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Development Strategy for Air–Ground Collaborative Multi-Modal Intelligent Robot System

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Abstract: An air–ground collaborative multi-modal intelligent robot system can adapt to air and ground environments, has multimodal characteristics and advanced intelligence, and can complete complex tasks. The system has broad application prospects in various fields and is a new driving force for global technological, social, and economic development. Considering the major demand for developing an air–ground collaborative multi-modal intelligent robot system in China, this study comprehensively analyzes the development status of the system in China and abroad and the existing problems in China. China currently lags behind the international advanced level in terms of air–ground collaborative intelligent robot system development; however, it still has the opportunity to achieve an advanced level as the system remains in its infancy at a global level. The system involves theories, key technologies, core components and units, platforms, system equipment, and system applications and aims to build related technical, core component industrial, intelligent robot equipment systems, and social applications. Moreover, we proposed a development layout, roadmap, and suggestions for system development. Research shows that the air–ground collaborative multi-modal intelligent robot system can be integrated into the future smart society in all aspects and be applied to fields such as smart medicine, education, housing, transportation, and manufacturing to contribute to the national economy and people's livelihood.
Keywords: intelligent robot; air–ground collaboration; multi-modal; artificial intelligence

1 Introduction

The 19th National Congress of the Communist Party of China clearly put forward the grand goal of building a powerful country with science and technology, a digital China, and a smart society. President Xi Jinping pointed out that robots are 'the jewel at the top of the manufacturing crown' at the 2014 Academician Conference of the Chinese Academy of Sciences and Chinese Academy of Engineering, and their research and development, manufacturing, and application are important indicators for measuring the level of technological innovation and high-end manufacturing in a country.

With strong support from national policies, Chinese robotics and intelligent system technologies are currently undergoing rapid development. The research and application of industrial, service, and special robots have been very mature, but these robots and intelligent systems are difficult to adapt to the land and air where humans live. It is difficult for a robot to meet the needs of a three-dimensional environment and multitasking.

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The air–ground collaborative multi-modal intelligent robot system is a robot and intelligent system that can adapt to the air–ground environment, has multi-modal characteristics, has advanced intelligence, and can coordinate to complete complex tasks. An air–ground collaborative environment refers to the space below 500 m represented by the city, including roads, buildings, non-structural terrain, and low altitude. Multi-modal features refer to motion modes such as wheeled, legged, crawling, and flying, including the variable motion modes of a single robot and the combined deformation of multiple robots. Advanced intelligence refers to autonomous intelligence, multi-body collaborative intelligence, and human–computer interaction intelligence. Complex tasks include disaster relief and three-dimensional transportation. The air–ground collaborative multi-modal intelligent robot system has broad application prospects in various societal fields and provides a new kinetic energy to promote global scientific, technological, social, and economic development.

The air–ground collaborative multi-modal intelligent robot system will become a technological breakthrough of the fourth industrial revolution and will cause a revolutionary change in human society. The first industrial revolution was represented by the steam engine that ushered in the steam era. The second industrial revolution, represented by the large-scale application of electric power, ushered in an era of electric power. The third industrial revolution, represented by computer technology, ushered in an information age. At present, the fourth industrial revolution, represented by robots and artificial intelligence (AI), will lead humankind into an era of intelligence. An air–ground collaborative multi-modal intelligent robot system can complete complex tasks that usually require human intelligence. As technology continues to develop and mature, it will certainly bring about revolutionary changes in human society.

The air–ground collaborative multi-modal intelligent robot system is the cornerstone of a smart society, which opens the smart society and stimulates AI. The future smart society will inevitably be a state of ubiquitous information networks, intelligent infrastructure, digitized industrial development, refined social governance, and convenient inclusive services. In a smart society, humans can use smart robot technology to build a new social system. All walks of life may undergo significant business changes through smart robot applications, and an increasing number of professional positions will be replaced by smart robots. Mankind will usher in an era of man–machine symbiosis and integration. Driven by this kind of developmental momentum, the science and technology of multi-modal intelligent robots will inevitably lead future science and technology development.

2 Development status

In recent years, robots and intelligent systems have attracted significant attention from various countries and relevant policies have been introduced to support the development of relevant technologies and industries [1]. At present, the theories and equipment of ground/air robots, and intelligent systems are mature, but robots and intelligent systems that can simultaneously adapt to ground and air environments have broad application prospects in various societal fields, and are the inevitable development direction in the future, attracting increasing attention from countries globally [2]. There is a large gap in ground, air robots, and intelligent systems between China and the United States or Europe; but with the ground and air collaborative robot system still being in its infancy worldwide, China has the potential to surpass all. At present, the theory and key technologies of multi-mode intelligent robots based on ground and air collaboration have not yet formed a system, so China must take the lead and seize the commanding heights.

2.1 Foreign development status

Robots and intelligent systems are the strategic focus of the global competition in science and technology. Developed countries are competing to formulate major strategies for robot development, with a focus on supporting the development of related technologies and industries. In 2017, the United States launched the *National Robotics Program* version 2.0 [3] with the goal of establishing a leading position in the next generation of robotics technology and applications. Russia released its *National Artificial Intelligence Development Strategy until 2030*, aiming to make its robots take the leading position in the world to improve people's quality of life and ensure national security [4]. Europe invested 2.8 billion Euros to create the world's largest private-funded robot SPARC innovation program, with the goal of robots fully entering human life [5]. The Japanese government issued the *New Robot Strategy* [6] and established the Robot Revolution Council to maintain its dominant position as a robot power.

Robots and intelligent systems that can simultaneously adapt to air–ground environments have wide application prospects in all fields and are an inevitable development direction in the future. All countries are investing in increasing

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their strategic advantages. US robots and intelligent system technologies are in a leading position, and the system and equipment are practical. The folding wing transition amphibious platform designed and manufactured by Terrafugia in the United States is the world's first flying car. It is a mature industrial product that combines fixed-wing aircraft and automobiles [7]. Both ground and air robots in the United States are expanding. The flying car strongly supported by the United States is a multifunctional troop carrier that is intended to conduct tasks such as troop projection, humanitarian assistance, and natural disaster relief [8].

2.2 Domestic development status

China has incorporated the intelligent manufacturing and robotics project into a new round of national science and technology major project for 2030 and launched the Robot Industry Development Plan (2016–2020) [9]. It is clearly designed to solve the bottleneck problem that restricts the development of the Chinese robot industry and realize the autonomy of the Chinese core technology of robotics and industry to support the sustainable development of the intelligent robot industry.

At present, aircraft and unmanned vehicles related to robots and intelligent systems and their related discipline systems are relatively mature, and a complete industrial chain has been formed. However, the relevant theories and technologies of the air–ground collaborative multi-modal intelligent robot system belong to emerging and interdisciplinary disciplines, and its contents cover mechanical engineering, control science and engineering, computer science and technology, weapon science and technology, material science and engineering, information and communication engineering, optical engineering, chemical engineering and technology, and other disciplines, while relying on new interdisciplinary innovations. At present, the theory and key technology of air–ground collaborative multi-modal intelligent robots have not formed a system, so China must take the lead and occupy the commanding heights.

Air–ground collaborative multi-modal intelligent robot systems are one of the core technologies limited by foreign countries. Therefore, it is necessary to develop an autonomous system. In 2018, the United States Department of Commerce announced a ban on the export of 14 representative emerging technologies such as AI and robots to China. In 2019, the United States banned the export of relevant technologies for maps, software, and high-precision optical sensing devices for robots and systems. In June 2020, the United States restricted Hong Kong's access to high-tech technologies and products such as robots and AI. The core components of high-end robots are monopolized by Japanese, US, and European companies, and the sale of high-end models is prohibited in China. The performance indexes of key components such as servo motors, retarders, servo controllers, and sensors developed in China are far lower than the international leading level, and more than 70% of the components depend on imports [10]. Most advanced robots developed abroad use customized components. According to the system performance, component index requirements were proposed for customized development. Most robotic research in China is focused on the assembly mode of industrial components. The platform performance is limited by the component performance. There is a generation gap between China and foreign countries in terms of core components, which restricts the development of intelligent robots. Therefore, China urgently needs to build an independent system from component to system.

The development of the air–ground collaborative multi-modal intelligent robot system is based on the theory and technology of perception, fusion, and decision-making; key components such as execution and calculation; bionic, multi-domain, reconfiguration, collaboration, and other platform systems; and multi-scene applications to solve the problems restricting intelligent robot development and break the blockade by foreign countries on advanced robots in China.

There is a large gap between China, the United States, and Europe. However, air–ground collaborative robot systems are still in their infancy, and there is a possibility of transcendence. Chinese research in this field has achieved fruitful results in recent years. Most recently, the Beijing Institute of Technology has studied water, land, and air multi-domain motor transport vehicles based on longitudinal double culverts, which integrate three main functions: high-speed driving on water, high mobility driving on land, and controllable multi-degree-of-freedom driving in air, and can realize a comprehensive and efficient motor transport capacity under various climatic conditions, complex terrain, and traffic conditions [11]. Research on air–ground collaborative robot systems in China and abroad has just begun, and at the same level, we have the possibility of transcendence.

3 Problems in development

China currently attaches significant importance to the development of robots and intelligent systems, and has issued several major national policies to support it. The number of robots in China has surpassed the number of first-mover countries to become the highest in the world. However, there are still problems associated with the development of an air–ground collaborative multi-modal intelligent robot system.

The first is the lack of development planning and support for an air–ground multi-modal robot system. The development plan of current robots and intelligent systems in China primarily supports research on industrial, service, special, and other types of robots, which can only face a single motion scene or task and do not have wide applicability. Air–ground multi-modal robot systems have broad application prospects in various fields of society and are an important part of the future smart society. The United States and Europe have formulated several strategies and plans to conduct research; thus, China urgently needs to build a first-mover advantage in this field to achieve strategic leadership.

Second, the core components of air–ground multi-modal robots have become a key restricting factor. Core components are the foundation that restrict the performance of robots and intelligent systems. At present, there is a large gap between the Chinese high-end robot system drive and perception core components and the international leading level, and high-end components are severely restricted by foreign countries. The performance indicators of the key components developed by domestic robots are far below the leading international level, and the key components rely on imports [12]. Simultaneously, the core components of air–ground multi-modal robots have not formed a mature industrial chain system, such as automobiles and airplanes, and the industrial component performance does not match the robotic system requirements.

Third, the entire chain, from theoretical research to equipment and applications, has not been formed. Theoretical and technical research on robots and intelligent systems is not closely related to equipment application requirements. It is necessary to address national strategies, put forward application requirements, and overcome related technologies. Universities and research institutes lack communication with equipment research and development, and system application units. After breakthroughs in related technologies, the period for obtaining applications on equipment is too long, and the platform function design is not organically integrated with the application requirements. Therefore, a full-chain development model should be adopted from basic research, key technology, system integration, equipment development, and achievement transformation to industrialization. We must aim at cutting-edge academic innovation, cross-discipline integration, and produce original results, with a focus on industrial development, creating a good product layout, and forming sustainable development capabilities.

Fourth, there is a lack of organic integration between AI and robotic hardware systems. At present, AI is biased toward computer majors, limited to data processing, and not integrated with task-execution robots and intelligent system ontology. AI cannot independently respond to environmental changes. In numerous applications, robots require human supervision. Simultaneously, the perception ability of AI is still relatively weak; however, it has advantages in data processing. Conversely, the ability to analyze and understand AI is too weak, and there is a significant gap in the ability to focus on relevant information compared with the human brain. The lack of research on perception and action intelligence of robots and intelligent systems has not attracted sufficient attention.

4 Development goal and plan

Aiming at the foreign development of air–ground collaborative multi-modal intelligent robot systems and the existing problems, this paper proposes suggestions for the development objectives, research layout, and development roadmap.

4.1 Development goal

Aiming at the national strategic needs of intelligent technology, advanced manufacturing, and national security, the air–ground collaborative multi-modal intelligent robot system includes theories and key technologies, core components and units, platforms and system equipment, and system applications. These allow us to build related technical, core component industry, and intelligent robot equipment systems, and social applications to meet the strategic needs of national security and economic and social development and lead to the development of a smart society.

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4.2 Development plan

Theories and key technologies include heterogeneous reconfiguration technology of multi-modal robots, real-time planning of robot cooperative tasks, multi-scale perception and information fusion, high dynamic cross-regional organization network theory, intelligent group cooperation, and confrontation online decision-making.

The core components and units include high explosive effort drivers, high-density power supplies, integrated joints, and other executive components and units; bionic sensing, autonomous navigation, multi-dimensional communication, and other sensing components and units; and intelligent components and units, such as computing units, intelligent chips, and network computing systems.

The platform and equipment system include bionic robots, such as humanoid, quadruped, serpentine, and insectoid; land movement, aircraft, and other air–ground mobile robots; reconfigurable robots, such as robot systems with variable single platform mode or multi-platform combined deformation; and air–ground cooperative multi-robot communication and commanding systems, and human–computer interaction cooperative control systems.

The system application includes the formation of an unmanned crew to maintain the safety of the city, substituting humans to work in dangerous environments after earthquakes or nuclear leakage, and building a smart city three-dimensional traffic system to improve travel efficiency.

4.3 Development roadmap

4.3.1 Short-term goal (by 2025)

China should achieve breakthrough in key technologies such as heterogeneous reorganization of multi-modal robots, modeling and identification of complex environments, and autonomous condition detection and estimation. It is necessary to develop executive components and units such as high-explosive effort drivers, high-density power supplies, integrated joints, and other executive components and units; sensing components and units such as autonomous navigation and multidimensional communication; and intelligent components and units such as computing units and network computing systems. It also needs to develop bionic robots, such as humanoids, quadruped, serpentine, and insectoid; land movement, aircraft, and other air–ground mobile robot platforms; air–ground collaborative multi-robot communication and command and control systems. Approximately 80% core components and units should be self-developed and controllable, the technical maturity of the platform and system equipment should reach level 6, and a multi-platform autonomous collaborative task demonstration will be realized.

4.3.2 Medium-term goal (by 2030)

China should achieve breakthroughs in key technologies such as real-time planning of robotic cooperative tasks, multi-scale perception and information fusion, survivability in harsh environments, and reliability design. It is necessary to develop executive components and units, such as biomimetic drives; sensing components and units; and intelligent components and units, such intelligent chips. It also needs to develop reconfigurable robots, such as robot systems with variable single platform modes and multi-platform combined deformation, and human–computer interaction cooperative control systems. All core components and units should be self-developed and controllable, the technical maturity of the platform and system equipment should reach level 8, and the demonstration and verification of typical applications such as disaster rescue and three-dimensional transportation will be realized.

4.3.3 Long-term goal (by 2040)

China should achieve breakthroughs in the high dynamic cross-regional organization network theory, intelligent group cooperation, and confrontation online decision-making technology, develop components and units for execution, perception, and intelligent integration, develop intelligent unmanned crew, form the industrial system of robot core components and intelligent robot equipment systems, and reach extensive application.

5 Development proposals

With respect to the global goals and arrangement of the development of Chinese air–ground collaborative multi-modal intelligent robot systems, this paper proposes the following specific development suggestions.

5.1 Formulating an overall development plan for the air–ground collaborative multi-modal intelligent robot system according to the national strategies to seize predominance

Focusing on national strategies, the competent authority needs to formulate policy guidelines to conduct top-level design and overall planning for the development of an air–ground cooperative multi-modal intelligent robot system. Efforts should be focused on the formation of an industrial chain of technological innovation, including cutting-edge foundations, key technologies, equipment/product development, and transformation of scientific research achievements. Strategic resources need to be effectively gathered for collaborative innovation by forming an industry–university–research consortia with high-level domestic and foreign research institutions and industry leaders, to explore effective synergy mechanisms and to form a coordinated development model with complementary resource advantages. Persistent systematic research should be conducted for meeting significant social needs to promote basic science research, basic applied science research, and key technology breakthroughs in China, and to effectively transform the research achievements into industrial development advantages for satisfying the country security, economic and social development strategy needs, and leading to the development of a smart society.

5.2 Formulating a research and development plan for core components to form a proprietary development system for the core components and units of air–ground multi-modal robots

A unique research and development system needs to be established for the research of air–ground multi-modal robot core components to form a mature industrial chain, much like automobiles and airplanes. Considering the system requirements, we need to propose core component indicators and conduct systematic research. A new type of integrated industrial system should be established to ensure long-term and stable research and development investment, and contribute to tackling key scientific and technological issues. A process cooperation mechanism should be established for research of multi-modal robot core components, and the evaluation and incentive mechanism should be optimized to mobilize the enthusiasm of enterprises to participate.

5.3 Enhancing the integration of AI software algorithms and robot system hardware and jointly performing research projects

It is recommended to publish a theoretical and key technology research plan for both the AI algorithm software and robot hardware, enhance the industry’s emphasis on robot intelligence, and deeply integrate AI with robot perception and behavioral intelligence, such that AI research not only manages data processing, but also integrates intelligent systems and robotic hardware systems, using perception and actuators, independently responds to environmental changes, and completes complex tasks.

5.4 Exploiting the technological advantages of various regions and units to open the ecological chain from technology to industrialization and application

It is necessary to integrate innovative resources such as scientific research institutions and high-tech enterprises, conduct research and development, and establish a sharing mechanism. Efforts should be made to enhance the in-depth cooperation between scientific research units and upstream and downstream enterprises, with breakthroughs in core technology research capabilities and engineering integration capabilities as the key points. Through collaboration between upstream and downstream innovation resources, we should improve the innovation and industrial chains of robots and intelligent systems, and build advanced robots and the intelligence system industry.

5.5 Training teams of professionals in interdisciplinary and emerging disciplines

Aiming at the basic theories and key technologies of air–ground multi-modal robots, we will improve the field discipline layout, establish robotics, promote the construction of first-level disciplines in the robotics field, and increase the number of doctors and masters in robotics-related disciplines. We should encourage colleges and universities to expand the content of robotics education on an original basis and attach importance to the intersection of robotics and professional education in mathematics, computer science, physics, biology, and other disciplines. It is necessary to encourage universities, research institutes, and enterprises to cooperate in the development of robotics.

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5.6 Conducting demonstration projects

It is necessary to cooperate with the aerospace, fire fighting, and earthquake departments, to promote the construction of aerospace and rescue demonstration bases for air–ground multi-modal robot systems and to promote the formulation of guidelines for the Chinese robot rescue industry. With the help of inter-governmental cooperation strategies and institutions led by China (i.e., the Belt and Road initiative, China–Africa cooperation, Shanghai Cooperation Organization, and Asian Infrastructure Investment Bank) to promote China's air–ground multi-modal robotic system technology and related products and promote China's global technology deployment.

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