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Strategic Research on Disruptive Technologies in Mechanical and Vehicle Engineering

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Abstract: Existing and potential disruptive technologies in the fields of mechanical and vehicle engineering were identified through a literature review and expert interviews; these include bionic intelligent technologies, shaftless rim propulsion technologies, intelligent unmanned aerial vehicle technologies, ultra-loop train technologies, and microelectromechanical systems. The innovative and disruptive advantages of these five technologies were analyzed. Finally, recommendations were made for the development of such disruptive technologies in mechanical and vehicle engineering.
Keywords: mechanical and vehicle engineering; disruptive technologies; bionic intelligent technology; shaftless rim propulsion technology; intelligent unmanned aerial vehicle technology; ultra-loop train technology; MEMS

1 Introduction

Every technological, industrial, and energy revolution in history was accompanied by the emergence of disruptive technologies. For example, radio and aircraft technologies emerged during World War I; radar, digital computer, missile, and nuclear technologies emerged during World War II; integrated circuits, artificial satellites, and laser technologies emerged during the Cold War; and the Internet, global positioning systems, and stealth technologies thrived after the Cold War. These disruptive technologies, accompanied by continuous improvement in their performance and functions, eventually replaced conventional technologies and introduced new markets. From the perspective of historical evolution, a country can only maintain its leading position in the world with a keen understanding, mastery, and development of disruptive technologies. The United States, Russia, and many other countries have established specialized agencies to accelerate research on disruptive technologies. China should also conduct research on disruptive technologies to discover and capitalize on new opportunities.

Strategic research on disruptive technologies in mechanical and vehicle engineering covers a wide range of technical fields, including more than 10 sub-fields, such as machinery, microelectromechanical systems (MEMS), additive manufacturing, robotics, aviation, aerospace, marine vehicle equipment, automobiles, rail transit, and integrated vehicles. Almost all the industries involved are large-scale, technology-intensive, and highly correlated, and have become a strategic focus for many countries.

The wide development of various technologies characterized by innovation and high technology has motivated each country to seize the opportunity and take advantage of the rapid development in the field of mechanical and

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vehicle engineering and identify disruptive technologies in a timely and accurate manner; thus occupying a leading position with regard to global technology development.

2 Current development of disruptive technologies in mechanical and vehicle engineering

The Department of Mechanical and Vehicle Engineering of the Chinese Academy of Engineering is divided into mechanical engineering; ship and ocean engineering; aerospace science and technology; weapon science and technology; power and electrical equipment engineering and technology; and transportation engineering. There are many disciplines in these fields, and engineering technology is developing rapidly. According to a literature review and expert interviews, disruptive technologies in the fields of mechanical engineering, aerospace, marine vehicle equipment, and rail transit were identified.

2.1 Developments in mechanical engineering

2.1.1 Intelligent manufacturing technology

Intelligent manufacturing is the core technology for developing an extensive and robust manufacturing industry. Enterprises have emerged in China to actively formulate and implement their own plans for developing intelligent manufacturing. This technology will be vigorously developed and widely applied in China’s manufacturing industry.

2.1.2 Potential disruptive MEMS applications

In the future, four trends will redefine the market for MEMS: new devices, such as micro-mirrors and environmental sensors; new applications, such as pressure sensors for position (height) sensing; disruptive technologies, including packaging, new materials (e.g., piezoelectric thin films and 300-mm/12-inch wafers; 1 inch ≈ 3.333 cm), and new designs such as nanoelectromechanical systems and optical integration technology.

2.2 Developments in aerospace vehicles

Autonomous unmanned systems include the four following types: unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned surface vessels (USVs), and unmanned underwater vehicles (UUVs) [1]. Such systems can function independently within specific boundaries and perform self-selection through rules and strategies. They can also learn autonomously, improve strategies, and even make optimal choices in unpredictable circumstances for achieving established goals and tasks. Autonomous unmanned systems are advanced systems that demonstrate high levels of intelligence and involve many disciplines and categories.

China has demonstrated remarkable achievements in autonomous unmanned systems, but the development of key technologies is mutually independent for different types of unmanned systems, such as UAVs, UGVs, USVs, and UUVs. Moreover, no cooperation mechanism has been developed in the research and application of generic technologies, such as autonomous control, measurement control and communications, interoperability, and high-precision navigation in military and civilian unmanned systems. Overall, the level of China’s autonomous unmanned systems is below those of international technology.

The technological inflection points for autonomous unmanned aerial systems mainly include unmanned-system machine learning, manned/unmanned fast-switching robots, miniature flapping-rotor aircraft, intelligent cluster technology, near-space superhigh-speed UAVs, and environmental awareness. It is expected that unmanned-system machine learning and manned/unmanned switching robot technology will be realized and applied around 2020; miniature flapping-rotor aircraft and near-space superhigh-speed UAVs will achieve great breakthroughs around 2025; major breakthroughs will be made in autonomous unmanned aerial system technology after 2030; and widespread application of these technologies will be achieved around 2035.

2.3 Developments in marine vehicle equipment

With regard to ecofriendly marine technology, the energy efficiency design index (EEDI) rules formulated by the International Maritime Organization have been in effect since January 2013. To enter the international market, shipbuilding enterprises and equipment suppliers must transform ships that do not meet the EEDI requirements [2]. The major global ship research institutions, advanced shipbuilding enterprises, and related research entities are researching and developing novel energy-driven ships (e.g., liquefied natural gas fuel, wind-sail diesel engine hybrid power, and fuel-cell propulsion ships), novel green ships (high-efficiency and energy-saving), ecofriendly and pollution-free paints, ballast-water-free ships, low-emission and high-efficiency power plants, lightweight materials, and other technologies.

Table 1 presents predictions of the maturity and technological inflection points of autonomous unmanned technology.

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Table 1. Maturity and technological inflection points of autonomous unmanned technology.

Technology name	Technical maturity	Predicted technological inflection points
Manned/unmanned fast-switching robot technology	Level 6	Around 2020, visual perception and location technology will see practical applications. Furthermore, manned/unmanned fast-switching driving robot technology will see great breakthroughs, e.g., ground driving vehicles, owing to improvements in the control system and execution system technology.
Miniature bionic air vehicle technology	Level 5	Around 2025, progress will be made in aircraft design technology, MEMS manufacturing, and energy batteries. The size limitation of the original bionic aircraft will be surpassed, and the practical development of centimeter- and millimeter-scale micro-bionic aircraft technology will be realized, driving the development of micro-bionic technology.
Intelligent cluster technology	Levels 4 and 5	Around 2025, progress will be made in individual intelligent autonomous and group collaborations; breakthroughs will be achieved in group awareness and situation sharing technology; self-networking communications of intelligent clusters will see practical applications; and the practical development of intelligent cluster technology will be promoted.
Unmanned-system machine-learning technology	Levels 3 and 4	Around 2025, machine learning algorithms will be developed for completing new tasks, gradually expanding from the field of UGVs to unmanned aerial and maritime systems, which will promote the wide application of unmanned-system machine-learning technology.
Autonomous unmanned system technology	Levels 3−5	Around 2030, manned/unmanned fast-switching driving robots, bionic aircraft, intelligent cluster technology, autonomous environmental awareness technology, and unmanned-system machine learning are expected to achieve landmark results and promote the practical development of autonomous unmanned system technology.

2.4 Developments in rail-transit technology

Innovations for the comprehensive and systematic improvement of active safety assurances, coordinated optimization of transport organization, interconnection, and whole-process service have become a major trend in the development of global rail-transit science and technology; however, it is still a weakness in China's rail transit.

China has not yet realized cotransport with various means of transportation; thus the strengthening of the interconnection and emergency handling linkage among various modes of regional rail transit is a matter of urgency. The standardization, serialization, and intellectualization of energy-supply system technology and equipment for rail transit, as well as the innovative application of new energy sources and energy-utilization modes, have become the main focus of the development of energy-related technology for rail transit.

3 Prospects for disruptive technologies in mechanical and vehicle engineering

3.1 Prospects for mechanical engineering

According to the literature, MEMS is a disruptive technology in the field of mechanical engineering. Moreover, disruptive technologies are suspected to exist in technical fields, such as high-end computer numerical control machine tools, advanced forming equipment, key mechanical basic parts, there-dimensional printing, and robots.

MEMS technology, which is supported by micro-nanoscale theory, can achieve functions such as micro-sensing, micro-processing, micro-control, micro-transmission, and micro-confrontation by integrating micromechanics, microelectronics, micro-optics, micro-energy, micro-flow, and other technologies based on micro-nano manufacturing. The integration of functional modules can lead to single- or multi-purpose frontier technologies [3]. MEMS technology, which has been increasingly used in recent years, has interdisciplinary characteristics and wide applications, and its continuous development is of great significance for maintaining China's technological leading position.

3.2 Prospects for aerospace vehicles

3.2.1 Existing and suspected disruptive technologies in aerospace

The disruptive technology in aerospace vehicle engineering is greatly influential. It is important for China to identify and develop disruptive technologies in aerospace vehicle engineering and strategically take advantage of the new technological, industrial, and military revolutions.

According to recent technological developments in aeronautics and astronautics, as well as technological breakthroughs in the basic disciplines, the existing and suspected disruptive technologies were identified according to three technological categories: energy and power, aircraft, and spacecraft technologies. The energy and power technology fields include vertical takeoff and landing engines, scramjet engines, solar aircraft, and all-electric aircraft. The aircraft technology fields include supersonic passenger aircraft, unmanned intelligence, aircraft carriers, ultralong-endurance UAVs, and bionic intelligent cluster technology. The spacecraft technology fields include reusable rockets, large rockets, and interstellar high-speed aircraft.

3.2.2 Scramjet technology

The hypersonic aircraft is “another milestone of trans-era significance after the invention of the aircraft, breaking through the sound barrier and entering space and is another development direction in the field of aeronautics and astronautics in the future” [4]. When a hypersonic aircraft is flying at speeds above Mach 5, it must use a scramjet to complete its mission. As the core technology of hypersonic aircraft, scramjet technology will promote breakthroughs in air-breathing jet engines. The scramjet is suitable for long-term supersonic or hypersonic flight in the atmosphere or across the atmosphere, boasting characteristics such as a simple structure, a low cost, easy maintenance, and a good performance.

3.2.3 Bionic intelligent cluster technology

Bionic intelligent cluster technology is based on bionic micro-air vehicles and intelligent cluster technology. The development of bionic aircraft will lead to breakthroughs in the design concepts and technical constraints for the design process of large spacecraft. Miniature air vehicles (MAVs) have the potential of providing excellent concealment and can fly in narrow spaces. MAV research has made little progress and is facing technical bottlenecks with regard to design, energy, navigation, and micro-manufacturing in the process of breaking through the centimeter/millimeter level, but there is still great potential for MAV development.

For the development of current MAVs, miniature fixed and rotor wings face the constraints of theoretical and technical bottlenecks, as well as efficiency constraints; thus, it is necessary and innovative to design and develop high-efficiency bionic aircraft. The development of cooperative cluster technology can overcome the shortcomings of the traditional single MAV, which will subvert the traditional single-aircraft combat mode and thus provide a significant revolution in military affairs.

3.2.4 Reusable space launch technology

Reusable space launch technology is based on reusable launch vehicles (RLVs). An RLV is a multi-purpose air vehicle that can repeatedly travel between Earth’s surface and space, boasting great advantages such as speed, safety, reliability, and a low cost. In the development of space vehicles toward lower cost and higher reliability, reusable space vehicles will resolve the current dilemma of the high costs of space vehicle launches and lay a foundation for the exploration and development of outer-space resources. In the process of continuous human development toward space, taking the leading technological role will remain the top priority in military technology and other fields in the long term.

3.3 Prospects for marine vehicles

Thus far, no definite disruptive technologies have been identified in the fields of marine development equipment, marine scientific research equipment, marine defense equipment, and marine vehicle equipment. However, there are potential disruptive technologies in technical fields, such as the innovative technologies for flammable ice mining ships and marine power-shaftless rim propulsion systems, ship greenization technologies for innovation and development, and marine data resource technology.

As stated by Wu Yousheng, global marine vehicle equipment exhibits a new trend that is based on “ship greenization technology,” and focuses on “comprehensive integration,” “intellectualization,” and the “deep/open sea” [5].

3.3.1 Green marine vehicle technology

The energy-saving technology of marine vehicle equipment has undergone continuous development. At present, the development direction of ship greenization technology mainly includes 1) the overall technology of green ships, including ship design optimization, lighter ships, and less ballast water or ballast-water-free ships; 2) the power technology of green ships, which is also the focus of developing ship greenization technology; and 3) green ship operation technology, including ship energy-efficiency control and shore power technology. Related technologies that are comparatively mature or under development include low-speed and long-stroke design technology, technology for reducing fuel consumption during continuous operation at maximum power points, gas fuel technology, and wind turbine hybrid technology.

3.3.2 Comprehensive integration and intellectualization

With the increasing demands for marine vehicle engineering, marine vehicle equipment is being gradually developed in the direction of functional comprehensive integration and intellectualization. Integration includes equipment and function integrations. Intellectualization includes the intellectualization of the ship itself and information intellectualization of the network between the ship and shore.

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3.3.3 Polar and far-reaching marine vehicle equipment technology

With the continuous development of deep-sea science, and the increasing depth of deep-sea underwater operations, Japan's unmanned remote-controlled underwater vehicles have been submerged to depths of >10,000 m. Newly developed deep-sea underwater vehicles can be applied to many scientific research activities, such as marine mineral and biological resources and marine energy development, as well as marine environmental surveys. The United States, the United Kingdom, Russia, and other traditional marine powers have proposed the concept of deep-sea space stations. The United States plans to develop deep-sea space stations, the UK is planning to develop an underwater version of a "Star Wars" system, and Russia is planning to develop a new generation of deep-sea space station equipment systems [6].

Marine vehicle engineering equipment suitable for deep-sea support and operations will become the focus of future demands. Other technologies include innovative technologies for flammable ice mining ships, marine power-shaftless rim propulsion system technology, and technology for ship greenization, innovation, and development. The disruptive technologies include energy-saving devices, dual-fuel main engines, and lightweight design technology. Additionally, attention should be paid to the development of marine data resource technology, as well as nuclear power and deep-sea manned space stations.

3.4 Prospects for rail transits

The development of rail-transit technology includes the following.

(1) System integration and generic technologies in the field of rail-transit systems: comprehensive safety assessment and collaborative safety assurance technology, intellectualization technology for holographic perception and ubiquitous integration, key technologies for global efficiency evaluation and comprehensive efficiency improvement, and decoupling and adapting technology of the rail-transit system.

(2) Vehicle technologies: the key technology of high-speed wheel-rail vehicle systems, the key technology of maglev vehicle systems, the key technology of freight rail transit acceleration, guiding vehicle system diversification technology, urban-material rapid-transfer vehicles based on an urban rail network, and exploration and research of new modes and technologies for guiding transportation systems.

(3) Infrastructure technology: rail transit line construction and capacity maintenance technology, safety and operation guarantee technology based on air–space–vehicle–ground information integration, and infrastructure power-supply systems.

(4) Operation management technology: in-depth big data applications of rail-transit operation and management information, the Internet Plus rail-transit precision service mode, convenient and high-speed passenger transport, efficient and fast freight, multimodal rail-transport organization and coordination, intelligent operation, and emergency response.

(5) Technologies related to innovation capacities: the platform for the comprehensive testing, verification, and evaluation of the rail-transit system safety; platform for comprehensive data application services of the rail-transit system; and platform for comprehensive efficiency research and evaluation of rail-transit systems.

Faced with the challenge of continuous innovation of rail-transit power, China urgently needs to develop the next generation of high-speed railway equipment technology. This technology must be faster, more economical, more ecofriendly, and safer than the current technology to maintain a competitive advantage over the sustainable development of high-speed railways in China, while integrating competitive new technologies and intelligent new products. For example, the core technology of the next generation of high-speed railway development is the bogie technology of high-speed trains with sufficient intelligence and self-adaptability. This includes the gauge-changing technology needed for railway "going global," technology for lightweight vehicle bodies made of new materials, technology for high-power electronic transformers, permanent magnet motor and its traction control technology, all-electric braking technology, in-phase power supply technology, energy-saving transformer technology, equipment condition monitoring technology, technology for the application of new materials and new processes, large-capacity wireless communication and more accurate mobile blocking technology, and intelligent transportation organization and dynamic dispatching technology. Additionally, the technologies for heavy-haul trains with increased capacity and the transformation and upgrading of existing railways will be key areas of rail-transit technology development.

Rail transit has been developed and diversified from traditional trunk railways. Urban rail transit has developed rapidly, with new technologies continuously emerging. The 100% low-floor new urban tram technology is extensively applied in China, and research on new technologies, such as fuel cells, supercapacitors, and wireless energy transfer is fairly active, involving new technologies for the energy creation, energy transfer, and energy storage of power-supply systems. Moreover, extensive attention is being paid to the technology of straddling or hanging monorail trains to avoid interference with ground traffic, the technologies of auto-running "lift-car" trains for the "last kilometer" of rail transit and low-cost virtual track trains. With the opening and operation of maglev trains along the Changsha Airport Line, people have high expectations of maglev trains. Additionally, China initiated the research on medium-speed (200 km/h) and high-speed (up to 600 km/h) maglev systems as part of the 13th Five-Year Advanced Rail Transit Special Project.

The manned test of the 603-km/h low-temperature superconducting maglev train in Japan and start of the construction of the Tokyo–Nagoya (eventually to Osaka) operation line confirmed the viability of superconducting maglev technology for faster rail transit. The technology of China's high-temperature superconducting maglev trains with independent intellectual-property rights has become the optimum mode of ultrahigh-speed ground rail transit at approximately 1,000 km/h owing to its unique self-levitation, self-steering, and self-stability features. Additionally, ultrahigh-speed ground rail transit using vacuum pipelines has attracted considerable attention. The world's first high-temperature superconducting maglev experimental system based on vacuum pipelines established by Southwest Jiaotong University in 2014 has attracted considerable attention from international academic circles and was called a "super chute" by *Spectrum*, the flagship publication of the Institute of Electrical and Electronic Engineers. With the introduction of and engineering research on the hyperloop concept, based on vacuum pipelines in the United States, near-sonic-speed ground rail transit is nearing its application stage.

4 Suggestions for the development of potential disruptive technologies in mechanical and vehicle engineering

According to the foregoing analyses and expert opinions, we proposed five potential disruptive technologies in mechanical and vehicle engineering. Within the overall development plan, priority should be given to the support of the development of these five technologies.

4.1 Bionic intelligent cluster technology

Bionic intelligent cluster technology is based on the emergence of bionic micro-air vehicles and intelligent cluster technology, and its miniaturization is important for aircraft design. Thus, bionic intelligent cluster technology has great potential as a disruptive technology.

The collaborative cluster technology will realize autonomous control and formation flying of clusters through capability complementation and action coordination, which will greatly enhance the combat efficacy of micro-air vehicles. Moreover, the operational mode is completely new and disruptive, able to significantly improve the operational effectiveness of traditional weapons.

For bionic intelligent cluster technology, the following are required: resolving the conflicts between multiple UAVs in a limited space; satisfying the functional requirements in a low-cost and highly decentralized form; developing a dynamic self-healing network with distributed cluster intelligence; distributed detection; reliability; and a decentralized ad hoc network to enhance the fault resistance, self-healing, and information-sharing efficiency.

UAV cluster confrontation is an important form of future air battles. China should expand the relevant research, ranked among the world's first-class bionic intelligent cluster UAV technology nations, and take a leading role in the development of potential disruptive technologies able to undermine this form of warfare.

4.2 Marine power-shaftless rim propulsion system technology

The shaftless propulsion system adopts a structural design that subverts the existing electric propulsion systems and a shaftless rim propulsion thruster designed on the basis of rim propulsion technology. The shaftless rim thruster has an integrated motor and thruster based on integrated design and manufacturing. The shaftless rim propulsion system features excellent propulsion efficiency, innovative design theory, and wide applicability; moreover, it can overcome many shortcomings of traditional propulsion systems and is highly disruptive [7].

4.3 Intelligent UAV technology

UAV technology covers a wide range of fields and has broad prospects in both military and civilian applications. Intelligent UAVs have comprehensive environmental and battlefield situation awareness, perform autonomous decision-making based on a big data knowledge base, and exhibit high dynamic adaptability.

The main focus areas for disruptive intelligent UAV technology are UAV flight control technology, collaborative development from a single-purpose intelligent UAV to a multi-purpose intelligent UAV, intelligent UAV technology and sensors, and intellectualization of the UAV platform. The deep integration of artificial-intelligence technology and UAVs will have a disruptive impact on traditional fields.

4.4 Ultra-loop train technology

Ultra-loop train technology can reduce the friction caused by moving parts and air resistance. The train pipeline is made of an aluminum alloy, and the capsule compartment adopts a special design. The transverse acceleration in the pipeline loop of the ultra-loop train is lower than that of subways; thus, the carsickness of passengers can be prevented. This technology will become a model for the new generation of ground vehicles and subvert the traditional ground-vehicle systems owing to its innovative design and wide applicability.

The superconducting maglev technology uses superconducting materials to achieve levitation and has the following characteristics: no need for a power supply; the ability to levitate using superconducting blocks; and no need for wheels, as electromagnetic propulsion is used [8]. The high-temperature superconducting maglev theory

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and its applications include two aspects: 1) the electromagnetic properties of high-temperature superconducting blocks in the axisymmetric field, and the corresponding applications in bearing and flywheel energy storage; 2) the electromagnetic properties of high-temperature superconducting blocks in translational symmetric fields, and the corresponding applications in rail transit and launch systems. Currently, supersonic technology is mainly used in aircraft. The flying speed of supersonic and hypersonic vehicles is >5 times the speed of sound (>5 Ma), i.e., approximately 6,000 km/h. However, ultra-loop trains encounter the "ground thermal barrier" generated by supersonic running; thus, supersonic technology, if applied to rail transit with a controlled cost, will become a key technology for the commercialization of scientific research.

Three companies: Hyperloop Vehicle Technologies (HTT) and Hyperloop One of the United States, and China Aerospace Science & Industry Corp., have announced that they will develop transportation systems faster than 1,000 km/h. China Aerospace Science & Industry Corp. proposed the establishment of a space supersonic ground transportation system, including the construction of a 1) regional intercity flying train network with a transport speed of up to 1,000 km/h; 2) national super-city group flying train network with a transport speed of up to 2,000 km/h; and 3) a Belt and Road flying train traffic network with a transport speed of up to 4,000 km/h [9].

4.5 MEMS technology

Similar to microelectronic technology, MEMS technology will have a revolutionary impact on human society, e.g., in the mass production of low-cost, reliable microsatellites [10]. MEMS have many advantages. The effective torque transfer does not rely on rigid transmission devices; thus, more buffer devices can be added. Moreover, the power exhibits a split design; thus, the transmission chain is relatively short, making the control design simple and convenient. Medical micromechanical devices, e.g., nanorobots, that were essentially impossible in the past will appear in the near future with the development of MEMS. Even for pharmacological effects that cannot be achieved through a complex chemical molecule, they may one day be achieved through a programmed microdevice, which will be a disruptive revolution in the healthcare field. The pharmacology discipline may shift its focus from introducing pharmacological effects to designing the pharmacological process through microelectromechanical devices. Such a change will completely resolve the existing medical dilemma. Additionally, through MEMS technology, energy collected from the environment can be converted into electrical energy, and batteries can finally be replaced.

The trends of MEMS technology development include miniaturization, low power consumption, high precision, high integration, and sufficient intelligence. The features of MEMS technology differ significantly depending on the application environment and field, and have strong specificity; thus, MEMS technology is not easily monopolized by advanced countries. The development of MEMS requires diversified innovation under the same technology platform and innovation in different fields. Such multipoint professional innovation in different fields can enable whole-product upgrading, allowing China to exploit its large industrial scale and long industrial division chain to form a new type of industrial cluster network, realize the market development of large leading enterprises and small specialized enterprises, and thereby introduce a pathway for MEMS development.

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