Research on the Development of Intelligent Space System (ISS)

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Abstract. First, the research scope of Intelligent Space Systems (ISS) is clarified, and then the domestic and foreign development of intelligent space systems in three directions is investigated, including intelligent information processing, autonomous task planning and intelligent information interconnection. By comparing and investigating, the scientific problems existing in the development of intelligent space system at present are put forward, and the analysis of the development trend of key technologies of intelligent space system in the future is finally formed.

Keywords: Intelligent Space System · Artificial Intelligence · intelligent information processing · autonomous mission planning · intelligent information interconnection

1 Introduction

Intelligence and networking are the development trend of future space systems. The United States, Europe and other countries and regions have intensively released a number of strategic plans, and regard intelligent technology as a strategic and basic key technology to reshape the space system, drive technological innovation, achieve leapfrog development, and drive the development of new industries. The next generation space architecture of the United States attaches great importance to the integration of advanced technologies with artificial intelligence as the core and the space field. There is a risk that China's space technology and its gap will be further widened. The white paper "2016 China's Aerospace" issued by the State Council Information Office clearly stated that we should accelerate the deep integration of industrialization and informatization, and realize the transformation of aerospace industry capabilities to digitalization, networking and intelligence. It shows that China is accelerating the construction of intelligent space systems and improving the comprehensive capabilities of space equipment.

At present, there is no unified definition of the concept of intelligent space system at home and abroad, but "automation, autonomy and intelligence" is the main vein of spacecraft technology development, which has become the consensus in the industry [1]. In 2006, the Space Operation and Support Technical Committee (SOSTC) of the American Institute of Aeronautics and Astronautics (AIAA) investigated and analyzed

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the industrial level of spacecraft autonomy and intelligence at that time, and divided it into six levels [2], from low to high, including manual operation, automatic notification, manned ground intelligent reasoning, unmanned ground intelligent reasoning, on orbit intelligent reasoning and autonomous thinking spacecraft. Chinese Academician Yang Jiachi also discussed the connotation of autonomous system in the article "Development of intelligent autonomous control technology in China's space program" [3] published in 1995: "Autonomous or semi autonomous operation means that no one participates in the control loop of the system completely or partially. Highly autonomous system is a system that can operate in an uncertain environment without external interference for a long time. More advanced autonomous system has the basic elements of intelligence and learning, and can adapt to a wider range of unpredictable environmental changes".

Combined with the research description and consensus on space intelligent technology in the domestic and international space industry, this paper defines the intelligent space system as a intelligent spacecraft, a ground intelligent control center and an intelligent user terminal, as shown in Fig. 1. It is a space-ground integrated intelligent system with autonomous perception, prediction, decision-making and collaboration capabilities. Space intelligent spacecraft has a strong ability of intelligent autonomous execution, self-management and self-learning. The ground intelligent control center has strong computing power and is responsible for large-scale data processing tasks and training tasks of intelligent information processing models, while the intelligent user terminal can provide an intelligent human-computer interface to support users to put forward task requirements or control commands through text, voice, gesture, etc.

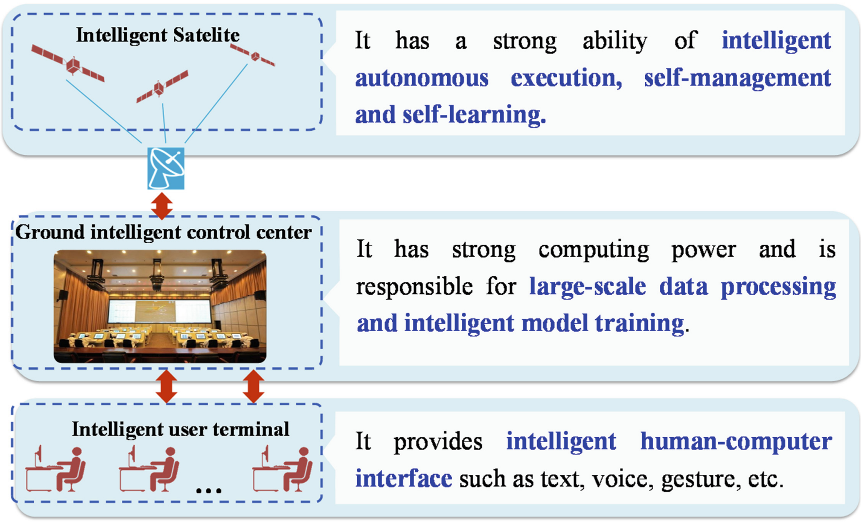

Fig. 1. Composition of Intelligent Space Systems

Figure 2 shows the concept of space intelligent spacecraft. Its basic components include intelligent processors, multiple sensors, intelligent algorithms and models, and hardware components supporting its operation. Under the condition of limited on-board

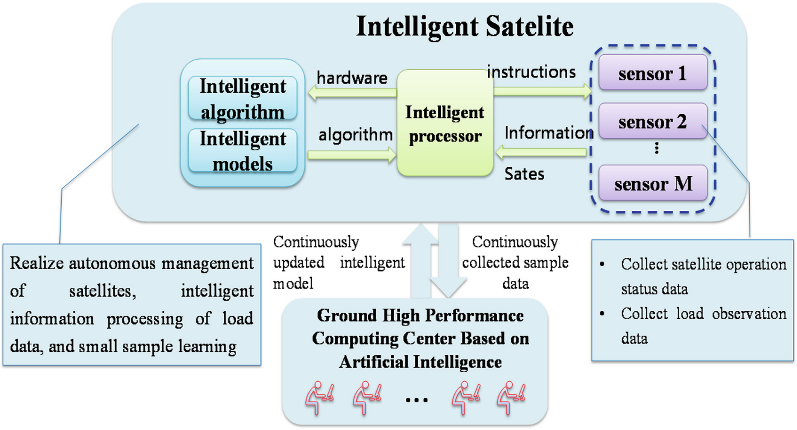

Fig. 2. Composition of Intelligent Spacecraft

resources, a large number of data processing and model training are completed on the ground; With the enrichment of on-board resources, the satellite will have stronger intelligent processing and learning capabilities.

At present, the overall technical level of spacecraft has basically achieved automation. However, the operation management mode based on the "big loop of heaven and earth" relies heavily on the ground station. From user demand proposal, ground planning, instruction upload, to satellite task execution, data download, ground information extraction, etc., the task delay is hour level, which is difficult to adapt to information assurance requirements such as strong real-time, high security and reliability [4]. The effective way to solve these problems is to realize intelligent information processing, autonomous task planning, intelligent information interconnection technology and improve the intelligence of space intelligent system.

Through target detection, target recognition, situation awareness and other technologies, intelligent information processing enables satellite systems to have autonomous situation awareness, greatly improving the timeliness of user information acquisition. Autonomous task planning includes intelligent task planning of agile remote sensing satellites, intelligent organization and collaborative planning of multiple spacecraft, autonomous planning of space operation tasks of robots and autonomous path planning of deep space probes. Based on intelligent information interconnection technology, multiple satellite agents can be connected into a space space system collaborative network with high adaptability and anti damage capability to ensure information connectivity under operational conditions. This paper focuses on the space segment of intelligent space system, namely, space intelligent spacecraft, and conducts in-depth research in three directions: intelligent information processing, autonomous task planning, and intelligent information interconnection. It sorts out the problems and key technologies in all directions, and analyzes the future technology development trend.

2 Development of Intelligent Space Systems Abroad

The United States has always been at the forefront of artificial intelligence research in the world. In the 2016 National Strategic Plan for Research and Development of Artificial Intelligence, the United States has identified the development of artificial intelligence as a national strategy; In February 2019, the Department of Defense's Strategic Outline of Artificial Intelligence issued by the U.S. Department of Defense clearly stated that the Joint Artificial Intelligence Center (JAIC) should take the lead to promote national security and prosperity by using AI; In March of the same year, the US Department of Defense established the Space Development Agency (SDA), proposed a seven tier architecture of the National Defense Space Architecture (NDSA), and expected to establish a distributed and AI supported operational management capability. In addition, the European Union, Germany, France, Britain, Japan, Canada, Russia and other governments and defense departments have also introduced AI development strategies.

2.1 Development of Foreign Intelligent Information Processing

As early as 2009, the military tactical star - 3 (Tacsat-3) satellite [7] launched by the United States carried the "Advanced Rapid Response Tactical Military Imaging Spectrometer" (ARTEMIS), which is based on on-board hyperspectral image processing technology and has the capability of automatic identification of on-board targets to send target information to combat users or portable terminals. In 2018, the European Space Agency (ESA) proposed to develop an Earth observation satellite equipped with an artificial intelligence processor, through which the satellite can autonomously study and judge the imaging target and the data content transmitted to the ground. Through on orbit intelligent processing technology, effective information is directly sent from the satellite to the operational users, which shortens the information acquisition time of "from sensor to shooter" in military applications.

In May 2016, NASA installed a set of onboard intelligent software AEGIS for the Curiosity Mars Probe, which can identify scientific targets from the navigation camera images and immediately measure them without going through round-trip communication with the Earth. The autonomy of AEGIS has been rapidly adopted as a tool for scientists to explore, and has affected the planning of the Curiosity exploration mission. In 2020, Lockheed Martin will launch its first intelligent satellite, carrying a payload named Pony Express 1, which has strong space-based computing and in orbit data analysis capabilities and provides strong flexibility.

In general, in terms of intelligent information processing technology, foreign space intelligent spacecraft have realized the transplantation and application of some mature ground algorithms. Its main purpose is to extract and recognize targets in images under various backgrounds through on-board data processing, retain only the extracted effective information, reduce the occupation of transmission bandwidth, and improve the image download speed.

2.2 Development of Foreign Autonomous Mission Planning

In terms of autonomous task planning, some technical experiments of autonomous task planning management with simple planning and decision-making algorithms have been carried out on the satellite. The United States loaded the autonomous planning package on the EO-1 satellite launched in 2000, realizing the autonomous planning capability of the satellite [8, 9]. The "Behavior Planning, Scheduling, Execution and Re planning" (CASPER) program of EO-1 satellite generates task planning based on the data of the on-board scientific analysis module, and can take the initiative to shoot when returning to the disaster point again according to the preliminary judgment of the load. The automatic reasoning system was studied in the launch management test of the "Tactical Sat-3" (TacSat-3) launched in 2009. In order to improve the target recognition capability and verify the target recognition algorithm based on statistical principles, NASA launched the "Intelligent Payload Experiment" (IPEX) technology test satellite in 2013 to improve the technical maturity of the HyspIRI satellite's intelligent payload module (IPM) in NASA's ten-year earth science survey mission, and improve the technical level required for the generation of near real time, low delay autonomous products related to future Earth observation missions. IPEX was launched on December 6, 2013 and stopped operating on January 30, 2015.

In 2018, the Japanese Falcon 2 probe achieved a fully autonomous landing of asteroids based on terrain recognition [10]. ESA has developed an interstellar trajectory planner for the Rosetta comet detector. Using the Monte Carlo tree search strategy, the optimal skimming and circling trajectories of multiple target comets are finally obtained [11]. DeepSpace 1 (DS-1) of the United States has achieved some autonomous technologies, including autonomous navigation technology, autonomous remote decision-making technology, autonomous software testing technology and automatic code generation technology [12, 13], and completed the exploration mission of crossing asteroids, Mars and comets.

In terms of autonomous mission planning, foreign countries have carried out some on orbit technology experiments with simple planning and decision-making algorithms, which are still at the exploratory stage and cannot replace the unified and centralized mission planning process on the ground. The development prospects of the ground unified mission planning and multi satellite distributed autonomous mission planning are not clear. The refined autonomous task planning and management oriented to onboard resource capability is a hot spot of future technology development.

2.3 Development of Foreign Intelligent Information Interconnection

Until July 2022, the "Starlink" system led by SpaceX has launched more than 2750 satellites and will reach 42000 low orbit satellites in the future, providing high-speed broadband services worldwide and laying a network foundation for collaborative planning and implementation of multi satellite missions. As early as 2006, the United States demonstrated formation flying and on orbit autonomy technology based on TechSat21. In 2018, the "BlackJack" project was launched to verify the on-board computer and processing system through the development of an on-board processor test called "pitboss", so as to achieve the collaborative management of low orbit large-scale constellations. In 2019, the US Space Development Agency (SDA) proposed a seven tier architecture of the National Defense Space System (NDSA), which uses a large LEO constellation composed of hundreds of satellites to build a next-generation space-based information network system. Star Link and Black Jack will be the important foundation of their tracking layer and operation management layer. They will provide automatic space-based operation management capabilities through command and control, task allocation, task processing and distribution to support the closure of the time sensitive kill chain of campaign scale and provide support for the warfighters to deal with various emerging threats. Since 2020, Lockheed Martin has launched satellites to verify SmartSat technology. At present, it has verified space-based computing and network communication technology through carrying loads.

The space information system of the US military has experienced a "spiral" development of "single satellite system → space satellite earth network → S&C4ISR integration". At present, the space system has achieved unified and comprehensive systematic development, and the "Star Earth Network" has been adopted to realize mutual connection, mutual visit and information integration. In the future, we will gradually promote the construction of S&C4ISR system and the continuous integration to GIG (Global Information Grid), realize the seamless connection and organic integration of space system and US military combat information system, and lay a physical foundation for the scheduling of multi satellite resources, the connection and integration of multi-source information.

3 Development of CHina's Intelligence Space System

The development of intelligent space system in China is still in its infancy. Intelligent technology is mainly embodied in intelligent information processing, autonomous task planning, intelligent information interconnection, etc.

In July 2017, the State Council issued the Development Plan for a New Generation of Artificial Intelligence, which proposed to build an autonomous unmanned system intelligent technology system and support platform, systematically layout artificial intelligence at the national level, deploy and build the first mover of China's artificial intelligence development, and clearly pointed out the strategic goal of the development of a new generation of artificial intelligence in three steps, so that by 2030, China's artificial intelligence theory, technology and application will generally reach the world's leading level, Become a major AI innovation center in the world. From the "Made in China 2025" issued by the State Council in 2015 to the government work report of the State Council in March 2019, AI has been upgraded to "Intelligence Plus". The Chinese government continues to pay attention to and attach great importance to the development of AI, and has upgraded AI to a national strategy.

3.1 Development of Intelligent Information Processing in China

The "Aerospace Tsinghua No.1" microsatellite launched in 2000 has realized a set of on-board image processing system and adopted cloud detection technology; In 2009, a satellite was equipped with an ocean target detection and processing device, and its ship detection rate was more than 90%, which can be processed in real time, reducing the original data rate from 1Gb/s to about 12Mb/s; Jilin No. 1 Spectral 01, 02 and 03 satellites launched in 2019 are equipped with automatic identification, search and positioning of forest fire points and sea ships by applying artificial intelligence technologies such as deep learning. In addition, a satellite of space infrastructure is equipped with real-time data processing equipment, which can complete the radiation correction, cloud judgment, region extraction, region splicing, geometric correction and other processing functions of high-resolution original images on orbit, generate image products, and quickly distribute image products to users. In addition, in terms of chip research and development for intelligent information processing, currently, the market has launched high energy efficiency and low delay artificial intelligence chips for ground reasoning, such as Nvidia Tesla P series GPU chips, Xilinx and Intel led FPGA chips, Xilinx FPGA architecture of the new multi-core heterogeneous computing platform ACAP, etc., but no aerospace chip products with long-term on orbit application capabilities have been formed.

In general, the spacecraft has good measurement, calibration, data acquisition and other capabilities, has carried out in orbit verification of processing technologies such as ocean target detection and recognition, cloud detection of optical remote sensing satellites, and is carrying out preliminary research on multi-source information feature level fusion processing technology for visible, infrared, and SAR images, but lacks the perception and cognitive ability for in orbit data.

3.2 Development of Autonomous Mission Planning in China

“Chang’e-3” and “Chang’e-4” [14, 15] detectors use active and passive optical sensors (laser radar and optical camera) to achieve autonomous obstacle detection and avoidance (HDA) operation [16, 17]. At a distance of 2.4 km from the lunar surface, the optical camera is used to take pictures of the lunar surface to obtain a large range of gray-scale images of the lunar surface. According to the texture, gray-scale and light and dark information in the images, identify and extract rocks, craters and other features to obtain a rough distribution map of obstacles. After that, the safe landing area is comprehensively determined according to the mobility of the detector and other factors; At a distance of 90~100 m from the lunar surface, the detector hovers and uses the lidar to obtain accurate lunar surface elevation information. Based on the elevation information, obstacles are identified and safe landing points are determined. The “Yutu” lunar rover in the “Chang’e 3” and “Chang’e 4” missions can autonomously achieve navigation, attitude determination and positioning, environmental awareness, obstacle avoidance planning, emergency obstacle avoidance, motion coordination control and safety monitoring before and during the movement, so as to ensure that the inspector can safely drive to the target point according to the requirements of the ground instructions [18, 19].

In terms of mission planning, China’s satellite ground intelligent mission planning technology has been relatively mature [20–23], and has been applied in satellite user units for a long time. At present, the reconnaissance, operation, measurement and control, and management of domestic on orbit satellites are conducted under the guidance of human beings. The operation management scheme [24], which is formulated on the ground and uploaded for execution, is adopted. The on orbit flight process and mission process are highly dependent on ground operation control. Compared with the explosive development demand of future satellite mission scale, we still have a big gap in the basic research and engineering application realization of satellite autonomous mission planning; At present, the spacecraft only has the basic functions of “meta task” analysis, instruction arrangement and execution, and does not have relatively advanced autonomous planning capabilities [25–27].

3.3 Development of Intelligent Information Interconnection in China

The development of China’s space-based information network, Internet and mobile communication network is uneven, showing the characteristics of “weak in the sky and strong in the earth”. Each satellite system is built autonomously, with obvious segmentation. The number of satellites is seriously insufficient, and the type of satellites is relatively single. What is more striking is that the satellite did not realize spatial networking, and could not play the integrated networking effectiveness of space-based information system. At present, the space-based network lacks unified planning and design, has not yet achieved the advantages of integrated networking, and has not formed the system service capability to support the joint use of informatization.

The Beidou Global System is the core of China’s space-based space-time reference network. Beidou-3 is the largest constellation system built in China. It has provided global users with all-weather, all-weather, high-precision positioning, navigation and time service. Beidou-3 adopts inter satellite link technology, designs reasonable network protocols and task planning, realizes autonomous operation management of the navigation constellation, and ensures long service life, high reliability and high precision measurement of the inter satellite link of the navigation constellation [28]. Without the support of the ground station, the Beidou Global Navigation Satellite System has the capability of 60 day autonomous navigation service.

However, the Beidou 3 information system cannot support the application requirements of the constellation network flexible management and control, and its network management and control can only adopt the full static management mode, relying entirely on the ground instructions. Under the control mode of “one satellite, one tube”, the operation efficiency is limited, and there are still problems such as fault free adaptability, inability to meet emergency/burst transmission tasks, and failure to support random access.

4 Development Trend of Key Technologies of Intelligent Space System

4.1 Development Trend of Intelligent Information Processing Technology

Most of the on-board data of spacecraft are transmitted to the ground for processing, which cannot meet the requirements of high timeliness such as emergency disaster reduction or operational applications. The improvement of intelligent information processing capability on board can greatly shorten the system loop, reduce the system delay, improve the accuracy of information extraction, and improve the application efficiency of space-based systems. At present, a few satellites have successfully achieved in orbit disaster monitoring, marine target detection, extraction and positioning, but their detection accuracy is not high enough to support practical applications. On orbit intelligent information processing technologies such as infrared, spectrum and radar are still in the research stage. The future on orbit information processing system needs to complete the information extraction of on orbit load data and measurement and control data, and has the capabilities of environment autonomous perception, intelligent target discovery, type recognition, target tracking, etc.

The main scientific problems faced by intelligent information processing include: 1) Multi-target alignment in multi view scenes: in complex battlefield environment, due to different loads, orbits and satellites, the data from different views of the same target have large differences in shape and appearance, which leads to the decline of information processing accuracy; 2) Limited sample problem: The amount of load, state and other data obtained through sensors is large, but the effective samples for specific targets and space-time are limited, which belongs to small sample data, and it is difficult to learn accurate models from them; 3) On-board computing and storage resources are severely limited, and conventional complex and advanced intelligent algorithms need to consume a lot of resources, so the problem of algorithm lightweight must be solved. In addition, due to the constraints of satellite scale and time-space relationship, the available resources of medium and low orbit spacecraft for target reconnaissance in a single area in a specific time are very limited, and the task needs must be met through intelligent coordination and planning of constellation and cluster spacecraft. In order to solve these problems, it is necessary to focus on intelligent automatic induction, information extraction and knowledge reasoning of limited sample data in the follow-up research; Carry out research on light-weight deep learning network model under limited resources, carry out model sharing based on migration learning, light-weight deep learning network model, multi-source heterogeneous data association and intelligence generation and other key technologies.

4.2 Development Trend of Autonomous Mission Planning Technology

Due to the complexity of space flight mission process, tight TT&C resources and high requirements for reliability and safety, the rationality of mission planning is an important factor for the successful completion of space missions [29]. At present, the operation management mode of spacecraft relies heavily on the ground station, and the delay from user demand to satellite task execution is too long, which is difficult to adapt to the requirements of strong real-time information assurance [30, 31]. In the future, intelligent spacecraft will have the ability of optimal autonomous trajectory planning for the points of interest, and can autonomously realize task decisions such as staring at static targets and active tracking of moving targets; It is capable of intelligent organization and collaborative planning of multiple spacecraft, realizing intelligent organization and autonomous task collaboration of multiple satellites on orbit, and completing orderly division of labor and collaborative work. Taking the intelligent detection robot as an example, the system will reduce the difficulty of autonomous operation of the robot and avoid the impact of extreme terrain conditions on the surface of the detection body through autonomous path planning.

The scientific problems faced by autonomous task planning include: 1) With the increase of the scale of satellite task planning and scheduling, its solution space expands explosively, which makes it extremely difficult to solve; 2) The dynamic adjustment of task planning may cause resource conflicts, so resource constraints and resource utilization of original planning tasks should be fully considered; 3) The spacecraft needs to make task decisions in high dynamic and strong real time according to the changes of sensing information, and must solve the fast computing problem of intelligent task planning technology. In order to further improve the accuracy and autonomy of autonomous task planning, key technologies such as dynamic task planning for multi-target tracking under complex boundary conditions, rapid multi task conflict resolution and intelligent optimization technology need to be tackled in the follow-up research.

4.3 Development Trend of Intelligent Information Interconnection Technology

At present, the space system nodes have not yet achieved interconnection, which is not conducive to flexible scheduling and collaborative use of resources. The future intelligent space system supports the integration of heaven and earth and intelligent information interconnection. Users can obtain the required information in real time, and multiple spacecraft can work together. For example, high orbit census satellites can provide target guidance for low orbit detailed survey satellites through inter satellite networks to achieve collaboration. In addition, in the future, intelligent space systems will have a huge amount of sensors and communication resources. They need to have efficient control over space-based network nodes, computing nodes and routes, and have highly adaptive and damage resistant intelligent information interconnection capabilities to ensure flexible networking and information connectivity; On this basis, the integration of communication, navigation, remote sensing and other space-based nodes into a network can be realized, and satellite resources can be configured in real time to cope with dynamic changes.

The scientific problems faced by intelligent information interconnection include: 1) Dynamic changes in link bandwidth and large differences in bandwidth; 2) Large space link distance range, long delay and strong intermittency will cause the problem of not being able to connect frequently; 3) Self repair of damaged network nodes and links; 4) Intra satellite and inter satellite resources are difficult to share on the network. The key technologies that need to be studied in depth to solve the above problems include: 1) Intelligent routing technology oriented to the characteristics of space-based networks; 2) Node dynamic access management technology; 3) Network topology dynamic adjustment technology adapting to dynamic link; 4) Network congestion management and fault self recovery mechanism; 5) Information sharing mechanism based on asynchronous message transmission.

5 Conclusion

In this paper, intelligent space system is studied from three aspects: intelligent information processing, autonomous task planning and intelligent information interconnection. Based on the research on the development at home and abroad, combined with the development status of relevant technologies of intelligent space system, the existing scientific problems are analyzed, and the development trend of key technologies of intelligent space system is summarized.

After nearly half a century of development, intelligent space systems in various countries have gradually achieved different degrees of autonomous control, and are still accelerating the pace of space intelligence technology research. At present, our country has preliminarily verified the intelligent data processing capability through deep learning and other artificial intelligence technologies on Jilin No.1 and Tianzhi No.1. In the future, China should vigorously develop fast and accurate on-board intelligent technology, and promote its application in intelligent space systems as soon as possible. At the same time, it should speed up the transformation of applications. It can consider the combination of industry, education and research to promote strategic cooperation between the aerospace industry and domestic technological advantaged institutions. We should make choices and reasonable arrangements in basic algorithm research, hardware product development, and mature algorithm engineering, so as to launch models and practical applications as soon as possible.

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