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Cooperative control and experiment for multi-robot assembly of a solar power satellite

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Abstract

The extra-large scale of a solar power satellite (SPS) and the complexity of its various structure modules make on-orbit assembly highly challenging, making it difficult to efficiently complete the task relying solely on humans or a single robot. Hence, a collaborative approach involving different types of robots is essential. The on-orbit assembly of an SPS could be practically performed by using different space robots, such as crawling robots and flying robots. The crawling robots carry out long-distance assembly of SPS structure modules, and the flying robots could perform orbital transfer and module transport. However, the research on effective collaboration among multiple robots for the assembly tasks remains insufficient. To address this challenge, this paper investigates the cooperative control and experimentation for multi-robot assembly of an SPS. Trajectories for both flying and crawling robots are carefully planned to ensure effective collaboration during the assembly mission. The design objective is to enable robots to cooperatively assemble SPS structure modules. A ground experiment system is also developed to demonstrate the proposed assembly method. A crawling robot specifically designed for cooperative assembly is used in the ground experiment, and a multi-DOF mechanical arm is adopted to represent flying robot. The robustness of the proposed approach will be demonstrated through consistent and repeatable experiments. This work provides insights into the safe, efficient, and accurate assembly of SPS, with potential applications in space exploration and large-scale infrastructure development.

Keywords: Multi-robot, Cooperative control, On-orbit assembly, Assembly experiment.

Nomenclature

Θ = Robot Joint Angle Vector/rad
θ = Robot Joint Angle /rad
$\boldsymbol{p}_e$ = Position of Robot end effector
τ = Robot Joint Torque/N·m
δ = Error Limitation
e = Error Between Planning Data and Actual Data

Acronyms/Abbreviations

SPS: Solar Sower Satellite
PD: Proportional-Derivative Controller
SVD: Singular Value Decomposition
RANSAC: Random Sample Consensus

1. Introduction

Since Glaser proposed the concept of building Solar Power Satellites (SPS) in Science [1], there has been growing consensus among researchers that space solar power holds promise as a clean and sustainable energy solution. However, the structure of an SPS is vast and complex. However, the structural complexity and large scale of SPS make it impractical to manufacture and launch the entire system from Earth due to the limitations of rocket payload capacities. instead, modular design and on-orbit assembly have become essential. The on-orbit assembly of SPS is a challenging task because of the large-scale and long-duration involved. Relying solely on human astronauts for this task is impractical due to the risks and costs. Fortunately, advancements in space robotics offer a promising alternative.

On-orbit assembly technology has gradually evolved from manual operations to automation. Initially, astronauts performed manual assembly, such as during the construction of the International Space Station. However, this method is costly and risky. With the development of space robotics, robots have started to take over on-orbit assembly tasks, leading to greater modularization and automation in the process.

Several researchers have conducted studies on robotic assembly in space. For instance, Nicolas Lee[2] and colleagues from the California Institute of Technology's Jet Propulsion Laboratory (JPL) [3] explored the modular assembly of space telescopes, while Yang [4] focused on control strategies for dual-arm robot collaboration. Boning et al. from MIT [5, 6] experimented with dual-arm robots docking flexible modules, using linear optimization controllers to analyse system behaviours. Guang Yang [7]examined the effects of perturbations on dual-arm robots during the assembly of large space structures, providing theoretical insights into assembly dynamics. Xue [8] reviewed the development of on-orbit assembly technologies and highlighted the need for further improvements, particularly in module interfaces and robotic assembly techniques.

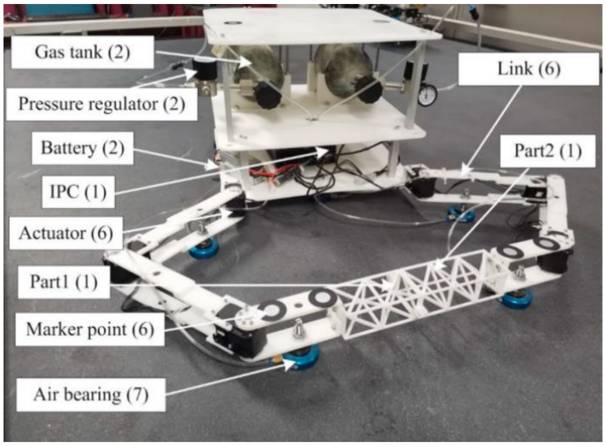


Fig. 1. Free-flying dual arm robot assembly experiment [4]

Despite these advancements, assembling ultra-large structures like SPS remains a complex task. It requires collaboration among multiple robots due to the scale, duration, and complexity of the operations. Recent advancements in swarm robotics [9] provide a theoretical basis for multi-robot collaboration. Cheng et al. [10] designed on-orbit assembly tasks for SPS using multiple space robots to handle complex tasks, aiming to complete the assembly. Katherine McBryan from the US Naval Research Laboratory (NRL) [11] compared the advantages of fixed and crawling robots in assembling space structures.

Given the strengths and limitations of different types of robots, this paper proposes a collaborative approach using both crawling and free-flying robots. Crawling robots are lightweight, propellant-free, and cost-effective, with the ability to expand their workspace as the structure grows. However, they must remain attached to the structure. In contrast, Free-flying robots are highly mobile and have a large range of movement. In the proposed approach, free-flying robots transport the modules to the crawling robots, which then perform the assembly and docking tasks. This system leverages the strengths of both types of robots. We present task planning and cooperative control methods for multi-robot assembly, and validate them through ground experiments.

2. Task Description

In the SPS system, numerous truss structures support the solar panels and microwave transmission antennas. Assembling these truss structures is a key step in the on-orbit assembly of SPS. Therefore, this paper focuses on using multiple robots to assemble modular space truss structures, which are widely applicable to the construction of SPS.

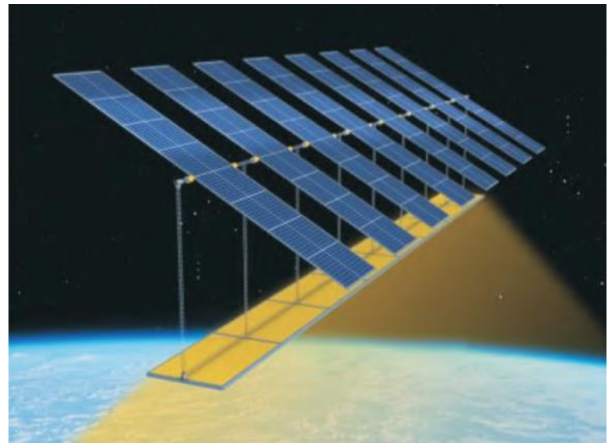


Fig. 2. Modular multi-rotary joints SPS concept[12]

The task described in this paper involves assembling a rectangular truss structure using multiple robots. Free-flying robots are responsible for transporting the pending truss module(hereinafter referred to as module), while three-arm crawling robots dock the segments with the existing structure(hereinafter referred to as structure). As shown in Figure 3, the space truss initially forms a U-shaped structure, and the robots must complete it into a rectangular shape by docking to both ends of the U-shaped segment simultaneously.

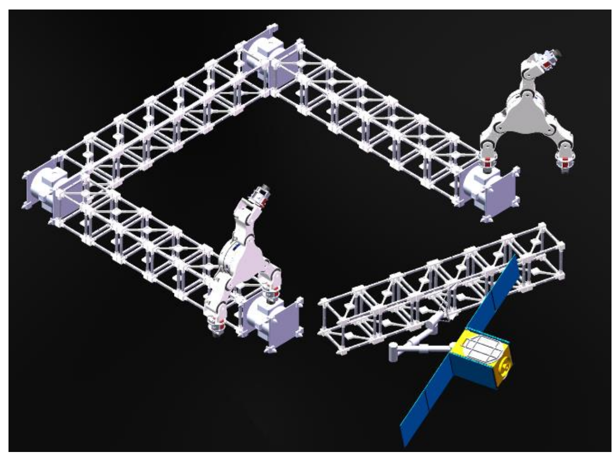


Fig. 3. Concept of multi-robot on-orbit assembly

In real-world scenarios, space truss structures are often folded during launch and then deployed in orbit. These structures can span tens or even hundreds of meters, which creates potential errors at both ends during the docking process. A single robot would not be able to achieve the necessary precision for such large structures, so collaboration among multiple robots is essential to ensure accurate and stable assembly.

3. Multi-Robot Collaborative Assembly Control

3.1 Collaborative trajectory planning

To control the collaborative docking of two crawling robots, this section analyses the forward and inverse kinematics of the robots and performs collaborative trajectory planning based on these analyses.

The task is divided into three distinct phases.

First is the Pre-assembly Phase, during which the crawling robots position themselves at the ends of the existing structure, preparing to receive the new module. Simultaneously, a free-floating robot transports the pending module near the docking area.

The second is the Transfer Phase: Once the free-floating robot arrives, it holds its position and orientation relative to the assembly site. The crawling robots then observe the pending module's position and orientation, and each robot grasps the module. Once both robots have successfully grasped it, the free-floating robot releases the pending module.

The third is the Docking Phase, the crawling robots collaboratively adjust the position and orientation of the module to align it with the existing structure. Finally, they manipulate the module to complete the assembly.

In the kinematic modelling of the crawling robots, one leg of the three-legged robot is ignored, focusing only on the two arms for the analysis.

Considering planar motion, the forward kinematics of the crawling robots can be expressed by the following equation:

$$\begin{pmatrix} \boldsymbol{p}_e \\ \theta_e \end{pmatrix} = \boldsymbol{J}(\boldsymbol{\Theta}, \mathbf{r_s}) \qquad \boldsymbol{\Theta} = [\theta_1, \theta_2 \ldots, \theta_j]^T, j = 6 \tag{3-1}$$

where θ_j represents a single joint angle, and $\boldsymbol{\Theta}$ represents the vector of all joint angles of a single robot. $\boldsymbol{p}_e = [\boldsymbol{x_e}\ \boldsymbol{y_e}]^{\boldsymbol{T}}$ is the position of end effector, and θ_e represent the attitude of end effector. $\boldsymbol{J}(\boldsymbol{\Theta}, \mathbf{r_s})$ is a mapping from the robot joint angle vector $\boldsymbol{\Theta}$ and the fixed position $\mathbf{r_s}$ of the crawling robot to the position and orientation of the robot end effector.

Through the inverse kinematics, the following equation is derived, which calculates the joint angles required to achieve a given position and orientation of the end effector. These equations allow the calculation of the joint angles needed for the docking task:

$$\boldsymbol{\Theta} = \boldsymbol{J}^{-1}(\boldsymbol{p_e}, \boldsymbol{\Theta_e}) \tag{3-2}$$

After successfully grasping the module, the movements of the two crawling robots must satisfy the following collaborative constraints to ensure proper alignment during docking. These constraints are defined in terms of the end effectors' positions and orientations:

$$\begin{cases} \theta_{e2} - \theta_{e1} - \pi = 0 \\ |\boldsymbol{p_{e1}} - \boldsymbol{p_{e2}}| - L_s = 0 \end{cases} \tag{3-3}$$

To meet these constraints, path planning can be performed in Cartesian space to generate the trajectories of the robots. By solving the inverse kinematics equations derived earlier, the corresponding joint angle trajectories for each robot can be determined.

When the robots are not grasping a module, the collaborative constraints do not apply. In this case, a fifth-order polynomial trajectory planning method is used, as it provides smoother velocity profiles.

It is important to note that while the Cartesian coordinate trajectory is defined by three parameters (two for position and one for orientation), the robots have four joint angles. To resolve this redundancy, the following constraint is introduced to fix the extra degree of freedom:

$$\theta_1 = -\theta_3 \tag{3-4}$$

Under this constraint, the joint angles can be obtained.

$$\theta_1 = -\theta_3 = \frac{\pi}{6} - acos\left\{\left(\left|\begin{pmatrix} x_e \\ y_e \end{pmatrix} - L_1\begin{pmatrix} cos\,\theta_e \\ sin\,\theta_e \end{pmatrix} - \begin{pmatrix} x_0 \\ y_0 + L_1 \end{pmatrix}\right| - L_3\right)/2L_2\right\} \tag{3-5}$$

$$\theta_2 = \frac{\pi}{2} - acos\left\{\left(\left|\begin{pmatrix} x_e \\ y_e \end{pmatrix} - L_1\begin{pmatrix} cos\,\theta_e \\ sin\,\theta_e \end{pmatrix} - \begin{pmatrix} x_0 \\ y_0 + L_1 \end{pmatrix}\right| - L_3\right)/2L_2\right\} - atan\left(\frac{y_e - L_1 sin\,\theta_e - y_0 - L_1}{x_e - L_1 cos\,\theta_e - x_0}\right) \tag{3-6}$$

By applying the above equations, the trajectory planning for the robots can be completed, ensuring smooth and precise assembly operations.

3.2 *Cooperative controller*

In the previous section, we developed collaborative trajectory plans for the robots. This section focuses on the design of the controllers used to track these trajectories. During task execution, the robots must exchange information in real-time to form a closed-loop control system, which helps minimize operational errors. The control architecture is illustrated in Fig. 4.

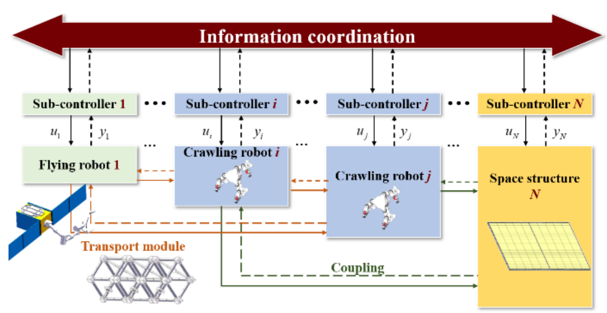


Fig. 4. Information Exchange control architecture

In the Fig.4, solid lines represent physical signals, such as current from controllers, physical contact, and force interactions between the robots and the structure. Dashed lines represent information flows, including wireless communication of sensor data, such as joint angles of the crawling robots, the position and orientation of the free-flying robot, and assembly status information like vibration data.

The control objective is to enable the robots to collaboratively complete the docking and assembly tasks. To achieve this, the crawling robots must track the planned trajectories discussed in the previous section. Since trajectory tracking is not perfectly error-free, and there is a risk of large deviations on either side, the two robots must react to each other's actions and implement fault-tolerant control. The primary control objectives can be expressed as follows:

$$|\boldsymbol{\Theta}_i - \boldsymbol{\Theta}_i^{tr}| < \delta_\theta \tag{3-7}$$

where $\boldsymbol{\Theta}_i$ is the joint angle vector of robot i, and $\boldsymbol{\Theta}_i^{tr}$ is the planned trajectory of robot i. Equation (3-7) ensures that the joint angles of the robots follow the planned trajectory.

Once the module is grasped, an additional collaborative control objective is introduced:

$$(\theta_{e2} - \theta_{e1} - \pi)\,|\boldsymbol{p}_{e1} - \boldsymbol{p}_{e2}| < \delta \tag{3-8}$$

This product represents the arc length deviation caused by the angular and positional errors of the end effectors. The crawling robots must adjust their movements to minimize deviations, preventing internal stress in the module that could result in structural damage. Based on the control objectives, we design the following collaborative PD controller:

$$\tau_i = K_p e_{\theta j} + K_d \dot{e}_{\theta j} + K_{pc} e_{\theta cj} + K_{dc} \dot{e}_{\theta cj} \tag{3-9}$$

where K_p , K_d , K_{pc} , K_{dc} are the proportional coefficients. $e_{\theta i}$ and $e_{\theta ci}$ are the errors between the actual joint angles and the planned joint angles. θ_i^{tr} is the planned trajectory joint angle, derived from the planning in the previous section. θ_j^c is the collaborative trajectory joint angle, calculated in real-time based on the task execution status of the two robots.

$$\begin{aligned} e_{\theta j} &= \theta_j - \theta_j^{tr} \\ e_{\theta cj} &= \theta_j - \theta_j^{c} \end{aligned} \tag{3-10}$$

θ_j^c is obtained using the inverse kinematics equation:

$$\boldsymbol{\Theta}_{\mathbf{ci}} = \boldsymbol{J}^{-1}(\boldsymbol{p}_{eci}, \boldsymbol{\Theta}_{eci}) \tag{3-11}$$

$\boldsymbol{p}_{eci}, \boldsymbol{\Theta}_{eci}$ are obtained based on the actual end position and coordination constraints of the other robot.

Equation (3-7) ensures that the crawling robots accurately track the assembly trajectory, while Equation (3-8) prevents the module from experiencing excessive internal stress. The collaborative control objective (3-8) is prioritized over individual tracking (3-7), and thus, the gains K_p and K_d numerically larger than K_{pc} and K_{dc}.

3.3 Simulation Result

A simulation was conducted to validate the performance of the designed controller. In the simulation, two crawling robots collaborated together to dock and assemble the module, following the designed trajectory. The simulation results, shown in Fig.5, demonstrate that the controller successfully guided both robots to track their joint angle trajectories. The data points in the figure correspond to the planned trajectory, and the robots were able to closely follow the planned path, meeting the control objective (3-7).

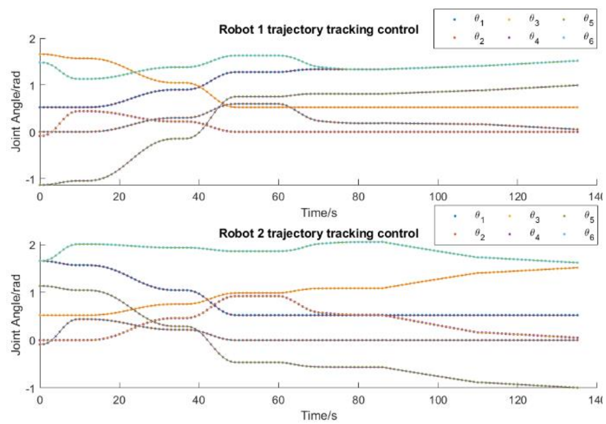


Fig. 5. PD controller trajectory tracking

For the collaborative control objective (3-8), we introduced a fault scenario. Between 5-10 seconds after grasping, motor 2 of Robot 1 stopped responding to control signals due to communication interference, with its torque output $\tau_2 = 0$. This caused motor 2 to deviate from its planned trajectory, resulting in positional and angular errors in the module.

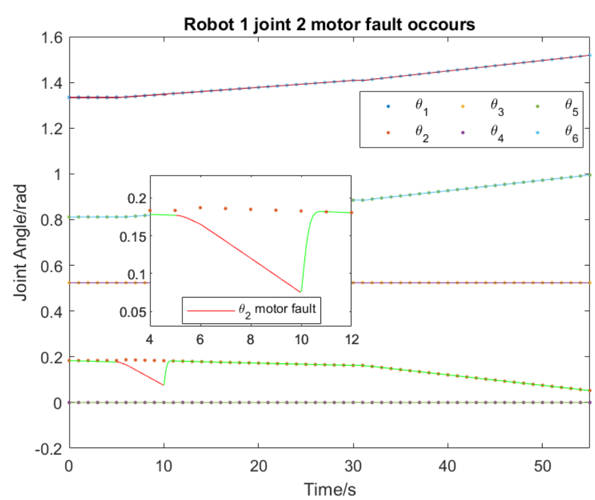


Fig. 6. Motor fault in Robot 1

However, under the collaborative control system, Robot 2 adjusted its joint angles to compensate for Robot 1's deviation, maintaining coordination between the two robots. Fig.6 and 7 show the results of angle coordination during the fault.

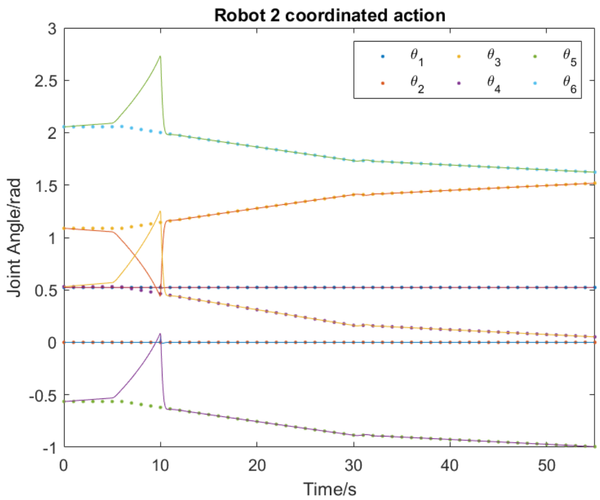


Fig. 7. Coordinate action of Robot2

Comparing the cooperative controller to a non-cooperative PD controller (as shown in Fig.8), the error deviation was significantly larger without coordination, while with the cooperative controller, the deviation remained within acceptable error limits. These results indicate that the cooperative controller effectively handles robot failures and maintains task precision.

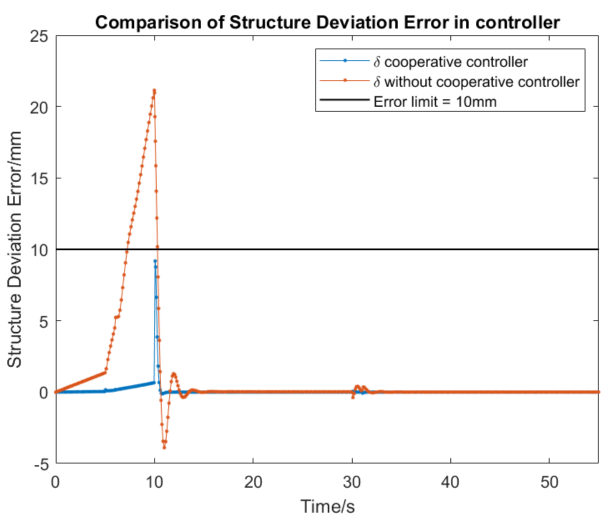


Fig. 8. Deviation error in different controller

4. Multi-Robot Assembly Experiment

This experiment demonstrates the collaborative assembly of modules using multiple robots. The experimental setup consists of the following components:

1. Fixed-base robotic arm: imitates a free-floating robot to simulate the transport of assembly modules.
2. Two own design crawling robots: This is used to perform the final collaborative assembly and docking tasks.
3. A camera measurement system: This simulates the feedback control during the assembly process, similar to what would be done by a free-floating robot.

The crawling robots are designed with three legs, each with three rotational degrees of freedom: two planar and one spatial. This design allows the robots to perform precise assembly tasks in a planar environment. The experimental robot's central body contains the power and control systems, while its three legs are arranged symmetrically, giving it high stability and operational flexibility. The robot can handle a variety of assembly tasks and is well-suited for collaborative operations with other robots.

For gravity compensation, the system employs balancing wheels, which provide the robots with three degrees of freedom for planar translation and rotation. The balancing wheels slide on a platform, providing support force to counteract gravity.

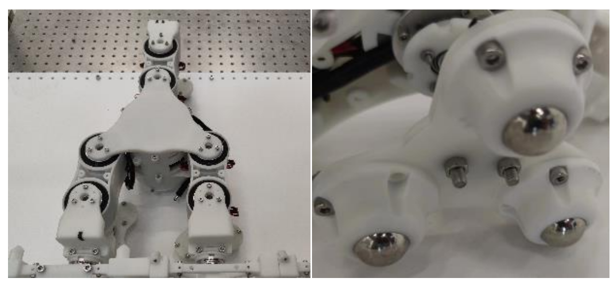


Fig. 9. Crawling robot and balancing wheel

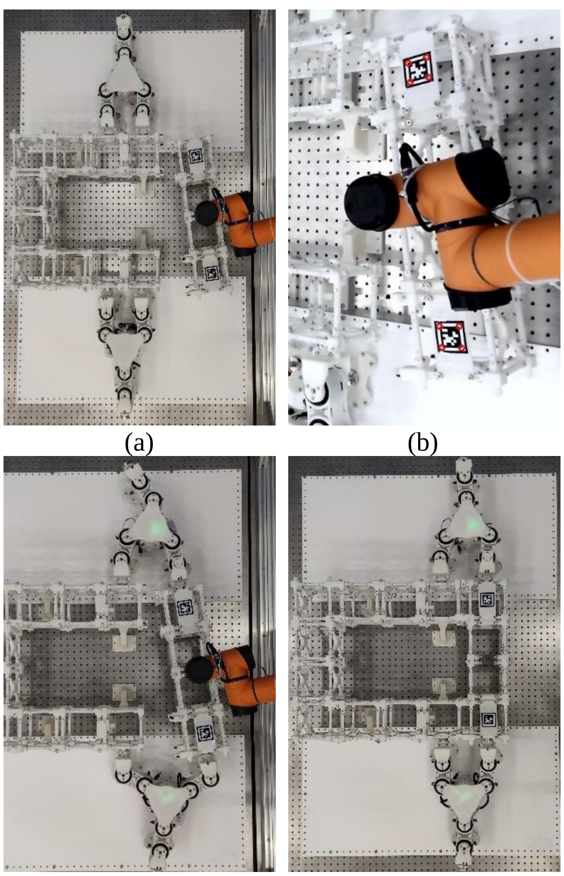
The camera system uses a distortion-free lens industrial camera paired with AprilTag visual markers for precise 3D position detection.

Fig. 10. Camera and AprilTag

In this experiment, we use the AprilTag system as a visual reference for tracking the assembly module's position. The AprilTags are placed on the module, and the camera detects the tags to calculate the accurate 3D position of tags. The system offers adaptability under various lighting conditions and resolution changes, making it highly suitable for this task.

During the experiment, two AprilTags are symmetrically arranged at both ends of the module(as shown in Fig.11 (b)). The camera identifies AprilTags and calculates the center point of the module by averaging the positions of the two tags. The orientation of the module in the world coordinate system is obtained by connecting the positions of the two tags and calculating the rotation angle. To ensure accurate detection, camera calibration is essential. We employ the Zhang Zhengyou calibration method [13].

In addition to internal calibration, the transformation matrix between the camera's coordinate system and the world coordinate system also need to determined. This is achieved by positioning multiple AprilTags with known world coordinates. The camera captures these tags, then solve the transformation matrix between tag using SVD and RANSAC fusion methods.



(a) (b) (c) (d)

Fig. 11. Sequence of experiment

Fig.11 illustrates the sequence of events during the experiment:

1. Fig 11.a: The manipulator arm transports the pending module to the specified position.

2. Fig 11.b: The camera detects the module, and the position of module will be input to the host controller and generates control commands for the crawling robots

3. Fig 11.c: Robots grasp the pending module, completing the transfer of the assembly module.

4. Fig 11.d: The robots adjust the module's position and orientation collaboratively to complete the docking and assembly.

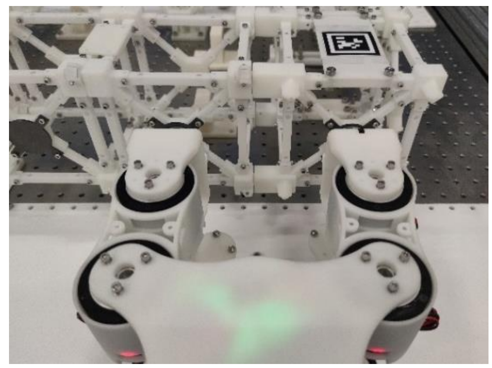


Fig. 12. Docking of structure

The experiment successfully demonstrated the ability of the three robots to collaborate and perform the assembly. Fig.12 shows the docking point of the module and the pre-assembled structure. The experiment verified the effectiveness of the collaborative assembly strategy.

5. Conclusion

This project proposed a multi-robot collaborative assembly strategy for a space solar power satellite (SPS). The task was divided between different types of robots: a free-floating robot for transporting modules and crawling robots for docking and assembling the truss ends. The free-floating robot was leveraged for its wide range of mobility, while the crawling robots were chosen for their strong operational capability and long mission durations, requiring no propellant.

We performed task analysis, designed collaborative robot strategies, and developed an experimental platform to demonstrate the feasibility of the proposed assembly scheme. The custom-designed crawling robots successfully completed the collaborative assembly task, validating the overall approach.

However, there are still some limitations in our research, our future work will focus on:

1. Control System Improvements: The current control design is relatively simple and lacks the flexibility needed for compliant coordination during docking. Currently, the robots rely on position control, and more

advanced force control mechanisms are needed to prevent internal stress from positional errors.

2. Increase Task Complexity and Scalability: The current setup only involves one free-floating robot and two crawling robots for a relatively simple assembly task. As the number of robots and modules increases, the complexity of task planning, dynamics, and control will grow exponentially. Future work will focus on large-scale assembly tasks with more robots, addressing the challenges of coordination and control in such scenarios.

Acknowledgements

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