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Autonomous Cooperative Robots for Space Structure Assembly and Maintenance

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Abstract

This paper describes the autonomous cooperative robots that assemble and maintain large-scaled flexible structures such as space solar power system. The technological challenge and its demonstration scenario toward autonomous assembly are discussed. The ground testbed developed for confirming feasibility is described.

1. Introduction

Currently International Space Station (ISS) has been constructed on-orbit since 1998 and it is a great example that large-scaled structures (LSS) are gradually assembled piece-by-piece. On-orbit assembly will become one of key technologies to future missions such as space solar power system (SSPS) and large space telescope.

Because ISS construction is based on combination of extra-vehicular activity (EVA) and teleoperated robotic arms, quite complex assembly operation has been achieved by using the skills and experiences of the trained astronauts. In the case of SSPS[1] (Figure 1), its assembly with minimum duration and its handling of the flexible structures will be one of key issues from the economical points of view. Therefore it becomes essential to utilize autonomous multiple robot system to rapidly and gently assemble the large flexible SSPS on orbit with the minimum resources of human operation.

This paper describes the autonomous or semi-autonomous multiple robots that assemble and maintain large-scaled structure and its components. The technological challenges to enable autonomous assembly and the scenario toward demonstrating technologies on orbit are discussed in the next section. The ground testbed developed for confirming feasibility is described in the third section.

2. Technologies and Demonstration Scenario

2.1 Technological challenges

Because of launch vehicle capability limitation, restricted mass and appropriate stowed structures are only transferred into orbit. Therefore, it is likely to execute assembly operation to construct LSS on on-orbit. For the case of SSPS system that requires several kilometers by kilometers in size, on-orbit assembly is inevitable and simultaneous operation using multiple robots becomes quite feasible and may even be essential, because repeated tasks are expected. The SSPS autonomously assembly seeks for operational simplicity and efficiency, and reduced human risks.

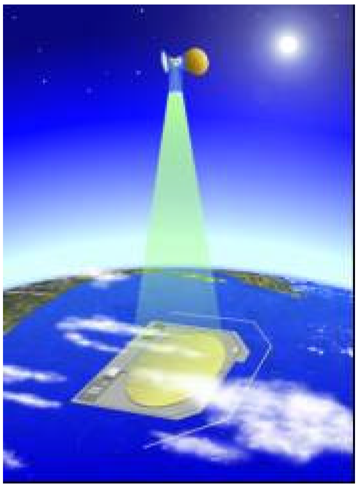

Figure 1 Concept of Space Solar Power System

There are a large number of technological challenges needed to solve in order to assemble and maintain the large scaled structure such as SSPS. The Assembly and maintenance tasks include (1) transportation and handle of inertial components, (2) assist and check-out of deployable or inflatable structures, (3) locomotion and suppression of flexible structure, (4) repair and exchange of large structures and components, (5) inspection and diagnostics of structure. These tasks are preferable to be performed autonomously with minimum operational resources.

Several challenging technologies are identified from these tasks.

- Handling of a variety of structures
- Transportation on flexible or inflatable structures
- Capture and connection of deployable structures
- Autonomous detection of structure malfunctions
- Limited time required for the tasks

There are a variety of structures needed to handle on orbit. The structures may possess high density to low, and small in size to very large after deployment. The robot system should be capable of handling such characteristics. For high-density components, the robot system performs transportation for a long range and installation into the predetermined location on the structures. For reliability and efficiency of transportation on flexible or inflatable platforms, the cooperative robot system may be employed. The autonomous operation may be realistic as the goal and execution plan of the tasks are predetermined in advance.

For low-density components, the robot system assist automated process of deployment and inflation, and eventually capture and join flexible structures each other. The assisting robot may consist of multiple robot system to monitor from the multi-view points, diagnosis, detect malfunctions, and restore. For assembly of the flexible structure, cooperative robot system may be essential to measure the wide area of the structure, estimate the large motion, capture the handle of structure, and connect the structure each other on flexible platform.

In order to acquire such technologies necessary to autonomously assembly the space structure, on-orbit technological demonstrations becomes logical step. Three different kinds of steps are considered to develop SSPS.

2.2 Component level on orbit demonstration

The first step is component level demonstration for autonomous assembly. Figure 2 is concept of component level demonstration. In this first step, the following technologies will be demonstrated by using ISS Kibo (Japanese Experimental Module) exposed facility.

- transportation and assembly skill on flexible structure
- deployable and/or inflatable structure and its assist and check-out
- mechanical and electronic joint with robot friendly mechanism
- coordinated control for multiple robots
- teleoperation to semi-autonomous or full-autonomous operation
- transmit energy after antenna assembly
- phase adjustment experiment of micro wave

The Kibo exposed facility is unique on-orbit testbed that provides the stable power, heat and signal resources and the assistance from the manipulators and the astronauts.

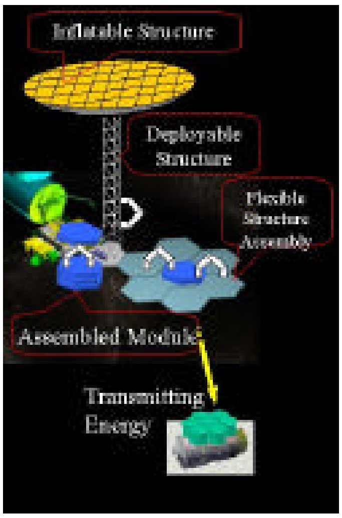

Figure 2 Component Level Demonstration

In order for robot to assemble and transport the structure, power supply and signal line between robots and astronaut must be secured. We have proposed the information structures[2] (Figure 3) that contain the power and signal lines embedded in the structure and that possess not only mechanical but also electronically joint mechanism driven by robot arm. Therefore, during assembling experiments, power and signal for the robot operation will be supplied from Kibo facility through the information structure.

The transmitting energy requires the power resource, while the phase adjustment experiments requires signal line to synchronize. Because the information structures are employed as assembled antenna modules, transmitted power can be supplied from the Kibo exposed facility through the information structure. The synchronized signals may be communicated through electric wires in the structure.

At the beginning of operation, the crew resources are needed to teleoperate robot assembly process. In general, mating process is one of difficult and takes time to complete. The efficient assembly operation to minimize operation and its time will be tested by crew support.

The deployment and the inflation will be demonstrated on the exposed facility. The robot support may be used to monitor the deployment and inflation process, and to check-out visually or physically.

In this concept the power transmitted from antenna may be possibly received by H-II transfer vehicle (HTV).

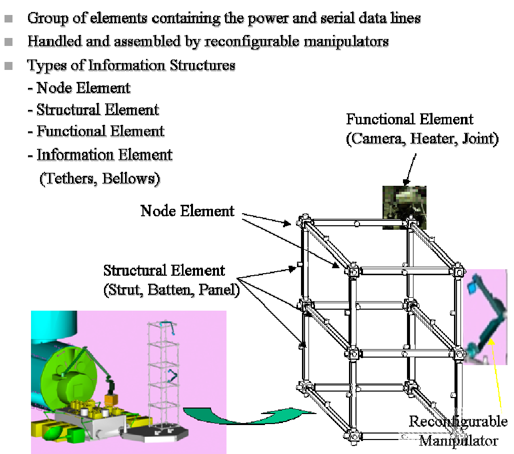

Figure 3 the Information Structures

2.3 Subsystem level on orbit demonstration

The second step is sub-system level demonstration necessary for the autonomous assembly of SSPS. Figure 4 is concept of subsystem level demonstration. In this step, the following technologies will be demonstrated by using co-orbit platform to ISS.

- assembly and maintenance of generating solar power panel and transmitting antenna
- assembly and maintenance of solar reflecting mirror
- micro wave energy transmission through the mirror and generator
- multiple robot cooperation between robots and operational semi-autonomous operation

Because the platform is co-orbiting with ISS, assembly operation can be continuously monitored from ISS operation site and the assembled structure and components are transfer from ISS.

2.4 System level on orbit demonstration

The third step is system level demonstration. In this step, based on the previous two on-orbit demonstration, one tenth scaled model is constructed, and transmitting power to the ground is demonstrated. The following technologies are verified at this level.

- Autonomous assembly of deployable structures by multiple robot system
- Orbital control of large-scaled structure, health

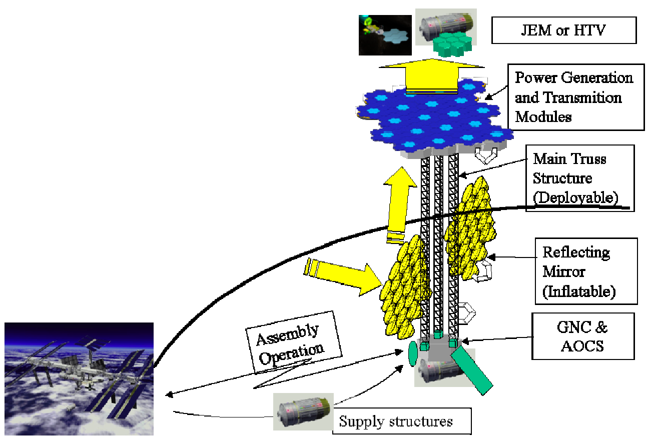

Figure 4 Subsystem Level Demonstration

monitoring, and exchange of the components or modules

- Energy transmission to the ground

3. Cooperative Robots Ground Testbed

Multiple robots ground testbed has been developed to verify feasibility of assembly and maintenance by autonomous multiple robot system. Several demonstration tasks are setup and performed by ground based robot system. This particular testbed is utilized to demonstrate capability of two or more multiple cooperative robots work together in the same task. In this section, robot system and its handling structures are discussed.

3.1 Flexible structure assembling experiments

Based on the scenario to construct the large space structure, it is required to assemble the flexible structure. The robot on the vibrated structure representing the flexibility is assumed to be trying to capture the flexible structure (Figure 5). To capture the structure, the robot requires estimation and prediction of the motion of the flexible structure. However in the most of cases, a robot is not large enough to follow the motion of the large flexible structure. Therefore another global sensing robot is needed. This sensing robot mounted also on the vibrated environment measures relative position and orientation of the flexible beam with respect to the capturing robot. Because two on-orbit robots are virtually connected by using the information structure, two ground robots can also be communicated through the network.

The flexible structure represents the deployable structure after deployment where one of flexible end is fixed as the base while the other end is free. The flexible structure hinged at the base is sideways long and can passively rotate around except torsional direction. The size of flexible structure is 4 [m] long with 0.15 [Hz], which corresponds to 1/10 scale model of the actual system.

The goal is to capture, handle and assemble the vibrated structure. The robot requires gentle handling while structure moves relatively large space and may oscillate very easily. Multi robots are needed to guide capture event to sense relative position of the structure and the robot. The robot cooperation technology will be demonstrated in this testbed.

3.2 Locomotion experiments on flexible structure

The locomotion is one of the key technologies for assembling large-scale structure. It is unlikely that robots are large enough to handle large structure. Rather, robot has to move around to transport or pick-up-and-place components. Walking on the flexible structure is challenging tasks needed to achieve. In this testbed, walking type robots have been developed and robots are been tested under the flexible structure. The walking efficiency is one of the indexes to evaluate the robot system.

The walking robot employees the concept of

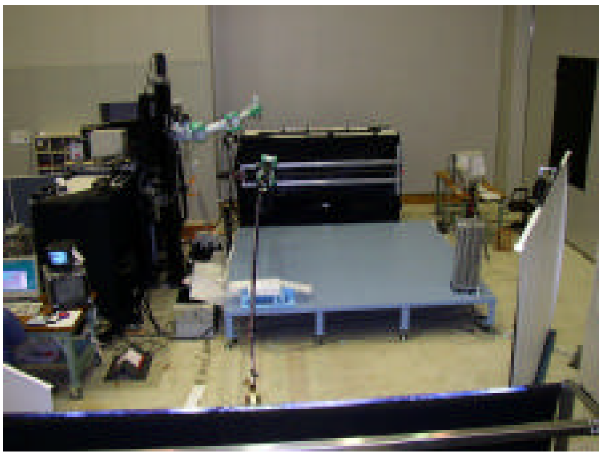

Figure 5 Flexible Structure Assembly Testbed

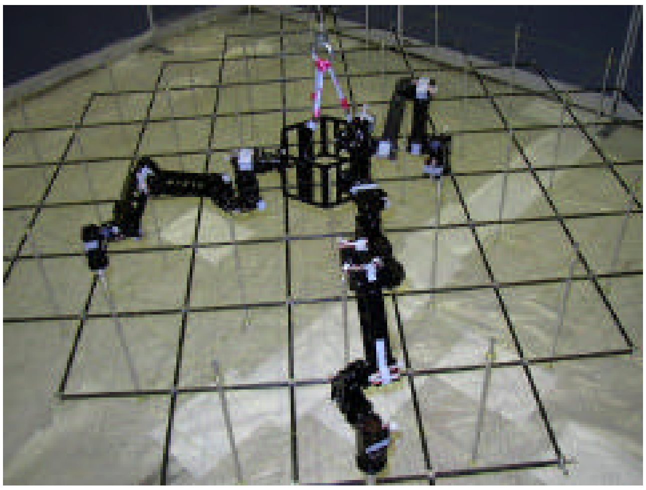

Figure 6 Autonomous Locomotion Testbed

reconfigurable brachiating robot system[3] where three or more seven-degrees-of-freedom manipulators are connected each other and used as legs of locomotion. The walking robot is designed to step 400[mm] pitch access points which corresponding to 1/25 scale model for actual systems (Figure 6).

3.3 Inflatable structure assembling experiment

The inflatable structure is one of the promising candidates as large supporting structure. The inflation itself may be performed without robotic assistance, however, handling and connecting inflatable structures to the other structure requires robotic operation in order to construct large structure.

Handling the inflatable structures contain unique challenging task from the view of robotics. As the inflatable structure is very thin shell type structure, its hard grip may cause severe damage to the structure. The soft grasping technique is required for robots not only to handle them but also to walking on them. In order to reduce concentrated stress and large forces, multi contact points may only be adequate by multi robot system.

The ground test model of inflatable structures, shown in Figure 7 are based on carbon fiber reinforced plastics (CFRP) with inner coating for inflation by gas. The heat plasticity materials are used for stiffening structure. The inflatable tube (75 [mm] diameter) creates circumference of 2 [m] square shape that stretches thin inside films. The mass ratio to area is 1.0 [kg / m^2], which corresponds to 1/10 to 1/100 of actual system mass ratio. The experiment will be conducted using the multiple robots accessing on the several grasping points to carry such structure without large stress inside the structure.

3.4 Experiments with other types of structures

The self-deployment structure will be certainly employed to compose large space structure. Assisting deployable structure by robotic operation may not be needed, however, monitoring requirement during deployment of structure may be well-performed by robot and fixing the stacked deployable structure may be feasible candidate for robot operation.

The ground testbed prepares for deployable experiments where robot can monitor deployment process and assist the deployment if necessary. Figure 8 shows photos of deployable structure experiment.

Carrying and handling the condensed component may another task for robot needed to perform. The 50 [cm] by 50[cm] by 2[m] sized box, whose density is the same as one of launched mass, is handled and inserted into receptor by multi robot system. To compensate boxed component’s gravity on the ground, low friction balancer hangs the center of the mass on the component. The balancer is capable of covering 2[m] by 2[m] by 2[m] translation direction and 10[deg] rotational direction by ball joint. Figure 9 shows photos of condensed component of ground model.

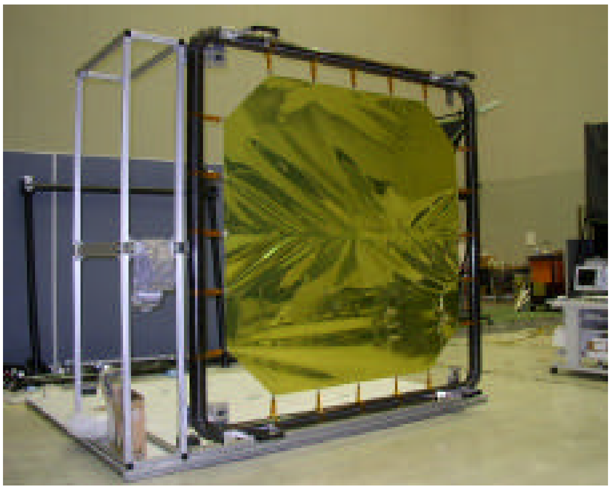

Figure 7 Inflatable Structure Assembly Testbed

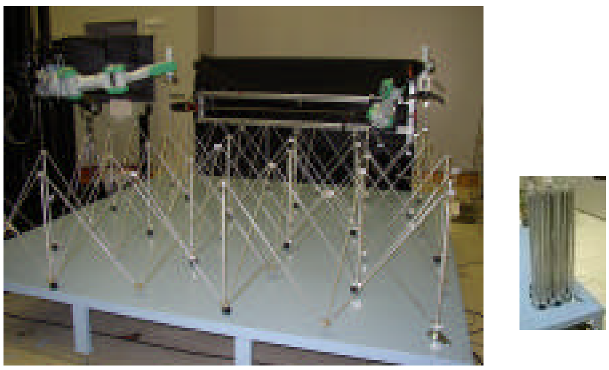

Figure 8 Deployable Structure Assist Testbed
(Left : Deployed,　Right : Stowed)

3.5 Structure Diagnosis Experiments

The structure has own diagnostic function embedded inside the structure. It finds its emergency on losing the structure connection. The structures request robots to inspect possible location and robots will visit candidates of inspection points without intervene by human operators. Figure 10 shows demonstration of self-detection of losing connection and autonomous inspection by robot.

4. Conclusions

On-orbit robot system is necessary to construct large space structure such as SSPS (Space Solar Power Satellite). The robot system requires dealing with several different kinds of characteristics in structural viewpoints. The flexibility in the structure is one of important characteristics to be realized.

In this paper, the list of potential problems needed to tackle is identified in order to assemble and maintain large space structure. The on-orbit demonstration scenario proposed consists of three steps. The ground testbed is developed to verify and simulate on-orbit environment.

According to the preliminary experimental results, it is notified that such autonomous multiple robot system has great advantages for system robustness and efficiency of operation.

Reference

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Figure 9 Condensed Component Insertion

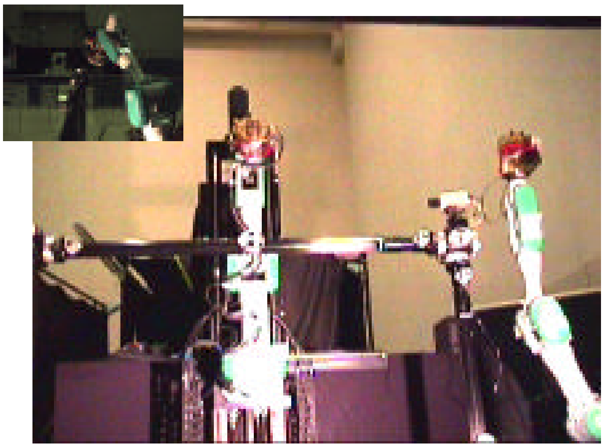

Figure 10 Autonomous Structure Diagnoses