Robotics Experimental Study for SSPS Walking and Assembly Technology

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Abstract
JAXA has been studying Space Solar Power System (SSPS) concepts for several years and believes that autonomous robots will play an important role in their development. In the study, there are two types of robotics tasks required for SSPS on-orbit construction: a locomotion task and an assembly task. The locomotion task is defined as moving around on light-weight structures, while the assembly task is defined as capturing and connecting vibrating structures for assembly after self-deployment. These tasks are vital to the SSPS operation. This paper presents a strategy and experiments for the locomotion and assembly tasks using the ground testbed for SSPS on-orbit assembly developed at JAXA.

1. Introduction
On-orbit assembly of the International Space Station (ISS) has been underway since 1998 and is to be completed by 2010. More than forty assembly operations will be performed before the completion of the ISS. ISS on-orbit assembly is based on a combination of a robotic arm teleoperated from inside the ISS and extra-vehicular-activity (EVA) astronauts.

The Space Solar Power System (SSPS) is based on the concept of an on-orbit energy station transmitting energy to the Earth. JAXA has been studying design concepts for SSPS for several years, as shown in Fig 1. It is larger than the ISS by a factor of 10 or more in both size and weight. As with ISS assembly, on-orbit assembly is required for SSPS construction. In contrast to the ISS case, assembly with minimum time duration and handling of the flexible structures will be key issues from an economics point of view. Autonomous robots, or a team of robots, will play an important role in the development of SSPS by rapidly and gently assembling the large, flexible SSPS on orbit with minimum requirement for human intervention.

In the study, two types of robotics tasks required for SSPS on-orbit construction are identified: a locomotion task and an assembly task. The locomotion task is defined as moving around on light-weight structures, while the assembly task is defined as capturing and connecting vibrating structures for assembly after self-deployment. These tasks are vital to the SSPS operation. This paper describes a strategy and experiment results for the locomotion and assembly tasks using the ground testbed for SSPS on-orbit assembly developed at JAXA. In the next section, the strategy to permit moving around on highly light-weight structures is discussed. Walking experiments are performed by employing a four-legged robot. In the third section, a strategy for assembling a vibrating structure is discussed. The experiments confirm strategy and feasibility by estimating and tracking the structural vibration.

Fig. 1 Concept for Space Solar Power System
2. Locomotion Strategy and Demonstration

Mobility is essential for constructing and maintaining a large-scale system, which involve transporting and inspecting components widely spread over the structure at routine intervals or on demand. Walking on the structure was tentatively selected as the primary mobility on SSPS for this study because it has no significant impact on the design of the structure when compared to the rail on the structure used at ISS.

The strategy for moving around on highly light-weight structures is to employ a four-legged robot capable of walking gently and precisely, yet reasonably rapidly, on the fragile structures.

The following technical challenges were identified to be solved.

1. Path planning to generate walking steps
   By specifying the goal and providing constraints on the system, a nominal sequence of steps leading to the goal position is generated. Alternative sequences are also calculated to secure the path to the goal.

2. Tip adaptation to follow vibrating structure
   To adjust the position of a free leg due to structure vibration and/or the misalignment of the attaching feet, the free leg tip needs to be precisely tracked and controlled using onboard sensors such as vision and/or accelerometers. In our experiments, a camera mounted on the tip of each leg is used to measure the relative distance between the structure and robot.

3. Technique for moving on fragile structures
   The walking pattern at each step is designed specifically to prevent excitation and damage to the structure. The resulting algorithm may be applied to the technique for lowering force and torque on the structure. The reaction torque at the end of each leg attached to the structure is kept to almost zero so as not to damage the structure, using the redundancy in the degrees of freedom of the walking robot.

4. Reasonably speedy locomotion
   To be economically feasible, the walking speed has to be reasonably fast. Within actuator limitations, dynamics parameters such as inertia could be reduced for a fast stepping motion.

5. Careful motion planning and control for collisions and floating object avoidance
   Collisions and floating objects have a significant affect on system performance. Careful motion planning and control are highly recommended to avoid collisions within the robot itself or with the environment. By always keeping its remaining three legs attached to the structure during the stepping motion, the four-legged robot may eliminate the floating condition.

6. Autonomous walking under resource limitations
   Autonomous walking is preferable due to the reduction in communications resources required for real-time operation and the concomitant minimization of ground monitoring telemetry. The robot support system on orbit takes over the significant functionality of the autonomous system.

7. Long-duration power supply and efficient walking
   The power supply module will be mounted on the walking robot to maintain independence from the system resources. A long-duration power supply is needed and efficient walking is required.

In order to solve the technical challenges listed above, a ground experiment platform has been set up. It consists of a four-legged robot, its support system, and a light-weight structure, as shown in Fig. 2. The four legs are identical, and each is connected to the body. Each leg consists of seven joints and an effector, with a camera at the tip to allow it to attach to the structure. Each joint is composed of a DC servo motor with a harmonic drive and a joint controller, which connects the joints via a serial bus network. In the

![Fig. 2 Ground platform for walking experiment](image)
body of the robot, PC-board computers were implemented to receive commands from the support system and to send commands to each joint via a wireless LAN. A nickel metal-hydride battery that runs for about an hour was also installed in the robot body.

A gravity compensation system provides zero gravity to the walking robot by supporting its weight around the center of mass. The supported point is permitted to move smoothly in a vertical direction by hanging the total weight of the robot using an air cylinder, while the supported point is permitted to move horizontally by a passive rotational mechanism. The gravity of each leg is compensated for via software by providing additional torque to each joint.

As a preliminary confirmation, autonomous locomotion was tried. A path planning algorithm generated a sequence of walking steps, and a stepping motion was then executed, following the generated trajectory. At the end of the stepping motion, the trajectory was adjusted based on vision information. Figures 3 and 4 show examples of measurement results from the camera mounted at the leg tip, along with the trajectory as adjusted by vision.

The locomotion task was successfully demonstrated. Fig. 5 presents the sequence of steps during autonomous walking.

3. Flexible Structure Assembly - Strategy and Demonstration

The strategy for assembling a vibrating structure is to employ multiple robots to estimate, capture, and connect large-scale vibrating structures. To estimate the vibrating motion, a Kalman-filter-based algorithm developed at MIT and JAXA was implemented in the

Fig. 3 Image processing measurement made during insertion (left, before; right, after)

Fig. 4 Insertion adjustments by vision

Fig. 5 Autonomous sequence of walking steps
laser sensor mounted on the robot at the JAXA air table testbed, as shown in Fig. 6. Vibration estimating experiments were successfully performed to verify accurate estimation, as shown in Fig. 7.

To track and capture the vibrating structure, the robot measures the global vibrating motion while a second robot tracks and captures the structure by communicating with the global sensing robot. This cooperative robot system may be necessary in order to search the area of structural vibration, predict the significant motions, capture the structure, and connect the structures together on the flexible platform.

Experiments to confirm the feasibility of using cooperating multiple robots have been successfully conducted, demonstrating the tracking of flexible structures. The testbed for the tracking and capture of the flexible structure is illustrated in Fig. 8.

4. Conclusions

In this paper, we select two types of tasks required for SSPS on-orbit assembly. The locomotion task has technical challenges involving the transport of its components to the construction site. The assembly task may require multiple robots for sensing and efficiency. Walking robot and flexible structure tracking experiments have been successfully conducted.

Reference


