmosphere, and in high-altitude, high-speed scouting planes or nozzle internal flow in jet engines. Strong aerodynamic heating, air ionization, impact waves, burning, and other problems accompany such rapid motion. Theoretically, problems in plasma flow, impact wave, rarefied air dynamics, and heat transfer under complex flow can be barely simulated through the currently applied Navier–Stokes equation-based numerical simulation method. The direct Monte Carlo simulation and Fokker–Planck equation methods must be improved. Real experimental methods should further develop sensors that are resistant to the high temperatures and impact forces found in supersonic systems and wind tunnels. Drag/heat reduction techniques under investigation include the use of needles, reverse and internal jets, plasma boundary layer control, laser energy deposition, bottomward direction of aircraft exhaust, sacrificial surface layers for ablation, and internal insulation at the front end of an aircraft. The manufacture of jet orifices and gas supply systems, experimental techniques, and numerical simulation techniques for complex curved surfaces should have increased capabilities.

(4) Cooperative control of multirobot systems

As the cross development in artificial intelligence (AI), automation, and computer science, the interactions of multiple robots have become an important subject of study in engineering control. Communication, coordination, scheduling, cooperation, and control among robots have all been studied, and highly coordinated collective dynamic actions have been observed; multirobot cooperation can be applied to accomplishing substantial complex work that no single robot can complete. Multirobot control methods are known to be robust and can reliably solve actual problems. Traditional multirobot production systems employ a centralized control structure and ignore the possibility of cooperative behavior. Such systems cannot adjust to production patterns involving small quantities and numerous varieties of products, and lack smart manufacturing ability. As the manufacturing industry develops toward ever larger and more complex operations, there is a pressing need for cooperative multirobot systems with improved compliance, consistency, and optimization performance.

(5) High-performance nano-biosensors

Nano-biosensors are very important for modern biotechnology. The trend in this area is toward small, portable, fast, highly sensitive, integrated, and inexpensive devices. High-performance nano-biosensors of current interest include immunosensors, surface plasma resonance biosensors, mycotoxin ultratrace sensors, and tumor biomarker sensors. Ultratrace and highly selective nano-biosensors are an imminent requirement because conventional biosensors lack sensitivity and selectivity in the detection of mycotoxins and tumor cells. Such devices, based on novel biocompatible nanomaterials such as metal sulfide quantum dots, nanocomposites, graphene oxide, and two-dimensional nanomaterials, could greatly improve the sensitivity, response rate, and selectivity of biosensors, and is likely to become a dominant research topic in the field.

(6) Information security and privacy protection in the IoV

The IoV is a new intelligent system that integrates wireless communication technology into the modern automobile industry. It incorporates advanced technologies, such as big data, cloud computing, and AI, substantially contributing to road planning, resource scheduling, and traffic improvement. However, because of its large network scale, open communication environment, and predictable mobile track, the IoV is extremely vulnerable to attacks, system crashes, and privacy leaks. Safeguarding the IoV is therefore a major goal of academics and automotive industry researchers. Proposed secure communication methods, such as aggregate signatures and periodic certificate ignoring, have improved verification and communication efficiency, which can solve the problem of the high communication overhead of digital signature communication based on Public Key Infrastructure (PKI). Privacy protection proposals such as anonymous authentication, shared certificates, and group signatures can reduce the number of vehicles using unique certificates, thereby enhancing user privacy. Location privacy protection schemes such as *k*-anonymity, mixed zones, and group navigation can prevent the location server from knowing the actual place from which a location request originates. Such research can effectively improve the communication efficiency and safety of the IoV. However, as driverless technology rapidly develops, the IoV will face an increasingly complex network environment and ever greater data-processing demands. IoV information security and privacy protection will be a long and arduous task.

(7) Integration of design and manufacturing based on topology optimization and additive manufacturing

Both topology optimization and additive manufacturing are major innovations in design and manufacturing. The integration of the two has become a leading priority in the development of China's high-end equipment industry. Currently, it is mostly implemented by a serial method that attempts to fabricate the optimized designs through additive manufacturing. Research on more sophisticated topology optimization methods for additive manufacturing remains limited. On the one hand, many additive manufacturing components must still meet the requirements of traditional processes, such as casting, sheet metal, and machining. Consequently, the advantages and potentials of additive manufacturing are difficult to maximize. On the other hand, existing topology optimization methods do not consider the design of the structure from the perspective of multi-material, multi-scale, and multi-component integration, and the special constraints of the additive manufacturing process are hardly considered at all. Such circumstances inevitably result in structural performance being sacrificed, given the current serial mode of design and manufacturing. Although existing research has achieved initial results, it cannot reveal its design principles from the depth of material–structure–process integration. Structural models of mechanical behavior, influencing mechanisms of process constraints, topology optimization design with a complex overall structure, design tool development, and material applications of additive manufacturing constitute a bottleneck for additive manufacturing and structural innovation design.

(8) Self-adaptive target capture by tethered space robots

As human activity in space increases, the number of lost or retired spacecraft and the amount of orbital debris increase as well. The use of robots to remove unwanted materials in space is thus gradually becoming a prevalent research topic in the aerospace industry. Tethered robots are an effective solution for capturing and dragging large targets with complex motion, but they can easily collide, oscillate, or roll in microgravity or vacuum environments. Tethered space-robot technology requires advances in attitude measurement techniques and coordinated control systems based on vision. Collision analysis, real-time dynamics, and control design should be improved to ensure the reliability of tethered space robots in the target-capture process.

(9) Hybrid power systems with renewable energy and fuel cells

Internal combustion vehicles bring people convenience and comfort, but also cause serious environmental pollution and consume fossil fuels. Almost all countries are therefore researching green and renewable energy. Hybrid power systems based on renewable energy and fuel cells have become attractive particularly to the automotive industry due to their lack of emissions. Hybrid systems also have high power density, high stability, and a wide range of operating temperature. These advantages make them preferred power sources for solving energy and environmental problems in the future. Currently, the main and auxiliary energy sources are commonly used to simultaneously supply energy to the multi-energy power system structure. Research on the structure and optimization of hybrid systems, and selection of reasonable control strategies for the proper distribution of power between the various energy sources, are the core issues of current hybrid power system research, which is complicated by the diversity of hybrid power systems, the complexity of their control systems, and their weak dynamic performance.

(10) Resource scheduling and risk assessment for smart grids

Smart grids are grids of a new type closely integrating modern sensing, communication, information, and control technologies into the traditional framework. Seamless connection and real-time interaction between the elements of a smart grid can be ensured through the application of distributed intelligence, broadband communication, and automatic control, resulting in a more reliable, safer, cheaper, and more environmentally friendly grid. The keys to building a smart grid are the establishment of a strong and flexible grid structure, access to renewable and distributed energy, integration of open power–information communication systems, and construction of an efficient network of emergency centers. Because the scale of power systems is continually expanding, the risks of grid operation are increasing, and resource scheduling tasks are becoming increasingly complicated and arduous. Thus the development of new resource-scheduling and risk-assessment methods for smart grids is necessary to improve the flexibility, security, and reliability of power systems.

1.2 Interpretations for three key engineering research fronts

1.2.1 Intelligent manufacturing based on the IIoT

We are currently in an era of intense global competition, sometimes called a new industrial revolution. In the national development strategies of many countries, including German Industry 4.0, American Advanced Manufacturing, Made in China 2025, British Industry 2050, and the Japan Revitalization Strategy, intelligent manufacturing is ranked as an important direction for the future development of industry. Research on the IIoT, a crucial enabling technology for intelligent manufacturing, has become widespread. This includes research on the interconnection of entities in the manufacturing field; information modeling and fusion; innovative application modes; and optimization of manufacturing resources allocation. Current research and development in intelligent manufacturing based on the IIoT proceeds in three dimensions (life cycle, system level, and intelligence) and six directions (intellisense, ubiquitous connectivity, precision control, digital modeling, real-time analysis, and iterative optimization).

The life cycle dimension includes the application of the IIoT to chained sets of interrelated activities (such as design, production, logistics, sales, and services) that focus on collaboration and interconnection between enterprises. The system level dimension focuses on the application of the IIoT at the equipment, control, shop floor, enterprise, and supply chain coordination levels, that is, on interconnections mostly within a single enterprise. The intelligence dimension concentrates on entity collaboration, system integration, information fusion, and emerging business patterns including the transformation from manufacturing to services and product predictive maintenance. Intellisense research explores the effective use of sensors, including radio-frequency identification (RFID) systems, as a means to obtain information on different aspects of a product's life cycle. Ubiquitous connectivity research investigates methods of interconnecting machines with each other, with people, and with the environment. Digital modeling studies the mapping of manufacturing resources to digital spaces, including the abstract modeling of the full elements of the production. Real-time analysis studies visualization and conducts visual analysis of manufacturing resource data, exploring the intrinsic link between industrial resource states in virtual and real spaces. Precision control studies the precise information interaction and seamless cooperation of manufacturing resources in the IIoT. Iterative optimization studies self-learning and improvement methods, and explores the optimal configuration of manufacturing resources, processes, and environments in the IIoT.

Although some important progress has been made in the three dimensions and six directions of intelligent manufacturing research based on the Internet of Things, such research faces the usual problems posed by the complexity and diversity of interconnected technologies and protocols, different depths and widths of applications, cyber security and data safety, as well as other issues. In recent years, HCPS, new 5G mobile networks, software-defined networks, edge computing, and digital twins have attracted a lot of attention. Ternary systems and frameworks, large-bandwidth communication, low latency and superior connection, automated and programmable networks, device-side edge computing, and virtual digital and physical device spaces mapping are all important topics in this field.

The four countries/regions producing the most core papers in intelligent manufacturing based on the IIoT are China (7), Germany (6), Sweden (6), and Italy (6). The three countries/regions with the greatest average number of citations are Germany (38), Brazil (28), and France (23.75), as shown in Table 1.2.1. Among the 10 countries/regions with the most core papers, substantial collaboration is initiated between China, Switzerland, and Sweden, as shown in Figure 1.2.1. The four institutions with the most core papers are ABB Corporate Research Center (4), Beijing University of Posts and Telecommunications (3), Tsinghua University (3), and University of Padua (3). The three institutions with the highest average number of citations are Asea Brown Boveri Corporate Research Center (34), Cisco Systems (34), and Center Communication Systems Research (34), as shown in Table 1.2.2. Among the ten institutions with the most core papers, substantial collaboration is initiated between the ABB Corporate Research Center, Beijing University of Posts and Telecommunications, and Tsinghua University, as shown in Figure 1.2.2. The three countries or regions with the most citing papers are China (71), Italy (61), and the USA (52), as shown in Table 1.2.3. The institutions with the greatest number of citing papers are ABB Corporate Research Center (12), National Research Council (Italy) (11), Federal University of Santa Catarina (7), and University of Padua (7), as shown in Table 1.2.4.

1.2.2 High-energy density solid-state lithium batteries

Liquid electrolyte lithium batteries, limited by material and device structure constraints, have reached their theoretical engineering limits for several key indicators, including energy density, safety, and cycle life. Further improvements in materials or processes cannot easily be translated into major improvements in performance. Therefore, new energy-storage materials and matching device structures must be developed to meet the future need for high specific energy. Liquid electrolyte batteries use a small-molecule organic solvent, which is flammable and easily degraded, initiating a series of chain reactions that reduce battery performance. Solid-state batteries use solid electrolytes instead of liquid, and possess potential advantages in energy density, safety, and cycle life.

Table 1.2.1 Countries or regions with the greatest output of core papers on "intelligent manufacturing based on the IIoT

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	7	33.33%	97	21.09%	13.86
2	Germany	6	28.57%	228	49.57%	38.00
3	Sweden	6	28.57%	106	23.04%	17.67
4	Italy	6	28.57%	76	16.52%	12.67
5	USA	5	23.81%	70	15.22%	14.00
6	Switzerland	4	19.05%	68	14.78%	17.00
7	France	4	19.05%	95	20.65%	23.75
8	Canada	3	14.29%	66	14.35%	22.00
9	Brazil	2	9.52%	56	12.17%	28.00
10	South Korea	2	9.52%	22	4.78%	11.00

Table 1.2.2 Institutions with the greatest output of core papers on "intelligent manufacturing based on the IIoT"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	ABB Corp Res	4	19.05%	39	8.48%	9.75
2	Beijing Univ Posts & Telecommun	3	14.29%	49	10.65%	16.33
3	Tsinghua Univ	3	14.29%	49	10.65%	16.33
4	Univ Padua	3	14.29%	43	9.35%	14.33
5	City Univ Hong Kong	2	9.52%	39	8.48%	19.50
6	KTH Royal Inst Technol	2	9.52%	44	9.57%	22.00
7	Royal Inst Technol	2	9.52%	14	3.04%	7.00
8	Asea Brown Boveri Corp Res	1	4.76%	34	7.39%	34.00
9	Cisco Syst	1	4.76%	34	7.39%	34.00
10	Ctr Commun Syst Res	1	4.76%	34	7.39%	34.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "intelligent manufacturing based on the IIoT"

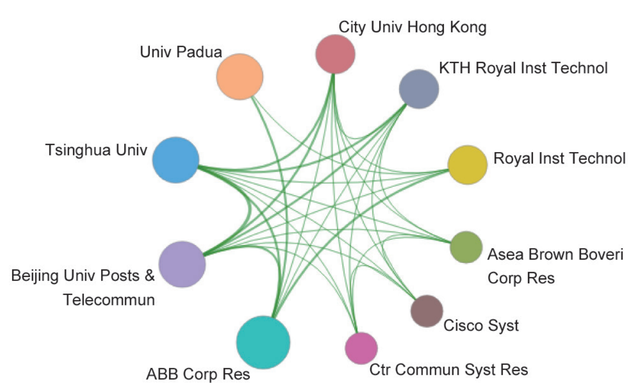

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "intelligent manufacturing based on the IIoT"

Table 1.2.3 Countries or regions with the greatest output of citing papers on "intelligent manufacturing based on the IIoT"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	71	18.88%	2017.8
2	Italy	61	16.22%	2017.6
3	USA	52	13.83%	2018.0
4	Germany	47	12.50%	2017.7
5	Sweden	27	7.18%	2017.7
6	UK	22	5.85%	2017.9
7	Brazil	22	5.85%	2017.9
8	South Korea	20	5.32%	2017.7
9	Spain	20	5.32%	2017.8
10	France	19	5.05%	2017.6

Table 1.2.4 Institutions with the greatest output of citing papers on "intelligent manufacturing based on the IIoT"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	ABB Corp Res	12	15.79%	2017.7
2	Natl Res Council Italy	11	14.47%	2017.4
3	Univ Fed Santa Catarina	7	9.21%	2017.9
4	Univ Padua	7	9.21%	2017.3
5	KTH Royal Inst Technol	6	7.89%	2017.8
6	Beijing Univ Posts & Telecommun	6	7.89%	2017.8
7	Berlin Sch Econ & Law	6	7.89%	2017.3
8	Old Dominion Univ	6	7.89%	2018.2
9	Natl Inst Stand & Technol	5	6.58%	2017.6
10	Univ Texas Dallas	5	6.58%	2018.4

By matching the high-voltage positive electrodes and selecting compact structure modes, they effectively avoid the side reactions caused by small organic molecules. Therefore, solid-state batteries are believed to be the most promising generation of high-specific-energy electrochemical power sources.

Despite the great advantages that solid-state batteries potentially afford, several major challenges hinder their adoption for large-scale usage. The first is that of exploring a practical high-performance solid electrolyte exhibiting high ionic conductivity under the condition of various rates and establishing suitable manufactory processes to avoid damaging the desired interface microstructures. Materials genomics, which uses cutting-edge technology such as AI and machine learning to discover and optimize new materials, provides a more efficient way to design and develop high-performance solid electrolyte materials than the traditional trial-and-error method. This emerging approach will undoubtedly accelerate the evolution of solid-state batteries. Another challenge involves material-matched preparation technology and techniques that are based on surface/interface mass transfer and interface impedance. Material systems and structural processes certainly need to be changed systematically to match the changing manufacturing processes. Integrated roll-to-roll preparation is currently considered a promising direction for research. Another bottleneck is that the performance life cycle of solid-state batteries remains unclear. Life cycle monitoring can take as long as ten years; understanding changes in performance over such a long time is very challenging. Big data analysis, including AI and deep learning, will be required to address the performance attenuation of batteries over their entire life cycle.

Solid-state batteries can meet the need for high energy density to a certain extent, but the ultimate goal of research on electrochemical power devices is to match that of conventional fuels. Metal–air batteries based on solid electrolyte materials can, in theory, come close to achieving this, with specific energy densities near 11 430 W·h/kg. Such batteries are currently the focus of intense research and development, but there are serious challenges yet to be overcome on ways to deal with side effects caused by air anodes, stabilization of metal cathodes, and improvement in cyclic performance. Important science and engineering topics will involve research on catalytic mechanisms, structural design, and module packing and power management. In the future, research will give way to development, and the focus will shift to material systems, engineering, and processes.

The four countries or regions that have produced the most core papers on high-energy density solid-state lithium battery engineering are India (20), Slovenia (5), the USA (2), and Hungary (2). The countries or regions producing the highest average number of citations are Slovenia (39.2), India (30.35), and the USA (28), as shown in Table 1.2.5. There is extensive research cooperation between India and Hungary, as shown in Figure 1.2.3. The institutions with the most core papers are Institute of Chemical Technology (17), University of Ljubljana (5), and Jozef Stefan Institute (3). The institutions with the highest average citation numbers are Jozef Stefan International Postgraduate School (55.5), Jozef Stefan Institute (49.67), and University of Ljubljana (39.2), as shown in Table 1.2.6. More cooperation transpires between the University of Ljubljana, the Jozef Stefan Institute, and the Jozef Stefan International Postgraduate School than with other institutions, as shown in Figure 1.2.4.

The countries or regions with the most citing papers are China (113), India (100), Malaysia (30), and Italy (30), as shown in Table 1.2.7. The institutions that have produced the most citing papers are Institute of Chemical Technology (50), University of Ljubljana (16), Chinese Academy of Sciences (13), and University of Malaya (13), as shown in Table 1.2.8.

Table 1.2.5 Countries or regions with the greatest output of core papers on “high-energy density solid-state lithium batteries”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	India	20	76.92%	607	73.31%	30.35
2	Slovenia	5	19.23%	196	23.67%	39.20
3	USA	2	7.69%	56	6.76%	28.00
4	Hungary	2	7.69%	48	5.80%	24.00
5	China	1	3.85%	25	3.02%	25.00

Table 1.2.6 Institutions with the greatest output of core papers on “high-energy density solid-state lithium batteries”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Inst Chem Technol	17	65.38%	528	63.77%	31.06
2	Univ Ljubljana	5	19.23%	196	23.67%	39.20
3	Jozef Stefan Inst	3	11.54%	149	18.00%	49.67
4	Jozef Stefan Int Postgrad Sch	2	7.69%	111	13.41%	55.50
5	Univ West Hungary	2	7.69%	48	5.80%	24.00
6	Malaviya Natl Inst Technol	2	7.69%	39	4.71%	19.50
7	Ecol Engn Inst Ltd	1	3.85%	29	3.50%	29.00
8	FJP CCN Domzale Kamnik Doo	1	3.85%	29	3.50%	29.00
9	Clarkson Univ	1	3.85%	31	3.74%	31.00
10	Ecosphere Energy Serv LLC	1	3.85%	31	3.74%	31.00

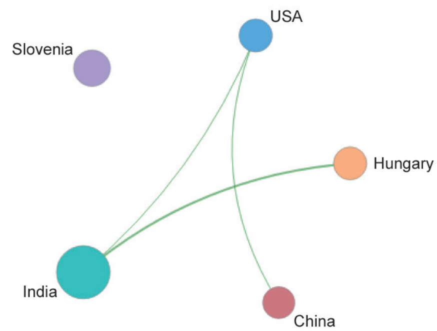

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "high-energy density solid-state lithium batteries"

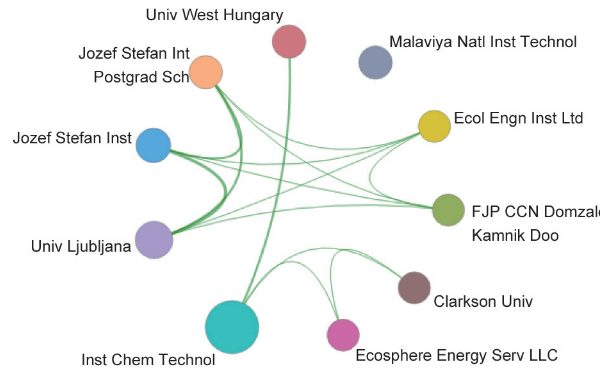

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "high-energy density solid-state lithium batteries"

Table 1.2.7 Countries or regions with the greatest output of citing papers on "high-energy density solid-state lithium batteries"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	113	27.49%	2017.0
2	India	100	24.33%	2016.7
3	Malaysia	30	7.30%	2016.7
4	Italy	30	7.30%	2016.6
5	Iran	29	7.06%	2016.9
6	Slovenia	22	5.35%	2016.2
7	USA	19	4.62%	2017.1
8	South Korea	19	4.62%	2016.6
9	Spain	18	4.38%	2016.4
10	Poland	16	3.89%	2017.6

Table 1.2.8 Institutions with the greatest output of citing papers on "high-energy density solid-state lithium batteries"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Inst Chem Technol	50	33.56%	2016.5
2	Univ Ljubljana	16	10.74%	2016.1
3	Chinese Acad Sci	13	8.72%	2017.4
4	Univ Malaya	13	8.72%	2016.5
5	Jozef Stefan Inst	10	6.71%	2015.7
6	Univ Chinese Acad Sci	9	6.04%	2017.1
7	Natl Res Council Italy	8	5.37%	2017.6
8	Harbin Inst Technol	8	5.37%	2016.6
9	Natl Inst Technol	8	5.37%	2017.3
10	Korea Adv Inst Sci & Technol	7	4.70%	2016.3

1.2.3 Drag/heat reduction in supersonic flow

At present, most of the problems in supersonic flow are theoretically studied by numerical simulations based on the Navier–Stokes equations. The Monte Carlo direct simulation method and the Fokker–Planck equation, which can simulate thin air conditions, shock waves, and plasma, are rarely used, due to a lack of sophisticated software. Existing hypersonic wind tunnels can be used to perform experiments in this area, and provide mature noncontact testing techniques. However, the lack of sensors that can withstand temperatures of 1000 °C and high impact forces leads to difficulties in effectively contact testing many heat flow and heat transfer details. Research on high-temperature-resistant sensors based on silicon nitride, sapphire, platinum alloys, and other materials is expected to solve such problems, although substantial requirements will still be placed on the insulation and refrigeration technologies of sensing systems.

When hypersonic vehicles and spacecraft re-enter the atmosphere, the airflow can reach speeds in excess of Mach 6 and be accompanied by strong aerodynamic heating, air ionization, and aerodynamic load. Moreover, the air is thin at high altitudes and in near-earth space. Therefore, using the Navier–Stokes equations for numerical simulations is inherently difficult. The once-promising idea of adding a needle to the front end of the hypersonic aircraft has largely been abandoned because of the ease of ablation. At present, heat insulation for a spacecraft is mainly achieved by optimizing the aerodynamic shape, preparing a sacrificial layer on the outer surface that will be lost to ablation, and preparing a heat insulation layer on the inner surface. Research has been conducted on drag reduction (or even incidental heat reduction) achievable by the use of reverse jets, plasma boundary-layer control, laser energy deposition, and direction of aircraft exhaust at the bottom of an aircraft.

For high-altitude and high-speed scouting planes, the airflow speed is generally between Mach 2.5 and 6 that leads to strong aerodynamic heating, but generally not to an extensive ionization of the air. These planes ordinarily fly at altitudes of less than 30 000 m in an environment satisfying the conditions of a continuous medium, and therefore they can be analyzed by numerical simulation methods based on the Navier–Stokes equations. The drag can be reduced by adding a needle at the front end of the aircraft, and the heat can be reduced by preparing an insulating layer on the inner surface.

When the problem of nozzle internal flow occurs in jet engines, especially in turbojets and ramjets, the airflow velocity after nozzle expansion is generally above Mach 2.5, and the temperature is often above 1400 °C so that the air is largely a plasma, and the heat exchange is intense. Theoretical analysis based on the Fokker–Planck equation is needed in these circumstances. Research addressing this situation has mainly focused on heat reduction, whether by an ablation sacrificial layer on the outer surface, thermal insulation on the inner surface, or thermally protective jet flow in the boundary layer. A few studies have also explored drag reduction and improvements in engine efficiency, using surface microstructures and jet flow control.

The countries or regions producing the most core papers in engineering development focusing on drag/heat reduction in supersonic flow are China (34), Iran (10), the UK (3), and Azerbaijan (3). The countries or regions with the greatest average number of citations are Iran (29.5), Australia (20), and China (19.15), as shown in Table 1.2.9. Among the top 10 countries or regions, China, the UK, and Azerbaijan display the most cooperation, as shown in Figure 1.2.5. The institutions producing the most core papers are National University of Defence Technology (29), Babol University of Technology (5), and Islamic Azad University (5). The institutions with the highest average number of citations are Babol University of Technology (40), Islamic Azad University (35.8), and Isfahan University of Technology (35.5), as shown in Table 1.2.10. Among the top 10 institutions, Islamic Azad University and Babol Noshirvani University of Technology display the most cooperation, as shown in Figure 1.2.6. The countries or regions with the most citing papers are China (174), Iran (36), and India (22), as shown in Table 1.2.11. The institutions producing the most citing papers are National University of Defence Technology (89), Harbin Institute of Technology (27), and Khazar University (15), as shown in Table 1.2.12.

Table 1.2.9 Countries or regions with the greatest output of core papers on "drag/heat reduction in supersonic flow"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	34	70.83%	651	66.23%	19.15
2	Iran	10	20.83%	295	30.01%	29.50
3	UK	3	6.25%	30	3.05%	10.00
4	Azerbaijan	3	6.25%	29	2.95%	9.67
5	India	1	2.08%	15	1.53%	15.00
6	Japan	1	2.08%	7	0.71%	7.00
7	Australia	1	2.08%	20	2.03%	20.00
8	Pakistan	1	2.08%	8	0.81%	8.00
9	USA	1	2.08%	10	1.02%	10.00
10	Russia	1	2.08%	7	0.71%	7.00

Table 1.2.10 Institutions with the greatest output of core papers on "drag/heat reduction in supersonic flow"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Natl Univ Def Technol	29	60.42%	601	61.14%	20.72
2	Babol Noshirvani Univ Technol	5	10.42%	170	17.29%	34.00
3	Islamic Azad Univ	5	10.42%	179	18.21%	35.80
4	Khazar Univ	3	6.25%	29	2.95%	9.67
5	Babol Univ Technol	2	4.17%	80	8.14%	40.00
6	Isfahan Univ Technol	2	4.17%	71	7.22%	35.50
7	Nanjing Univ Aeronaut & Astronaut	2	4.17%	21	2.14%	10.50
8	Chinese Aerodynam Res & Dev Ctr	2	4.17%	13	1.32%	6.50
9	Amirkabir Univ Technol	2	4.17%	15	1.53%	7.50
10	Indian Inst Space Sci & Technol	1	2.08%	15	1.53%	15.00

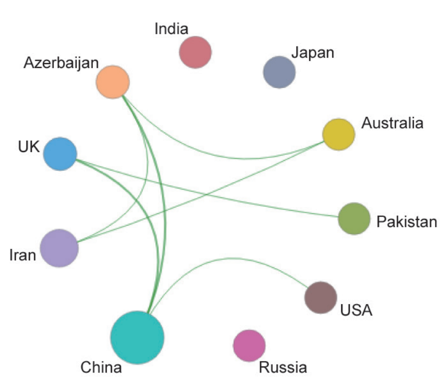

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "drag/heat reduction in supersonic flow"

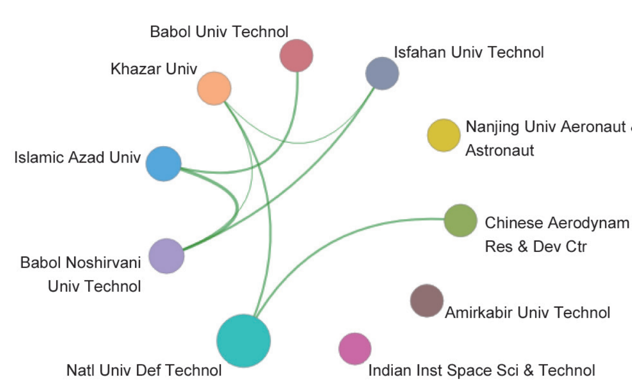

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "drag/heat reduction in supersonic flow"

Table 1.2.11 Countries or regions with the greatest output of citing papers on “drag/heat reduction in supersonic flow”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	174	62.37%	2017.1
2	Iran	36	12.90%	2017.0
3	India	22	7.89%	2017.3
4	Azerbaijan	15	5.38%	2018.0
5	UK	9	3.23%	2017.4
6	France	7	2.51%	2018.0
7	Russia	4	1.43%	2017.3
8	USA	4	1.43%	2017.8
9	Sweden	3	1.08%	2017.7
10	Australia	3	1.08%	2017.7

Table 1.2.12 Institutions with the greatest output of citing papers on “drag/heat reduction in supersonic flow”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Natl Univ Def Technol	89	39.73%	2016.6
2	Harbin Inst Technol	27	12.05%	2017.5
3	Khazar Univ	15	6.70%	2018.0
4	Babol Noshirvani Univ Technol	14	6.25%	2016.7
5	Beihang Univ	13	5.80%	2017.5
6	Nanjing Univ Aeronaut & Astronaut	13	5.80%	2017.8
7	Islamic Azad Univ	12	5.36%	2016.8
8	Northwestern Polytech Univ	11	4.91%	2017.9
9	Isfahan Univ Technol	11	4.91%	2017.0
10	Babol Univ Technol	10	4.46%	2017.3

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

In the previous section, we examined the top ten engineering research fronts in mechanical engineering (broadly defined). In this section, we will examine the top ten development (as opposed to research) fronts in the field (Table 2.1.1). Six of these fronts are characterized by in-depth traditional research: “propulsion systems for near-space hypersonic vehicles,” “design and manufacturing technology of high-efficiency gas turbine engines,” “wave-energy power generation and collection,” “novel high-efficiency hydrogen fuel cells,” “marine electric propulsion systems,” and “development and application of electromagnetic stealth metamaterials for aircraft”. There are also four other fronts that are newly emerging: “human–computer interaction systems based on deep learning,” “3D bio-printing technology,” “visual sensing and recognition for driverless vehicles, and “interception of unmanned aerial vehicles (UAVs).” Table 2.1.2 shows the annual number of core patents published from 2013 to 2018. “Human–computer interaction systems based on deep learning” and “visual sensing and recognition for driverless vehicles” are the most significant directions of patent disclosure in recent years.

(1) Propulsion systems for near-space hypersonic vehicles

A near-space hypersonic vehicle is a high-speed aircraft that is intended to be flown mainly at altitudes in the range of 20–100 km and at speeds above Mach 5. In addition, this

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	Propulsion systems for near-space hypersonic vehicles	217	338	1.56	2015.8
2	Human–computer interaction systems based on deep learning	603	1214	2.01	2017.3
3	3D bio-printing technology	195	363	1.86	2016.7
4	Design and manufacturing technology of high-efficiency gas turbine engines	765	2878	3.76	2015.4
5	Visual sensing and recognition for driverless vehicles	348	1745	5.01	2016.8
6	Wave-energy power generation and collection	147	214	1.46	2015.6
7	Interception of UAVs	121	523	4.32	2016.8
8	Novel high-efficiency hydrogen fuel cells	1464	1918	1.31	2015.5
9	Marine electric propulsion systems	141	176	1.25	2015.7
10	Development and application of electromagnetic stealth metamaterials for aircraft	242	348	1.44	2015.9

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	2013	2014	2015	2016	2017	2018
1	Propulsion systems for near-space hypersonic vehicle	25	42	25	43	33	49
2	Human–computer interaction systems based on deep learning	16	14	23	48	130	372
3	3D bio-printing technology	3	6	29	41	55	61
4	Design and manufacturing technology of high-efficiency gas turbine engines	123	160	112	148	112	110
5	Visual sensing and recognition for driverless vehicles	8	15	33	57	112	123
6	Wave-energy power generation and collection	28	26	15	20	21	37
7	Interception of UAVs	4	7	11	11	43	45
8	Novel high-efficiency hydrogen fuel cells	253	257	216	208	263	267
9	Marine electric propulsion systems	21	24	16	21	39	20
10	Development and application of electromagnetic stealth metamaterials for aircraft	26	40	32	34	53	57

vehicle possesses fast response, strong defense penetration, and flexible maneuvering, all of which belong to a strategic field of competitive development among great countries. Current development work focuses mainly on three types of hypersonic vehicles: cruise vehicles, horizontal take-off and landing vehicles, and reusable space vehicles. Basic technical problems that need to be addressed include the overall design of the aircraft and multidisciplinary optimization; aerodynamic layout taking into account the wide speed and high lift-resistance ratio; hypersonic propulsion; integration of the aircraft/propulsion system; structural thermal protection and energy management; optimization of multifunctional structure design; and advanced highly dynamic control. Of all these, propulsion technology plays a decisive role and is a frontier development field. Ultra-high-speed air-breathing propulsion technology based on hypersonic combustion and expansion of the working boundary is expected to solve the problem of combustion issue and energy conversion in the presence of extremely high air flow. Much work is focused on multi thermal cycle combination and match optimization, as well as cycle work mode conversion, which are the key and premise for promoting the combined aerospace propulsion technology into practical research. The working capability of wide-range efficient combination is the basic support that requires the integration of thermal cycle optimization, advanced combustion organization, flow control, lightweight structure, and residual control to improve the comprehensive efficiency of the full-speed domain.

(2) Human–computer interaction systems based on deep learning

Human–computer interaction (where the “computer” can be either hardware or software) has increasingly been studied using AI technology such as deep learning. This leads to the development of the new generation of intelligent interactive systems that are able to receive and process peripheral instructions, text, speech, gestures, expressions, and other inputs from human users and to output information in the ways that humans perceive as natural. Deep learning has achieved more significant results in speech recognition, image recognition and segmentation, and machine translation than any previous technology. However, it still faces many issues, such as the syntax ambiguity in speech, boundaries definition of word, and semantics ambiguity. Similarly, there are multiple objects and targets, and the dependencies between the foreground and its background in image recognition. There are many different training methods for deep learning, e.g., single- and multi-node multi-graphics processing units (GPUs). But the training of deep learning involves very high energy consumption. Nevertheless, in future human–computer interaction systems, deep learning seems certain to retain its dominant position, and it is still the most challenging point.

(3) 3D bio-printing technology

In recent years, the manufacturing and regeneration of live tissues and even organisms have become feasible. The integration of manufacturing technology with biology demonstrates the extraordinary advance of modern science and technology, and is certain to have even greater industrial value in the future. One area in which great technical progress has been made is the use of 3D printing to manufacture or repair living biological tissues and organs. Research has been largely moved forward in the following directions. 1) Manufacture of complex biological structures. The focus is on further studying human functional organs (e.g., heart tissue). This involves understanding the nerve signal regulation; converting simple mechanical support tissues into functional tissues through neuroregulation; analyzing the symbiotic fusion of 3D printed and human host tissues, and realizing the regeneration and functional recovery of human organs. 2) Brain tissue manufacturing *in vitro* with the assistance of 3D printing. This involves the bionic design and precision manufacture of various types of neuron, and the ability to print neuron combinations corresponding to the targeting functional site. 3) Bioenergy transformation organization, i.e., building and efficiently controlling devices such as artificial muscles and bio-batteries that convert or release energy more efficiently, and develop efficient devices for energy storage and release for soft tissue. 4) Biomechanical symbiosis that involves the development of manufacturing technology of multi-cell types and multi-materials to build hybrid robots with living tissues or organs with flexible motion, to provide an innovative manufacturing foundation for such lifelike soft robots.

(4) Design and manufacturing technology of high-efficiency gas turbine engines

Gas turbine engines, especially aircraft engines, have been at the forefront of engineering development as technological progress imposes ever more stringent requirements for materials, design, and manufacturing. These engines have been called the “jewels in the crown of the industry.” To improve the performance of gas turbine engines, the following lines of development are being actively pursued: 1) design and manufacturing of blades, including the development of low aspect-ratio, hollow, resin- and ceramic-based composite, single crystal, cast cool, and super-cooling blades; 2) design and manufacturing of bladed disks and rings, including powder-metallurgical superalloy turbine, titanium alloy, hollow double-spoke turbine, hot isostatic pressed and molded, superplastic isothermally forged, and counter-rotating disks and rings; 3) low-emission combustion technologies, including lean oil direct mixing, lean premixed pre-evaporation, partial evaporation with rapid mixing, lean direct injection (LDI), and multipoint LDI (MP-LDI); 4) design and manufacturing of coatings, including thermal-barrier ceramic and wear-resistant coatings; and 5) complex structure additive manufacturing and design integration, including complex shell structures for the control and injection of fuel.

(5) Visual sensing and recognition for driverless vehicles

Driverless technology can be divided into three modules: perception, decision-making, and control. Environmental awareness is both the key to achieving completely driverless vehicles and the main factor limiting the development of such vehicles today. At present, driverless vehicles rely on cameras and laser radar for recognition of their surroundings. Vision-based environmental perception systems contain more image information than radars. Monocular cameras have fast operating speeds but can only capture single images and miss scene-depth information. Binocular stereo-vision is favored by many researchers because it is relatively simple, is only slightly influenced by lighting, and provides abundant information that can be used to identify road conditions. In recent years, 3D vision reconstruction using real-time stereo-matching has been rendered practical by improvements in computer hardware. The analysis and processing of images for visual recognition are usually implemented with convolutional neural networks. From the collected image information, the traffic scene can be intelligently identified and predicted, thereby reducing the occurrence of traffic accidents and injuries. An increasing number of research institutions and universities are now working on such vision-based assisted-driving and driverless systems.

(6) Wave-energy power generation and collection

Wave energy, a type of renewable clean energy, has a high density and wide distribution surface. The development and utilization of such energy could be important in addressing the energy crisis, environmental pollution, and climate change. Scientific research on wave energy mainly aims at two goals. The first is to evaluate reserves of wave energy and their temporal–spatial distribution, thereby providing effective guidance for the design of wave energy power stations and conversion devices. The second is the design, development, and experimental operation of wave energy power conversion and generation devices. At present, the main methods of wave energy power generation are the oscillating float, cross-wave, oscillating water column, and soft bladder methods. Compared with the other possibilities, the offshore oscillating float has a simpler structure, lower cost, more flexible location, more convenient transportation and maintenance, and higher efficiency, making it the mainstream technology of wave energy power generation at present. However, offshore devices can easily be affected by catastrophic events in the complex and variable marine environment. Moreover, ocean waves possess many challenging features, such as their instability, huge reserve, wide distribution, and difficult utilization. Many difficult tasks regarding the use of wave energy resources in power conversion and power collection still remain to be undertaken. These include deepening the understanding of nonlinear waves, optimizing the design of wave energy devices, improving their response speed and conversion efficiency, enhancing their stability and reliability, and reducing the manufacturing, installation and maintenance costs.

(7) Interception of UAVs

With advances in information, control, communication, and other fields of technology, UAVs have come into widespread use in the civil and military fields. The problem of illegally flown UAVs poses a serious threat to public safety and even national security. Therefore, countermeasures should be developed as soon as possible. At present, anti-UAV technology mainly involves direct detection and interception. The former utilizes ground-view reconnaissance, radar detection and tracking, aerial early warning, and satellite reconnaissance technologies to detect and track UAVs accurately. The latter includes electronic countermeasures (interference blocking); ground fire and high-energy laser weapons (damage capture); and monitoring and control technology based on photoelectric, radar, and other monitoring systems with data-chain interference technology. Although interference blocking is simple, low-cost, and utilizes easy-to-carry systems, the electronic countermeasure signals are highly demanding on the environment and susceptible to the influence of other electromagnetic signals in space. Moreover, this technology is ineffective against UAVs which are not controlled externally. Damage capture is suitable for complex environments, but it is complex and expensive, and it causes permanent damage to the UAVs, interfering with evidence collection. To enable the efficient identification and capture of UAVs in complex environments, an anti-UAV technology should be developed that is portable, uses intelligent tracking, and incorporates a multi-means multilevel defense system.

(8) Novel high-efficiency hydrogen fuel cells

To address both energy shortage and environmental pollution, increasing attention has been paid throughout the world to the development of green and efficient energy technology. Hydrogen fuel cells convert the chemical energy in hydrogen into electrical energy through chemical reactions. This technology has attracted increasing attention owing to its freedom from pollution, high energy-conversion efficiency, and other advantages. However, it has several shortcomings, such as the high cost of hydrogen production, the immaturity of hydrogen storage technology, and the incompleteness of the hydrogen transmission system. Novel high-efficiency hydrogen fuel cells technology is a core cutting-edge technology in the new-energy field. Development focuses on the core materials of hydrogen fuel cells; design of advanced and high-performance hydrogen fuel cell reactors and key auxiliary system components; hybrid fuel cell power systems; hydrogen production, transportation, and storage; and construction of a refueling infrastructure. The transition from carbon energy to hydrogen energy will be ongoing, and hydrogen fuel cells will realize their value in new-energy vehicles, distributed power generators, and other applications.

(9) Marine electric propulsion systems

Propulsion system is generally composed of a power station, power station management system, power distribution system, speed control system, propulsion motor, monitoring system, and propeller. The ship is propelled by the propulsion motor that drives the propeller or other actuators. This system is widely used on large tankers, surface warships, engineering ships, submarines, and other types of ships. Power generation, propulsion motor improvements, harmonic suppression, electronic automation, high-power energy storage, power supply and distribution, and motor control technologies are all subjects of active current development. Modeling and simulation will also play an important role in improving the performance of electric propulsion systems on ships. Particularly important goals of current development work include the following: 1) replacing the DC electric propellant and AC/DC electric propulsion system with an AC electric propulsion system; 2) developing superconducting power propulsion; 3) developing a submarine fuel cell propulsion system to replace lead-acid batteries; 4) meeting high-power requirements with magnetic fluid propellants, water-spraying thrusters, and other high-efficiency thrusters; and 5) developing integrated all-electric propulsion systems.

(10) Development and application of electromagnetic stealth metamaterials for aircraft

Electromagnetic metamaterials are artificially structured materials containing sub-wavelength arrays of plasmonic resonators engineered to present optical properties that are usually either difficult or impossible to obtain in naturally occurring materials and composites. The traditional principle of aircraft stealth is to reduce detectability either by changing how the radar wave is reflected or by absorbing it. Metamaterials, however, can actually change the propagation route of the wave (i.e., bend it) to achieve orbiting and stealth, thereby providing a new research perspective for radar stealth absorption materials. Aircraft electromagnetic stealth metamaterials need to be thin and light, with an absorption bandwidth sufficient to cover the lightning and infrared bands, strong enough to resist impact and corrosion, and easy to maintain. Although some significant progress has been made, several problems, such as limited bandwidth, significant increase, complexity, and difficultly in large-scale manufacture, remain to be solved. In view of these problems, research on the electromagnetic stealth metamaterials of aircraft mainly focuses on the following topics: 1) broadband metamaterials with good absorption properties; 2) tunable active metamaterials; 3) flexible electromagnetic stealth metamaterials, and 4) 3D printing of electromagnetic stealth metamaterials.

2.2 Interpretations for three key engineering development fronts

2.2.1 Propulsion systems for near-space hypersonic vehicles

(1) Ultra-high-speed air-breathing propulsion systems

Dynamic propulsion at relatively low speeds (subsonic and supersonic) is already a mature technology; hypersonic air-breathing (ramjet) propulsion with Mach numbers $< 6–7$ is a developing and maturing one. Therefore, the frontier of development is ultra-high-speed air-breathing propulsion technology at even greater Mach numbers. Such a technology is an inevitable choice for the space industry that now requires a higher and wider speed domain than ever before. When the flying Mach number exceeds 10, the Mach number in the combustion chamber after the compression of the air-in channel correspondingly increases, even reaching the hypersonic combustion regime ($Ma \geq 5$). Therefore, combustion issue and energy release under extremely high-speed conditions have become the primary technical difficulties in this field, which the USA and Australia have been particularly interested in exploring. The second flight test of the X-43A, conducted by NASA in 2004, was the first time that combustion was observed in an ultra-high-speed air-breathing super-combustion stamping engine with flight Ma = 10, as well as the first occasion that the propulsion system was shown to work in practice. Afterwards, the USA and Australia jointly executed the HyShot, HyFire, HyCAUSE, and other flight test verification programs, which focused on reaching a flying Ma of 8–12 (ultra-high-speed flow). They also conducted basic research on combustion and achieved outstanding progress in ultra-high-speed air-breathing propulsion system verification. To solve the difficulty of fuel-air mixing and utilize the advantages of premixed, shock wave-induced combustion, engine precursor fuel injection was emphasized, and the shock induced combustion ramjet (SHC ramjet) has become the subject of intensive research.

(2) Wide-area combined cycle propulsion systems

The outstanding feature of the proposed horizontal take-off and landing hypersonic aircraft (other than its flying Mach number) is its broad flight range, with working stages ranging from the subsonic to the hypersonic. This greatly exceeds the working capability of existing traditional power propulsion systems, so combined cycle propulsion has becomes possible choice. It solves the problem of wide-area working capability, and it also achieves high-performance across the wide speed domain. At present, two types of combined cycle propulsion schemes based on traditional power have been developed, namely, rocket-based and turbo-based combined cycles. However, challenges in terms of performance, engineering implementation, and task suitability still exist. Even so, combined cycle propulsion schemes with wide adaptability and high performance remain at the cutting edge so far as optimization of power composition and the thermal cycle are concerned. Combined cycle propulsion systems based on turbine, ramjet, and rocket represent an important development direction. In recent years, the former US aerospace company Aerojet has experimented with a “TriJet” three-way cycle propulsion scheme in which the pilot rocket ramjet channel is used to solve the problems of wide-speed range and modal conversion relay. The British company Reaction Engines, Ltd., has proposed a combined cycle synergistic air-breathing rocket engine that integrates turbine, rocket, and ramjet features with deep pre-cooling technology. Considering the needs of practical research and development, engineers should focus on solving the key problems of thermal cycle matching optimization, system integration, and dynamic mode conversion.

(3) Detonative propulsion technology

The release and conversion of chemical energy through fuel combustion is critical for propulsion systems; two processes are involved, namely, deflagration and detonation. Traditional aerospace power propulsion devices based on deflagration have developed to a mature stage, but can hardly improve their performance and propulsion efficiency. Detonation features an ultrasonic combustion wave closely coupled with a shock wave, and it is a self-compressed combustion mode described by similarity equations. The thermal efficiency of detonation is higher than that of isobaric combustion. Detonation is expected to break through the existing energy cycle efficiency bottleneck and become an inevitable choice for propulsion technology due to its high performance. At present, the research in this area mainly focuses on the detonating combustion organization mode. Pulse, continuous, and stationary detonation engines have been introduced and investigated. Detonative combustion is gradually changing from a theoretical research topic into one with practical applications. Among the varieties of detonation engine, the continuous rotating mode has the most potential and is expected to trigger a major transformation of spaceflight. At present, mastering the propagation mechanism of controlled continuous detonation is the core problem to be solved. The integration of the detonative combustion mode with traditional power types (turbine, stamping, and rocket) in a combined cycle is also critical for future progress.

The top three countries in this field in terms of core patent disclosure volume are China (100), the USA (51), and Russia (40), whereas the top three countries in terms of the average number of citations are the USA (3.43), Canada (2.75), and China (1.53) (Table 2.2.1). Cooperation exists among the USA, China, and Canada, as displayed in Figure 2.2.1. The three institutions with the most core patent disclosures are Nanjing University of Aeronautics and Astronautics (15), Xiamen University (8), and Boeing Co. (7) (Table 2.2.2). From the current sample data, little cooperation is present among the major patent-producing institutions (Figure 2.2.2).

2.2.2 Human–computer interaction systems based on deep learning

In modern world, it is increasingly important that computers are able to naturally interact with humans by receiving and processing text, voice, gestures, expressions, gaze,

Table 2.2.1 Countries or regions with the greatest output of core patents on "propulsion systems for near-space hypersonic vehicles"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	100	46.08%	153	45.27%	1.53
2	USA	51	23.50%	175	51.78%	3.43
3	Russia	40	18.43%	8	2.37%	0.20
4	South Korea	6	2.76%	1	0.30%	0.17
5	Canada	4	1.84%	11	3.25%	2.75
6	India	4	1.84%	0	0.00%	0.00
7	France	3	1.38%	2	0.59%	0.67
8	Germany	3	1.38%	1	0.30%	0.33
9	Brazil	2	0.92%	1	0.30%	0.50
10	Japan	2	0.92%	1	0.30%	0.50

Table 2.2.2 Institutions with the greatest output of core patents on "propulsion systems for near-space hypersonic vehicles"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UNUA	15	6.91%	40	11.83%	2.67
2	UYXI	8	3.69%	16	4.73%	2.00
3	BOEI	7	3.23%	20	5.92%	2.86
4	UNBA	5	2.30%	7	2.07%	1.40
5	UNDT	5	2.30%	6	1.78%	1.20
6	BEIT	5	2.30%	2	0.59%	0.40
7	ACFL	4	1.84%	13	3.85%	3.25
8	CAMH	4	1.84%	8	2.37%	2.00
9	UNAC	4	1.84%	5	1.48%	1.25
10	CAER	4	1.84%	3	0.89%	0.75

UNUA: Nanjing University of Aeronautics and Astronautics; UYXI: Xiamen University; BOEI: Boeing Co.; UNBA: Beihang University; UNDT: National Defence University of People's Liberation Army; BEIT: Beijing Institute of Technology; ACFL: Advanced Ceramic Fibers LLC; CAMH: Institute of Mechanics, Chinese Academy of Sciences; UNAC: United Technologies Corp.; CAER: Beijing Institute of Near Space Vehicles System Engineering.

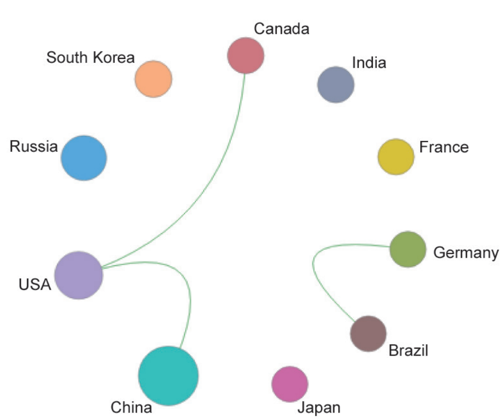

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of "propulsion systems for near-space hypersonic vehicles"

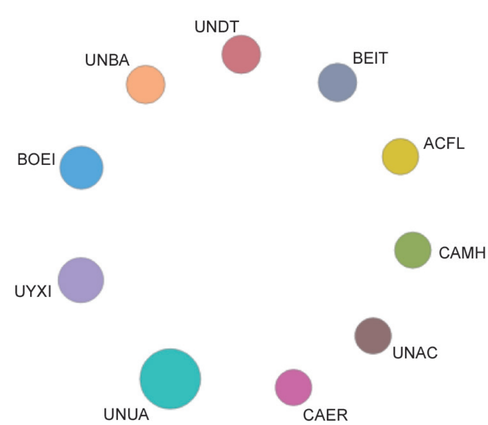

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "propulsion systems for near-space hypersonic vehicles"

and peripheral instructions as input, and ideally providing output in these forms when possible. In recent years, human–computer interaction systems have been gradually implemented into many real applications, such as the speech recognition in car navigation system; the motion recognition in wearable computers, stealth technology, and immersive games; haptic interaction technology in virtual reality; remotely controlled robots and telemedicine; the speech recognition in call routing, home automation and speech dialing; the silent speech recognition technology, for people with language impairments; the eye tracking technology for advertising and other websites; and brain-wave based human–computer interface systems for people with language and mobility impairments. However, many problems are yet to be addressed in these systems, including low rates and high time delay of vision-based gesture recognition, the low accuracy of the image-based multi-target recognition and segmentation as well as the high time and energy consumption for dealing with large amounts of data. New algorithms are urgently needed to improve accuracy and efficiency.

The research on human–computer interaction system has naturally focused on deep learning for complex pattern recognition that has achieved remarkable results in data mining, image recognition and segmentation, machine translation, natural language processing, multimedia learning, speech recognition, recommendation and personalization technology. However, deep learning-based human–computer intelligent interaction systems still have many issues, such as the syntax ambiguity in speech, boundaries definition of word, and semantics ambiguity. Similarly, there are multiple objects and targets, and the dependencies between the foreground and its background in image recognition. There are many different training methods for deep learning, e.g., single- and multi-node multi-GPUs. But the training of deep learning involves very high energy consumption. Nevertheless, the further study should be based on the real applications, investigate the new deep learning models to increase the final accuracy and recognition speed, and eventually enable machines with analytical learning capabilities to process text, images, sound, and other data accurately in real time in human level.

The top three countries in this field in terms of core patent disclosure volume are the USA (231), China (225), and South Korea (57), whereas the top three countries or regions in terms of the average amount of citations are Canada (4.9), the USA (4.31), and India (2.45) (Table 2.2.3). Cooperation exists between the USA and Canada, as well as the USA and China, as illustrated in Figure 2.2.3. The top three institutions in terms of core patent disclosures are International Business Machines Corporation (28), Sichuan Yonglian Information Technology (13), and Samsung Electronics Co., Ltd. (10) (Table 2.2.4). From the current sample data, little cooperation is present among the major patent-disclosing institutions (Figure 2.2.4).

2.2.3 3D bio-printing technology

Further to the usage of traditional materials such as wood, metal and silicon, the manufacturing technology has been progressed to build living matters. During this still-incomplete transition, the function-driven innovation in the new products should be encouraged, which could be carried out in the following directions.

(1) Design and manufacture of the function-based living organ structure

To develop the cell/gene based structural and functional design theory, one should fully understand the progressing characteristics of self-growth for the living organisms. The existing mechanical design theory, which was solely based on structural design and mechanical function, needs to be transformed to focus on the integration of structure, stimulator, function and progressing. Future design methods should incorporate such characteristics of life as biological stimulators, functional symbiosis, and evolution. The laws governing the self-reproduction and self-replication of cells and genes should be better understood, so that the designed artificial structures can better emulate the behavior and life cycle of natural ones. The manufacture and engineering control of biodegradable, activatable, and growable structures should also be studied.

(2) Regulation and maintenance of 3D printed life units

In 3D cell printing, the living organ unit is the basis for tissue growth and development. The organic combination of organic cells or genes is the core of late functional presentation, and the accumulation of living organ units of single cell and gene at micro-/nano-scale is normally required during the manufacturing process. The principle of accumulation and the relationship between its effects should be comprehended, in order to maintain the adjustable probability in terms of the 3D

Table 2.2.3 Countries or regions with the greatest output of core patents on "human–computer interaction system based on deep learning"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	231	38.31%	995	81.96%	4.31
2	China	225	37.31%	91	7.50%	0.40
3	South Korea	57	9.45%	19	1.57%	0.33
4	Japan	26	4.31%	7	0.58%	0.27
5	India	20	3.32%	49	4.04%	2.45
6	Canada	10	1.66%	49	4.04%	4.90
7	Germany	5	0.83%	0	0.00%	0.00
8	Israel	4	0.66%	3	0.25%	0.75
9	Ireland	4	0.66%	0	0.00%	0.00
10	Australia	3	0.50%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "human–computer interaction system based on deep learning"

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	IBMC	28	4.64%	67	5.52%	2.39
2	SYIT	13	2.16%	0	0.00%	0.00
3	SMSU	10	1.66%	10	0.82%	1.00
4	MICT	8	1.33%	8	0.66%	1.00
5	EBAY	6	1.00%	1	0.08%	0.17
6	INEI	6	1.00%	1	0.08%	0.17
7	AMAZ	5	0.83%	68	5.60%	13.60
8	PURS	5	0.83%	6	0.49%	1.20
9	BAI	5	0.83%	3	0.25%	0.60
10	DRTC	5	0.83%	0	0.00%	0.00

IBMC: International Business Machines Corp.; SYIT: Sichuan Yonglian Information Technology; SMSU: Samsung Electronics Co., Ltd.; MICT: Microsoft Corp.; EBAY: Ebay Inc.; INEI: Jinan Inspur High & New Technology Investment; AMAZ: Amazon Technologies Inc.; PURS: Pure Storage Inc.; BAI: Bonsai AI Inc.; DRTC: Dalian Roiland Technology Co., Ltd.

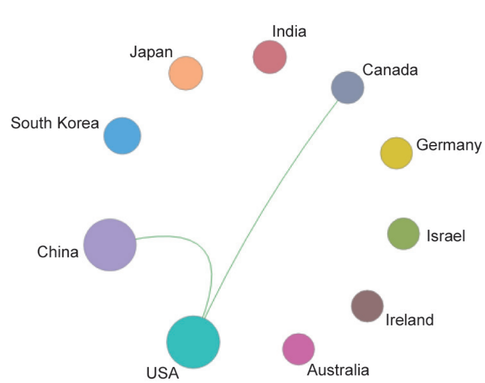

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "human–computer interaction system based on deep learning"

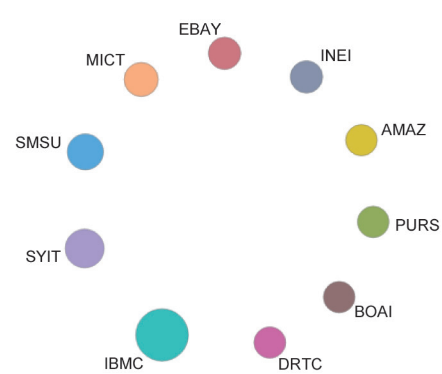

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "human–computer interaction system based on deep learning"

structure and time-dependent function. The most important feature of 3D printing is the application of living organs, and the activity of the living organs is essential. Therefore, the physiological and biological environment needs to be adopted in the printing process, including the supplement of nutrients and the necessary gases, etc.

(3) Function formation mechanisms and component function formation

It is not enough to simply print an exact copy of a biological structure, since the structure's eventual function must also be considered, and the relationship between function formation and the design and manufacturing process should be understood and developed. Multicellular systems especially change their functions over time, even on short time scales, for example by releasing energy (as muscle cells do), or by transferring information through intercellular interaction (as neurons do). These time-dependent patterns of functionality and change must be understood and emulated for the development of multi-functional devices.

(4) Manufacturing and functional evaluation of multifunctional devices or organizations

Based on the understanding of the development, functional growth, and structure of living organ units from an engineering point of view, to design a living organ with the prerequisite structure and functional growth characteristics, the following problems should be tackled: 1) how to adjust the cell or gene combinations via 3D printing technology, 2) how to control the printing process to reduce the damage for cells, and 3) how to regulate or stimulate the function of the formed organ or device. Moreover, the effects of 3D printing on function formation should be investigated; biological functions should be evaluated and measured; systematic research should be developed starting from the life units, functional design, undamaged printing to the forming of function, to provide technology for the manufacturing of life organ or devices.

(5) Brain-inspired design and manufacture

Deep learning of AI is based on model hypothesis, data training, accumulative learning, and even by the use of bio-inspired genetic algorithms to evolve, for example, airplanes instead of birds. Brain-inspired technology includes implanting chips into re-created or artificial brains using 3D printing methods, building powerful biochips by learning the interconnection of neurons, or using genes to imitate a living brain. Moreover, how to connect the manmade brain with the host tissue for information collection, decision making or motion actuating remains an innovative research field.

The top countries or regions in terms of core patent disclosure volume in this field are China (143), the USA (28), and South Korea (6), whereas the top three countries or regions in terms of the average number of citations are Sweden (21.5), the USA (3.11), and Japan (1.25) (Table 2.2.5). Collaboration exists between the USA and Sweden as well as the UK and Italy, as shown in Figure 2.2.5. The top three institutions with core patent disclosures are Xi'an Jiaotong University (6), Tsinghua University (5), and Jilin University (4) (Table 2.2.6). From the current sample data, no cooperation is present among the major patents output institutions (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents in the engineering development front of "3D bio-printing technology"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	143	73.33%	177	48.76%	1.24
2	USA	28	14.36%	87	23.97%	3.11
3	South Korea	6	3.08%	0	0.00%	0.00
4	Japan	4	2.05%	5	1.38%	1.25
5	Taiwan of China	3	1.54%	3	0.83%	1.00
6	Sweden	2	1.03%	43	11.85%	21.50
7	Germany	2	1.03%	3	0.83%	1.50
8	Italy	2	1.03%	1	0.28%	0.50
9	UK	2	1.03%	0	0.00%	0.00
10	India	2	1.03%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of “3D bio-printing technology”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYXJ	6	3.08%	11	3.03%	1.83
2	UYQI	5	2.56%	3	0.83%	0.60
3	UYJI	4	2.05%	40	11.02%	10.00
4	EBAY	4	2.05%	26	7.16%	6.50
5	CAAT	4	2.05%	6	1.65%	1.50
6	UYZH	4	2.05%	6	1.65%	1.50
7	XPCB	4	2.05%	5	1.38%	1.25
8	USWCH	4	2.05%	4	1.10%	1.00
9	UYPO	4	2.05%	0	0.00%	0.00
10	UYBC	3	1.54%	6	1.65%	2.00

UYXJ: Xi’an Jiaotong University; UYQI: Tsinghua University; UYJI: Jilin University; EBAY: Ebay Inc.; CAAT: Shenzhen Institute of Advanced Technology; UYZH: Zhejiang University; XPCB: Xi’an Particle Cloud Biotechnology Co., Ltd.; USWCH: West China Hospital, Sichuan University; UYPO: Postech Acad-Ind Found; UYBC: Beijing University of Chemical Technology.

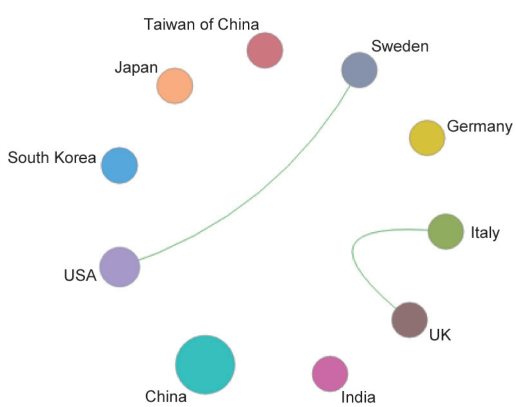

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “3D bio-printing technology”

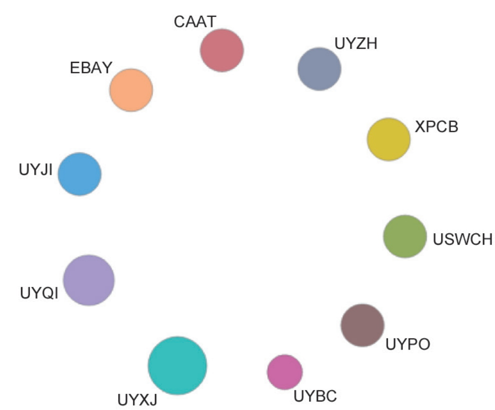

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “3D bio-printing technology”

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