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Modular robotic manipulator and ground assembly system for on-orbit assembly of space telescopes

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Abstract
In the field of astronomical observation, large space telescopes are key tools for deep space exploration. However, the aperture of space telescopes is limited by the ability to fabricate large monolithic mirrors or lenses and by severe restrictions on the overall volume and mass capacity of the launch vehicle. The use of robots for autonomous assembly while in orbit is a promising option for the deployment of large-aperture space telescopes. In this paper, we describe a modular robotic manipulator that offers high precision and flexibility. A space telescope ground assembly system is then designed, the key components of which are a redundant robotic manipulator and a reconfigurable telescope unit. The ground-based assembly of the space telescope is implemented through a combination of trajectory planning, visual perception, and robotic supple control techniques, validating the ability of the robotic manipulator to automatically assemble modular space telescopes. Finally, the developed robotic manipulator is used to conduct ground assembly demonstration experiments, and the modular space telescope is assembled according to the assembly task plan, accumulating technical experience for future space telescope assembly tasks in orbit.

Keywords
Space telescopes, modular structure, robots, on-orbit assembly, ground demonstration

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Introduction

With advances in science and technology, astronomy continues to stretch mankind's horizons to new depths of the universe. Telescopes are the most effective tools for studying the morphology, structure, kinematic properties, physical state, and evolutionary stages of celestial bodies. Compared with ground-based telescopes, space telescopes offer greatly improved observational capabilities because they are not affected by interference from the Earth's atmosphere.[1] Currently, astronomical telescopes for observing different wavelengths are being sent into space to deepen our knowledge of the universe, including the Gamma Ray Observatory, Advanced X-ray Astrophysics Facility, Infrared Telescope, Hubble Space Telescope, and James Webb Space Telescope. Despite the impressive results that have been achieved in astronomy, several fundamental questions remain unanswered because their study requires larger-aperture space telescopes.

Currently, there are three main technical solutions used for the on-orbit deployment of large-aperture space telescopes: monolithic devices, unfolding devices, and on-orbit assembly. The main problems with "monolithic" primary mirrors are the difficulties involved in manufacturing and integrating components, and launching the whole structure. The best-known application of a monolithic primary mirror is the Hubble Space Telescope (2.4 m aperture).[2] In response to the problems of monolithic space telescopes, researchers have proposed "deployable"

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primary mirrors, in which the telescope is collapsed for launch and then deployed in orbit. The James Webb Space Telescope is a recent example: the primary mirror measuring 6.5 m in diameter and composed of 18 hexagonal mirror segments was collapsed to 4.47 m to adapt to the 5.4 m fairing inner diameter of the Ariane 5 launch vehicle.[3] However, further increases in the aperture of the telescope cannot be accommodated by existing rocket capacity, even if the deployment design is adopted. In view of the problems of monolithic and unfolded models, and the future development needs of large-aperture space telescopes, the on-orbit deployment of a large space telescope through on-orbit assembly is a more promising option. On-orbit assembly involves launching the modules of a space telescope into orbit separately and assembling them by means of on-orbit assembly and calibration.[4,5] This solution provides a breakthrough in the deployment of traditional space telescopes, revolutionizing the field of space telescopes, and providing a viable solution for realizing very-large space optical systems with apertures of tens or even hundreds of meters.[6,7]

Many conceptual design solutions and technologies for the on-orbit assembly of large-aperture space telescopes have been proposed.[8,9] For example, Boeing has proposed a technical solution for an autonomously assembled space telescope of 10 m aperture that can be assembled in orbit, whereby the very-large aperture telescope is divided into multiple components for easy loading into the launch vehicle and robots are used for assembly in space.[10] The US company Bauer has presented a 10 m aperture Modern Space Telescope Concept,[11] which is assembled by space robots at the solar-terrestrial L2 point. NASA has developed a design concept for an expandable space observatory (10–50 m aperture) that could be assembled in space by robots, astronauts, or both.[12] Northrop Grumman proposed a three-stage on-orbit assembly process for the Evolvable Space Telescope,[13] with an overall aperture of 20 m. Moreover, the Modular Demonstration of Evolvable Space Telescope is being developed for the International Space Station.[14] The concept of on-orbit assembly has attracted considerable attention from scholars. Lee et al.[15] introduced the concept and structure of a robotically assembled modular space telescope, and realized the assembly of the main mirror structure by means of a six-legged robot that can walk on a truss. Jackson et al.[16] designed a micro-space robot for on-orbit assembly tasks, considering the trade-off between the robotic manipulator structure and the size of its base spacecraft. Mishra et al.[17] developed a joint simulation framework that allows the assembly process of a space telescope to be simulated as an on-orbit assembly task using a reconfigurable multi-robotic manipulator system. She et al.[18] investigated the conceptual design and on-orbit assembly task planning problem for a large space telescope, with various algorithms used to optimize the robot's assembly path. Martínez-Moritz et al.[19] designed a space telescope assembly planner that computes an assembly sequence based on a set of different semantic, structural, and physical constraints. In recent years, although robotic mission architectures for the on-orbit assembly of large space telescopes have been refined,[20,21] and various technologies for on-orbit assembly using robots have been proposed,[18,19] most research remains at the conceptual design or simulation stage, and is stuck in the top-level paradigm design of the assembly process. Therefore, the design of a set of equipment for the validation of on-orbit assembly-related technologies is urgently required.

To date, the development of scale demonstration and validation systems, represented by MoDEST and OpTIIX, has marked the progress of research into on-orbit assembly, from the initial program demonstration stage to the development of scale engineering prototypes. Jiang et al.[22] proposed a conceptual design for a 10 m aperture modular space telescope and a robotic assembly strategy, and completed an assembly experiment of the sub-mirror module and the central module using KUKA's iwwa-7 robot to verify the feasibility of its control strategy. Hao et al.[23] demonstrated the assembly of a space telescope by two 6 degree-of-freedom (DOF) robotic manipulators on the ground, validating the concept of robotic assembly for future large space optical telescopes. Koch et al.[24] introduced an underwater microgravity simulation demonstration system, which was used to show the assembly process of the main mirror lens of large telescopes in microgravity environment. Letier et al.[25] developed a new generation of standard robotic interface for on-orbit servicing, which can effectively support robotic operations of space telescopes assembly on orbit in future. However, existing research is mainly oriented toward conceptual designs for the on-orbit assembly of large space telescopes and the experimental verification of the unit technology, without building a whole telescope assembly experimental system to verify the overall process.

To realize the ground assembly of space telescopes and provide a verification platform for the related technologies of on-orbit assembly, this paper studies a modular space telescope ground assembly demonstration system. The robotic manipulator used to complete the ground assembly demonstration task was designed using a modular design concept,[26–28] which effectively improved the maintenance interchangeability of the robotic manipulator, reduced design costs, and allowed for rapid reconfiguration according to different operational task requirements. Moreover, the redundant design of the robotic manipulator's degrees of freedom improves the flexibility and reliability of the robotic manipulator.[29,30] The ground assembly is completed by the developed modular redundant robotic manipulator, which verifies the autonomous assembly technology and paves the way

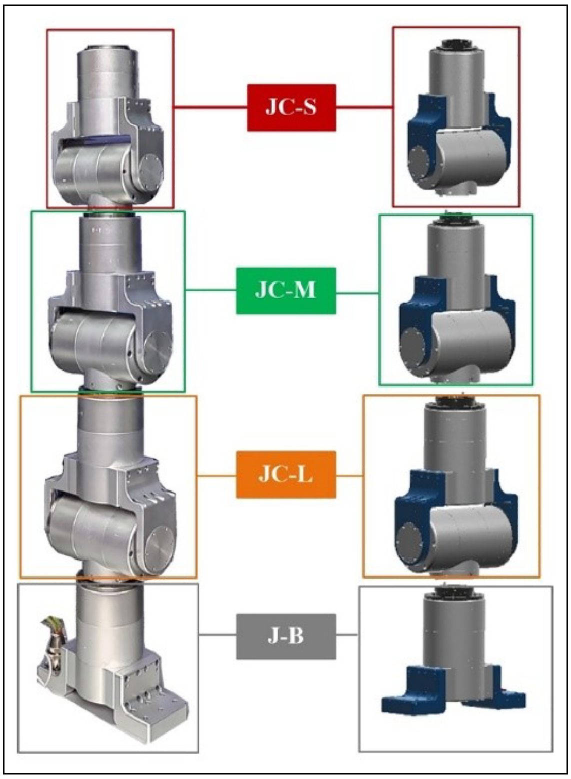

Figure 1. Physical and exploded model view of the robotic manipulator.

for the ground verification of large space telescope on-orbit assembly technology.

The remainder of this paper is structured as follows. Section 2 introduces the modular robotic system designed for telescope assembly. Section 3 describes the Modular Space Telescope Ground Assembly Demonstration System. Section 4 presents experimental results from the ground assembly of the modular space telescope. Finally, section 5 summarizes the conclusions from this study.

Modular redundant robotic manipulator for on-orbit assembly

Mechanical overview

The modular redundant robotic manipulator for on-orbit assembly can be quickly constructed and disassembled from modular joint assemblies, as shown in Figure 1. The input and output of each joint is fixed with male and female ejector spring-type electrical connectors, which can be installed through a mechanical interface to achieve a rapid connection between mechanical and electrical components. There are no cable connections between the joints, and only one cable is needed to realize communication and supply power to the system. The designed robotic manipulator has a total length of 1200 mm, a maximum joint outside diameter of 166 mm, a total weight of 28 kg, and a maximum load capacity of 10 kg. To avoid collisions and interference between modules in the process of assembling the space telescope while in orbit, the robotic manipulator should have a high repeat positioning accuracy index. Using the high-precision FARO laser tracker, the repeat position accuracy and attitude accuracy of the end of the robotic manipulator were measured at approximately 0.1 mm and 0.035°, satisfying the assembly accuracy requirements of the space telescope.

Modular joint structure

The horizontal and vertical joints form a modular joint assembly through two connecting plates, as shown in Figure 2, enabling pitch −100° to 100° and roll −170° to 170° movements, and maximum movement speed up to 10 r/min. The main connection plate is fixed with a rectangular connector and a circular connector male tip, and the connectors are attached to each other by a cable, which is arranged in the recess of the main connection plate. The main-

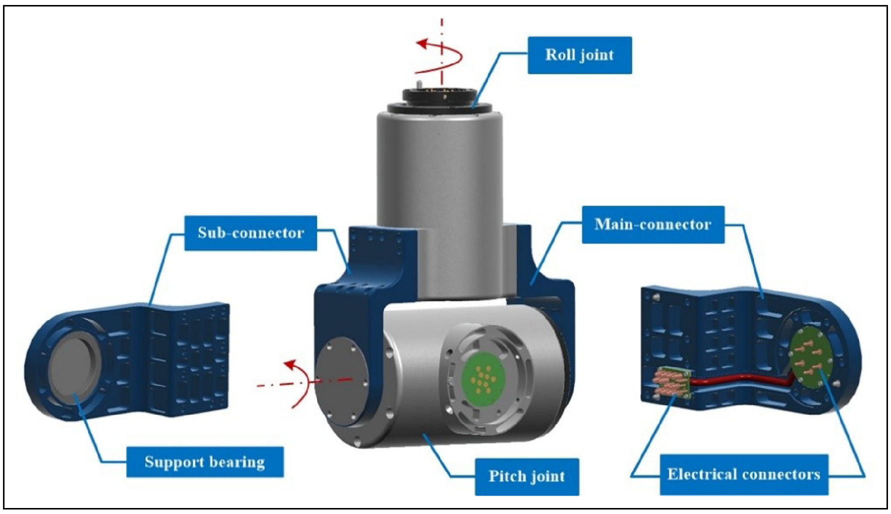

Figure 2. Diagram of joint assembly.

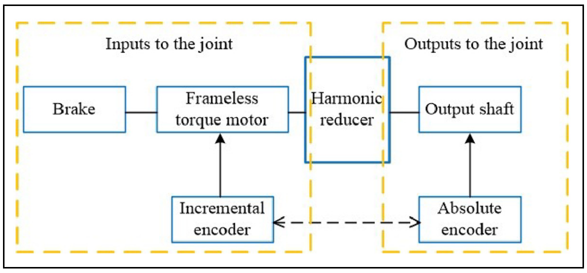

Figure 3. Schematic diagram of joint function.

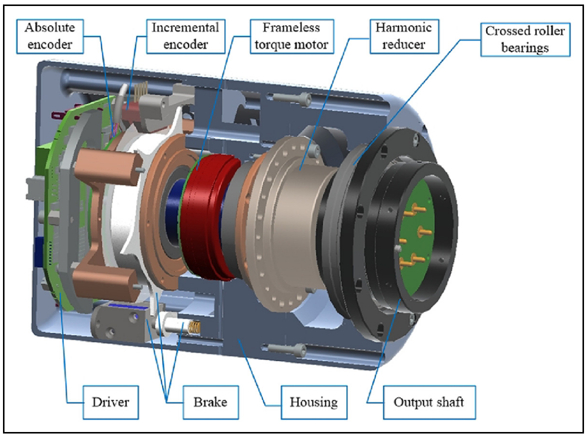

Figure 4. Schematic diagram of the internal structure of the joint.

connector not only realizes the mechanical connection between the horizontal and vertical joints, but also achieves power and signal transmission between the joints, which improves the reliability of the system. The sub-connector is fitted with a rolling bearing that effectively improves the stiffness of the pitch and roll joint connection. Both the main-connector and sub-connector are made of aluminum alloy 7075 and have a lightweight design, which effectively reduces the mass and increases the load capacity of the joint assembly.

The robotic joints are modular in design, and all joints have the same internal structure, mainly consisting of frameless torque motors, harmonic reducers, position-measuring sensors, and brakes, as shown in Figure 3. The robotic joint uses a frameless torque motor that is decelerated by a harmonic reducer to amplify the motor torque and transmit it to the joint output, which drives the rotation of the joint. The motor side is connected to an incremental encoder to measure the motor speed and the joint output is connected to an absolute encoder to measure the joint position. The joints are equipped with a brake and are connected to the motor shaft to provide braking protection in the event of a power failure.

Figure 4 shows the internal structure of the robotic joint, with a split pin brake integrated into the rear end of the motor. The brake claw disks are fixed to

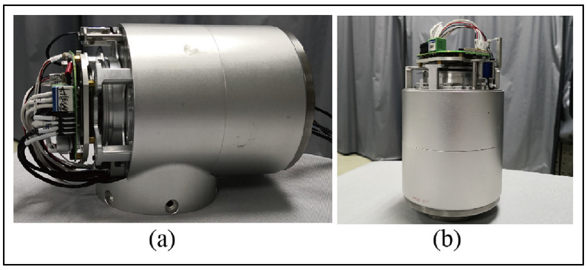

Figure 5. Physical view of the joints: (a) horizontal joint and (b) vertical joint.

the motor input shaft, with a clearance size of 45° between the disks. After deceleration by the harmonic reducer, the actual angular clearance of the output shaft is 0.28°, which allows for braking protection. The absolute and incremental encoders are placed at the rear end of the joint, and the incremental encoder disk is fixed to the brake jaws and connected to the motor rotor. The output shaft passes through the hollow motor shaft and is connected to the absolute encoder rotor, resulting in a more compact joint. The joint actuators are integrated into the individual joints and the joint cables are hollowed out to avoid exposure and tangling of the wiring and to improve the reliability of the joints. The designed horizontal and vertical joints are shown in Figure 5.

Electronics overview

The designed controller drives the frameless torque motors in each joint, and the electric unit supplies the controller unit with power. The controller integrates encoders, brakes, motor control, and other functions, and uses EtherCAT for communication. EtherCAT supports a wide range of industrial protocols and enables high-speed control of multiple axes while maintaining close synchronization of the clocks in the nodes.

To ensure the security of the robotic system, the designed robotic manipulator power supply system is divided into a motor power supply system and a logic power supply system. The motor power supply system supplies the motors and controllers of the joints, and the logic power supply system supplies the encoders and brake solenoids. The power is transferred between the joints via quick-change electrical connectors, as shown in Figure 6.

Kinematic modeling and analysis of the robotic manipulator

The forward and inverse kinematic models of the robotic manipulator are the basis for path planning. Figure 7 shows the coordinate system established by the robotic manipulator. The kinematic model of the robotic manipulator was established using the modified Denavit–Hartenberg (DH) parameter method.

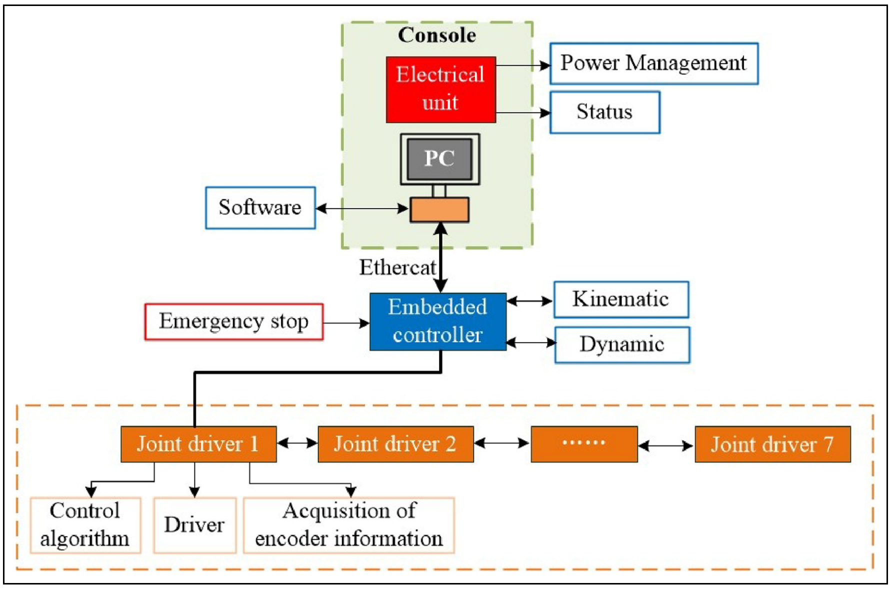

Figure 6. Block diagram of the electrical system of the robotic manipulator.

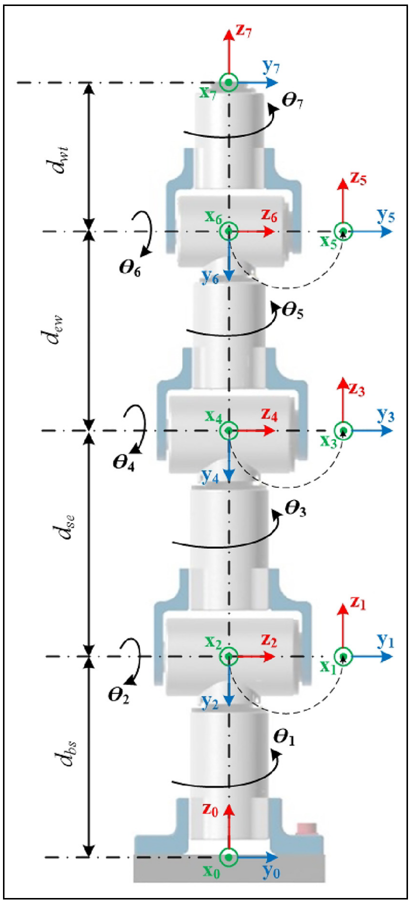

Figure 7. Definition of the robotic manipulator coordinate system.

The DH parameters of the manipulator are listed in Table 1, where α_{i-1} denotes the joint angle between two adjacent joints, a_{i-1} is the distance between two adjacent axes of rotation, d_i denotes the distance of the joint axis from one rod coordinate system to the other, and θ_i refers to the angle of rotation of one rod relative to the other with respect to the joint axis.

Table 1. Table of robotic manipulator DH parameters.

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	d_{bs}	θ_1
2	$-\pi/2$	0	0	θ_2
3	$\pi/2$	0	d_{se}	θ_3
4	$-\pi/2$	0	0	θ_4
5	$\pi/2$	0	d_{ew}	θ_5
6	$-\pi/2$	0	0	θ_6
7	$\pi/2$	0	d_{wt}	θ_7

The transformation matrix ${}^{i-1}_{i}T$ for the position relation of linkage i with respect to linkage $i-1$ can be deduced from the DH parameters of the robotic manipulator as:

$$
{}^{i-1}_{i}T = Rot(X_{i-1}, \alpha_{i-1})Trans(a_{i-1}, 0, 0)\cdot Rot(Z_i, \theta_i)Trans(0, 0, d_i). \tag{1}
$$

We then obtain the positional matrix ${}^{0}_{7}T$ of the end coordinate system of the robotic manipulator with respect to the base coordinate system as a function $fkine(\Theta)$ of the joint variable $\Theta = [\theta_1, \theta_2, \cdots, \theta_7]^T$ as:

$$
{}^{0}_{7}T = fkine(\Theta) = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{6}T\,{}^{6}_{7}T. \tag{2}
$$

Equation (2) shows the position and attitude of the end-effector with respect to the base coordinate system and describes the forward kinematics of the designed 7 DOFs redundant robotic manipulator. As the robotic manipulator is redundant, the damped

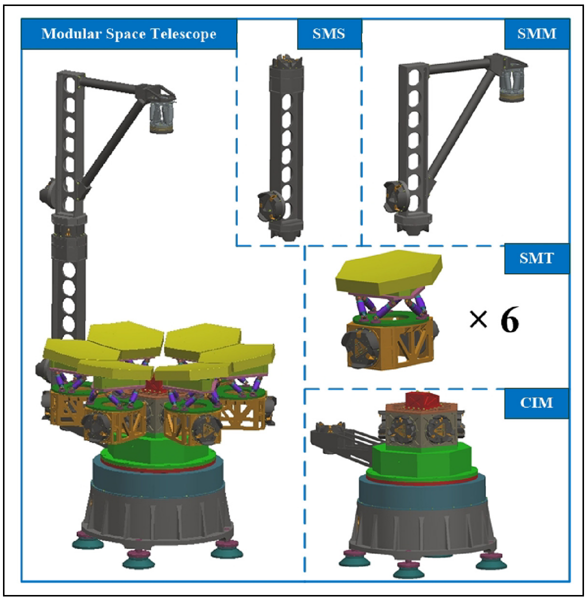

Figure 8. Modular space telescope system.

least-squares method and gradient projection is used to solve the inverse kinematic model.[31]

Space telescope ground assembly demonstration system and assembly process

The ground assembly demonstration system is oriented toward a modular space telescope structure. The goal is to demonstrate the feasibility of constructing a space telescope using a standard adapter interface and a suitable robot by autonomously assembling the various sub-modules of the telescope with a robot.

Design of a modular space telescope system for ground assembly demonstration experiments

A modular space telescope system for ground-based assembly demonstration experiments was first designed. As shown in Figure 8, the modular space telescope system for the ground assembly demonstration experiment has a coaxial optical system structure with an aperture of 1 m. There are nine modules, including a central imaging module (CIM), six segmented mirror tiles (SMT), a secondary mirror module (SMM), and a secondary mirror support module (SMS). The CIM integrates the optical detection device and the power supply device, and is equipped with a standard adapter active end connection around the CIM for locking the individual sub-modules. Furthermore, considering the limitations of the robot's operability, a one-dimensional turntable is mounted on the CIM, which enables precise positional control of its rotating parts.

Table 2. Dimensions and quality parameters for each module.

Module	Dimension (mm)	Mass (kg)
CIM	$\phi600\times700$	85
SMT	$\phi370\times350$	8
SMM	$\phi160\times800$	4.5
SMS	$600\times110\times700$	7.5

After rotating the adapter active end interface to the designated assembly position and transmitting the in-position signal to the general control system, the robot is ready to assemble the corresponding module. On each side of the SMTs, there is a passive end connection adapter for gripping the robotic manipulator and the docking and locking of the main mirror. The mirrors of the SMM are also mounted on a parallel mechanism for precise positional adjustment and are equipped with two standard passive end connection adapters at the lower end for gripping the robot and locking the mounting. The SMS is used for the transfer and fixation of the SMM and the CIM. It is equipped with two standard passive end connection adapters at its lower end for gripping the robot and locking the mounting with the CIM, and a standard active end adapter at its upper end for fixing the SMM. The dimensional envelopes and masses of the individual modules are shown in Table 2.

Modular space telescope assembly coordinate system construction

The robotic manipulator-based system for the ground-based on-orbit assembly demonstration of space telescopes is shown in Figure 9. During the robot assembly of the modular space telescope, the spatial relationship between the end of the robotic manipulator and the individual modules needs to be determined. Thus, various coordinate systems are constructed for the space telescope assembly system. The meaning of each coordinate system is given in Table 3. Laser tracker measurements allow the interrelationship between two fixed coordinate systems, namely the robot base coordinate system $\{B\}$ and the mirror base coordinate system $\{S\}$, to be established.

Assembly process for space telescope

In accordance with the modular structure of the space telescope, the assembly process shown in Figure 10 was developed, whereby the primary mirror section is assembled first, followed by the secondary mirror section. During the assembly of the main mirror section, the SMTs are assembled in sequence to ensure structural stability during the assembly of the telescope structure, as shown by steps 1–6 in Figure 10. During

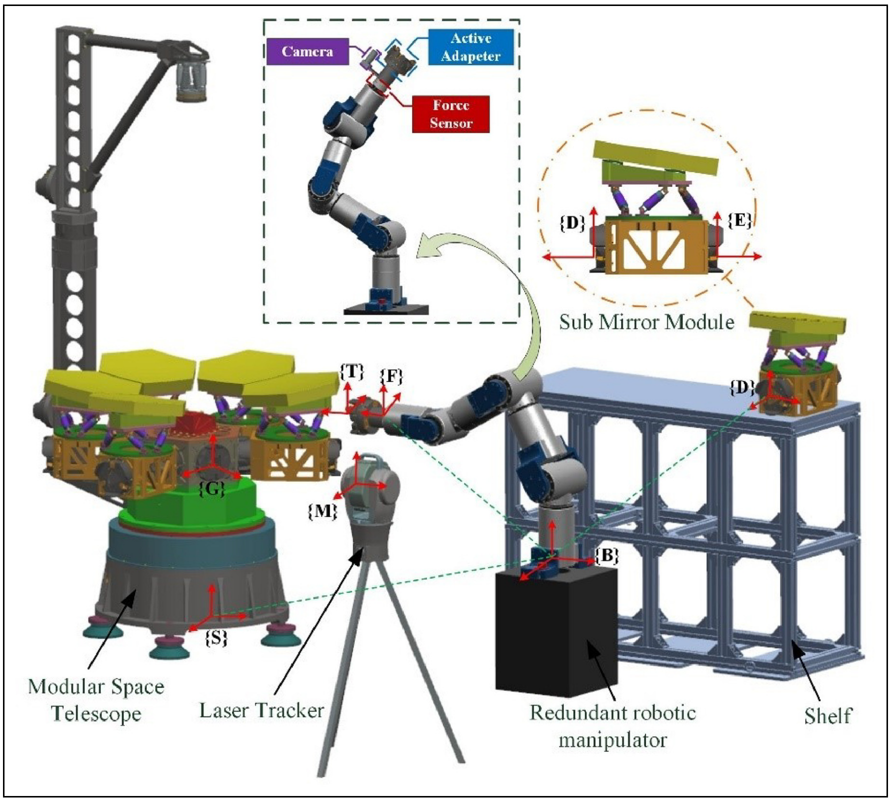

Figure 9. System and established coordinate system for ground-based on-orbit assembly demonstration of space telescopes based on robotic manipulators.

Table 3. Coordinate systems established in the system for the on-orbit assembly demonstration.

Coordinate symbol	Meaning of coordinates
$\{B\}$	Robot base coordinate system
$\{F\}$	Robot flange coordinate system
$\{T\}$	Tool coordinate system
$\{G\}$	Target coordinate system
$\{S\}$	Mirror coordinate system
$\{D\}$	SMT robot side coordinate system
$\{M\}$	Measuring coordinate system

the assembly of the secondary mirror section, the SMS and the SMM are assembled in turn to complete the telescope system structure, as shown by steps 7 and 8 in Figure 10.

In the assembly process, the space telescope modules on the carrier frame are assembled on the main mirror frame of the space telescope by means of the redundant robotic manipulator. The specific assembly process is shown in Figure 11. In particular, adaptive impedance control[32] is used to ensure a suitable contact force at the end of the robotic manipulator as the actuator docks with the telescope module. With reference to the adaptive impedance parameters in the work of Duan et al.,[32] an initial damping factor $b = 100$ and an update rate $\sigma = 0.5$ were used to obtain stable force tracking values in the experiments.

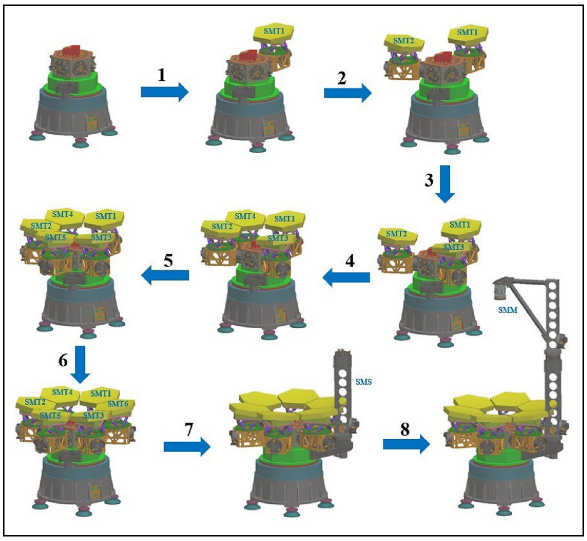

Figure 10. Assembly process of the space telescope.

Modular space telescope assembly ground verification experiment

This section describes the results of assembly demonstration experiments using the designed modular space telescope ground demonstration system. The space telescope pre-assembly ground test site is shown in Figure 12, where SMTs 1–3 have been assembled on the central imaging module; SMTs 4–6, the SMS, and the SMM are placed on the storage bracket; and

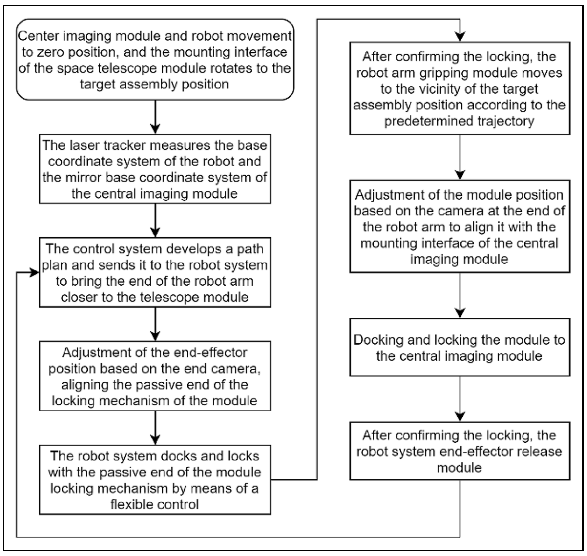

Figure 11. Flowchart of the operation of the modules of the robotic manipulator assembly.

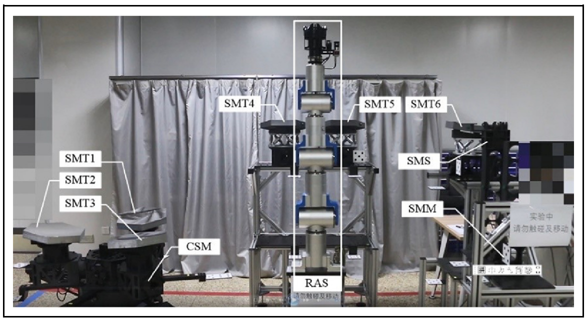

Figure 12. Experimental setup for the assembly of a space telescope.

the robotic assembly system is in the zero position. As the assembly process of SMTs 1–3 is the same as that of SMTs 4–6, this experiment only considers the assembly process of SMTs 4–6, the SMS, and the SMM.

The process of the space telescope assembly test is shown in Figure 13. SMTs 4–6, the SMS, and the SMM are assembled sequentially, as shown in Figure 13. The main steps in assembling each module are shown in Figure 13, where the assembly process of SMT 4 is shown in steps A1–A5, the assembly process of SMT 5 is shown in steps B1–B5, the assembly process of SMT 6 is shown in steps C1–C5, the assembly process of the SMS is shown in steps D1–D5, and the assembly process of the SMM is shown in steps E1–E5.

When assembling each module of the telescope, the robotic system must grip, move, assemble, and release the module in turn. Moreover, after the current module has been assembled, the CIM must be rotated to the next module. The control strategies for the robotic manipulator picking up the modules from the storage and assembling them on the CIM are similar, which can be roughly divided into two stages: approach and docking. Next, the assembly process of SMT4 is used as an example to illustrate the control strategy of different stages. In the first stage, the bi-RRT algorithm in our previous work[29] was used to find the path points during the assembly process of SMT 4, while the OBB algorithm was used to determine whether there was a collision between the manipulator joint and the obstacle, and the time-optimal asymmetric S-curve trajectory planning algorithm[33] that we developed for the redundant robotic manipulator was used to quickly plan a suitable motion trajectory for the end-effector of the robotic manipulator moving to the gripping point near the passive end of the adapter of SMT4. Then, based on an improved uncalibrated visual servo strategy for hyper-redundant manipulators in on-orbit automatic assembly proposed in our previous work,[34] fine adjustment of the end-effector was completed by the robotic manipulator's end camera, which ensured that the active end adapter of the robotic manipulator was aligned with the passive end adapter of SMT4. In the second stage, adaptive impedance control[32] was used to ensure a suitable contact force at the end of the robotic manipulator when the actuator docked with the telescope module. After docking, the active end adapter of the robotic manipulator performed the locking action, as shown in Figure 13(A1). Next, the robotic manipulator lifted the SMT upward off the storage table and moved it to the mounting point position according to the planned path, as shown in Figure 13(A2). Guided by vision and force control, the passive end adapter of the SMT docked with the active end adapter of the CIM, and the active end was activated. This completed the locking of SMT4 in the CIM, as shown in Figure 13(A3). The active end adapter of the robotic manipulator then unlocked, releasing the SMT and stepping back to a safe position, as shown in Figure 13(A4). Finally, the robotic manipulator returned to its original position while the CIM rotated to the next mounting position, as shown in Figure 13(A5). The above process was repeated as necessary until the space telescope was fully assembled, as shown in Figure 14.

As the adapter active end interface to be assembled on the CIM is rotatable, each SMT should be assembled in the same position, only the initial position of the SMTs is different, therefore the trajectory and speed of movement when assembling the different SMTs are similar and are not shown here to avoid redundancy. Only the motion of the joint is analyzed during the assembly process of SMT4. Figures 15–17 show the angle, velocity, and acceleration, respectively, of the joints of the robotic manipulator as a function of time during the assembly of SMT4. The joints of the robotic manipulator have a smooth displacement curve and guarantee a smooth movement speed during the movement of the module. In the assembly process, the end-effector of the robotic

Figure 13. Modular space telescope ground assembly experimental process: (A) assembly of SMT4, (B) assembly of SMT5, (C) assembly of SMT6, (D) assembly of SMS, and (E) assembly of SMM.

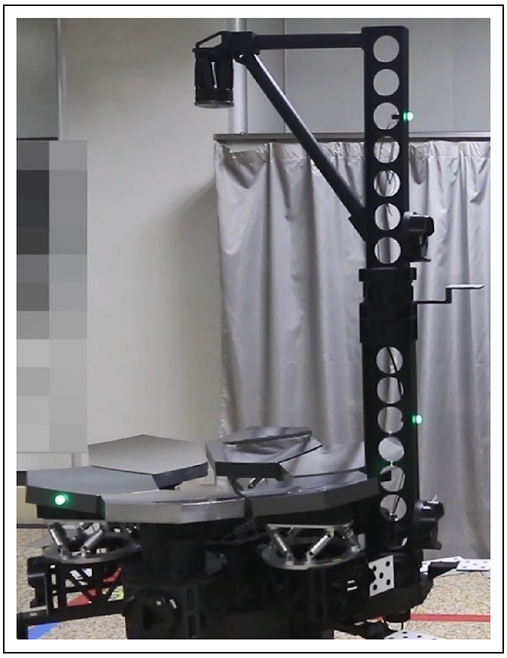

Figure 14. Completed assembly of the modular space telescope.

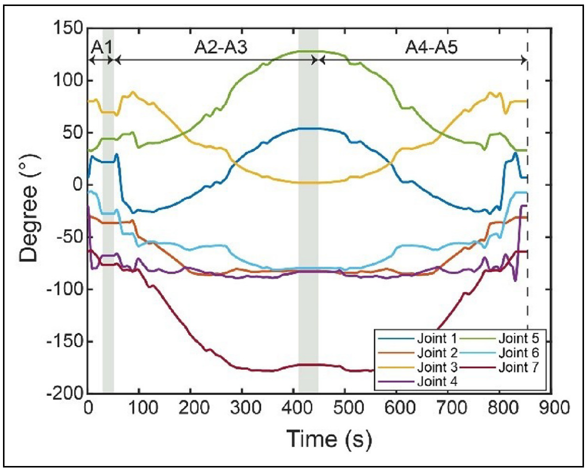

Figure 15. Variation of the joint angles of the redundant robotic manipulator during the assembly of SMT4 with time, where the gray area indicates the locking and releasing process of the module.

manipulator flexibly reaches the target point. Moreover, the docking between the end-effector of the robotic manipulator and the telescope module is precise, the adapter locking is reliable, and the power supply and signal transmission are stable. Finally, the precision assembly of each module of the telescope is successfully completed according to the predetermined assembly plan (see Supplemental Movie 1). This experiment demonstrates the flexibility and good load capacity of the designed modular redundant robotic manipulator.

Conclusion

In this paper, we have described a modular space telescope ground assembly demonstration system,

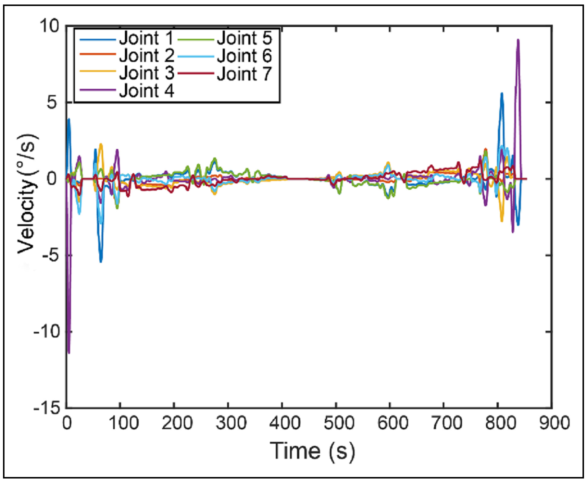

Figure 16. Variation of the joint angular velocities of the redundant robotic manipulator with time during the assembly of SMT 4.

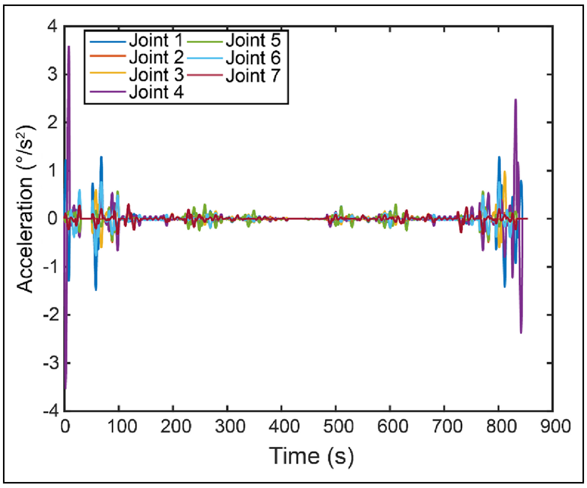

Figure 17. Variation of joint angular accelerations with time during the assembly of SMT4 by the redundant robotic manipulator.

including the development of a redundant modular robotic manipulator and a modular space telescope system. This system is suitable for the validation of current on-orbit assembly methods. Combining the robotic manipulator's path planning, visual perception, and supple control technologies, a functional verification test of the autonomous robotic assembly of a space telescope was completed on the ground. The experimental system decomposes a given assembly into a sequence of tasks, which are then mapped to specific operations of the robotic assembly system. These operations validate the flexibility and load capacity of the self-developed redundant robotic manipulator, with the capability to achieve modular telescope assembly. The designed system for ground-based on-orbit assembly of space telescopes provides an important validation platform for future on-orbit assembly technologies, including trajectory planning, force control, and visual servoing of robotic manipulators in on-orbit assembly. Currently, the main limitations of the system are gravity and the payload of the robotic manipulator, which limit the achievable size of the assembled structure. Future demonstrations of the assembly of larger aperture telescopes will be made possible by gravity compensation, simulating the weightlessness of the robotic manipulator in the space environment.

Declaration of conflicting interests

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Supplemental material

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