Review Article

A Survey of Space Robotic Technologies for On-Orbit Assembly

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The construction of large structures is one of the main development trends of the space exploration in the future, such as large space stations, large space solar power stations, and large space telescopes. It is one of important development tendency, which aims to make full use of space robots to assemble space structures autonomously in the aerospace industry. Considering that on-orbit assembly is an effective method to solve the problem of construction of large-scale spatial structures, it is necessary to motivate and facilitate the research of space robotics technologies for on-orbit assembly. Therefore, in this paper, the development status of space robot technology and the relevant space robot on-orbit assembly technology in recent decades are summarized. First, based on the space robot motion planning and assembly sequence planning, the development of space robot planning algorithms is introduced. For space robot assembly task, the space robot assembly method is summarized. From the control point of view, how to solve the vibration suppression and compliant assembly of on-orbit assembly is reviewed, which provides a reference for the autonomous intelligent assembly of space robots for large-scale structures in space. In order to simulate the space assembly scene on the ground, this paper introduces the development of ground verification experiments and provides ideas for the effective verification of space on-orbit assembly technology. In summary, though some of these problems have been satisfactorily solved in the past research, further research is still necessary in the future. Finally, it looks forward to the future research direction of space machine on-orbit assembly.

1. Introduction

One of the major development trends in the aerospace industry is the construction of large-scale structures, such as large-scale space solar power stations, large space telescopes, and large space reflectors. However, due to their large size, such structures cannot be carried directly into space by rockets or spacecraft. Therefore, these large structures need to be broken down into multiple modular units, which are brought into space by a launch vehicle and then assembled. This is an important task of on-orbit servicing (OOS): on-orbit assembly [1]. Space on-orbit assembly is to connect different components in space to build corresponding space facilities. On-orbit assembly has long been recognized as an efficient method for building large space platforms. At the same time, on-orbit assembly technology is a common key technology to support subsequent manned moon landings, high-orbit space stations, solar power plants, on-orbit services, on-orbit construction, and other major national special projects and major projects, and it is of great significance to promote the development of the aerospace field. Space robot is a systematic science. The study of space robot can drive control technology, dynamics technology, and redundant degree of freedom path planning technology, vision technology, and sensing technology. The research of space station robot can also promote advanced crossover such as human factor engineering and technology research. Therefore, the use of space robots to carry out on-orbit assembly technology research has the dual significance of promoting the development of the aerospace field and pulling related technological breakthroughs.

This paper reviews the development status of space robots and discusses the key technologies of space-on-orbit assembly, including space robot motion planning, on-orbit assembly methods, and space-ground consistency experiments for space-on-orbit experiments. The technical
difficulties of space robots at present and the future development trend of on-orbit assembly of space robots are prospected.

2. Research Status of on-Orbit Assembly of Space Robots

The aerospace industry has been researching and practicing on-orbit service technology for decades. As early as 1985, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) began to jointly study orbital assembly. They use the space shuttle to complete the EASE/ACCESS experiments in the STS-61-B mission, as shown in Figure 1(a) [2]. In these experiments, the truss structure was constructed on-orbit using a manual assembly technique at a workstation, which laid the foundation for the subsequent development of the International Space Station (ISS) program.

In 1993, the space shuttle Endeavour was launched into space to dock with the Hubble Space Telescope due to a malfunction in its work. And as shown in Figure 1(b), with the assistance of some auxiliary tools such as the remote manipulator system (RMS), the astronauts assemble some components of the Hubble telescope and successfully repair the telescope [3]. Thereafter, the space shuttle Atlantis delivered S0 truss components to the International Space Station in the 8A-STS-110 mission in April 2002. With the help of Canadarm2, two astronauts completed the assembly of the S-Zero (S0) Integrated Truss Structure through several extravehicular activities (see Figure 1(c)) [4].

It can be seen that the space on-orbit assembly task can be completed by space robots and astronauts in collaboration. Although manual assembly by astronauts has proven to be an effective method for constructing space structures [7], this method has many limitations. For example, if the spatial structure to be assembled is very large, thousands of assembly parts and complex assembly steps are required. In this case, it would be impractical for astronauts to do manual assembly. Additionally, astronauts face high risks and high costs when conducting extravehicular activities. Therefore, it is very necessary to use space robots to autonomously complete on-orbit assembly tasks.

In 2014, the US Naval Research Laboratory proposed the idea of using robotic tools to assemble space structures in the DARPA Phoenix Technologies program (see Figure 1(d)) [5]. And in October 2017, the astronauts on the International Space Station assembled launched a satellite consisting of six HISats, two deployable solar arrays, and an electro-optical imager, which was in preparation for the subsequent study of on-orbit assembly [5].

Another NASA mission project called Dragonfly was designed to enable robotic self-assembly of satellites in Earth orbit, which completed its first major ground demonstration successfully in September 2017 [6]. The Dragonfly concept involves the semiautonomous robotic assembly technology of geosynchronous equatorial orbit (GEO) communications satellites. As illustrated in Figure 1(e), the satellites will be launched as a whole but need to be assembled on orbit finally.

At the same time, the Skyworker space robot designed by Carnegie Mellon University (see Figure 2(a)) is actually a mobile robotic arm that can walk and work on space structures. This space robot is designed to complete the transportation and assembly tasks of some massive objects [8]. NASA designed a flexible, small and portable hexapod walking robot LEMUR (see Figure 2(b)) to perform delicate assembly, inspection, and maintenance tasks in some small areas on the space structure [9]. NASA Johnson Space Center has developed a humanoid space robot Robonaut with a dexterous multifingered manipulator (see Figure 3(c)), which can use tools instead of astronauts to complete work in a narrow operating space [10].

In 1992, China proposed a “three-step” strategy for China’s manned spaceflight. In the past nearly 30 years, manned spacecraft have been successfully launched many times, achieving long-term in-orbit flight in space, such as the space rendezvous and docking between the Shenzhou spacecraft and the “Tiangong.” Liu Hong completed a series of ground verification experiments on the Tiangong-2 robotic arm system, such as hand-eye fusion technology, teleoperation technology, and screwing tasks [11]. China is gradually advancing the construction of the Chinese space station. In May 2021, the “Tianhe,” the core module of the Chinese space station, has been successfully launched and achieved in-orbit operation. Its core module has a 7-DOF redundant robotic arm, including three wrist joints, three shoulder joints, and one elbow joint, which can autonomously or assist astronauts to complete on-orbit operations or maintenance work outside the capsule [12], as shown in Figure 3(a). Up to now, the robotic arm can accurately realize the module indexing of the Chinese space station. This will provide important hardware and technical support for the orbiting operation of the Chinese Space Station.

For the assembly of large-scale structures in space, China proposes the concept of multirobot on-orbit assembly antenna as shown in Figure 3(b). The large arm is equipped with the small arm to complete the on-orbit assembly of large components. For the configuration of large-scale structures in space, Zeng Lingbin et al. proposed a sunflower-like helical paraboloid structure modularization theory and a generalized on-orbit assembly method [13, 14], which provided a certain theoretical basis for the spatial layout of large-scale structures. Qi proposed a cell structure configuration robot model, and the robot is composed of multiple cell unit structures, which can realize the on-orbit assembly task of a robotic arm-like truss [15].

In general, the space on-orbit assembly technology has developed from manual operation to autonomous work. The working environment has changed from simple auxiliary astronaut operations to repair and assembly. The task scene has also changed from a single small object to a large space structure. However, as far as the development of space on-orbit assembly technology is concerned, it has not yet been matured and applied. With the needs of large-scale space structures, the assembly process has the characteristics of large size of the assembled object, flexible vibration, and high requirements for assembly accuracy. Therefore, in this case, multirobot systems are required to cooperate to
Figure 1: Examples of on-orbit assembly: (a) the EASE/ACCESS assembly experiments [2], (b) the repairing to the Hubble Space Telescope [3], (c) the assembly of the S0 truss structure [4], (d) the US NRL’s plan to use robotic tools for assembly [5], and (e) the Dragonfly project for robots self-assembly of satellites [6].

Figure 2: The autonomous space robots: (a) Skyworker [8]; (b) LEMUR [9]; and (c) Robonaut [10].

Figure 3: Domestic space robotic manipulator: (a) space manipulator [12] and (b) the concept of space on-orbit assembly.
complete high-precision operations [16]. Compared with single robot, multirobot system has better adaptability, robustness, and scalability [17, 18]. Therefore, multirobot systems are suitable for performing complex on-orbit assembly tasks, which will be an important way to construct large-scale spatial structures in the future [19].

3. Space Robot Assembly Planning Method

There are two ways for space robots to complete tasks: remote operation and autonomous operation. From the perspective of development history, there are mainly the following typical cases of space remote control robot systems: the remote manipulator system (RMS) carried on the US space shuttle, the European Space Agency’s remote control manipulator system, and the maneuvering service of the International Space Station. The Remote Manipulator System (RMS) carried on the US space shuttle, the European Space Agency’s remote control manipulator system, and the maneuvering service of the International Space Station, and the remote control manipulator system of the Japanese experimental cabinet [20]. The USA successfully completed the concept test of on-orbit vertical space structure assembly in 1985, and then, the Oak Ridge National Laboratory of the USA verified the feasibility of using similar hardware to build a space remote control robot. Akin and Bowden et al. proposed a method to inspect and repair large space structures through a ground-based remote robotic control station [21]. With the continuous development of robotics, people have begun to study fully autonomous space robot systems, which are mainly used in the on-orbit assembly, inspection, and maintenance of large space structures [22]. Path planning for multirobots is also divided into various stages, such as noncooperative target capture, handling, and assembly. In order for the space robot to perform on-orbit assembly tasks, it is assumed that the spacecraft carrying one or more robotic arms should first plan the assembly sequence and approach the target workplace with a reasonable trajectory, and the robotic arm also needs to reach the target position through motion planning methods. Therefore, in the assembly process, it is necessary to consider both the assembly sequence planning and the motion planning of the space robot.

3.1. Assembly Sequence Planning. An especially critical step in product development is the planning of assembly sequences, which describe the details of assembly operations in how different parts should be placed in a product. When a space robot assembles a large space structure, with the increase in the complexity of the structure and the number of parts in the product, the demand for assembly sequence planning is also increasing. In the early days, the assembly sequence for the product was generally planned manually. However, this method consumes a lot of human resources and is less efficient. In the 1980s, with the development of computer technology, research on the use of computers for assembly sequence planning began to emerge gradually [23].

Proper assembly planning should consider a range of factors such as assembly tools, fixture requirements, operational safety, and ergonomics. And virtual reality technology allows people to virtually interact with the assembly process, thereby planning the assembly sequence more efficiently [24]. Jayaram and Connacher et al. define virtual assembly as “making or assisting assembly-related engineering decisions by means of computer tool analysis, prior modeling, visualization, and data representation without the need for a real product and associated support” [25]. Ritchie and Dewar et al. proposed a method for assembly sequence planning using immersive virtual reality and verified its effect on an assembly product in an industrial environment [24]. Relying on virtual reality technology, the geometric and physical properties of product parts can be easily displayed, and the professional knowledge and skills of the assembler will greatly affect the assembly effect [26]. Holt et al. also pointed out that a key part of the assembly sequence planning process using the virtual assembly method is the professionalism of the planner [27]. The traditional assembly planning method is greatly affected by human factors. At the same time, the increasing complexity of assembly structure and the diversification of assembly evaluation criteria also bring difficulties to assembly sequence planning. Computer intelligent assembly methods can make up for this deficiency and improve the efficiency and reliability of assembly sequence planning. De Fazio and Whitney et al. generated assembly sequences using knowledge-based algorithms [28]. De Mello and Sanderson proposed a compact representation of all possible assembly plans to increase the flexibility of the assembly system and obtain the optimal assembly sequence [29, 30].

Yu and Guo proposed an auction algorithm based on the consensus-based bundle algorithm (CBBA) for on-orbit assembly task assignment in space to solve the complex assembly tasks in the spacecraft on-orbit assembly process and meet the time and energy constraints and condition. At the same time, considering the replanning problem of new task update during assembly, a real-time reassignment algorithm based on local consensus is proposed to deal with dynamic on-orbit assembly tasks [31]. While Wu and Hang et al. designed a multiagent task planning model, in the process of robot cooperation, the robot will cooperate with other robots to obtain its task sequence according to its own characteristics and finally complete the overall planning goal of the task [32].

Zadeh combines fuzzy logic and intelligent algorithm and proposes the soft computing method [33]. Hard computing emphasizes accuracy, certainty, and rigor, while soft computing obtains the best possible solution to the problem through calculation, reasoning, and decision-making. Therefore, soft computing is very suitable for solving complex assembly sequence planning problems with diversity and uncertainty. There have been many applications of soft computing to solve assembly sequence planning problems [34]. For example, Su utilizes case-based reasoning to solve this problem [35]. In addition, intelligent algorithms such as immune algorithm [36, 37], ant colony algorithm [38, 39], and genetic algorithm [40, 41] also have many applications in assembly sequence planning. For example, Jiang and Li et al. have studied the on-orbit assembly strategy of space
robots, and designed a robot with a ring-shaped mobile base and redundant manipulators, and the time optimal trajectory planning based on genetic algorithm can achieve efficient assembly [42].

3.2. Motion Planning Methods. According to the fixation and working mode of the robotic arm, space robots can be divided into four categories: free-floating mode, free-flying model, fixed-base model, and attitude control mode. Under the floating model, the spacecraft does not have any power system, its position and attitude are completely free, and it responds to the motion of the manipulator [43]. In contrast, the position and attitude of the free-flying model, that is, the base, can be controlled, and any attitude can be achieved. However, the former position and attitude are uncontrollable and difficult to work, while the latter needs to consume a lot of fuel, resulting in fuel waste and shortage [44, 45]. In the fixed base mode, the force exerted by the manipulator on the base is compensated, which is basically the same as the ground control technology, but still requires thrusters to control the position and attitude [46, 47]. The attitude control mode provides the required torque for the spacecraft by using the mechanical arm to generate reaction force control [48], such as a large flexible base in space. This mode provides more methods for the assembly of spatially sized structures of swarm robots.

Different from general robots or robotic arms, the environment in which space robots are located is more complex and random. For example, the randomness of free-floating objects in space will cause planning tasks to require dynamic planning, and path planning is more complicated. At the same time, due to the particularity of the space robot, such as the coupling effect between the space-floating base and the manipulator, under the condition of microgravity, the space robot system must satisfy the momentum conservation, which means that the base, the manipulator, and the joints of the manipulator are connected with each other, which influence each other [49]. In order to improve the working ability of the space robot, the degree of freedom of the manipulator is generally greater than or equal to 7, that is, it has redundant degrees of freedom, and the redundant manipulator poses a higher challenge to motion planning. When a space robot performs on-orbit assembly in space, a basic task is to move the spacecraft from one point to another in the state space [49, 50]. Motion planning is of great significance to the on-orbit operation of space robots. At present, there are several categories, dozens, or even hundreds of motion planning algorithms.

For the spacecraft itself, its state space is the displacement and rotation of the spacecraft in the Cartesian coordinate system, which is a 6-dimensional vector. Each of its states is a point in the graph. The state space of the robotic arm carried by the spacecraft is generally described by the configuration space. The state space of a robotic arm with n revolute joints can be modeled by an n-dimensional manifold [51, 52]. Therefore, the traditional Dijkstra, A∗, and other algorithms can be used for path planning.

Cohen et al. used the ARA∗ (anytime A∗) algorithm to solve the high-dimensional motion planning problem. The experiments on the 7-DOF robotic arm platform showed that the feasible path can be effectively planned, and the high-dimensional planning problem can be solved [53]. Guan and Liu decomposed motion planning into two sub-problems based on the A∗ algorithm: The path planning of the manipulator and the trajectory tracking control of each joint proposed a multirobot on-orbit collaborative motion planning algorithm, which can effectively solve the multirobot on-orbit assembly task [54].

Because the A∗ algorithm needs to construct the environment topology map, the planning method based on random sampling is also widely used. The planning method based on random sampling is more conducive to solving the robot planning problem in the complex environment and high-dimensional configuration space [55]. Li and Chou proposed a motion planning method suitable for swarm robots based on RPP [56], Burns and Brock proposed an improved probabilistic roadmap (PRM) sampling technique based on the idea of maximizing information gain and performed motion planning for a free-floating robot [57]. Rapidly exploring random tree (RRT) constructs a search tree directly from the starting point, which is also a random sampling method. The path of the robot is obtained by random sampling planning in the sampling space, and finally, the planned path is obtained from the search tree by the backtracking method [58]. As shown in Figure 4, the RRT method is used to plan the trajectory of the multiple manipulators. In order to improve the search efficiency, LaValle and Kuffner proposed a bidirectional search RRT method (Bi-RRT) and studied the motion planning of the spacecraft [59], and the Bi-RRT method is used to plan the trajectory of the spacecraft under constraints of obstacles [59]. In addition, there are the RRT-Connect method [60] which improves the node scalability and eliminates the disadvantage that traditional RRT is difficult to plan the optimal path and the RRT∗ [60] method with asymptotic optimality.

In spatial motion planning, commonly used intelligent bionic algorithms are also applied, including genetic algorithm, ant colony algorithm, and particle swarm algorithm. Ali and Babu et al. used a genetic algorithm to search in joint space for path planning of the robotic arm [61]. Machado and Azevedo et al. used genetic algorithm to plan the trajectory of the manipulator with redundant degrees of freedom [62]. While Samer and Mahmoud et al. used the ACO
algorithm to solve the multisolution problem of redundant degrees of freedom, which proposed an angle system between adjacent joints to make the motion of the manipulator itself more stable [63], particle swarm optimization (PSO) also has many applications in the planning of space manipulators [64]. Wang and Walter used the PSO algorithm to plan the trajectory of a space-floating manipulator [65]. Zhang and Ji et al. used a multiswarm particle swarm algorithm to optimize the perturbation of the space manipulator base [66].

The development of deep learning theory in recent years has enabled neural networks to process high-dimensional data end-to-end. Reinforcement learning (RL) is an area of machine learning concerned with how agents ought to take actions in an environment so as to maximize the cumulative reward [67]. When reinforcement learning is applied to the robot field, the rewards of robot behaviors are determined by the situation of the task and the robot state. Through the incentive of behavioral rewards, the robot can converge toward the target state. Because of its emphasis on interaction with the environment, reinforcement learning is suitable for robot behavior control and task planning. For example, Xu and Lu use Sarsa (λ) reinforcement learning method to plan the path of a multi-DOF space manipulator [68]. However, the traditional reinforcement learning method generally establishes the corresponding relationship between the states and actions of the robot by creating tables. This approach seems powerless when dealing with the complex and high-dimensional state input. In recent years, the development of deep learning theory has enabled neural networks to process high-dimensional data end-to-end. Manih and Kavukcuoglu combined the convolutional neural network with traditional Q-learning and proposed the DQN reinforcement learning method, which can process high-dimensional state input [69]. Sasaki and Horiuchi take visual information as state input and use the DQN method to control and plan a mobile robot [70]. In the application of space robots, Yan and Zhang et al. used Soft Q-Learning’s reinforcement learning method to plan the capture behavior of free-floating space robots [71]. Taking into account the main constraints of space robot path planning, Hu and Huang et al. constructed a multiconstraint model for path planning and proposed a multiconstrained reward deep deterministic policy gradient algorithm (MRDDPG) to solve free-floating path planning problem for space robots [72].

4. Space Robot Assembly Method

4.1. Assembly Methods. With the development of robotics and artificial intelligence technology, the capabilities of robots have become more and more powerful. The flexibility, reliability, and robustness of robots also have made significant progress, which lays the foundation for space robots to complete on-orbit assembly tasks. Badawy and McInnes used the super quadratic artificial potential field method to enable space robots to perform on-orbit assembly tasks [73]. This assembly method allows space robots to flexibly determine the behavior of each step and ultimately complete the assembly task efficiently. Peña-Cabrera and Lopez-Juarez attempted to use machine vision methods to achieve robotic autonomous assembly [74]. Navarro-Gonzalez et al. proposed a neural network learning method to enable robots to acquire assembly skills [75].

Large space truss structures are the basic components of large space systems such as space stations and telescopes. Space truss plays an important role in supporting, extending and fixing large-scale facilities in space. Therefore, it is very important to assemble the truss with space robots. Senda and Matsumoto studied the assembly method for free-flying space robots to assemble space trusses and improved the assembly method by using the reinforcement learning method to solve the multisolution problem of redundant degrees of freedom, which proposed an angle system between adjacent joints to make the motion of the manipulator itself more stable [63], particle swarm optimization (PSO) also has many applications in the planning of space manipulators [64].
technologies [76]. Article [77] introduced NASA’s design of space trusses and the methods of space robots assembling trusses. Oegerle and Perves proposed a method for space robots to assemble truss structures of large-scale space telescopes [78]. When some complex assembly tasks need to be accomplished efficiently or in parallel, it is pretty difficult for a single robot to perform. Such tasks can be accomplished by a swarm of space robots in collaboration. Ueno et al. proposed that multirobot collaborative assembly would play a very important role in the future [79]. Whittaker and Statz proposed that when the assembly task is complex, the task should be accomplished by a swarm of space robots with different functions in collaboration [80]. Boning and Dubowsky applied the idea of multirobot collaboration in the study of space structure assembly [81]. As illustrated in Figure 5, the whole space robots swarm consists of heterogeneous robots, such as the transportation robots, remote observer robots, and assembly robots.

In the space robot multitask scenario, Lu and Fei et al. adopted the space multirobot multitask priority motion planning method to optimize the position of the space robot end [82]. Parker studied the fault tolerance and adaptive capabilities of heterogeneous cooperative robots and proposed a multirobot collaborative, behavior-based ALLIANCE distributed architecture [83]. Simmons and Singh et al. used a common collaborative architecture to achieve high-precision collaboration among three heterogeneous robots [84]. Tanaka and Yamamoto et al. proposed that a set of on-orbit service robots can be used to assist in different tasks, such as satellite assembly and disassembly, fuel replacement, and recombination [85]. Tatsch and Fitz-Coy proposed the concept of Heterogeneous Expert Robots for On-Orbit Servicing (HEROS), which is also a concept of using space multirobot systems to perform space tasks [86]. Rekleitis and Papadopoulos put the assembled components more efficiently onto the orbit by turning on/off the propeller of space robots and using the balancing force of the robot arm. Meanwhile, they used a controller based on inversion and Lyapunov stability to control space robots assembling cooperatively [87]. In the follow-up research, Rekleitis et al. proposed an optimal trajectory planning method for robotic assembly tasks, and this method can reduce excessive fuel consumption of free-flying space robots [88]. Du and Liu proposed the dynamic characteristics of the free-floating space dual-arm robot, and the ground microgravity test method based on air bearing verified the correctness of the model and provided experimental conditions for the robot’s on-orbit assembly [89]. The ground-based simulation verification experiments have laid the foundation for the on-orbit assembly of space robots. To the complexity and dexterity of space on-orbit assembly, Sun et al. adopted a 12-DOF three-arm branch robot, and proposed a method based on vision guidance and variable parameter impedance control, which can effectively complete the assembly of porous heavy plates [90].

With the large-scale of spatial structure, there are limitations in single-robot operation. Coordinated work with multirobot to complete assembly is the development tendency in the future. The assembly method of space multi-robot is developing in the direction of intelligence, distribution, and adaptation. But these methods involve the same optimization strategies, such as ensuring minimal resource consumption.

4.2 Vibration Suppression and Compliance Control Method.

Robotic compliant assembly refers to the robot’s control of position and force in specific assembly tasks. In any case, it is often necessary to control the position and force and achieve high-efficiency, high-precision, and compliant assembly through a certain structure or control method. The space robot is flexible or the base is flexible. In order to make the manipulator reach the assembly position accurately and avoid large force conflicts, it is necessary to perform vibration suppression control and compliant assembly control on the manipulator.

Due to the microgravity conditions in space, it is easy to cause vibration of large structures. Therefore, how to realize vibration suppression of on-orbit assembly has become a technical difficulty that needs to be solved in on-orbit assembly. Cao and Li et al. studied the on-orbit assembly strategy of space solar cell arrays, combined the Tschauner-Hemel equation and the elastic beam finite element model, and proposed a dynamic model of structural vibration under the influence of gravity gradient. Through analysis of single and multiple robot assembly strategies to minimize the vibration generated during the assembly process [91], Wang and Wu et al. constructed a relational matrix for solar satellite assembly, using a closed-loop distributed adaptive controller to suppress solar array vibrations [92]. She and Li et al. discussed the on-orbit assembly planning of large space antenna structures, established a vibration and robot mapping model during installation, and constructed a topology model in the system. A hybrid method of branch and bound and improved ant colony algorithm is proposed to optimize the assembly sequence. This method can obtain good assembly sequence and can suppress vibration disturbance [93].

In the assembly contact process, there is direct contact between the targets, and a certain amount of force (moment) will be generated, so compliance control is very necessary. The current compliance control methods can be divided into two categories: active compliance and passive compliance. Passive compliance refers to adding damping materials at the end effector to alleviate the impact of conflicting forces on the robotic arm. However, this method is completely dependent on the properties of the material, cannot be controlled, and has high uncertainty, so it is not suitable for spatial assembly scenarios. Active compliance refers to obtaining contact force information through sensors, using the information as a feedback input to the controller, and performing feedback control of the robotic arm to reduce the contact force and achieve the purpose of compliance control. Active force position control generally adopts traditional “force-position” hybrid control, impedance control, and other methods. These methods are also applied to spatial assembly tasks. Duan Jiaqi et al. proposed a coordinated twist and compliance control method for a dual-arm robot based on the torque-angle method for the assembly task of a space dual-arm robot [94]. With the maturity of random
technology, many scholars use intelligent algorithms to complete space-on-orbit compliant assembly. Control strategies for assembly tasks were reviewed by Deisenroth et al. [95]. Luo Jianlan et al. proposed a flexible hole insertion method based on the combination of a strategy search algorithm close to the hole position and a position-based impedance control [96]. Tadanobu et al. used long- and short-term neural network combined with Q-learning method to achieve high-precision shaft hole assembly task [97]. It can be seen that in the research on on-orbit assembly of space robots, differences with the ground environment need to be considered, such as microgravity conditions, and floating bases. These complex situations greatly increase the control difficulty of the manipulator, such as the vibration suppression problem mentioned above, and how to conduct ground experiments. At the same time, resources in space are limited, and energy consumption and efficiency issues of assembly tasks also need to be considered. The complex and random environment of space brings great challenges to the efficient planning and precise control of robots to complete various on-orbit assembly tasks.

5. Ground Experiment Verification Method

Due to the high cost of space on-orbit construction, the space manipulator and its related control system and other environments must be verified on the ground to ensure that all equipment can operate normally before the space on-orbit assembly. The biggest difference between the ground and space is whether there is gravity, so how to simulate zero gravity conditions is the key and focus of ground test verification. At present, there are five commonly used ground verification methods, namely, air flotation method, water flotation method, force compensation method, parabola method, and free fall method.

Air flotation and water flotation refer to the generation of a supporting force opposite to the direction of gravity through gas or water. The only difference between the two is the medium, and the principle is the same. The air flotation method uses the force based on the air gap to balance the gravity and can realize a variety of simulation methods from 2 degrees of freedom to 6 degrees of freedom. As early as the 1960s, the USA developed a triaxial air flotation table [98]. With the increasing enthusiasm of space exploration, countries have comprehensively promoted the research on air flotation platforms. The five-degree-of-freedom air flotation platform developed by the Georgia Institute of Technology has improved a good idea for the research and development of multidegree-of-freedom air flotation platforms for other units [99]. In China, the fifth and eighth academies of aerospace and major universities also have related research on air flotation platforms. The Harbin Institute of Technology has also independently developed a set of six-degree-of-freedom air flotation platform, which can effectively simulate space attitude and orbital motion.

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The water flotation method refers to the test and verification in the water. Similar to the unmanned submersible
with the carrier arm, coordinated control is required between the boat and the mechanical arm. Some universities have such experimental conditions. Massachusetts Institute of Technology has conducted a number of teleoperation experiments at the NASA Space Center [102], and the University of Maryland has explored the interaction between multiarm free-flying robots in an underwater environment [103]. As shown in Figure 6(b), the Eurobot WET model is lowered into the pool ahead of testing to verify the operational concept for Eurobot [104]. However, due to the requirements of water flotation on sealing and the influence of water resistance, the application of water flotation is far less than that of air flotation.

The force compensation method refers to unloading and compensating the gravity through the suspension device, which can be used for the microgravity test of the manipulator [105] (see Figure 6(c)). The tension force generated by the suspension rope is equal in magnitude to the force in the opposite direction of gravity to achieve a balance effect. Sato et al. developed a suspension electromechanical system that passively generates a balancing force [106], while Menon et al. used a combination of tensile cable and spring suspension to simulate a zero-micro gravity environment for related tests [107]. This method is relatively simple for site construction, but the gravity balanced by this method belongs to a static platform, which cannot be used to model the real zero-micro gravity dynamics, and stretching will generate a pulling force perpendicular to the direction of gravity, which cannot form a complete equivalent experiment [108].

The parabola method and the free fall method refer to the balance of gravity through the movement of the carrier or the free movement of the measured object. The parabola method is also known as the flight method. In order to explore more experiments to achieve microgravity environment, many scholars have studied the parabola method. The study found that when the aircraft performs parabolic motion, the microgravity effect can be obtained in a short time. Menon carried out the study with two flight tests of 30 parabolas each to determine the gravity situation [109]. Nohmi et al. conducted experiments on the attitude controller of the robot using the flight method [110]. The free fall motion method is free to release at a larger position. These two methods have a short existence time in microgravity, and the free fall method is easy to cause damage to the robot. This type of method is often used in astronaut training.

Effectively and accurately completing the ground verification test is the basic guarantee for space on-orbit assembly. The success of space on-orbit assembly can only be guaranteed if various cutting-edge theories and methods are equivalently verified on the ground. In the development of space on-orbit assembly technology, the development of ground verification methods has also become a key part. The space administrations or space institutes of various countries have also established corresponding laboratories, especially the air flotation experimental platform and the gravity compensation experimental platform with the purpose of completing the "space-ground consistency" experiment on the ground and ensuring the accuracy and feasibility of the experiment.

6. The Development Trend of On-Orbit Assembly of Space Robots

With the advancement and development of space robot technology, space robot on-orbit assembly technology has become a common key technology that all countries are concerned about. In the future, on-orbit assembly is also full of opportunities and challenges, which are mainly reflected in the following aspects.

(1) On-orbit assembly relies on space multirobot coordination

With the continuous improvement of task requirements, the system is more complex, the on-orbit tasks are developing from fixed to open, and multirobots are required to complete tasks collaboratively. Space robots are developing from a single robot to multirobots and robot groups, and the robot system is more flexible and complex. The complexity of the system makes the completion of extravehicular tasks require a variety of collaborative capabilities such as multirobot collaboration, human-machine collaboration, and human-human collaboration. It is required that the robot not only supports teleoperation, preprogramming, visual closed-loop, handle-controlled intelligent interaction, and the combination of various interaction methods, but also needs to establish a super presence and support intelligent interaction capabilities such as brain control, voice control, and eye movement control.

(2) More intelligent on-orbit assembly technology

The future work of space robots will become more autonomous and therefore need to be more multisourced in perception. Robots need to have multisource perception of objects under the conditions of complex lighting in space, have the ability to perceive and integrate their own state such as force perception, position perception, speed perception, tactile perception, product mode perception and have environmental perception capabilities such as temperature perception, gravity gradient perception and light condition perception. When there are no astronauts in the working environment, the robot needs to exert its intelligence and autonomy, and it needs to have autonomous decision-making functions, fault diagnosis and self-repair functions, autonomous mission planning, autonomous work, and learning capabilities.

(3) Diversified capabilities of space robots

The large-scale space structure has led to the operation range covering up to several hundred meters. The operating objects involve giant truss structures, high-precision optical equipment, and flexible solar wings. The robots not only need to have long-distance transfer and movement functions, but also need to have the ability to complete high-precision operations and flexible operations including clamping, rotating, pulling, cutting, and connector operation. The robot system needs to have the functions of robot group reconstruction, robot task reconstruction, and configuration reconstruction according to the task. The robot needs to determine the system configuration according to the task, the joints need to support the ability to quickly replace on-orbit, and the terminal needs
to be configurable according to the task. The self-maintenance and self-reconfiguration capabilities of robots are more prominent. In addition, the ability to use tools is also an important item that reflects the capabilities of robots.

Complex tasks require robots to have a division of labor. Some are engaged in auxiliary tasks such as handling, lighting, and vision, and some are engaged in tasks such as load connection, fixation, and disassembly. Robots engaged in auxiliary work and primary work have similarities in system composition, but differences in performance, making the pedigree of robotic systems for large-scale space missions clearer.

7. Conclusion

This paper reviews the achievements of the academic and aerospace industry researches on the on-orbit assembly of space robots over the past few decades. During the on-orbit assembly process, the space robot needs to reach the work position and capture the assembly components. Therefore, the motion planning of space robots is very important. In subsequent assembly operations, it is necessary to first plan the assembly sequence. Then, the space robot will take a specific assembly method to complete the corresponding assembly task. With the in-depth research of scholars, some problems have been satisfactorily solved, but some problems still need to be further studied in the future. For example, due to dynamic coupling, nonholonomic constraints, and dynamic singularity of space robots, it is very difficult to establish accurate dynamic models of space robot systems.

In the future, space on-orbit assembly tasks will be more complex, and the use of swarm space robots to cooperate to complete the assembly of space structures is a major research direction. However, today’s multirobot collaborative systems are not intelligent and efficient enough, so in-depth research is needed to strengthen the collaboration, perception, and interaction capabilities of space robots in orbital operations.

Data Availability

The data of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest to this work.

Authors’ Contributions

D. Li and Q. Tang contributed to conceptualization, writing manuscript, and reviewing. L. Zhong, W. Zhu, and P. Xu contributed to writing manuscript, visualization, and revising. All authors discussed the paper and revised the manuscript.

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