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Research on Maintenance and Replacement technology of Space Mechanical Arm

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Abstract: This paper presents the station arm structural components and discusses the importance and challenge of station arm maintenance. The article provides the main process of the maintenance of the space station robotic arm, including the troubleshooting, the replacement and maintenance of parts, and the calibration and testing of the system. At the same time, the article also points out that the mechanical arm failure may be caused by a variety of factors, including electrical failure, mechanical failure and environmental failure, and shows some classic cases and summarizes the experience. This paper shows the development process of maintenance technology and the current research status quo. Finally, it is pointed out that the maintenance of the space station robotic arm still faces many difficulties and risks, which need further research and improvement.

Keywords: Maintenance; Fault diagnosis; Parts replacement; System test; Space Mechanical Arm.

1. Introduction

In the endless journey to explore the universe, humans have been looking for new methods and technologies to better understand our universe, where the space robotic arm is the key device that plays a vital role in space exploration and missions. They are highly flexible and accurate, capable of performing various missions in extreme environments, such as repairing, replacing and installing space station equipment, and conducting scientific experiments. However, due to the long-term operation in space and affected by external factors, the robotic arm may fail or need component replacement and repair. This paper aims to introduce and discuss the key technologies for maintenance and replacement of space robotic arms, which will deeply explore the basic composition, maintenance process, and technical development and trends. By learning this, the reader will be able to understand how to effectively diagnose and troubleshoot the robotic arm, and to master the correct parts replacement and maintenance methods. This paper will also share some solutions to common faults and successful maintenance cases through case analysis and experience summary. This will help readers to better cope with the actual situation, improve the maintenance efficiency and success rate. Finally, we will look to the future direction and challenges of space arm repair and replacement technology. As space exploration continues to deepen and mission complexity increases, the requirements for robotic arm maintenance technology will also increase. We believe that through continuous research and innovation, the space robotic arm repair and replacement technology will play a more important role in the future, and make a greater contribution to the cause of human space exploration.

2. Space Mechanical Arm

Space mechanical arm itself is an intelligent robot, with accurate operation ability and visual recognition ability, both autonomous analysis ability can also be remote control by the astronauts, is a set of mechanical, visual, dynamics, electronic and control disciplines for the integration of high-end space equipment, is a space space development direction. With the rapid development of space technology, especially the birth and successful application of space station, space shuttle, space robots, etc., the space robotic arm, as a key technology of in-orbit support and service, has entered the space, and has attracted more and more people's attention. Through the actual use of the space shuttle and the International Space Station, the space robotic arm has shown strong application capabilities and broad application prospects, and played a great driving role in the development of space science and application. It can be said that it is the product of the increasing human space activities and the expanding scale of activities.

2.1. Structure and components of the spatial robotic arm

The space robotic arm is a complex and highly automated mechanical system, including sensors, control system and power supply. The joint is usually driven by the motor, the actuator is the key element of the mechanical arm movement, used to control the mechanical arm movement, the claw is used to grasp and release the load, the load sensor and hinge and gearbox play a central role in the movement and control of the mechanical arm. Overall, only the synergy of the various parts can ensure that the robotic arm can accurately and stably complete various tasks and play its important role in the space station.

2.1.1. Mechanical structure

The space station robotic arm is one of the key equipment for the construction, operation, maintenance and expansion of China's space station. The core cabin mechanical arm is composed of the inside part and the outside part. The cabin part is composed of the interface provided by the manipulator operating station and the space station for the robotic arm, which provides the guarantee of power supply, data, instructions and operation control for the robotic arm. The extravehicular part refers to the mechanical arm body, including joint, end effector, arm rod, central controller and visual system.

2.1.2. Sensor

The space station's robotic arm is also equipped with various sensors, such as force sensors, position sensors, and attitude sensors. These sensors measure the force, position and attitude of the arm to adjust and control the arm according to the real-time data.

2.1.3. Control system

Movement control of the robotic arm is achieved through a control system. The control system of the space station manipulator usually includes a central controller, actuator control circuit and feedback control circuit. These parts work together to perform various tasks by controlling the movement of the robotic arm and performing the movements.

2.1.4. Power supply

The station arm comes from solar panels and is stored and distributed through power converters and battery packs. Power supply is the basic guarantee of the mechanical arm, but also the prerequisite of its normal operation.

2.2. The significance of space robotic arm maintenance

The maintenance of the space mechanical arm is of great significance. First of all, the robotic space arm is an indispensable tool in space missions, responsible for material handling, maintenance tasks, scientific experiments and other work. If the mechanical arm fails, it will directly affect the execution and implementation of the task. Therefore, the maintenance of the space mechanical arm is not only of great significance to the reliability and long life of the mechanical arm, but more importantly, it can ensure the smooth progress of the mission and ensure the normal operation of the spacecraft. Secondly, repairing the space robotic arm can save costs. The cost of a space mission is very high. If the mission fails due to the failure of the mechanical arm, it will not only mean a waste of money invested in the early stage, but also need to plan and prepare the mission, which consumes more resources and time. Through timely maintenance of the robotic arm, the risk of task failure can be reduced and the cost waste can be reduced.

In addition, the maintenance of the mechanical arm can also improve the technical level. Through the fault analysis and repair of the robotic arm, engineers can learn more about the structure and working principle of the robotic arm, and accumulate more experience and knowledge. This will help to improve the technology level of related fields and promote the development of space technology.

3. Maintenance Process

In space missions, the space robotic arm is often used to assist astronauts in a complex series of operational missions, such as that capture aircraft, transfer payloads, and assemble modules[1,2]. However, due to the harsh space environment, heavy operation tasks and the complex structure of the robotic arm itself, its joints are prone to failure. At this time, if the joint fault is diagnosed and the relevant information is not obtained in time, not only will the mechanical arm fail to complete the predetermined task, but also may expand the impact of the fault and endanger the safe operation of the mechanical arm. Therefore, it is necessary to diagnose and troubleshoothe space arm joint, complete parts replacement and maintenance, and conduct system calibration and testing.

3.1. Fault diagnosis and remove

Among various fault diagnosis techniques, the method based on analytical model is one of the common methods, which can be divided into two steps: residue generation and diagnostic decision[3]. The residual is used to reflect the status of the diagnosed system, which is close to zero when the system fails; when the system fails, the residual will deviate from the zero value. Existing studies often use state estimation method to generate residuals, such as using state observer method, particle filter method, Kalman filter method[4-6], etc. The basic idea of these methods is to form the residuals by comparing the outputs of the actual system with the estimated outputs of the observer or filter.

However, the space robotic arm is affected by a series of external disturbances, including high-energy particles in space, the upper atmosphere and the vibration of the spacecraft. These perturbations cause the residual of the arm to fluctuate around the zero value, but do not mean that the arm joint fails at this time. To solve this problem, a prior threshold of the residue sequence should be addressed. In order to eliminate the influence of external perturbations on the residuals, many scholars have adopted various methods, such as neural network, set theory and feature structure configuration[7-9], to disrupt and decoupling the state observer, so that the residuals are only sensitive to the fault signal.

After the realization of fault detection, it is necessary to analyze the fault residual information, and identify the fault mode (including the fault location and fault degree), so as to realize the fault system recovery or fault tolerance control, so as to realize the fault troubleshooting. The common methods of fault residual analysis are neural network method, fuzzy inference method, statistical decision method and so on.

3.2. Parts Replacement and Maintenance

In order to repair the specified product, corresponding interfaces, including mechanical and electrical interfaces, need to be designed to ensure that various components of the repaired arm can be connected by the quick connection device. In joint design, the hand drive interface needs to be reserved and the hand drive tool design should be carried out to ensure that a uniform mechanical arm maintenance configuration can be adopted in joint failure to facilitate the on-track maintenance and replacement of the mechanical arm. In addition, it is also necessary to unify the joint and end replacement tooling, and design a common tooling installation interface on the fast connection device, in order to fix the special tooling on the fast connection device, and realize the replacement of the mechanical arm in any configuration and any interface.[10]

In order to assist the astronauts in the disassembly of the faulty parts and the installation of the new parts, and to maintain the overall posture of the mechanical arm during the maintenance process, the maintenance tools need to be designed. Maintenance tools are mainly divided into special maintenance devices and special disassembly tools. The special maintenance device adopts the modular design, and uses the maintenance interface for different types of ORU (On-Orbit Replaceable Unit), mainly including the separation mechanism and the follower mechanism, which can realize the separation and docking of the fault ORU in the vertical direction. Special disassembly tools mainly include expansion bolt disassembly tools and loose disassembly tools. The maintenance tools are designed to effectively support the astronauts in the maintenance work of the mechanical arm, and to achieve the required disassembly and installation tasks.

3.3. System Calibration and Testing

After completing the overall design of the in-orbit maintenance scheme of the space mechanical arm, it is necessary to verify its correctness, the rationality of the maintenance process, the feasibility of the maintenance device, and the man-machine working performance in the maintenance process. In order to obtain the important data of the maintenance process, it is necessary to carry out the corresponding ground maintenance test verification, including maintenance simulation verification, air float and suspension zero gravity verification, maintenance service verification, neutral tank test and on-orbit maintenance verification. The specific experiment contents are shown in Table 1 [10].

Table 1. Reptainability verification planning of space robotic arm

Maintenance link	Repair simulation	Validation of air floating suspension	Served to verify	Neutral tank test	On-orbit verification
Upside / assembly of spare parts	×	×	√	×	√
Astronaut / spare parts exit the module	√	×	×	√	√
Maintenance drill	√	×	×	√	√
Maintenance operation	√	√	√	√	√
Fault parts / tool return module	√	×	×	√	√

In addition, with the continuous development of industrial software, the three-dimensional simulation environment can be used to control the range of motion and operation action of the astronauts, to simulate the whole maintenance process, and visually reflect the performance of the maintenance scheme.for instance, Build a maintenance environment on the ground by means of air floating tooling and suspension zero gravity, Carry out the corresponding ground maintenance test according to the maintenance process, Can simulate the human-machine ergonomics of astronauts; Using the spacesuit verification test, Operating the robotic arm fault ORU in the case of simulated astronaut service, It can verify the accessibility, operation power, operation space, visibility, operation feedback, anti-drift, anti-error, operation identification and other indicators; Using the in-orbit verification test, Ensure that special tests are organized for verification after the rail, Mainly for the typical operation and key link of mechanical arm maintenance, Further verify the correctness of the maintenance design[10].

4. Maintenance Case Analysis

4.1. Common faults and solutions

In December 2017, the data from the Ministry of Communications of China showed that there were 77 shared bicycle companies had entered the market,with 23 million shared bicycles in total. The domestic users were nearly 221 million, accounting for 28.6% of the total number of netizens.According to the 2017 Entrepreneurship Valuation Rankings, ofo ranked 43rd with a valuation of 13.8 billion yuan, and Mobike ranked 52nd with a valuation of 10.5 billion. Ofo and Mobike stood out among shared bicycle companies[11].

4.1.1. Electrical accident

This kind of fault is mainly caused by the damage or abnormality of electrical components such as circuit, power supply, sensors or controllers. For example, the power supply voltage is too high or too low, the circuit short circuit or open circuit, the sensor signal distortion or loss, the controller software crash or crash, etc. The methods to solve this kind of fault are: checking and replacing the damaged electrical components, adjusting and stabilizing the power supply voltage, detecting and repairing circuit connections, restart or updating the controller software, etc.

4.1.2. Mechanical failure

This kind of failure is mainly caused by the wear or damage of mechanical factors such as mechanical structures, mechanical components, and mechanical connections. For example, mechanical arm joint stuck or loose, mechanical parts deformation or fracture, mechanical connection loose or off, etc. The methods to solve this kind of failure are: lubrication and adjust the mechanical arm joints, replace and repair mechanical parts, fastening and connecting mechanical connections, etc.

4.1.3. Environmental failure

This kind of fault is mainly caused by the influence of temperature, radiation, microgravity and other factors in the space environment on the space mechanical arm. For example, too high or too low temperature leads to change or damage of material properties, aging or failure of electronic components due to radiation, change or instability of kinetic parameters caused by microgravity, etc. The methods to solve this kind of fault include: the use of high and low temperature and radiation resistant materials and components, the design of reasonable thermal control system and shielding system, considering the impact of microgravity on motion control and compensation.

4.2. Successful case sharing

(1) The robotic arm of the US space shuttle has failed

In October 1985, the Space Shuttle Challenger (Challenger) was the STS-51-J mission. The reason is that the power line of the arm was damaged during the launch process, resulting in the arm can not work normally. To fix the problem, the astronauts carried out emergency repairs in the cabin, connected the backup power line to the robotic arm, and successfully completed the mission.[11]

(2) The mechanical arm of the experimental chamber is stuck

In March 2008, the small robotic arm of the Japanese Laboratory module (Kibo) on the International Space Station got stuck during tests. The reason is that one of the sensors of the arm fails, causing the arm to move normally. To solve this problem, the astronauts performed manual operations outside the cabin , liberating the mechanical arm from the stuck position, and successfully completed the task. The manual operation took about 40 minutes, longer than expected.

(3) The International Space Station's robotic arm will impact

In May 2021, the Canadian Arm 2 (Canadarm2) of the International Space Station found a small hole hit by space junk, damaging the arm bar and insulation. This was a "lucky impact" because the function of the robotic arm was not affected. To fix this problem, the astronauts plan to inspect and repair the of the robotic arm during future cabin exit activities.[12]

(4) Mechanical arm failure drill of the Chinese space station

In June 2021, the large robotic arm of the Chinese space station conducted a fault drill, simulating in-orbit maintenance and emergency response. During the drill, the flight control personnel and astronauts worked closely to carry out a variety of fault diagnosis and processing of the arm, and verified the reliability and safety of the arm.[13]

5. Technological Developments and Trends

5.1. Development process of space mechanical arm maintenance technology

The development of the space robotic arm can go back to the 1950s, when the American aerospace industry began studying robotic arm technology for the assembly and maintenance of satellites.

Nowadays, the maintenance and replacement technology of the space mechanical arm has made significant progress. Early studies focused on the design of rapidly replaceable end actor for lightweight robotic arms [14]. With the development of technology, researchers began to focus on how to design and study the rapid replacement interface of the mechanical arm joint in the laboratory chamber[15-17]. These studies lay the foundation for the development of automatic hand claw replacement devices for space robots. In order to improve the maintenance efficiency, some scholars put forward the idea of modular design of the joint part and the center hole of the joint, the connection of the joint, the end actuator, the arm rod, the central controller are using the fast connection device, the interface standard is unified, to facilitate the maintenance[18]. The mechanical arm joint adopts modular design, that is, the mechanical components of the seven joints forming the robotic arm are exactly the same as the drive control system, and are designed according to the maximum load conditions, and each joint can be interchangeable. A single joint adopts the design concept of mechatronics, which is a highly integrated electromechanical component, which makes it easier to replace and upgrade[19]. For example, in 1984, the astronauts on the space shuttle STS-41C mission successfully removed and replaced the attitude control system fault module in orbit. The maintenance of the mechanical arm joint mainly works through the special maintenance tools of the astronauts, which greatly tests the functional performance of the tools and the reliability of the in-orbit work.

5.2. Current research and application fields

At present, the research and application fields of space mechanical arm maintenance and replacement are very wide. Space mechanical arm maintenance research mainly focuses on the joint using modular design, the design of space mechanical arm joint rapid replacement interface, and design on the quick connection device general tooling installation interface, the special tooling fixed on the fast connection device, in order to realize the mechanical arm any configuration, any interface replacement.

At present, foreign research on the mechatronics technology of space robotic arm is mainly led by the International Space Station, German Aerospace Center and NASA, such as Canadian Arm 2, Japanese remote control robotic arm system, European space robotic arm, German Aerospace robotic arm, NASA rover robotic arm. The domestic research is mainly represented by the lunar rover arm, XX-4 arm and integrated arm. These mechanical arms all use mechatronics, with standard electrical and mechanical interface modular joints, which not only meets the requirements of large load, high precision, repairability, easy to replace the space arm, but also makes the research and development of the space arm more standardized, the standard more unified.

At present, some domestic scholars are studying the maintenance system of the end effector of the space robotic arm. He proposed a joint maintenance scheme of the robotic arm for three times. When the end actuator of the space mechanical arm fails, the first exit mission requires the astronauts to carry maintenance tools and maintenance spare parts, and complete the construction of the maintenance scene at the fault place. The second exit mission requires the astronauts to use the small robotic arm to go to the designated maintenance point, and remove the faulty parts of the end actuator before installing spare parts. The third exit mission requires the astronauts to dismantle the maintenance scene and bring the faulty parts and maintenance tools back to the cabin. This maintenance scheme requires a unified design of the maintenance interface, using special maintenance tools, and taking thermal control measures to ensure that the maintenance spare parts can be maintained at a working temperature of for at least three days after leaving the cabin[20].

5.3. Future development direction and challenges

Although the space robotic arm has made remarkable progress, it faces many challenges due to the requirements of its future development trend. First, the joint maintenance of the robotic arm needs to consider the constraints of the astronauts, such as the continuous operation length, maximum output torque, accessible operation range, visibility, etc.; second, the implementation of joint maintenance needs to consider the constraints of robotic arm configuration, space station attitude, astronaut coordination operation and the challenge of maintenance test, including simulation test, air float and suspension zero gravity verification, maintenance simulation verification, service verification and neutral buoyancy tank test.

6. Conclusion

Space station robotic arm maintenance is an important and challenging task. This paper analyzes and discusses the structure, function, cause of failure and maintenance methods of the space station manipulator, and aims to provide some references and suggestions for the operation and management of the space station manipulator. Mechanical arm failure may be caused by multiple factors, and common faults include electrical fault, mechanical fault, environmental fault, etc. In order to realize fault detection and elimination, the analytical model-based method can be adopted to reflect the status of the diagnosed system through residual difference generation and diagnosis decision. Moreover, neural network, set theory and feature structure configuration are used to interfere and decouple the state observer, so that the residual is only sensitive to the fault signal. Finally, the neural network method, fuzzy inference method, statistical decision method and other fault residual analysis methods are used to achieve the troubleshooting.

Today, the space station robotic arm maintenance still faces many difficulties and risks, such as technical complexity, personnel constraints, time constraints, high costs and so on. Therefore, some measures need to be taken to improve the efficiency and safety of the space station robotic arm maintenance, such as optimizing design, improving quality, enhancing training, improving planning, etc. In this paper, the problem of mechanical arm maintenance of the space station is preliminarily discussed, and many aspects need further research and improvement. It is hoped that this paper can provide some enlightenment and help for the theoretical research and practical application of space station robotic arm maintenance.

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