Applications and Challenges of Artificial Intelligence in Aerospace Engineering

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Zhenyu Qiu
College of Computer Information Engineering
Nanchang Institute of Technology
Nanchang, China
zhenyuqiu2023@163.com

Huan Zhao
College of Computer Information Engineering
Nanchang Institute of Technology
Nanchang, China
30476597@qq.com

Shijin Wang
Intelligent Space Technology Co.
Beijing, China
wsj@spaceis.cn

***Abstract*—With the development of aerospace technology and high-performance chip technology, artificial intelligence (AI) has been applied more and more in aerospace engineering tasks. Applications and key technologies of AI in aerospace engineering such as the intelligent design of space systems, intelligent management of space missions, active adaptability of spacecraft in complex missions and harsh environments, intelligent collaboration of spacecraft groups, and the autonomous ability of spacecraft in deep space exploration are reviewed and analyzed. And then the challenge from hardware and software of AI in aerospace engineering applications such as energy supply, information acquisition, transmission, processing, storage, and space environment threats are discussed. It is expected to further promote the application and development of AI in aerospace science and technology.**

Keywords—artificial intelligence, AI, aerospace engineering, key technologies, applications, challenges

I. INTRODUCTION

Artificial intelligence is a technical science that studies the theory, method, technology and application system used to simulate, extend and expand human intelligence. Space AI [1] can help spacecraft achieve autonomous intelligent perception, decision-making, collaboration and learning capabilities, including deep learning, reinforcement learning, multi-agent, etc., to enhance the active adaptability to complex tasks in uncertain environments in future space missions. Compared with ground artificial intelligence, the need for artificial intelligence in space systems is urgent, and the technical difficulty is also higher.

All the world's aerospace powers have strengthened the research and application of AI in aerospace engineering tasks. In the "Space Policy and Plan" formulated in 1998, NASA identified eight key technologies including artificial intelligence, intelligent control and robust multivariable adaptive control, etc. The 2025 plan of the United States Air Force, the 2020 plan of the United States Aerospace Command and the new millennium plan of NASA all put intelligent autonomous technology at the top of their development. For the potential application of artificial intelligence in space missions, the United States Aeronautics and Space Administration (NASA) and several international space organizations have established the International Conference on Space Artificial Intelligence, Robotics and Automation (i-SAIRAS) since 1990, which is held every two years [2]. In the field of space AI, a lot of research has been carried out, and many publications have been published.

In 1998, the International Institute of Electrical and Electronic Engineers (IEEE) discussed the strategic value of intelligent autonomous systems in expanding the number, capacity and bearing capacity of NASA's space missions in the future [3]. At the same time, IEEE also published a large number of papers on planning and scheduling, data mining, the reliability of autonomous systems and the architecture of intelligent systems. In 2010, artificial intelligence technology related to semantics was extensively studied in space mission applications, including natural language processing, on-orbit fault management, human-computer interaction and agent-based simulation architecture [4]. Among these researches, data mining, text mining and other key technologies are deeply discussed. Semantic technology is mainly used to simulate the process of human processing logic and reasoning problems, so as to realize the intelligence of the machine. This technology can be used not only for automatic analysis of spacecraft faults, but also for mission design and planning of space engineering.

In the space application of artificial intelligence, NASA and Google jointly used machine learning to discover the "second solar system"[5], whose data is from the Kepler Space Telescope launched in 2009. Based on the OASIS (CLEAR Execution) system, the intelligent perception decision system of MSL Curiosity Rover launched in 2011 combines computer vision and machine learning, and can find new scientific objectives of albedo characteristics by itself through training[6]. CIMON, an AI assistant deployed at the International Space Station in 2018, can communicate with astronauts by watching, speaking and listening [7].

With the technological update of processors represented by TPU, the improvement of computing power brought by cloud computing, the construction of satellite Internet and the wide application of big data, artificial intelligence technologies such as voice recognition, autonomous robots, and space autopilot have made continuous progress, and artificial intelligence is expected to be more widely used in space missions.

The space application requirements of AI such as space intelligent design, space intelligent perception, space intelligent interaction, space intelligent decision-making and control, and space intelligent cluster will be analyzed in this paper, and the challenges from hardware and software of AI in space applications will be discussed too.

II. The Need of Aerospace Engineering for AI

The need of space missions for AI mainly include intelligent design of space systems, intelligent management of space missions, active adaptability of spacecraft in complex missions and harsh environments, intelligent collaboration of spacecraft groups, and autonomous capabilities of spacecraft in deep space exploration such as autonomous judgment, autonomous decision-making, autonomous planning, and autonomous execution.

A. Intelligent Design of Space System

Intelligent design of space system refers to the technology that assists designers to complete optimization, layout, analysis and verification by intelligent means in the process of space system design, so as to improve the efficiency of space system design, the reliability and design performance of spacecraft, including the space environment adaptability design of spacecraft, reliability optimization design, smart material design, structural weight reduction optimization, mechanical property optimization, EMC design, Line layout optimization, controller aided design, etc. Key technologies used in intelligent design of space systems include genetic algorithm, simulated annealing algorithm, reinforcement learning, deep learning, etc.

Through space intelligent design, smart material design and preparation, intelligent design of key components of spacecraft, intelligent manufacturing of whole satellite, and intelligent modular satellite design can be realized.

In the design and development of smart materials for spacecraft, thermal control smart metamaterials, intelligent protection materials and on-orbit active repair materials have been developed against the threat of solar heat flow and space debris.

In space-based communication tasks, the use of artificial intelligence technology will help improve the efficiency of space-based communication networks. For example, using artificial intelligence and machine learning, spacecraft can seamlessly control the space communication system and make real-time decisions without instructions, so as to make full use of the space electromagnetic spectrum to transmit detection data to the ground. In addition, AI can also guide the spacecraft to make a timely decision on whether to shut down or turn on for severe space environment events, so as to reduce the space radiation damage caused by intense solar activities and avoid greater damage to the spacecraft system.

In the field of space mission planning and astronaut activity planning, the NASA had funded SHA (Stottler Henke Associates) software company developed a set of automatic scheduling system named as Automated Manifest Planner (AMP) for the Kennedy Space Center for the planning of space shuttle missions. In the later, SHA also developed the Intelligent Flight Activities Planner (IFAP) for the Johnson Space Center, which had been used for the activity planning of the space shuttle crew[8].

Using technologies such as 3D printing and virtual reality, Lockheed Martin and Boeing have realized the additive manufacturing of complex spacecraft components. Based on the optimization of digital genetic algorithm, the structural optimization of spacecraft components has been realized, and the manufacturing efficiency and structural performance have been greatly improved [9].

B. Intelligent Perception of Space Activities

Space intelligent perception refers to the perception and comprehensive judgment to the mission target, the surrounding environment and the state of the spacecraft by intelligent means. Facing the intelligent, autonomous and real-time requirements of the space system and space missions, considering on the particularity of the space environment, by introducing the machine learning method represented by deep learning, combined with intelligent means such as data mining, space intelligent perception can realize the situation awareness and high-precision measurement of the space system to the space environment, space targets and ground targets, and provide sufficient, high-precision and real-time information for ground situation awareness, On-orbit service, deep space exploration and other tasks of space system.

The key technologies of space intelligent perception include deep learning, 3D reconstruction, SLAM based on deep learning, system identification, statistical learning, etc.

The recognition of remote sensing satellite to ground or space targets, situation analysis, three-dimensional reconstruction of space environment, recognition and processing of detection targets, kinematics and dynamics parameter identification of space robots, health monitoring of spacecraft or astronauts, etc can be obtained by space intelligent perception.

In the field of deep space intelligent perception, as a typical application, Google and NASA jointly use the machine learning method and 15000 marked Kepler signals to train the machine learning model to distinguish the planet signals (the accuracy rate is up to 96%) by analyzing the tens of billions of data points of the Kepler Space Telescope, and find the eighth planet Kepler-90i, which revolves around the Kepler-90 galaxy, known as the second solar system. In addition, AI also discovered another star, Kepler-80g, the smallest planet in Kepler-80 galaxy [10].

The three important directions for NASA to use artificial intelligence technology in the Mars exploration mission are the automatic driving of the rover, the intelligent router which will allow the rover to independently adjust its driving route according to the schedule, and the rover will independently identify, classify, and collect samples of Martian rock core, soil and other chemical components[11-12]. The robot intelligent perception, autonomous decision-making and other new technologies can be used to build the lunar base and to achieve a high degree of "autonomy" of it. NASA's Frontier Development Laboratory (FDL) used artificial intelligence technology successfully to quickly and accurately model the 3D shape of asteroids.

In the field of intelligent perception in remote sensing, with the help of deep learning method, the remote sensing data is gradually extracted from low to high levels, and the main driving source of the data is discovered, so as to realize automatic processing of remote sensing images and improve the accuracy of remote sensing image classification. The NASA global sensor network named as Volcano Sensorweb uses the sensor network linked by software and the Internet to realize the autonomous satellite observation response capability and realize the observation of Iceland volcano eruption[13]. The hyper spectral remote sensing technology plan of the United States Naval Research Office and the Naval Research Laboratory has greatly reduced the space and temporal redundancy of hyper spectral data by adopting the real-time adaptive spectral identification system named as ORASIS for real-time processing and compression of satellite data.

In the field of manned spaceflight, intelligent perception can realize the interaction between robots and astronauts, and can also assist in completing autonomous fine operation in orbit. With the help of high-resolution cameras, infrared cameras and lighting equipment, the Robonaut-2 robot [14], which launched by the United States in February 2011, has achieved effective interaction with astronauts' helmet displays, headphones, microphones, data gloves and sports equipment, and completed communication, communication and refined operations with astronauts.

C. Space Intelligent Interaction

Space intelligent interaction refers to using intelligent methods for information recognition and processing and realizing the efficient information transmission technology between people and computers, robots and agents through voice, expression, gesture, EEG, VR/AR and other interactive means. Typical application scenarios include intelligent companion robot in space station, robot astronaut, voice command system of manned spacecraft, and manned exploration robot.

The key technologies of space intelligent interaction include natural language processing, speech recognition, gesture recognition, speech translation, EEG recognition, VR/AR technology, deep learning, etc.

With the development of artificial intelligence, hybrid reality and other technologies, intelligent interaction has shown great advantages in astronaut assisted operation and independent access to information. Intelligent interactive robots can share the simple manual operation work of astronauts, reduce the workload of astronauts and improve the efficiency of astronauts, relieve the psychological pressure of astronauts in orbit, perform fine operation tasks instead of astronauts, collection and display of aircraft status information, etc.

For example, the microgravity robot named as Astrobee [15] can set the state of the spacecraft before the astronauts enter it, monitor the environment of the spacecraft, and give early warning to the astronauts and ground controllers in case of emergency or fire; The SPHERES robot on the space station is equipped with Android operating system and can use mobile phones for intelligent interaction and control.

In the fields of virtual reality and augmented reality, NASA has complete the training of astronauts and the daily work of the International Space Station since the 1980s. By wearing helmet-type augmented reality equipment, astronauts can see holographic images containing technical auxiliary information through the display, free their hands during movement, and interact with the holographic images in the form of voice, gesture and gaze. Astronauts can complete on-orbit tasks under the guidance of these auxiliary information. In the field of science and technology communication, countries around the world are using VR technology to experience the space virtual journey, which can create a realistic and immersive atmosphere, and effectively integrate the observation data obtained by various spacecraft operating in orbit, so that the audience can obtain the sense of immersive satisfaction.

D. Space Intelligent Decision-Making and Intelligent Control

Space intelligent decision and intelligent control is the core of space artificial intelligence, which is to realize the transformation from data to decision. For spacecraft system, especially deep space probe system, spacecraft need to have a certain ability of intelligent decision-making and intelligent control.

Space intelligent decision-making is to independently select a series of orderly activities to form a planning plan by effective reasoning to complete the pending space tasks, based on the mission requirements of the spacecraft, the current status of the equipment, the actions that the spacecraft can take and their effects, and under the conditions of meeting the time requirements and resource constraints.

Space intelligent control is a decision and control method with intelligent reasoning and solution, which is based on the relevant theories and methods of artificial intelligence and combined with traditional mathematical models and methods.

The demand of space system for intelligent decision-making includes autonomous selection and sequencing of detection targets by deep space detectors, organization of construction and installation sequence by on-orbit construction system, arrangement of construction process by catalog construction, etc. The demand of space systems for intelligent control includes intelligent motion planning, motion control, force control, intelligent autonomous navigation of detectors, autonomous rendezvous and docking control for space robots under uncertain conditions.

The key technologies of space intelligent decision-making and intelligent control include intelligent decision support system (IDSS), strategy tree, knowledge representation, symbolic intelligence, reinforcement learning, deep reinforcement learning, Monte Carlo search method, RRT search method, adaptive dynamic planning, etc [16].

The typical application field of intelligent decision-making and control is deep space exploration. This is not only because of the long distance of deep space exploration and the large time delay of ground remote control, which is difficult to control in real time, but also because deep space exploration is facing a relatively harsh space environment, which requires the spacecraft to make timely and independent decisions according to the actual situation and take effective countermeasures.

The Deep Space 1(DS-1) [17] spacecraft in the New Millennium Program of the United States is the first spacecraft on-orbit control system that uses artificial intelligence to achieve unmanned monitoring. It has verified technologies such as autonomous navigation, autonomous remote agent, autonomous software testing and automatic code generation, and has achieved a certain degree of autonomous planning, diagnosis and recovery capabilities. The European Mars probe named as Mars Express (MEXAR-2) [18] intelligently predicts which on-board data packets may be lost due to memory conflicts, and optimizes the data download plan and generates commands required for actual transmission, which is also a typical application of space intelligent decision-making and intelligent control.

In the missions of the International Space Station and the Chinese Space Station, AI is an important part of space automation. By using artificial intelligence, the construction and reliability of manned space stations can be improved, especially in space rendezvous and docking, visual positioning and tracking, measurement and target recognition, fault diagnosis and health management, expert system construction, behavior planning and rapid search and rescue, etc.

E. *Space Intelligent Cluster*

In space missions, the space environment imposes strict constraints on the capabilities of single spacecraft such as satellites, space stations, robots or other space vehicles. The method of intelligent cluster is used to give full play to the advantages of a single spacecraft or payload, and combine different intelligent individuals organically to form an whole with perfect functions and performance to achieve specific space tasks, thus reducing the requirements and dependence on individual functions, and reducing the cost of a single space object.

The space system cluster intelligence has a good application prospect for the formation of satellite groups, formation flying robots, deep space exploration, base construction and others in the future. Cluster intelligence can effectively reduce the requirements for individual complexity, break the strict constraints imposed by the space environment on the individual capabilities of a single satellite, space robot or other space vehicles, and improve the task execution ability of the group by means of higher adaptive ability, collaborative ability, autonomy and other cluster behaviors [19].

The key technologies of cluster intelligence include Multi-Agent theory, cluster modeling method (particle swarm model, Vicsek model, Boyd model, etc.), cluster control method, machine learning method, formation technology, multi-robot cooperation technology, etc.

The typical application of space intelligent cluster is constellation/formation satellite. The constellation is established by placing satellites in the earth orbit to achieve global communication, and the formation of multiple satellites is used to improve the mission execution ability. By adopting the method of cluster intelligence, constellation or formation can realize autonomous operation. The "Star Link" Internet satellite system of the United States is one of the typical applications.

III. Challenges of Artificial Intelligence in Aerospace Applications

Although AI has been applied in different fields of aerospace engineering and has developed rapidly. However, whether in hardware or software, the aerospace application of AI still faces great challenges.

A. *Hardware Challenges of AI in Aerospace Applications*

AI is inseparable from big data, which poses great challenges not only in energy supply, but also in information collection, transmission, processing and storage.

First of all, energy supply is a major challenge of AI in space applications. T The application of AI requires a large amount of data and high-speed data calculation and processing analysis, and requires sufficient on-board power supply.

Second, the application of AI in aerospace engineering depends on reliable and massive information acquisition and acquisition data, which requires the development of payloads with different application and data acquisition ability, including image acquisition payload, sound acquisition payload, environmental detection payload, etc.

Third, high-precision space AI requires massive data, which should be timely and effective transmitted to the designated location, so the space system need to have high-speed data transmission capability.

Fourth, the implementation of AI algorithms requires strong computing power, especially the deep learning algorithm, which puts forward higher requirements for computing power. The development of chips represented by GPU and FPGA represents the development direction of big data processing.

Fifth, the valuable intermediate and final results from the generation, transmission and application of massive data will eventually saved in memory. Therefore, the space application of AI needs to have massive data storage capacity.

B. *Software Challenges of AI in Aerospace Applications*

With the introduction of different concepts such as "software defines satellite" and "software defines everything", software will play a key role in the application of artificial intelligence in aerospace. The collection, screening, processing and invocation of massive data generated in the application of AI in aerospace engineering need reliable and efficient software algorithms. At present, AI software, represented by deep reinforcement learning, has shown great application potential, but it still faces great challenges in expanding application and reliability.

First, the new algorithm is challenge of AI software in aerospace applications. For software represented by deep learning, how to achieve more efficient and how to solve the convergence and interpretability of software algorithms is one of the important challenges.

Second, the reliability of software is should be given more attention. Reliability is not only the algorithm of the software itself, but also the soft errors that may be caused by the attack of space high-energy particles. How to identify and correct the software soft errors timely is the key direction of AI in space application.

Third, the security of software is closely related to the uncertainty of the output of AI results. In the application process of artificial intelligence in aerospace engineering such as space manipulator, if there are errors in the autonomous perception process, it may bring serious consequences or serious accidents. Therefore, it is necessary to comprehensively consider the uncertainty of AI and practical situation, and give different software strategy in time.

Fourth, the learning ability of software is an important direction of AI in aerospace applications. The environment perception of the same hardware system will change at different times or in different application scenarios. Therefore, AI software needs to be able to adapt to the changes of environment or scenarios to provide new methods to solve problems.

IV. SUMMARY

AI is a strategic technology and an important driving force for the development of aerospace science and technology. For future aerospace engineering missions, especially deep space exploration missions and astronauts' on-orbit work, artificial intelligence will play an important role in the fields of information acquisition and rapid processing, risk identification and response, and intelligent autonomous decision-making and control. Only by system planning, carrying out the space application design of AI from the whole, and solving the application limitations and challenges in hardware and software, can we promote the rapid development and application of AI in aerospace engineering systems, and further promote the progress of human civilization.

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