

Progress and Development Trend of Space Intelligent Robot Technology

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ABSTRACT

It is a desirable option for the advancement of automation technology to employ space intelligent robots for space exploration and use as they are not constrained by physiological constraints. It is now the main area of development for the world's major space powers. Prior to reviewing theories and techniques for achieving largescale stable motion and intelligent dexterous manipulation, this study first examines robotic manipulators and humanoid robot systems for space station applications. The intelligent robot systems for satellite maintenance in orbit are then examined, and the associated multirobot cooperation technologies are examined. Lastly, we review the technologies of modular assembly and on-orbit manufacturing and explore intelligent robot systems for on-orbit assembly of largescale spatial structures. All things considered, this article examines the advancements in space robot technology and development patterns, offering a useful resource for more technical study in this area

Introduction

It is a decision that will inevitably be made as space automation technology advances, using intelligent robots to accomplish space exploration and resource usage [1]. China began with the successful launch of the Tianhe Core Module in 2021, and in addition to the ISS, it plans to establish a large-scale, long-term manned national space laboratory in 2021–2022, while also

progressively developing the China Space Station (CSS). The majority of ISS functions now depend on human astronauts. However, astronauts may have a number of physiological and pathological issues in the mid-to long-term microgravity environment, putting their health at considerable risk [2]. While doing duties outside the cabin, they run a significant danger to their health and safety.

Furthermore, humanity has sent around 7000 satellites into orbit since the Soviet Union successfully launched the first satellite in 1957; nevertheless, roughly 10% of them have failed. either failed in the first stage or failed to orbit appropriately. Even with high-reliability designs, many satellites still malfunction in the hostile space environment, and the majority of them are expensive, high-orbit satellites that are challenging to repair. Large-aperture antennas, large-diameter optical devices, large-scale solar power plants, and other large space structures are significant development goals of space utilization and development worldwide, and on-orbit assembly and maintenance of these mechanisms will primarily rely on space intelligent robots as space resource utilization continues to advance. Therefore, the development and use of space robotics to enable the on-orbit construction, assembly, and maintenance of space stations, satellites, and huge space structures is very important from a social and economic standpoint. However, space robots have difficulties with long-range stable motion, high-precision safe and dexterous manipulation, precision sensing, and high-precision measurement due to the hostile space environment, which includes microgravity,

complicated lighting, and powerful radiation. Consequently, this document will assess, evaluate, and condense the state of the art and future directions of space intelligent robots for the needs of satellites, space stations, and other major space structures that need on-orbit operations.

1. Space Intelligent Robot for

Space Station Applications In 2001, Canada launched the Canadarm II, a massive space manipulator designed to deploy, maneuver, and capture payloads during the building and operation of the International Space Station (Figure 1). With an arm reach of 17.6 meters, a total mass of 1640 kg, seven joints, four cameras, two linkages, and two end-effectors, it can carry 116 tons of spacecraft. Seven joints have a rotating range of $\pm 270^\circ$, and four cameras may operate constantly at 30 Hz. The robotic arm can move and crawl on the space station because it is symmetrical with regard to the elbow joint in the center and contains end effectors at both ends. In addition to helping the space station dock the spacecraft, Canadarm II may employ the manipulator to carry out precise operational duties in lieu of humans. This is crucial for docking assembly, aiding astronauts out of the cabin, and capturing large-mass cabins [3]. But because of its limited capacity for dexterous manipulation, astronauts are still needed to carry out risky extravehicular procedures. Thus, there is a pressing need for spaceintelligent robots for the upkeep and operation of space stations while they are in orbit. A special purpose manipulator system [4] (SPDM), also called Dextre, was created by the Canadian Space Agency in 2008. It has a maximum load of 600 kg, a total mass of around 1560 kg, and a position precision of 2 mm. The SPDM includes two 7-DOF robotic arms that can rotate around the waist, giving it a total of 15 DOF. It can only be deployed toward the conclusion of Canadarm II since it lacks mobility. Rough positioning and a broad range of movement are realized by Canadarm II. To lessen the

number of times astronauts leave the cabin, the SPDM primarily performs precise operational duties such loading and unloading, handling, fuelling, and operating tiny equipment. Some astronauts are still needed to do risky extravehicular procedures, and the dual-arm robot SPDM still has trouble performing some programmed duties in the microgravity environment [5]. The core module of the Chinese space station was successfully launched in April 2021 after the successful validation of the spacecraft intersection and docking technologies at the Tiangong No. 1 and No. 2 Space Laboratories. A huge space robotic arm and a tiny space robotic arm make up the Chinese robotic manipulator system (Figure 3(b)). The huge space manipulator has a length of 10.2 meters, a total mass of 800 kg, a weight of 25 tons of spacecraft, and a joint configuration scheme of "3-DOF shoulder +1-DOF elbow +3-DOF wrist." With a length of 5.0 meters, a total mass of 400 kg, and a load of three tons, the tiny space manipulator also has seven degrees of freedom. This arm can do dexterous manipulation and has a greater positioning accuracy. On both ends of the big manipulator are end adapters with conventional electrical, mechanical, and communication connectors. It may crawl and transfer on the cabin surface by docking with the target adaptor.

International Space Station "Mir" (Fig. E 1). cabin surface, which may facilitate astronauts' departure from the cabin and carry out a variety of cabin transportation, cargo handling, and extravehicular inspections. In the meanwhile, it may be used in conjunction with a tiny space manipulator to carry out a number of delicate and precise manipulation tasks and space station maintenance.

Humanoid robots can effectively support or replace astronauts on duty in the space station because they look like human astronauts, so there is no need to modify anything to make

them fit in. Humanoid robots can be controlled to perform human-like movements and operations. As a result, major aerospace nations like Russia, America, and Europe have identified robot astronauts as one of the primary research objectives for space intelligent robots. In particular, NASA's humanoid robot astronaut Robonaut2 (R2), which is being used to verify space intelligent operating technologies, entered the International Space Station (ISS) in 2011 [6–8] (Figure 4(a)). With 42 independent DOF and over 350 sensors, the R2 is a highly integrated mechatronic system that includes two arms with 7 DOF, two hands with 12 DOF, a neck with 3 DOF, and a waist with 1 DOF. Its most notable features are a human-like flexible arm, an end effector with a maximum speed of 2 m/s, and the ability to lift things weighing up to 18 kg. The gripping force of each skilled hand is 2.3 kg. In order to accomplish more accurate operation tasks, R2 uses a distributed control approach based on impedance. Nonetheless, the dynamic properties and motion mode of robot astronauts in a microgravity setting differ significantly from those in a land gravity setting [9, 10].

Figure 2: The Canadarm II and SPDM manipulator of ISS.

Simultaneously, sensors, particularly optical sensors, are greatly impacted by the harsh surroundings, such as complicated lighting conditions in space and high energy particle radiation [11], which creates significant technological obstacles for R2 dexterous handling at space stations [12]. Justin, a mobile robot in the form of a person, was also created by the German Aerospace Center DLR [13] (Figure 4(b)). It has a rated load of 20 kg, a mass of around 200 kg, and a working space diameter of 2.7 m. The robot has 51 degrees of freedom in total. It is the perfect tool for learning dexterous manipulation because of its lightweight, flexible arm and four-finger dexterous hand. The robot can rebuild the environment in three dimensions thanks to its stereo camera and motion detection sensor. In a multitask hierarchy, Justin may do many activities at once because to multiple driving degrees of freedom. The goal of this robot is to work alongside people to accomplish jobs, including housework and helping astronauts in space and other application areas. The Aerospace Agency of Russia



(a) China's space station (b) The robotic manipulator system of CSS Figure 3: China's space station

and robotic manipulator system.



(a) Robonaut2

Figure 4: Robot astronauts for on-orbit operation in the space station.

(b) as developed SAR-400 and SAR-401 [14] (Figure 4(c)). SAR-400 is a remote-controlled humanoid robot. Its ability to share the experience of touch with others and provide tactile feedback via the use of special gloves is among its most evident qualities. Essentially, by donning a sensory vest and a head-mounted display, humans may communicate their movements to the robot. These technologies enable the SAR-400 to do several sensitive and intricate tasks in hazardous situations. The SAR-400 humanoid robot may be mounted on the ISS crane to do activities like tightening bolts, moving cargo, checking the space station shell, and opening doors in lieu of people since it lacks legs. A better version of the SAR-400 is the SAR-401. SAR-401 performs better in terms of grip. ing and

more intricate processes. It can do over 50 tasks, including utilizing electric drills and opening and shutting doors. However, as of right now, SAR-401 and Justin, the two robot astronauts, are still in the ground research and verification phase. Additionally, two robot astronauts have been created by the Shanghai Academy of Spaceflight Technology (SAST) and the China Academy of Space Technology (CAST) (Figures 5(a) and 5(b)). A head, torso, neck with three degrees of freedom, waist with two degrees of freedom, two arms with seven degrees of freedom, and multi-DOF, five-finger dexterous hands make up both. The arm's end can support up to 10 kg of weight. The goal is to be used for additional space research and on-orbit maintenance services, including



(a) The robot astronaut developed by CAST



(b) The robot astronaut developed by SAST



(c) The robot astronaut developed by HIT



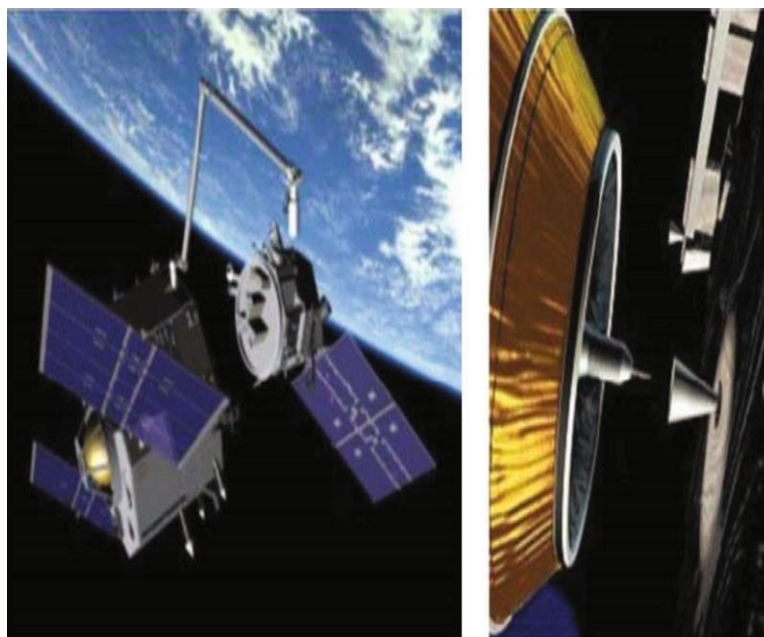
(d) The robot astronaut developed by BIT

Figure 5: Some robot astronauts developed by China.

manned lunar expeditions and space-station experiments [15]. Two seven-DOF humanoid robotic arms and two multi-DOF five-finger dexterous hands with a maximum load of 10 kg at the end of the arm are additional features of the robot astronaut created by the Harbin Institute of Technology (HIT) (Figure 5(c)) [16]. The Tiangong No. 2 Space Laboratory's man-machine on-orbit repair operation demonstrated and validated the arm. The Beijing Institute of Technology (BIT) created the robot astronaut ASTROBOT (Figure 5(d)), which has a weight of around 50 kg. Its head has two degrees of freedom, while each arm has six. The robot can perform bionic climbing motion in the microgravity environment thanks to the master-slave arm's coordinated control algorithm. In the meanwhile, a feedforward compensation control approach based on contact force is used to guarantee the stability of the ascending action outside the cabin. To achieve the compliance installation and maintenance activities of extravehicular components under space special illumination, a number of image enhancement algorithms and human-like dexterous handling algorithms have also been developed [17–19]. Chinese robotic astronauts are still in the early stages of developing critical technologies and conducting groundbased experiments.

An example of an intelligent robot for space station applications is the robot astronaut, which is also a research hotspot for space intelligent robotics. However, performing a variety of steady motions and safe dexterity exercises is challenging. terous manipulation in a tiny microgravity area [20], and

it is also challenging to successfully confirm the robot astronaut's three-dimensional mobility on the ground [21, 22]. Currently, there has been significant advancement in robot gait planning and dexterous manipulation based on human motion mechanisms [23–25]. On the other hand, human-oid robots in microgravity and those on the ground have quite different mobility mechanisms. A pressing scientific issue concerning robot astronauts is how to create a parameterized representation of the law and investigate the theory of motion planning and control tailored to the space environment. In the meanwhile, robotic manipulation relies heavily on machine vision, and advances have been achieved in image filtering, identification, and precise positioning techniques [26, 27]. The mirror-like coating of the space device may result in multiple refraction and reflection of light, highenergy particle radiation, and other complex interference environments, which can seriously interfere with the features of the operating objects and challenge the current image processing algorithms. Regretfully, there is a strong contrast between the illuminated and shadowed areas in the space [28]. For instance, the ISS's R2 robot astronaut has four RGB cameras and an infrared TOF camera on its helmet to give precise depth data and increase measurement accuracy [29]. Nevertheless, R2 finds it challenging to get beyond the complicated space environment's interference. NASA in 2016 gathered global image-processing techniques to support R2's reliable detection and precise location of handles, tools, and other targets [11]. In conclusion, the spacestation intelligent robot has improved in terms of accurate sensing and measurement, dexterous



(a) Satellite capture

(b) Docking mechanism

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Figure 6: The "Orbital Express" program of USA.

manipulation, and steady motion as a result of the advancement of intelligent robot technology. Researching the theories and techniques of human-like steady motion and dexterous manipulation via the cross-integration of bionics and robotics, which can transfer human talents to robotic systems, has great promise for the future.

2. Space Intelligent Robot for OnOrbit Maintenance of Satellites

Repairing malfunctioning satellites (such as solar panels and antennae), replacing parts, and supplying fuel are the primary responsibilities of the intelligent robot for satellite on-orbit maintenance. The primary method involves using vision or radar guidance to approach the target satellite, then using a robotic arm to capture and keep it. This strategy offers a crucial assurance for the satellite's safe functioning while in orbit. DARPA's 1999 proposal, "Orbital Express" (Figure 6), aims to confirm the efficacy of space operations as well as the service capabilities of on-orbit satellites, including capture, repair, and fuel replenishment. The Autonomous Space Transport Robotic Orbiter (ASTRO), manufactured by Boeing, serves as the tracking satellite in this concept. The NEXT Generation Serviceable Satellite (NEXTSat), constructed by Ball Aerospace, serves as the target satellite. The advanced video guidance sensor (AVGS) aboard ASTRO utilizes the difference between two pictures taken at different light wavelengths to remove background noise and stray light before autonomously locating the NEXTSat satellite. A docking mechanism connects these two spacecraft when NEXTSat is

visually check NEXTSat antennas, interface planes, solar panels, and other parts during the maintenance phase. It can even change parts on its own. Some essential technologies needed for the automotive industry are effectively shown by the "Orbital Express" initiative. Figure E7: The United States' FRENDD initiative. maintenance of satellites in orbit, including autonomous rendezvous, orbit control, capture and docking, on-orbit refueling, and on-orbit module replacement technologies. The "Orbital Express" software was unable to operate any noncooperative targets, but it was successful in capturing and repairing a satellite with a particular docking interface. A project on "spacecraft for the universal modification of orbits" (SUMO) was initiated by the United States in 2002. In 2006, it was renamed FRENDD (front-end robotics allowing near-term demonstration). Developing a space robot that can dock with spacecraft in orbit and confirming that it can autonomously dock, capture, refuel, and repair noncooperative space targets without a docking interface are the primary goals of this project [32]. With an end position precision of ± 2 mm and an angle accuracy of $\pm 0.4^\circ$, the goal of this job is to create a 7-DOF space manipulator system (Figure 7) that can provide high position accuracy prior to the capture stage. When attaching to the spacecraft during the capture phase, it may execute compliant control and guarantee the necessary stiffness. In 75% (95%) of the working area, the robotic arm can attain a working speed of 17 cm/s (6 cm/s) along the end effector's axis while maintaining a high degree of dexterity. It is now the new standard for space-level manipulators and has been shown to be very dependable.

The Phoenix Spacecraft Servicing Program (PSSP),

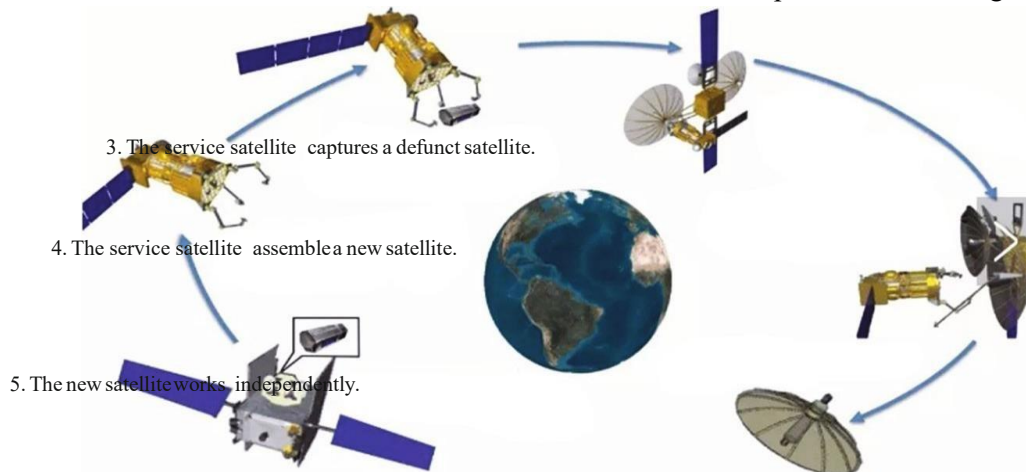


Figure 8: Execution process of Phoenix Spacecraft Servicing Program.

relocated to the region of the capture envelope [30, 31]. Using the visual servo-based robotic arm, ASTRO can

DARPA's newest space technology research project, was started in 2012. Its goal is to create joint

recovery technology to reuse usable components of retired or malfunctioning satellites for recycling. The cost of new space equipment, which has enormous economic value, is significantly decreased by integrating these outdated components into the new space system. First, the satellite is launched into orbit together with the Payload Orbital Delivery Systems (PODs) that hold the satellite modular functional components (Satlets). The PODs are expelled when they get close to the space intelligent robot. PODs are approached, grabbed, and stored in the system devices by the space robot. The space intelligent robot then locates the defunct satellite, removes any functioning parts (like the antenna) that are still working, and mounts them on the modular parts that the PODs are carrying. Building a "new" satellite in orbit is comparatively inexpensive [33]. Figure 8 displays the specific steps. POD design technology, modular satellite design technology, robotic arm design

technology, proximity measurement and identification technology, and flexible control and teleoperation technology are the main technologies used in this project.

In order to confirm the autonomous capture, docking, and on-orbit service technology of space robots to eliminate low-orbit satellites, Germany, Russia, Canada, and numerous other research institutions have collaborated to conduct research on the free-flying robot system TECSAS [34]. As shown in Figure 9, the project intends to deploy a client satellite and a service satellite equipped with a gripper system and a 7-DOF manipulator. Three control modes—autonomous, semiautonomous, and tele-operation—are used by the TECSAS project to record rolling and free-floating satellites. The technologies of robotic arm capture, free-floating robot route planning, teleoperation singularity avoidance, and model-based parameter estimation are the main topics of this research.

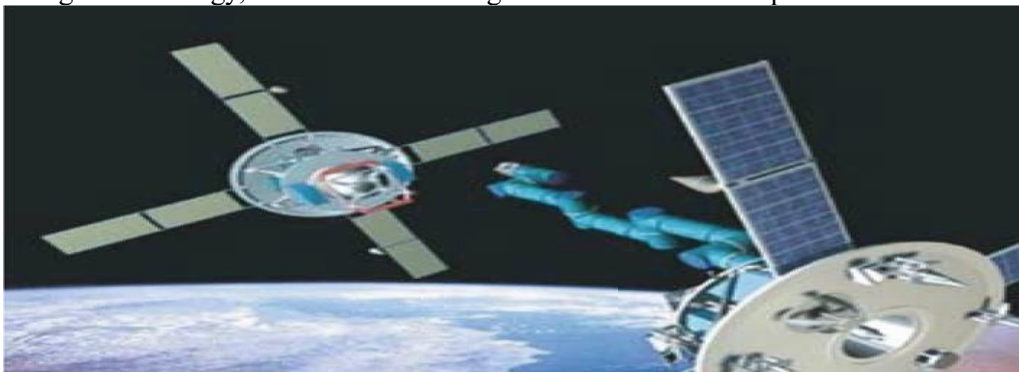


Figure 9: The free-flying robot system TECSAS of German.

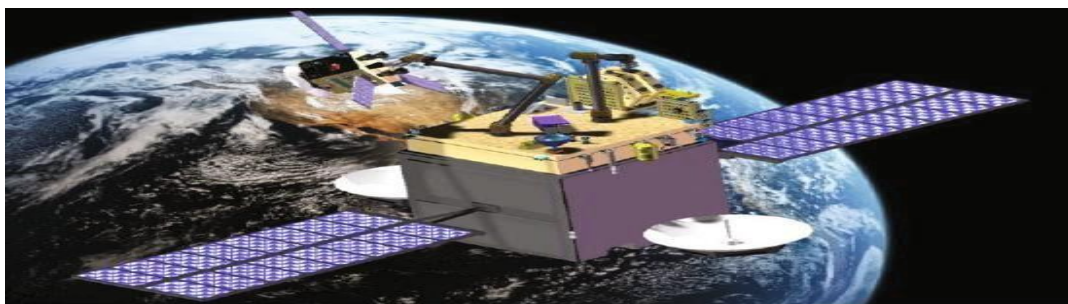


Figure 10: The dynamic simulation system of on-orbit satellite maintenance.

. However, owing to modifications in the concept, the project was halted after merely conducting on-orbit capture experiments.

In order to capture and repair satellites in orbit, the HIT, the China Academy of Launch Vehicle Technology (CALVT), and

TABLE 1: Other related projects of space robots for on-orbit satellite maintenance.

Project name	Country	Introduction of task	Time	Current status
Ranger	USA	Verify the technologies of ORU replacement, target monitoring, and multiarm coordination		
ETS-VII	Japan	Verify the technologies of ORU replacement, replenishment, and structural antenna assembly		
Rotex	Germany	Verify the technologies of multisensor manipulator and compliant control		
XSS-10	USA	Verify the technologies of orbital maneuvering and circumnavigation detection		
ROKVISS	Germany	Verify the key technologies of lightweight robotic arms in real space environments		
RRM	USA	Verify the technologies of remote operation-based fuel lling and faultfi maintenance		
1992-2001	Demonstration verification			
1992-1999	On-orbit presentation			
1993	On-orbit presentation			
2003	On-orbit presentation			

2004 The on-orbit maintenance system for space manipulators includes modeling, parameter identification, visual servobased position control, and compliance control. The development and validation of a quick replacement device tailored to satellite on-orbit maintenance, the dynamic simulation of the dual-arm robot, and the scene simulation of satellite on-orbit maintenance operations have all been completed by the BIT. Figure 10 displays a dynamic simulation of the satellite capture, disassembly, and assembly process. Numerous analogous tests have been carried out by the US, Germany, Japan, Canada, and other nations (Table 1), which has aided in the quick development and advancement of space intelligent robot technology [35– 45].

However, the design of high-precision rigid-flexible coupling manipulators, the technology of precise safe and dexterous manipulation, the technology of multirobot collaborative control, the technology of rapid tool change, and the design of tooling systems are all faced with significant challenges in the harsh space environment of microgravity and high-speed flight. In the meanwhile, modular and cellular satellites are also interesting research directions to increase the efficiency of satellite on-orbit construction and maintenance. The overall economic and social value of space robots for satellite-oriented on-orbit assembly and maintenance systems is high, which is important for advancing human exploration and space resource use.

3. Space Intelligent Robot for On-Orbit Assembly of Space-Oriented Large- Scale Structures Large-scale facilities and buildings in space will eventually significantly broaden human perspectives and constitute a crucial tool for space resource exploration and use. However, the majority of the large-scale structural facilities will be put up and maintained in orbit by space robots because of their enormous size and the difficulties of human building in space [46]. On-orbit manufacture and modular assembly are the primary methods to progressively

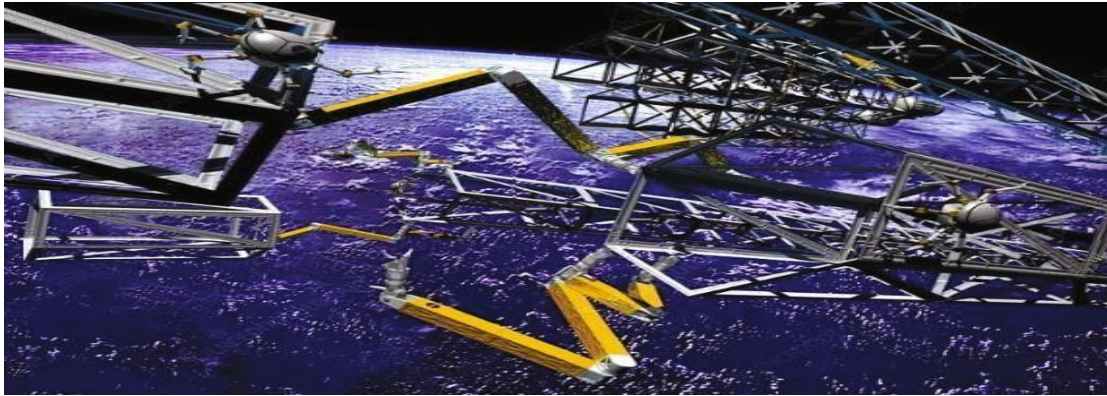


Figure 11: On-orbit assembly by Skyworker.

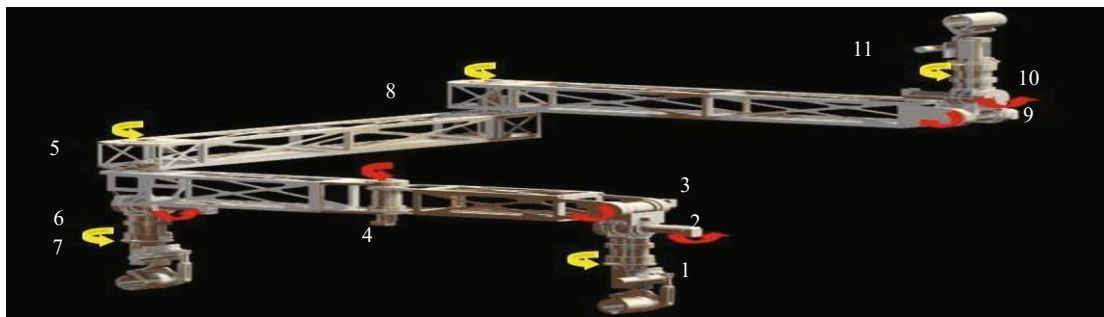


Figure 12: The joint configuration of Skyworker.

build and produce large-scale spatial structures in the orbit using raw materials or completed components [47], both of which are now undergoing design or verification. Carnegie Mellon University created the Skyworker (Figure 11), an attached mobile robot that moves by imparting a response force to objects without grasping handrails or hooks. Its three roles are maintenance, detection, and on-orbit assembly. Skyworker is primarily used for massive payload transportation, installation, and maintenance, including solar cell array construction in orbit [48]. In particular, there are eleven joints in Skyworker, which are divided into four categories (Figure 12). Every joint is joined by

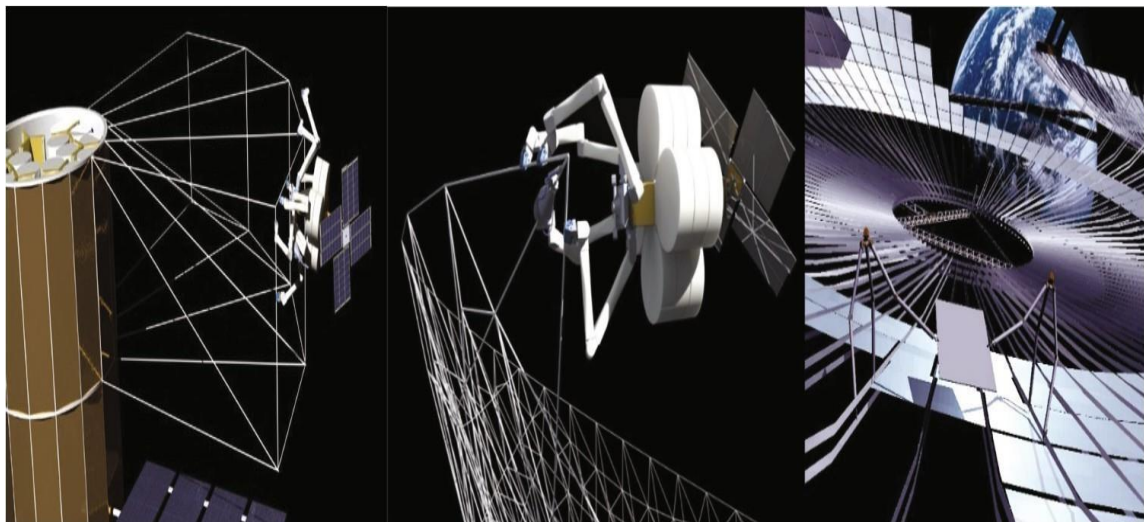
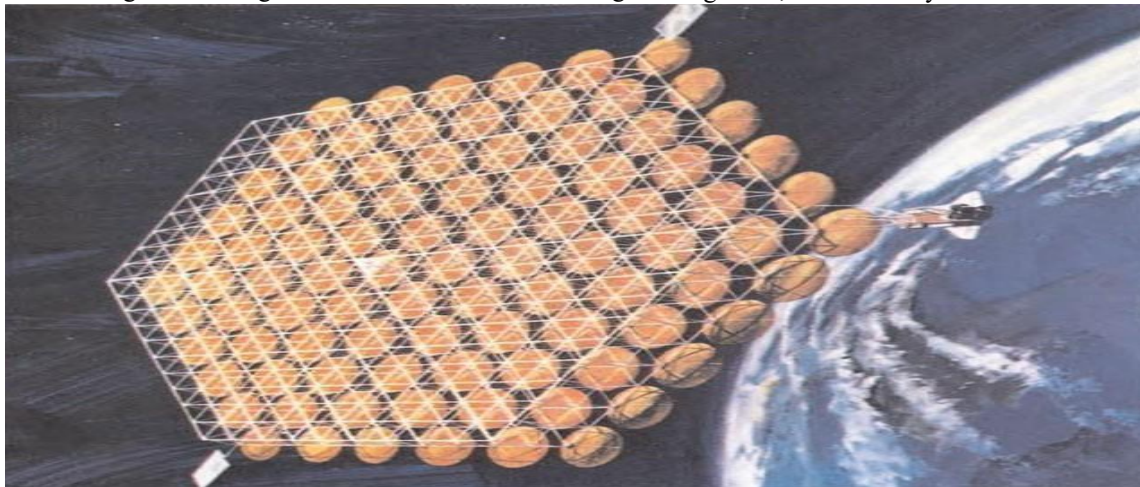


Figure 13: Manufacture of large-scale space structure by SpiderFab robot. the same powertrain design, which minimizes the amount of separate parts and produces a modular construction. Skyworker is designed to perform two main tasks: transportation and payload modification. The robot attaches to the structure with one end gripper and manipulates as needed with the other. In this case, Skyworker is a 9-DOF robotic arm. When transportation is done, the weight ranges from kilograms to tons, and the distance covered may reach half a kilometer. The robot is controlled via a distributed network of PIC-based motor controllers and the PC104 stack. The PID algorithm is carried out by the controller at 20 kHz, allowing for very precise motor position and speed control. Since each component must be assembled and integrated on the ground before the whole spacecraft is launched into orbit, the current process of producing spacecraft is really expensive and timeconsuming. The SpiderFab project was initiated in 2012 by Tethers Unlimited, Inc. (TUI), an American business that began developing new technologies for space manufacturing. The main objective of this project is to use a 3D printer and materials carried by the multiarm space robot to manufacture enormous trusses in orbit and assemble them there to construct a large-scale system [49], as seen in Figure 13. A groundbased truss manufacturing



are sent into orbit and then combined to form a larger array [51]. NASA, the European Space Agency, and the Canadian Aerospace Agency collaborated to create the massive space telescope known as the James Webb Space Telescope (JWST) [52] in order to facilitate a wide variety of astronomical and cosmological research. The primary mirror may have a diameter of 6.5 meters, and the area of the main lens is 7.3 times that of the Hubble Telescope [53]. The main mirror is separated into 18 hexagonal pieces since the construction is very complex and its diameter is more than that of the launch rocket (Figure 15). These parts are folded and sent into space. Under the guidance of high-precision micromotors and sensors, they will finish deployment, assembly, and positioning correction in orbit after

robot that can produce trusses at a speed of 5 cm/min has been built by TUI. These trusses may be used in the building of spacecraft and other systems. Costs might be greatly decreased if the SpiderFab robot system could eventually build the largescale system in orbit after just launching raw materials [50]. "The SpiderFab robot will help people build solar arrays, spacecraft structures, and massive radio antennas in the next ten years," said Rob Hoyt, chief scientist at TUI. Long-term goals for this technology include building infrastructure in space, recycling resources, and facilitating human exploration and widespread use of space resources. For the manufacturing and on-orbit assembly of ultralarge high-performance space antennas, NASA has proposed a space shuttle-based onorbit assembly method (Figure 14). This design calls for each autonomous unit to be transported to the location, unfolded individually, and then moored. Alternatively, a few pieces might be glued together on the ground, and after they

entering the designated orbit, guaranteeing that they can provide crisp photographs [54]. But the concept has been postponed beyond October 2021 because of dependability requirements and research money. The intricate design and massive volume of space-based solar power stations (SSPS) make it challenging to assemble them on the ground and send them into orbit as a whole. As a result, on-orbit assembly technology is essential for space exploration, commerce, and national security in addition to its practical applications. The researchers from the Chinese Academy of Space Technology have



Figure 15: The James Webb Space Telescope.

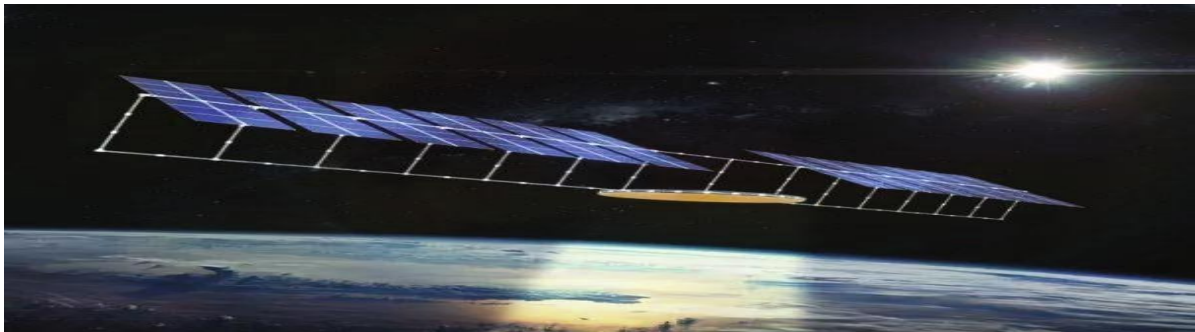


Figure 16: The concept design on multirotary joints SPS.

proposed the design scheme of two-stage symmetric reflected SSPS [55] and the concept design on multirotary joints SPS

[56] (Figure 16). Xidian University has proposed an innovative concentrator system of the space solar power station SSPS-OMEGA [57]. The scheme optimizes the material of the concentrating system and the layout of reflectors and demonstrates the feasibility of on-orbit assembly. The research of space on-orbit assembly construction in China started late, and the current research is still mainly focused on the cabin docking and module replacement technology in the early stage. The manufacturing and assembly of large-scale space equipment are still in its infancy, but the on-orbit manufacturing and assembly is undoubtedly one of the important plans of China's aerospace in intelligent manufacturing. For example, China first validated the technology of 3D printing in space in May 2020, realizing 3D printing of continuous carbon-fiber-reinforced composites in space [58].

Overall, space large-aperture antennas, large-aperture space telescopes, and large-scale solar power stations are of great significance to human beings for space exploration and space resource utilization. However, due to the limitation of the size of the carrier and the rocket carrying capacity, it is difficult to launch

the large-scale structure directly into the space, and it is also difficult for astronauts to carry out on-orbit assembly of large-scale spacecraft due to physiological limitations. Therefore, on-orbit construction of high-mass, large-size, and high-complexity spatial structures is the main development direction and research hotspot in the future. The core technologies comprise a micronano high-precision space measuring system, a large-range quick and stable moving mechanism, a large-inertia load handling system, and specialized tools and organized equipment.

4. Conclusion

An unavoidable option for raising the bar for space automation technologies is the space intelligent robot. The world's leading aerospace powers have undertaken several investigations into the development plans, implementation tactics, and essential technologies of space intelligent robots and have seen a number of triumphs. It primarily consists of the robotic manipulator and humanoid intelligent robot technologies for space station applications, the on-orbit assembly robot technologies for big space constructions, and the robot technologies for satellite maintenance. Additionally, China is

carrying out extensive research and demonstration on the main technologies and uses of space intelligent robots. However, the design of high-precision rigid-flexible coupling manipulators, high-precision safe and dexterous manipulation, multirobot collaborative control, and on-orbit assembly and maintenance of large equipment still face significant challenges in harsh and complex environments like microgravity and strong radiation. It is imperative that these important scientific problems be resolved in further studies.

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