Development of On-Orbit Assembly and Maintenance Technology with Space Robot

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Abstract：For life extension and construction of large space facilities, we hope to break through the weight and outline restriction of the rocket by using the on-orbit assembly technique with space mobile manipulators, in order to satisfy the need of large space facilities in the future space mission; on the other hand the space robot on-orbit servicing system should be built to recycle the bad spacecraft and this orbital succor and life extension of old spacecraft. Both sides need to research the on-orbit assembly and maintenance technology, especially the technology with space robot. This paper introduces the development of on-orbit assembly and maintenance technology with space robot and the key techniques are studied from all aspects, including system design, control, path planning, object identification, human-machine interaction and energy-saving operation. The on-orbit assembly and maintenance technology with space robot will have great impact on design and operation of spacecraft in the future.

Keywords：**Spacecraft, Space robot , Assembly, Maintenance**

1. Introduction

With the development of space exploration, new application requirements are put forward for large spacecraft or other large space facilities such as international space station. Large spacecraft is difficult to constructed by one shoot, limited by the bearing ability of rocket, so many countries are considering new ways to built large space facilities. On the other hand, in order to avoid the local fault on-orbit influence to the spacecraft mission or even the life, we hope to realize the orbital succor and life extension of old spacecraft by using the on-orbit maintenance technology. For the special space condition of the spacecraft, manual on-orbit servicing faces many problems, so the on-orbit assembly and maintenance with the space robots shows it's obvious advantages.

This paper introduces the development of on-orbit assembly and maintenance technology with space robot and the key techniques are studied from all aspects, including system design, control, path planning, object identification, human-machine interaction and energy-saving operation. The on-orbit assembly and maintenance technology with space robot will have great impact on design and operation of spacecraft in the future.

2. The on-orbit assembly and maintenance technology

The on-orbit assembly and maintenance technology is an important technology of on-orbit service, while on-orbit assembly is to construct an unit of satellite, space structure or other space facilities, and on-orbit maintenance is to repair the on-orbit space facilities and make them maintain the original performance or upgrade to high performance, including all the space activity for life extension. The on-orbit assembly and maintenance technology relates to the connection,

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substitute, construction, combine or reorganize of the satellite equipment or other modules of different space system. According to the history of the on-orbit assembly and maintenance technology, we can divide it into three stage: The forming stage of the on-orbit assembly and maintenance technology; The research stage of manual on-orbit assembly and maintenance; The research stage of autonomous on-orbit assembly and maintenance with space robot.

The astronaut can't participates the assembly or maintenance of extravehicular equipments directly for bad weather and safety reason, so the space robots are needed to replace human to complete these missions. The space robots are required to carry and operate huge loads on the spacecraft, from kilogram class to the ton class. The robot system can carry out these missions without human, and they can bear more bad environment, such as the stronger radiation of outer space and the high electric voltage or microwave. Therefore the on-orbit assembly and maintenance technology with space robot has good economy value and militaries value, and will be one of the important research aspect of the space application technology in the future [1-3].

3. Review of the on-orbit assembly and maintenance technology with space robot

3.1 The Space Robots on the International Space Station (ISS)

The space robots are essential for the construction and maintenance of the ISS [4-5], which are be used to support experiments, extra-vehicular activity (EVA) and scientific activities. In 1981，Canada designed and produced the highly successful robotic arms for the Space Shuttle fleet, the Remote Manipulator System (SRMS). In 1998, the SRMS played a critical role in the first assembly mission of the ISS, successfully mating the Unity node cabin of the USA and the Zarya cabin of Russia. Another successful mission was the repair of the Hubble Space Telescope where it was used as a mobile work platform for astronauts during numerous EVA works required to repair the faulty parts.

Currently the ISS is the unique Space Station, which provides the opposite cheapness, stabilizes, long-term of platform for the space robot exploration. There are three robots in the ISS. The most representative space station manipulator is the Canada’s Mobile Servicing System (MSS) [6-7], as shown in Fig.1, which is developed for the assembly and maintenance of the International Space Station (ISS). The MSS includes a large-scale Space Station Remote Manipulator System (SSRMS) (17. 6 m long, 7 degree-of-freedom) and a Special Purpose Dexterous Manipulator (SPDM) (3.5 m long, 15 degree-of-freedom). The system is initially installed on the US module of the ISS and has played a key role for servicing the ISS. In addition, the ISS is also equipped with another large space robotic system: the European Robotic Arm (ERA) (length 11.3 m, 7 degrees of freedom) and the Japanese Experiment Module Remote Manipulator System (JEMRMS) (length 9.9 m, 6 degree-of-freedom, with a 2m-long small manipulator installed at the end).

Figure 1　The SRMS　　　　　　　　Figure 2　The SSRMS

The Robotic Refueling Mission (RRM) is carried out by NASA and CSA, which provides the refueling service for life extension of spacecraft. The SPDM tools and satellite module are designed by NASA Langley Research Center. From 2011, three RRM tests are carried out by the SPDM, which demonstrates the robotic refueling technique for satellite without special interface. In the latest mission, the SPDM removes two screw caps and cut down two connection lines, and transform some fuel into the RRM module. The operating simulation and test pictures are showed in Fig. 3. The RRM is one of the key tasks to develop the on-orbit assembly and maintenance technology. After that, Robonaut 2, an upper-body dexterous humanoid robot, is used to complete more operational tests inside the ISS, including some maintenance and cleaning tasks such as inventory management, handrail cleaning, and data collection.

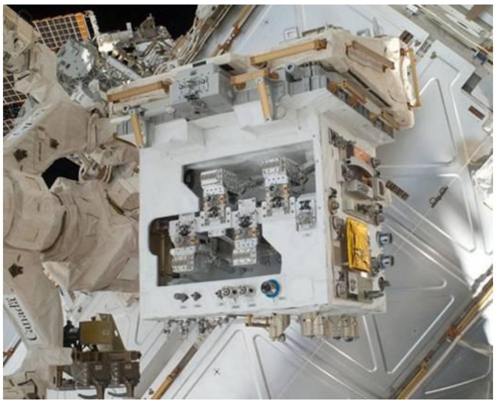

Figure 3　The Robotic Refueling Mission

Figure 4　Robonaut 2 in the ISS

European participate the ISS construction, developing a great deal of space robot operation research work. One of the successful example is the space robot system ROTEX of Germany, including several force sensors, heptameters, and infrared sensors and CCD sensors, which has six degrees of freedom and can perform fine dexterous tasks like the SPDM. Another space robot system is the JERICO developed by the ESA and Italy, which has seven degrees of freedom and more force sensors and position sensors and can carry out high accuracy operation tasks.

The deutsche orbital servicing mission (DEOS) and the orbital life extension vehicle (OLEV) are developed by the DLR recently, while the DEOS is aimed to validate the capture ability of non-cooperative target and the orbit transfer ability of spacecraft for recycling as shown in Fig. 5, and the OLEV is designed for life extension of spacecraft like the RRM task as shown in Fig. 6,. Both of them require to develop the on-orbit assembly and maintenance technology with space robot.

Figure 5　The DEOS system

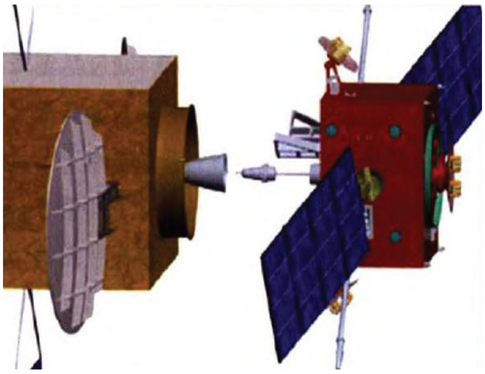

Figure 6　The OLEV system

3.2 The Skyworker Robot

Many initiatives under study by both the space science and earth science communities require large space systems. In the early 90's Skyworker is the first generation of mobile manipulators for orbital assembly (AIM), inspection and maintenance, as shown in Fig. 7, which is made by the Carnegie Mellon university[8]. The detailed design is carried out and the prototype is evaluated by several tests. Skyworker can autonomously transport and manipulate payloads of kilograms to tons over kilometer distances. In order to maximize the speed and efficiency of transport, while minimizing the forces, Skyworker utilizes a continuous gait, which allows the robot to maintain massive payloads at a constant velocity for power efficiency. Skyworker walks with a hand over hand gait, which achieves simple but efficient motion appropriate for prehensile motion on space facilities. The robot is demonstrating the fundamentals of continuous gait locomotion and is helping to identify key technologies for future development. Walking on the structure was tentatively selected as the primary mobility for this study because it has no significant impact on the design of the structure when compared to the rail used at ISS. Future work will continue to demonstrate the attached mobile robots are an essential part of orbital AIM.

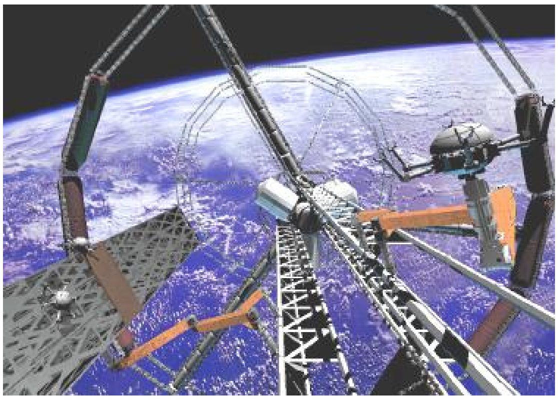

Figure 7 The Skyworker robot

3.3 The Truss assembly robot

Realizing the potential for automated assembly of space structures, researchers at NASA Langley Research Center develop a robotic system to assemble truss structures with equal length members, which is useful to the Space Solar Power System (SSPS). Truss assembly was selected because trusses form the primary support structure in many missions including telescopes and solar array fields. The work has been finished in the repeated autonomous assembly and disassembly of an 8m diameter structure composed of 102 truss members covered with 12 panels shown in Fig. 8, which occurred in an unstructured lighting environment[9]. The robot system includes three motion bases, a robot, two special purpose end-effectors and several cameras, which is assembled in rings on a rotary motion base. Structural assembly alternates between assembly of rings of truss elements and rings of panels. The installation begins with the removal of a element from the canister. The element is then transported to a prescribed location. Next the element is transported to the vision approach point, approximately 12 to 16 inches from the strut's final installation position. At this point a machine vision algorithm takes over to guide the robot to the structure. Following machine vision guidance to the target position, a force torque algorithm is used to provide final precision alignment maneuvers prior for contact installation. To improve the system reliability, different technology are developed including the use of complementary sensing technology and a hierarchical software scheme supporting system to be pauses or queries at any time during the assembly. In addition, the assembly process is designed to minimize the opportunities for collisions by operating the robot in large open areas with the protection of many sensors.

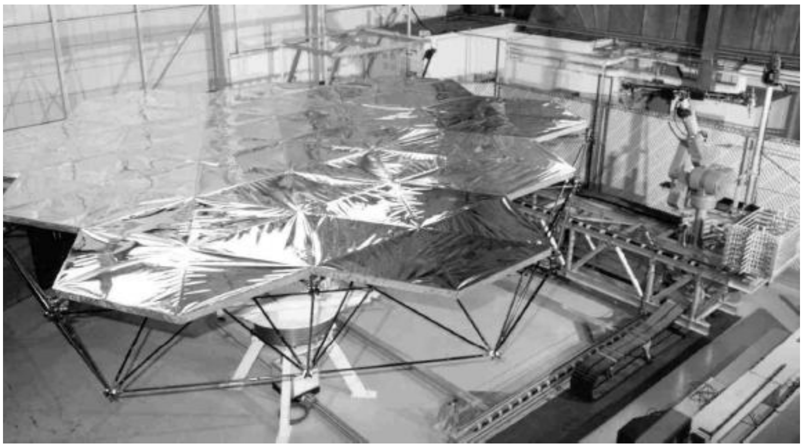

Figure 8 The Truss assembly robot system

3.4 The four-legged robot for the SSPS

JAXA has been studying the SSPS concepts for several years and believes that the on-orbit assembly and maintenance technology with space robot will play an important role in the future. There are two types of robots required for SSPS on-orbit construction: the locomotion robot and the assembly robot. The locomotion robot is used for moving around on light-weight structures, while the assembly robot is used for capturing and connecting vibrating structures for assembly after self-deployment. Taking advantages of two different robots, a high accuracy four-legged robot is built by JAXA, which can transport, assemble and dismantle components widely spread over the structure at routine intervals or on demand [10]. The strategy for moving around on highly light-weight structures is to employ a four-legged robot capable of walking gently and precisely, yet reasonably rapidly, on the fragile structures. A ground experiment platform has been set up, which consists of a four-legged robot, its support system, and a light-weight structure, as shown in Fig. 9.The strategy for assembling a large flexible structure is to employ multiple robots to estimate, capture, and connect large-scale vibrating structures. Experiments to confirm the feasibility of using multiple robots have been successfully conducted, demonstrating the tracking of flexible structures.

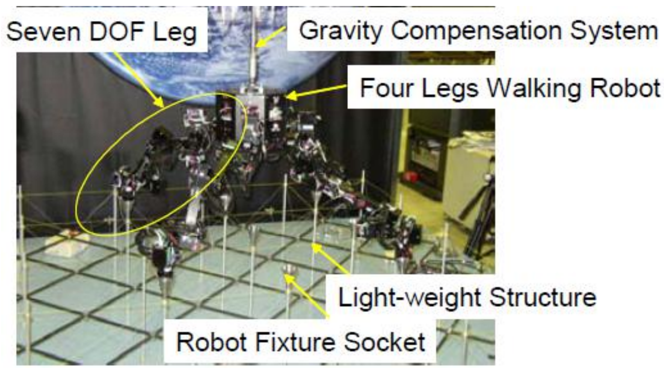

Figure 9 The JAXA four-legged robot

3.5 The MIT Cooperative Robotic System

Teams of cooperative space robots are researched by the robot laboratory of MIT for large space structure such as the construction of the SSPS in earth orbit. This work focuses on the design and control of robot teams performing construction tasks such as manipulation and assembly of space structures, which are flexible and lead to significant dynamic interactions between the robots and the structures [11]. Further, limited sensing and actuation in space present additional challenges. The control of the high-frequency robots is decoupled from the control of the low-frequency structures, which are experimentally validated using the MIT Microgravity Robotic System Testbed. The testbed consists of a flat table platform for space robot assembly experiments as shown in Fig 10. The space robots can float on air bearings to emulate 2D weightless conditions. Each robot has two 2-DOF manipulators and eight thrusters. Force/torque sensors are mounted on the robots along with joint encoders and sensors. The robots can operate in free-flying mode or free-floating mode and can be reconfigured to multi-manipulator assembly robot, which is verified by simulation and laboratory experiments[7].

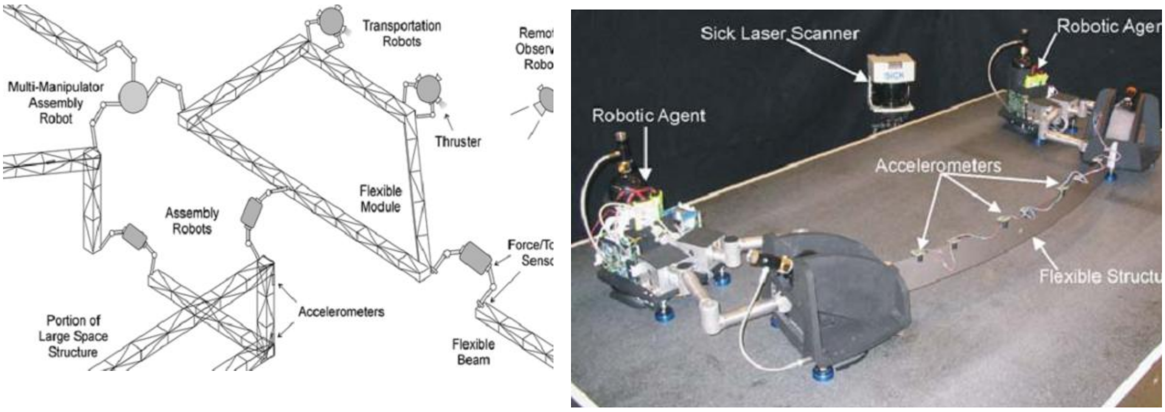

Figure 10 The MIT Cooperative Robotic System

3.6 The Front-end Robotics Enabling Near-term Demonstration (FREND) robot

Currently the FREND mission are carried out for on-orbit servicing of satellites by Naval Research Laboratory (NPL). One of the key technical challenges associated with the FREND mission is the ability to service satellites by space robot without pre-designed custom grappling interfaces, , as shown in Fig. 11, which constitute the majority of current on-orbit satellites. So the goal of FREND mission is to overcome this challenge and develop the space robot technologies of autonomously un-cooperative target grappling. One of the key components of the FREND is the development of a seven degree-of-freedom flight robot that can be used to grapple, inspect, and service most of current spacecraft, especially the geostationary Earth orbit (GEO) satellite. The FREND robot developed by Alliance Space systems, is integrated into a physical testbed under simulated orbital conditions in which machine vision, trajectory planning, force feedback control algorithms and special end-effecter are used to accomplish autonomous rendezvous and capture of a variety of spacecraft interfaces. It has been extensively used by NPL and proved to be very reliable and capable for performing on-orbit servicing tasks. Currently the FREND has already completed the first stage mission, carrying out the robot operation to demonstrate assembly technology, as shown in Fig. 12. In the next stage, NRL continues to advance the technology readiness to be spaceflight ready in terms of both software and hardware. Once ground development and testing are completed, an on-orbit demonstration of revolutionary new spacecraft operations will be ready to perform.

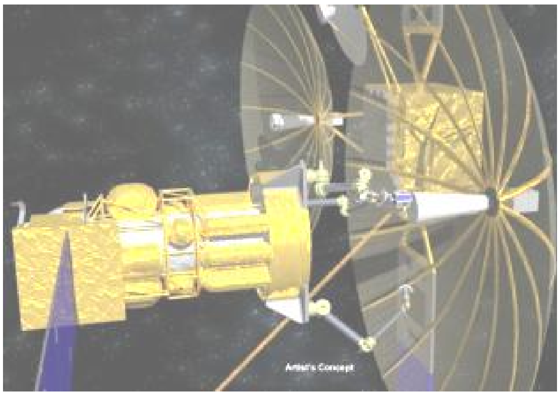

Figure 11　The FREND mission　　Figure 12　The FREND robot

4. The on-orbit assembly and maintenance technology with space robot of CAST

The on-orbit assembly and maintenance technology are also developed in China, including the large space robot for Chinese Space Station (CSS) as the example [12]. Since 2007, the Institute of Spacecraft System Engineering of CAST has started the research of the Chinese Space Station Manipulator system (CSSM). A principle prototype and an engineering prototype have been designed and constructed for the verification of the design concepts and associated new technologies, as shown in Fig. 13. The eight key technologies, such as the system design and analysis, kernel mechanism assembly design, modeling and simulation, control design, functional tests, and environmental tests have been accomplished. The CSSM system consists of two separate robotic arms, a Core Space Station Cabin's Manipulator (CSSCM) and an Experimental Space Station Cabin's Manipulator (ESSCM). The CSSCM is an 10.5-meter long, 7-DOF robotic manipulator and the ESSCM is a 5.5-meter long, 7-DOF robotic manipulator. The two robots can work separately or combined as one robotic system. The CSSCM is large and strong, capable of completing large payload handling, large-scale transportation, such as the docking operation of station cabins; while the ESSCM is flexible and compact, designed to complete small-scale and delicate operations.

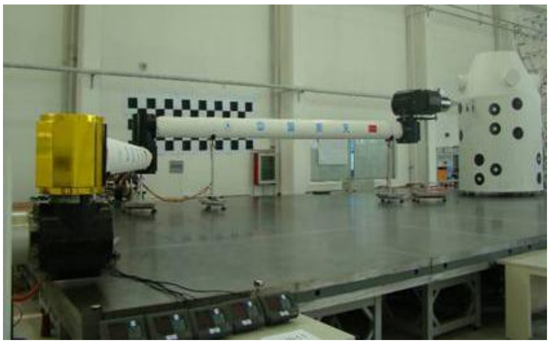

Figure 13　The principle prototype of CSSM

Recently, a space humanoid robot with changeable end-effector is developed by the Institute of Spacecraft System Engineering of CAST. The space humanoid robot has 31-DOF (which can be expanded to 44-DOF), hundred sensors and four operation modes. The changeable end-effector is useful in different mission, including multi-fingered dexterous hand and multifunctional tools. With the special interface of CSSCM, the space humanoid robot can easily realize large scope movement and smart operation. Experiments to confirm the reliability of the space humanoid robot have been successfully conducted, demonstrating the tracking of flexible structures. The design of the space humanoid robot with changeable end-effector has been qualified to be manufactured and tested, , as shown in Fig. 14, which lays the foundation to support the construction of the Space Station and the development of the on-orbit assembly and maintenance technology of China.

Figure 14 The prototype of space humanoid robot

5. Key Techniques Analysis

For large spacecraft system, it needs several times launching and assembling cost as the limitation of weight, especially the high orbital space station and the cosmonaut is not allowed to participate the assembling, monitoring and replacing of these facilities directly over a long period of time for load ability and safety. So the on-orbit assembly and maintenance technology with the intelligence robot is required and the key techniques are studied as follows:

(1) System design and optimization technique

Considering the characteristics of diversification, real time information interaction for the on-orbit assembly and maintenance mission, the robot requires more degrees of freedom and interfaces, which increase the difficulty of system design and decrease the reliability of work process. Therefore, the top-level plan and strategy design should be researched considering the special mission application in the system design of robot and the mechanical system should be developed for multi-function requirements including capture, connection replacement, reconfiguration, movement, refueling and so on. Otherwise, the long life and high reliability request of the system should be considered at the same time by using collaborative and redundancy design.

(2) High-precision servo control

The precision of space robot is influenced by various system errors and random errors, such as assembly backlashes, control errors and sensors errors which are very difficult to avoid. However, the system errors including the mechanical production errors, mechanical assemble errors, base body positioning errors, and the errors conducted by payload can be dealt with by proper calibration or control compensation to get higher control precision of manipulator's endpoint. Otherwise, the problems such as the complicated cable layout, signal interference and the disaccording of time-sharing control system are difficult to resolve. So the high-precision servo control architecture should be adopted to improve the performance of robot and dynamics and friction compensations should be added. To adjust the position of the robot due to structure vibration and the misalignment of target, the tip needs to be precisely tracked and controlled using onboard sensors such as vision and accelerometers.

(3) Multi-Constrained trajectory planning

For the trajectory planning, the conventional inverse kinematics solution should be extended to satisfy various constraints such as disturbance minimization, complex exterior layout, collision avoidance, minimal cost, trajectory optimization and so on. Collisions and obstacles have great significant influence on system performance. Careful trajectory planning and control are highly recommended to avoid collisions and obstacles in the environment. Different trajectory planning methods such as the least torque trajectory for capture operations, the least disturbance to the base, and the minimal time trajectory can also be implemented for special mission needs.

(4) Object recognition and measurement technique

Object recognition and measurement for space robot is usually implemented by a vision system with cooperative target, which is mature and used abroad in the space, but sub millimeter level or further distance measurement still have difficulty in improving accuracy. Recently, capturing technology of non-cooperative target, aiming at on-orbit servicing of spacecraft, has been a research focus in the field of space robot technique. In order to measure the relative pose between the two non-cooperative spacecrafts in the capture task, the method based on object recognition and measurement for the non-cooperative spacecraft should be studied in three parts: Camera calibration, object recognition and pose estimation.

(5) Human-computer interaction technique

The complicated mission of space usually needs the robot to have more degrees of freedom, the tradition method with front-panel instruction way of the direct control can't adapt for complicated actions, while the use of human actions and gestures to control the robot can replace complex program operations， and humans can manipulate and interact with the robots easily and conveniently． Human motion and gesture recognition based on video is an indispensable key technology in the new generation of human-computer interaction technique, which will become increasingly common．

(6) Long-duration power supply and energy-efficient operation technique

The independent power supply module should be mounted on the space robot system for long-duration power supply to maintain independence from the system resources. A long-duration power supply is needed and energy-efficient operation is required for life extension of on-orbit robot system.

5. Conclusion

The number of launched spacecraft has progressively increased year by year as the ability to exploit and apply technology in outer space has developed, therefore, great advantages and enormous economic benefits can be gained by the on-orbit assembly and maintenance technology, at the same time more complicated requirements are put forward for on-orbit service of different spacecrafts. As the latest trend of on-orbit service, the on-orbit assembly and maintenance technology with space robot will have great impact on design and operation of spacecraft in the future. This paper introduces the development of on-orbit assembly and maintenance technology with space robot and the key techniques are studied from all aspects, including system design, control, path planning, object identification, human-machine interaction and energy-saving operation. It is suggested that the ground demonstration and verification for flight mission considering Chinese national conditions should be started as soon as possible, which is very important for the construction of large orbital facilities.

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