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Design and Preliminary Ground Experiment for Robotic Assembly of a Modular Space Telescope

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ABSTRACT Large-aperture space telescope is the key equipment for studying the origin and evolution of the universe and various celestial bodies. Developing large-aperture space telescope is challenging and has become a priority in the field of optical engineering. Due to the mass and volume constraints of launch vehicles, it has to be designed and launched in modules and then assembled on-orbit by space robots. In this paper, we present a conceptual of 10-meter diameter modular space telescope together with robotic assembly strategy. To fulfill on-orbit assembly and maintenance of the space telescope, a novel assembly robot with a ring-shaped mobile base and a redundant stretchable manipulator is proposed. The time-optimal trajectory planning based on genetic algorithm is utilized to achieve efficient assembly. The preliminary ground experiment of assembling submirror modules of space telescope using the KUKA LWR iiwa-7 is carried to verify the feasibility of the proposed method, and the results show that the assembly task of telescope modules can be accomplished successfully with appropriate forces and torques.

INDEX TERMS Modular space telescope, robotic assembly, path planning.

I. INTRODUCTION

The space telescope plays a significant role in studying the origin and evolution of the universe and various celestial bodies. Developing and deploying the large-aperture space telescope has become a cutting-edge topic in the field of optical engineering worldwide [1]–[3]. The aperture size of telescope has been increasing continuously over time to achieve some specific goals, such as, enhanced light-gathering ability and improved angular resolution, for advancing our scientific understanding of planets, stars, and galaxies, as well as, our deep exploration into the universe. Getting rid of the atmospheric noise, the space telescope could have a more powerful imaging capability. However, due to the large size of large-aperture space telescope, its development is subject to severe limitations, such as overall launch vehicle volume, mass capacity, and unmanned maintenance.

With a 2.4-meter diameter mirror in the low earth orbit, the Hubble Space Telescope [4] has been worked for over two decades. Since it was launched to space in 1990, it has been maintained by astronauts or space robots for more than six times. As a successor, the James Webb Space Telescope (JWST) with a 6.5-meter diameter mirror will provide improved resolution and higher sensitivity. Being composed of 18 hexagonal modular mirror segments, the mirror subsystem of JWST is expected to be folded for launch and unfolded on-orbit in 2021 [5].

As JWST pushes the boundary of carrying capability (mass and volume) of exiting launch vehicles, it has been widely accepted that space telescopes with larger aperture could only be designed and launched in modules, and then assembled on-orbit by astronauts and/or robotic systems.

Many concepts of large-aperture space telescope have been proposed. In 2003, Basu *et al.* from Boeing Company [6] proposed a novel concept of a 10-meter aperture optical space telescope. The primary mirror of telescope has 18 or 36 segments, and can be assembled by a dual arm robot autonomously. In 2002, Muller [7] proposed an assembly and service strategy of a 20-meter aperture telescope, the Next Generation Space Telescope (NNGST). The primary mirror of NNGST has 126 segments, and can be assembled by existing space robots on International Space Station (ISS), such as Japanese Experiment Module Remote Manipulator System (JEMRMS), and Space Station Remote Manipulator

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System (SSRMS) with its Special Purpose Dexterous Manipulator (SPDM). In 2004, Oegerle *et al.* from National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC) [8] presented a conceptual design for a Thirty Meter Space Telescope (TMST) operating at ultraviolet-optical-near infrared wavelengths, which can be assembled in space by robots and/or astronauts. This conceptual space telescope was designed to be assembled, tested, and conducted science experiments and routine services across different Sun-Earth-Moon orbits. In 2016, Lee *et al.* from California Institute of Technology [9] provided an architecture and conceptual design for the robotically assembled, modular space telescope (RAMST) which enabled developing extremely large space telescopes. Based on this architecture, a 100-meter diameter space telescope was proposed through the satellite formation flying.

In order to validate the feasibility of on-orbit telescope assembly, Carpenter *et al.* presented the optical testbed and integration on ISS experiment (OpTIIX) [10] in 2012, which utilized the SPDM robot to assemble a 1.45-meter diameter telescope on ISS. After that, Baldauf *et al.* from Northrop Grumman Aerospace Systems proposed the Modular Orbital Demonstration of an Evolvable Space Telescope (MODEST) [11] for assembling a 1.5-meter diameter telescope on ISS, with its aim to break through the key technology of on-orbit assembly of space telescopes.

In the last two decades, the importance of on-orbit servicing (OOS) with space robot has received good attention and it seems that some foundation on space assembly has been established. In specific, the OOS addresses the maintenance of space systems in orbit, including repairing, upgrading, transporting, rescuing and refueling, using technologies that can enrich robotic assembly [12], [13]. On-orbit robotic assembly is a key technology that can enlarge the scale, while reduce the cost, of the large structures constructed in space. In engineering aspect, the OOS applications mainly focus on SSRMS [14] and SPDM [15] for ISS. Albeit some approaches for robotic on-orbit servicing and assembly are in development, most of them are only at the conceptual level [16]. Current typical missions, such as NASA's Restore-L(Low earth orbit) [17] with refueling satellite demonstration, and the Robotic Servicing of Geosynchronous Satellites (RSGS) supported by Defense Advanced Research Projects Agency (DARPA) [18] with multifunctional servicing satellite demonstration, are in the development stage, and have not been verified on orbit.

The former research of large-aperture space telescopes mainly focus on the modular and optical design, and usually utilize the existing space robot, such as SSRMS and SPDM to achieve space assembly, which consider little about the characteristic of space telescope. Therefore, a novel assembly robot for a 10-meter diameter modular space telescope is proposed in this paper, and the efficient robotic assembly method and preliminary ground experiment are studied.

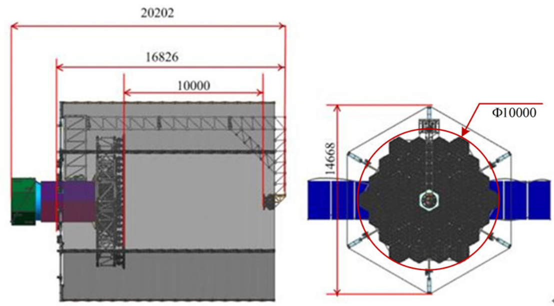

FIGURE 1. Volume envelope of 10-meter diameter space telescope.

The main contributions in this paper are given as follows:

(1) The concept of a 10-meter diameter modular space telescope and the robotic assembly procedure are proposed.

(2) A novel assembly robot with a ring-shaped mobile base and a redundant stretchable manipulator for space telescope is designed, which has the advantages of large workspace and small volume.

(3) A time-optimal trajectory planning method based on genetic algorithm is provided to achieve efficient assembly.

(4) The preliminary ground experiments of submirror assembly using a 7DOFs robot iiwa-7 are carried out to verify the performance of the proposed method.

The organization of this paper can be divided into six sections. After introduction, we present the modular space telescope design and robotic assembly procedure in Section II. Then, we propose a novel assembly robot for modular space telescope in Section III. The Section IV describes trajectory planning for space assembly robot, and Section V shows the preliminary ground experimental results. We finally conclude our paper in Section VI.

II. MODULAR SPACE TELESCOPE

A. DESIGN OF MODULAR SPACE TELESCOPE

The modular components of a 10-meter diameter space telescope are designed to be launched separately to the target orbit through several launches, and can be assembled on-orbit by space robots. Compared with the traditional monolithic or deployable space telescopes, the modular space telescope has its own superiority. The modular components not only support and act as a carrier for optical, electronic and thermal subsystems, but also take into account the structural characteristics and launch requirements, such as the space environment, space robots performance, and so on. In addition, the optical-mechanical structure needs to have the characteristics of light weight, moderate volume to meet the adaptability of optical, electrical and thermal space environment.

The coaxial reflective optical mode is utilized for the 10-meter diameter modular space telescope. The diameter of primary mirror is about 10 meters, and the volume envelope is about $\Phi 14.6\text{m} \times 20\text{m}$, as shown in Fig.1.

The proposed space telescope mainly consists of several modular components, such as the resource module, the submirror modules, the secondary mirror module, the secondary

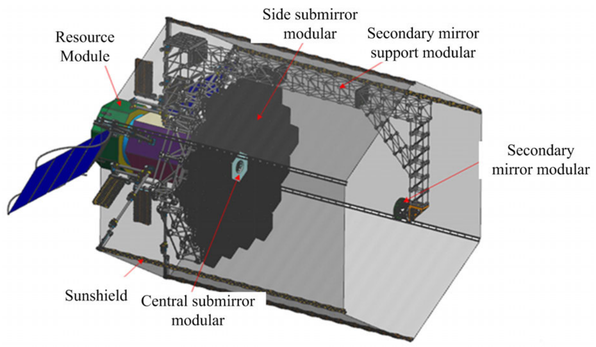

FIGURE 2. Configuration of 10-meter diameter space telescope.

TABLE 1. NUMBERs of ModuleS FOR space telescope.

Module	Number
Resource	1
Central submirror	1
Side submirror	60
Secondary mirror support 1	1
Secondary mirror support 2	2
Secondary mirror	1
Sunshield	6

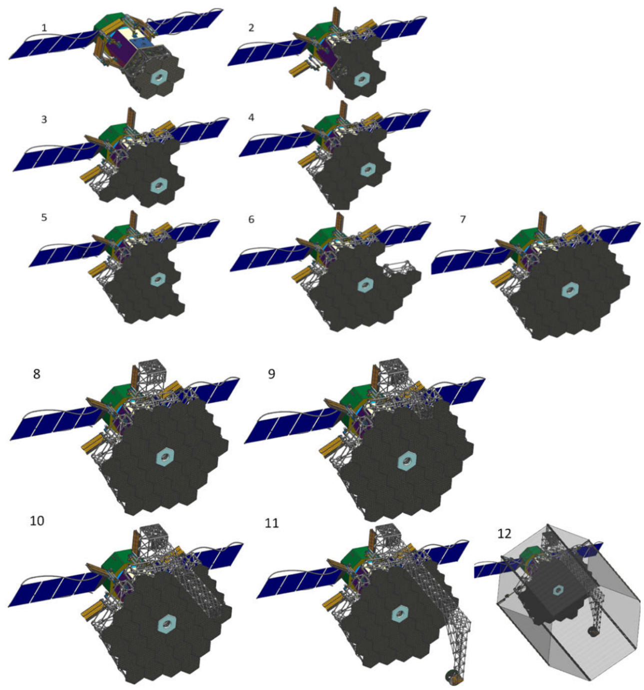

FIGURE 3. Assembly process of 10-meter diameter space telescope.

mirror support modules, and the sunshield, as shown in Fig.2. The resource module is used to control attitude control of space telescope, and berth for the space assembly robot. The submirror modules include the central submirror module and the side submirror modules. The central submirror module integrates the optical detection equipment, focal plane module and total power supply equipment, and is the reference base for side submirror modules assembly. In addition, each assembly module of space telescope is equipped with a standardized capture interface for space robot.

In order to meet the requirements of light weight and good thermal stability, the material of optical structure is mainly carbonization. Silicon carbide with high modulus and thermal conductivity is the main optical element. The mechanical structure materials are mainly carbon fiber composites and silicon carbide aluminum matrix composites. The all-carbide truss optical-mechanical structure composed of silicon carbide, carbon fiber composites and silicon carbide aluminum matrix composites has good thermal matching, thermal stability and high specific stiffness.

B. ROBOTIC ASSEMBLY PROCESS FOR MODULAR SPACE TELESCOPE

The 10-meter diameter modular space telescope includes several modules with different numbers, as in Table 1.

After all the modules of space telescope are launched into orbit, the 10-meter diameter space telescope can be assembled by space robots. The assembly process is shown in Fig.3. Firstly, six side submirror modules are assembled onto the central submirror module one by one in step 1. Secondly, the other 54 side submirror modules can be installed onto the inner side submirror modules sequentially in step 2-9. Thirdly, the secondary mirror support modules and secondary mirror modules need to be assembled, as in step 10-11. Lastly, the sunshield should be mounted at the outside of the submirror in step 12. After the space telescope is assembled by the robot, the optical wavefront alignment can be achieved by controlling the precise mechanism of each submirror module.

III. ASSEMBLY ROBOT FOR MODULAR SPACE TELESCOPE

A. REQUIREMENTS FOR ASSEMBLY ROBOT

The space robot is used to assembly all the modules to build the 10-meter aperture space telescope with high efficiency and safety. Therefore, the mission requirements for assembly robot are as follows:

(1) Capture, transport and assemble the side submirror modules, then construct the primary mirror subsystem.

(2) Capture, transport and assemble the secondary mirror support modules, then build the secondary mirror subsystem.

(3) Capture, transport and assemble the sunshield modules, then finish the whole sunshield subsystem.

According to the proposed conceptual design of the 10-meter aperture modular space telescope and assembly process, the function requirements for assembly robot are as follows:

(1) Accurate motion ability for multi-degrees of freedom (DOFs) manipulator to fit the precise position.

(2) Reliable grasp and release capability for end effector to maintain operation safe.

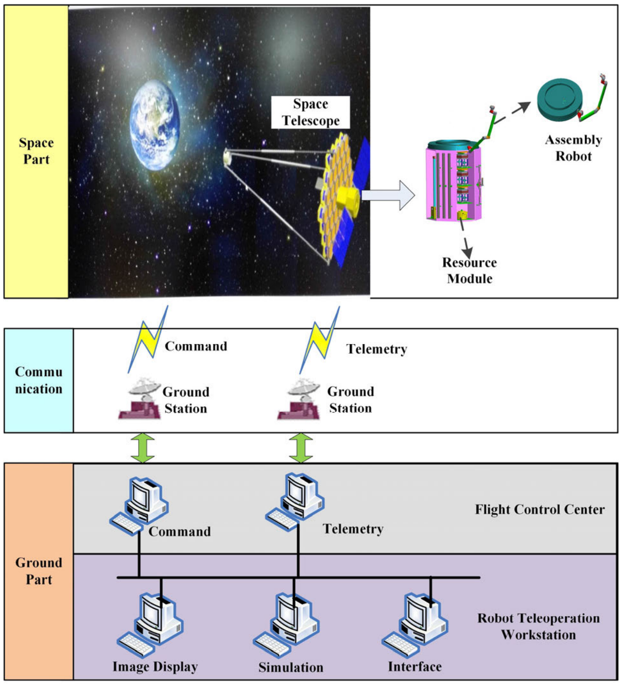

FIGURE 4. Assembly robot system for space telescope.

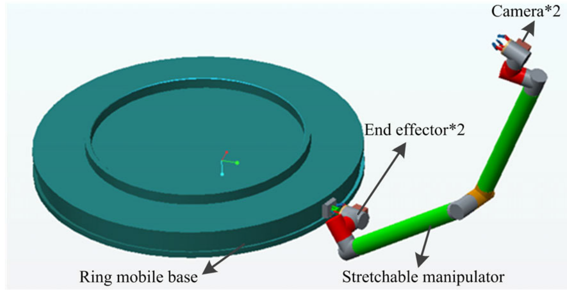

FIGURE 5. Assembly robot configuration for space telescope.

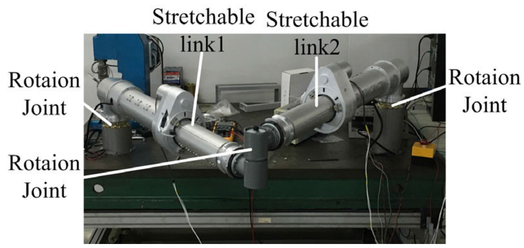

FIGURE 6. Stretchable manipulator for space assembly.

(3) Crawl ability or cooperation for multi-robots to adapt large workspace.

(4) Multi control modes, including accurate position control for free tasks, and compliance control for contact tasks.

(5) Dexterous manipulation with redundancy to adapt collision avoidance in complex environment.

B. ASSEMBLY ROBOT

1) ASSEMBLY ROBOT SYSTEM

The assembly robot for modular space telescope can be operated in autonomous or teleoperated mode to construct the 10-meter aperture space telescope. The assembly robot system for space telescope consists of the space part, the communication part and the ground part, as shown in Fig.4.

The space part consists of the space telescope modules and assembly robot. The assembly robot is used to capture, transport and assemble the space telescope modules. The communication part includes the relay satellites, ground communication station and communication network, which realizes the bidirectional data transmission between space and ground. The ground part includes the flight control center and the robot operation workstation. The flight control center is utilized to monitor the status of spacecraft, while the robot operation workstation is used to teleoperate the assembly robot with telepresence.

To fulfill on-orbit assembly and maintenance of the 10-meter aperture modular space telescope, a novel assembly robot consisting of a ring-shaped mobile base and a 9DOFs stretchable manipulator is proposed in this paper. Neither the position nor the attitude of space telescope is controlled during the in-orbit assembly process to save the limited fuel. The manipulator includes a central controller, two end effectors, and two cameras, as shown in Fig.5. It has a traditional 3-1-3 kinematic arrangement, and there are 3DOFs rotation joints and both the fore arm link and upper arm link have 1DOF to achieve the stretchable function. The manipulator is initially folded in the flank of the space telescope's resource module before launch, and moved onto the ring-shaped mobile base in autonomous or teleoperated mode. During the on orbit assembly stage, the stretchable manipulator can move along the ring mobile base, thus realizes 360 degree coverage of the task space. Compared with the existing proposed assembly robotic systems, the significant characteristics of this robot system are the large workspace and small volume.

The design and control of a stretchable manipulator is challenging according to the limited mass and volume. We employ the passive driving mode to control the extension of link, which utilizes the rotation of joint to drive the translation of link. The structure of stretchable link includes the inner link, outer link and locking mechanism. When the two side bases of the manipulator are fixed, the outer link can slide along the inner link both for link1 and link2 to expand or contract as the rotation joints drive, and then the locking mechanisms work to fix the link to form a new robot configuration. The stretchable prototype is shown in Fig.6.

2) KINEMATIC ANALYSIS

The fundamental requirement for assembly robot is that the robot should have the desired workspace. With the optimized DH model, the kinematic model for the 9DOFs stretchable assembly manipulator in this paper is built in Fig.7, and Table 2 presents the corresponding DH parameters.

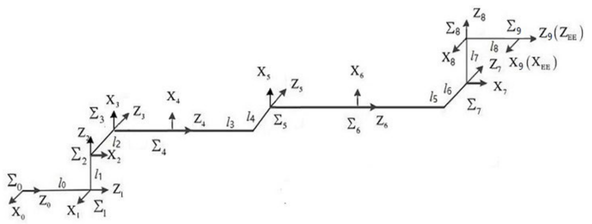

FIGURE 7. DH coordinates of 9DOFs stretchable manipulator.

TABLE 2. DH parameters of stretchable manipulator.

i	θ_i	d_i	a_{i-1}	α_{i-1}
1	θ_1	d_1	0	0
2	θ_2	d_2	0	$\pi/2$
3	θ_3	d_2	0	$-\pi/2$
4	0	d_3	0	$-\pi/2$
5	θ_5	d_4	0	$\pi/2$
6	0	d_5	0	$-\pi/2$
7	θ_7	d_2	0	$\pi/2$
8	θ_8	d_2	0	$\pi/2$
9	θ_9	d_1	0	$-\pi/2$

The homogeneous transformation matrix ${}^{\mathbf{i-1}}_{\mathbf{i}}\mathbf{T}$ of coordinate $O_i x_i y_i z_i$ against $O_{i-1} x_{i-1} y_{i-1} z_{i-1}$ can be expressed as

$$
{}^{\mathbf{i-1}}_{\mathbf{i}}\mathbf{T} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i \sin\alpha_{i-1} \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

where a_{i-1}, α_{i-1}, d_i and θ_i are the link length, link twist, link offset and joint angle, respectively.

The homogeneous transformation matrix of end effector coordinate against base coordinate, i.e. the forward kinematic model of the assembly manipulator ${}^{\mathbf{0}}_{\mathbf{9}}\mathbf{T}$ can be written as

$$
{}^{\mathbf{0}}_{\mathbf{9}}\mathbf{T} = {}^{\mathbf{0}}_{\mathbf{1}}\mathbf{T}{}^{\mathbf{1}}_{\mathbf{2}}\mathbf{T}{}^{\mathbf{2}}_{\mathbf{3}}\mathbf{T}{}^{\mathbf{3}}_{\mathbf{4}}\mathbf{T}{}^{\mathbf{4}}_{\mathbf{5}}\mathbf{T}{}^{\mathbf{5}}_{\mathbf{6}}\mathbf{T}{}^{\mathbf{6}}_{\mathbf{7}}\mathbf{T}{}^{\mathbf{7}}_{\mathbf{8}}\mathbf{T}{}^{\mathbf{8}}_{\mathbf{9}}\mathbf{T} \tag{2}
$$

As the assembly manipulator with 9DOFs is redundant, the damped least-squares method and gradient projection are used to solve the inverse kinematic model. Therefore, we can obtain the joint speed $\dot{\mathbf{q}}$ of the manipulator.

$$
\dot{\mathbf{q}} = \mathbf{J}^{*}\dot{\mathbf{p}} + \mathbf{K}(\mathbf{I} - \mathbf{J}^{+}\mathbf{J})\nabla\mathbf{H} \tag{3}
$$

where $\mathbf{J}$ is the Jacobian matrix, $\mathbf{J}^{*} = \mathbf{J}^{\mathbf{T}}(\mathbf{J}\mathbf{J}^{\mathbf{T}})^{-\mathbf{1}}$ stands for the pseudo-inverse matrix of Jacobian matrix, $\mathbf{H}$ is the gradient of performance index, $\mathbf{K}$ is the optimization coefficient, and $\dot{\mathbf{p}}$ is the pose of the manipulator.

The assembly domain of space telescope is changing in the whole assembly process. Therefore, the manipulator should have relatively small workspace in the initial assembly stage, and obtain large workspace in the final assembly stage.

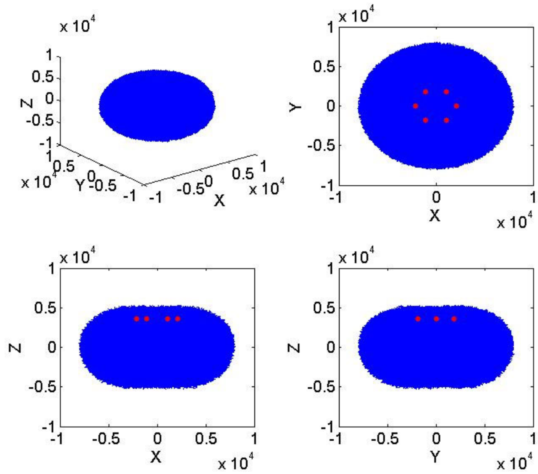

FIGURE 8. Workspace with the minimum extension(unit: mm).

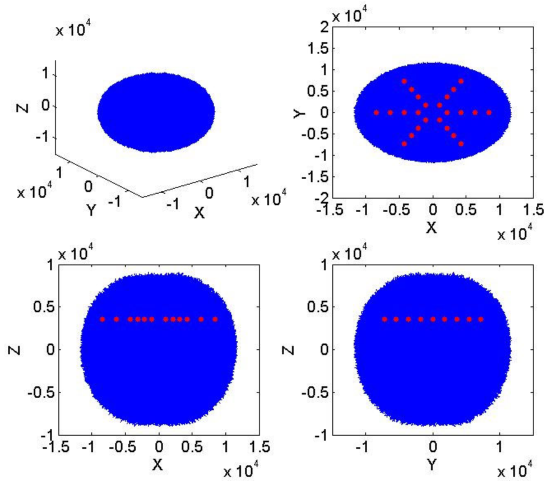

FIGURE 9. Workspace with the maximum extension(unit: mm).

In this paper, the Monte Carlo method is used to calculate the reachable workspace. In fact, fixing the manipulator onto a ring-shaped mobile base is equivalent to adding an extra degree of freedom onto the manipulator. According to the relative position of the manipulator and the pre-assembled submirror modules in the coordinate system, the reachable workspace of manipulator with the minimum and maximum extension are shown in Fig.8 and Fig.9, respectively. The results show that all the positions of pre-assembly submirror modules are within the manipulator's reachable workspace. In another word, from the first to the fourth layer, the assembly manipulator can fulfill different assembly tasks by stretching the length of the manipulator.

IV. TRAJECTORY PLANNING AND OPTIMIZATION

A. CUBIC B-SPLINE TRAJECTORY PLANNING

The cubic B-spline curve [19] has the characteristics of derivative continuity and local supportability, and it is utilized for joint trajectory planning of assembly manipulator.

The data point of joint trajectory $P_j (j = 0, 1, \ldots, n-2)$ can be expressed as

$$P_j(u) = \sum_{i=0}^{3} d_{j+i} N_{i,3}(u) \tag{4}$$

where $d_{j+i}(j+i = 0, 1, \ldots, n+1)$ refers to the control vertex of curve, $N_{i,3}(u)$ stands for the basis function of uniform cubic B-spline, and $u \in [0, 1]$ is the parameter. The basis function $N_{i,3}(u)$ can be calculated as

$$N_{i,3}(u) = \frac{1}{3!} \sum_{m=0}^{3-i} (-1)^m C_4^m (u + 3 - m - j)^k \tag{5}$$

where j is the index of control vertex. When we set $i = 0, 1, 2, 3$, the basis function $N_{i,3}(u)$ can be calculated as

$$\begin{cases} N_{0,3}(u) = \frac{1}{6}(-u^3 + 3u^2 - 3u + 1) \\ N_{1,3}(u) = \frac{1}{6}(3u^3 - 6u^2 + 4) \\ N_{2,3}(u) = \frac{1}{6}(-3u^3 + 3u^2 + 3u + 1) \\ N_{3,3}(u) = \frac{1}{6}u^3 \end{cases} \tag{6}$$

Then $P_j(u)$ can be obtained as

$$P_j(u) = \frac{1}{6}[u^3 u^2 u 1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} d_j \\ d_{j+1} \\ d_{j+2} \\ d_{j+3} \end{bmatrix} \tag{7}$$

Equation (7) can be written as

$$P_j(u) = R_0 + R_1 u + R_2 u^2 + R_3 u^3 \tag{8}$$

where R_0, R_1, R_2, R_3 can be calculated as

$$\begin{cases} R_0 = (d_j + 4d_{j+1} + d_{j+2})/6 \\ R_1 = (-d_j + d_{j+2})/2 \\ R_2 = (d_j - 2d_{j+1} + d_{j+2})/2 \\ R_3 = (-d_j + 3d_{j+1} - 3d_{j+2} + d_{j+3})/6 \end{cases} \tag{9}$$

The value of data point P_j is given to solve the control vertex d_{j+i} when we plan the joint trajectory of manipulator. The value set of P_j with $u = 0$ can be calculated as

$$P_j = (d_j + 4d_{j+1} + d_{j+2})/6 \tag{10}$$

The number of constraint condition and control vertex is $n-1$ and $n+1$, respectively. To facilitate calculation, two extra conditions are needed.

$$d_0 = d_1, \quad d_{n-1} = d_n \tag{11}$$

Therefore, we can obtain the previous control vertex $d_i(i = 0, 1, \ldots, n)$ with (10) and (11).

B. TIME-OPTIMAL TRAJECTORY PLANNING

1) OBJECTIVE FUNCTION

Each joint trajectory of assembly manipulator can be described by $m+1$ data points, which divides the whole joint trajectory into m segments. The objective function T for time-optimal trajectory planning can be written as

$$T = \sum_{j=1}^{m} \Delta t_j = \sum_{j=1}^{m} (t_j - t_{j-1}) \tag{12}$$

where T refers to the total motion time of manipulator, and Δt_j stands for the motion time in the jth segment of joint trajectory.

2) CONSTRAINT CONDITION

For multi-objective trajectory planning of space assembly manipulator, the limitation of displacement, speed, acceleration and torque are considered as the constraint conditions.

$$\begin{cases} q_j(t) \in \Theta \\ \dot{q}_j(t) \in \dot{\Theta} \\ \ddot{q}_j(t) \in \ddot{\Theta} \end{cases} \tag{13}$$

where $q_j(t)$, $\dot{q}_j(t)$ and $\ddot{q}_j(t)$ stands for the displacement, speed and acceleration respectively in the jth $(j = 0, 1, \cdots, m)$ segment trajectory, Θ, $\dot{\Theta}$ and $\ddot{\Theta}$ denote the available maximum values of displacement, speed and acceleration.

3) OPTIMIZATION

The assembly robot is a 9DOFs redundant space manipulator which has 2DOFs translation and 7DOFs rotation. Aiming at ensuring the reliability for space environment application, the optimization calculations for space robot can be carried out offline. Take the representative assembly of submirror modules for example, the assembly process described in Sec.II, is to assemble the modules from inside layer to outside layer, and the stretchable link is used to extend the workspace of manipulator. For simplicity, the extension and rotation of manipulator are controlled separately. Therefore, according to a specific assembly task, the two extension DOFs of manipulator can be controlled firstly to have appropriate workspace, and then the seven rotation DOFs of manipulator can be operated to accomplish the task.

The joint trajectory of manipulator is constructed through cubic B-spline curves, and the control vertex of each joint trajectory is solved with the given data points of joint trajectory to determine the constraint conditions. Take the assembly of the inner layer submirror modules for example, the data points of joint trajectory are shown in Table 3.

For a specific assembly task, not all the joints of manipulator are needed to move to transport and assemble the modules, so the trajectory planning is not necessary for all the joints. As in Table 3, we can find that the joint 1, joint 2, joint 6 and joint 7 do not need to move to assemble modules. Therefore, we can just conduct the time-optimal trajectory planning for joint 3, joint 4 and joint 5.

TABLE 3. Data Points of joint trajectory.

Data point	J1	J2	J3	J4	J5	J6	J7
1	0	90	0	-180	-180	-90	0
2	0	90	-15	-10	-170	-90	0
3	0	90	-5	70	-155	-90	0
4	0	90	-90	0	90	-90	0
5	0	90	-135	-60	105	-90	0

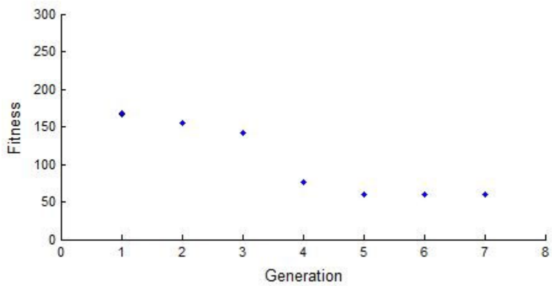

FIGURE 10. Best individual fitness.

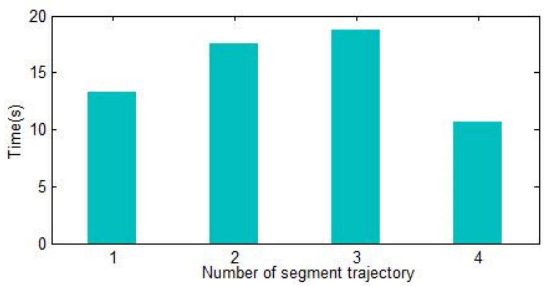

FIGURE 11. Motion time of each segment with optimization.

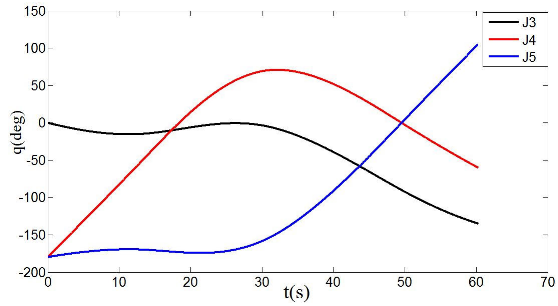

FIGURE 12. Displacement of the joints.

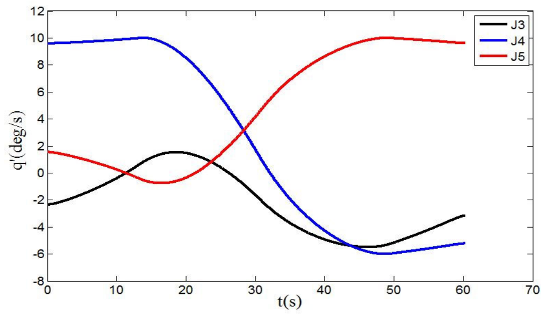

FIGURE 13. Speed of the joints.

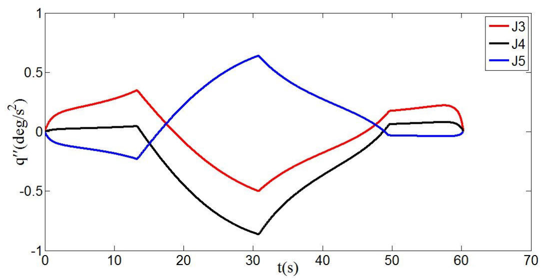

FIGURE 14. Acceleration of the joints.

According to the convergence and computational cost, Genetic Algorithm [20] is applied to work out solutions for the time-optimal trajectory planning of space assembly manipulator, with the motion time on each segment of the trajectory as the decision variable. Each decision variable is independent and not influenced by each other. With the joint constraint conditions of displacement, speed and acceleration, and minimum total motion time as the optimization objective, the operation parameters of genetic algorithm are designed.

With the population size $N = 50$, the competition scale $S_t = 2$, crossover probability $P_c = 0.8$, mutation probability $P_m = 0.1$, maximum evolutionary generation $T = 100$, optimization process and results of genetic algorithm are shown in Fig. 10 - Fig. 14.

Fig. 10 shows the relation between the best individual fitness and evolution generations. It can be found that the best individual fitness declines with the increase of evolution generation, and finally remains stable around the optimal value. Fig. 11 displays the motion time of each segment trajectory when the objective function reaches the optimal value. The displacement, speed and acceleration of the joint 3, joint 4 and joint 5 are obtained in Fig. 12, Fig. 13 and Fig. 14 respectively. The displacement and speed of the joints are continuous, and ranges within $[-180°, 100°]$, $[-6°/s, 10°/s]$, respectively. Moreover, the acceleration of joints belongs to $[-1°/s^2, 1°/s^2]$, which is within the appropriate boundaries.

V. PRELIMINARY GROUND EXPERIMENT

In this section we test the preliminary performance of the proposed method in this paper through a scaled submirror assembly experiment. The experimental system mainly consists of KUKA LWR iiwa7, the side submirror module and the central submirror, shown in Fig.15. The side submirror module is a hexagon cylinder whose side length is about 150mm and height is about 120mm. The central submirror module and the iiwa7 are fixed onto the experimental table. The assembly interface uses the V-groove structure and the clearance is less than 0.2mm.

The control mode and the Cartesian trajectory of KUKA LWR iiwa7 are planned to assemble the side submirror

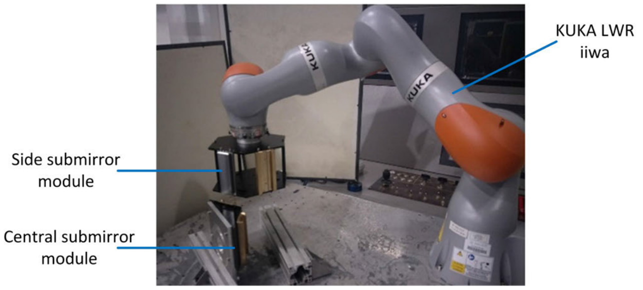

FIGURE 15. Experiment setup for submirror assembly.

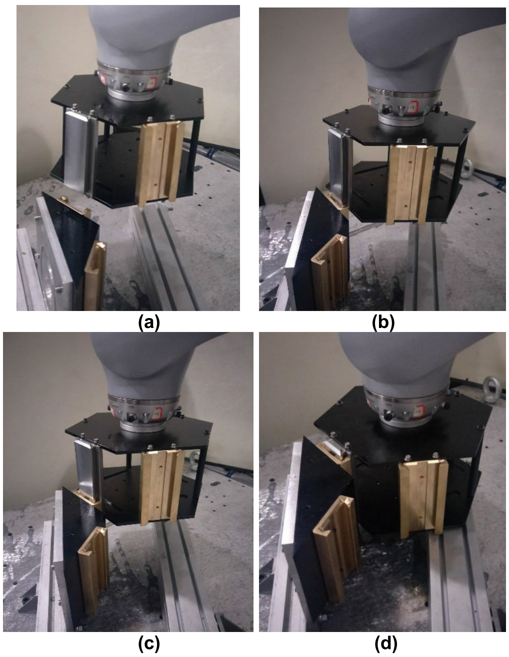

FIGURE 16. Experimental process for submirror assembly.

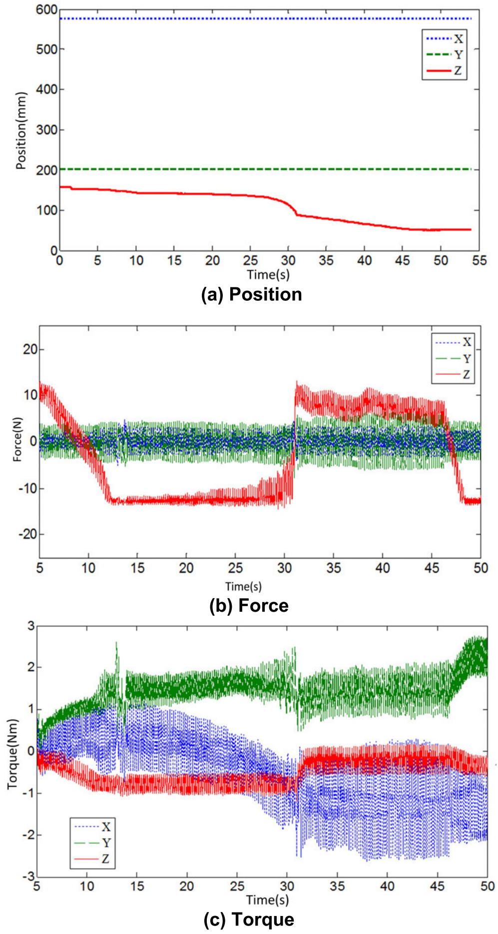

FIGURE 17. Preliminary experimental results for submirror assembly.

module to the central submirror module of space telescope. The robot is controlled in different modes during the submirror assembly process to guarantee the success of assembly task. At the initial positioning stage, after grasping the side submirror module, the end of manipulator is quickly controlled to the pre-assembly position of the central submirror module in position control mode (Fig. 16(a)). Then at the initial inserting stage, Cartesian impedance control mode is used to maintain the compliance insertion of side submirror module (Fig. 16(b)). At the subsequent inserting stage, Cartesian impedance control with superimposed oscillating force (Fig. 16(c)-(d))) is utilized to guarantee the side submirror module fully insert into the central submirror module with appropriate force.

The preliminary experimental results of submirror assembly are shown in Fig. 17. The completion time of robot assembly is about 50 seconds. From the position curve of manipulator in Fig. 17(a), the Cartesian position of manipulator changes little in X-axis and Y-axis, but decreases approximately from 160mm to 60mm in Z-axis. This indicates that the insertion direction of the submirror assembly is in Z-axis and the insertion distance is about 100mm. The forces in X-axis and Y-axis are about zero because the manipulator is compliant in the Cartesian impedance control mode during insertion process. In order to guarantee the success of insertion in Z-axis, the superimposed oscillating force varies from −12N to 10N is utilized, shown in Fig. 17(b). The positive force at the initial stage guides the manipulator to insert, and the oscillating force at the middle stage ensure the smooth insertion, and the negative force at the last stage indicates that the manipulator has assembled the module to the target completely. The torque of manipulator changes and is lower than 3Nm (Fig. 17(c)), which indicates that the orientation errors between the side submirror module and the central submirror module change during the assembly process.

VI. CONCLUSION

Large-aperture space telescope on-orbit assembled by space robots is a research frontier of the international optical engineering field. In this paper we proposed a conceptual of 10-meter diameter modular space telescope, which could be assembled by a novel space robot system with large workspace and small volume. The workspace of robot is analyzed, and time-optimal trajectory planning based on genetic algorithm is utilized to optimize the movement of robot. The preliminary experiment of the submirror assembly with LWR iiwa7 is accomplished to verify the proposed method.

The novel assembly robot and control strategy for space telescope proposed in this paper has important application foreground for on-orbit construction and service of large space infrastructure. Based on the current preliminary results, we will continue to research the control strategy for space assembly, and improve the autonomous control through artificial intelligence.

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