A New Space Robot End-effector for On-orbit Reflector Assembly

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ABSTRACT

In Earth orbit, astronomical observations are possible free from absorption or disturbances by the Earth's atmosphere. Therefore, some large space telescopes and large space radio telescopes are planned for the future. Launch vehicle payload bay diameters impose severe restrictions on the sizes of these telescopes, and so , structures larger than the payload bay have to be deployed or assembled in orbit. Structures assembled in orbit may have a finer surface accuracy and can be made more rigid than deployable structures. When assembling such large structures, space robots have to move around on the structure. It is necessary to supply power and electronic signals to a robot arm from the structure under construction. Therefore, the power supply line and the communication network have to be incorporated in the structural elements, and the composition which has the connector attaching mechanism of a line was studied. We discuss the design of a telescope reflector which can be assembled in orbit, with its networks and connecting mechanisms suitable for robot tasks. The characteristics of the new end-effector mechanisms and their suitability for onboard assembly tasks were confirmed by test using a two dimensional ground test arm. The test results are also described in this paper.

1 - INTRODUCTION

In Earth orbit, there is little atmospheric absorption in the millimeter wave band. So, there is satellite-based telescopes are well suited for the radio-wave astronomical observations in this frequency band. HALCA is the world first VLBI satellite launched in 1997. It is a radio telescope satellite which has an 8m diameter mesh deployable reflector, and carried out many observations in the 1.6GHz and the 5GHz frequency band[1][2]. In order to observe finer structure of objects, observations in higher frequency bands are expected and a reflector with a large aperture and high surface accuracy is needed. space-VLBI needs space radio telescopes, and milimeter Space-VLBI and furthermore, sub-milimeter space-VLBI have a big frontier. However, payloads launched to an orbit are restricted by the diameter of the rocket fairing, which is about 4m diameter at the maximum. Structures larger than this must be either deployed or assembled in orbit. As the size of a complex deployable structure increases, its surface accuracy generally decreases, since, for instance, a huge number of hinges may be required. For this reason, the authors are studying a rigid reflector structure which can be assembled using space robots[3][4]. Since a robot arm will be in the closed link state where both ends are fixed during the assembling task, position error correction by compliant motion is required. On-orbit assembly is analyzed, and this paper describes a suitable design for a space robot arm end-effector and an assembly type reflector (Fig.1) intended to carry out this task. Moreover, we are actually prototyping a space robot end-effector with built-in electric connectors, and joint compliance control system. And ground testing has verified that the end-effector mechanism and robot arm control characteristics which are suitable for assembly operations.

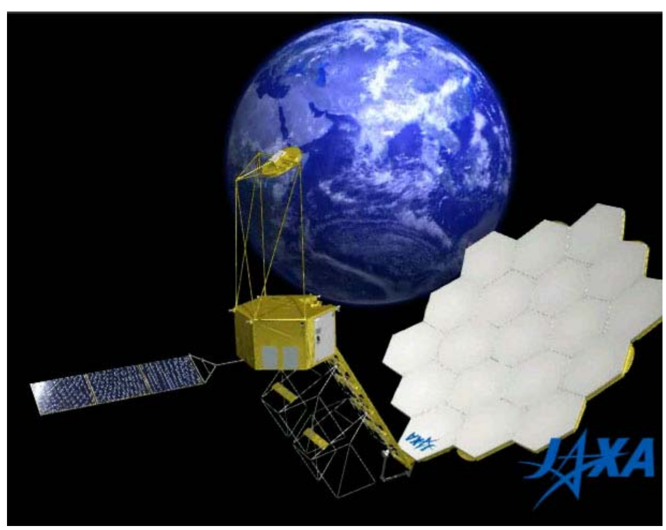

Fig.1 Artist's conception of a space radio telescope assembled on-orbit

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2 - TARGET WORK OF ON-ORBIT ASSEMBLY

On-orbit assembly work by a space robot is analyzed and studied the assembly of the reflector of a radio telescope into a typical model.

2.1 Target Structure and Size

Launch vehicle payload bays generally have a circular cross section. Hexagonal elements are therefore considered to be of a suitable shape, since they approximate a circle and can be connected to form a honeycomb structure. Then, we study connecting hexagonal panels together, making up a reflector of nearly circular aperture. A nearly circular reflector can be built with 18 elements. If the maximum diameter of the hexagonal panel is set to 3.5m, a reflector can be constructed up to a diameter of about 15 m. Space antennas with hexagonal reflectors are planed for ETS-VIII and for VSOP-2. These antennas will be deployed in orbit, but could be a good prototype for future in-orbit assembly type antennas.

2.2 Limitation Conditions

The radio telescope structure to be assembled in orbit is expected to be lightweight and simple, so that only a small number of rocket launches are required. Then, the following conditions were required for missions of on-orbit assembly work.

a. Only one launch is required to carry and build the structure.
b. One robot arm is used for assembly.

3 - SETUP OF ASSEMBLY WORK

3.1 Strategy of Space Robot Work

The method of assembly of the reflector using one small robot arm was considered, and the following strategy was set up:

a. All structural connectors are passive, and are designed to move by local internal forces.
b. A grapple fixture, and electric power connector and signal line are formed in each reflector segment, enabling the inchworm movement required for structural assembly.
c. Reflector segments are contained and carried in a container which can be attached to a grapple fixture on the structure.

This container is used also for reflector assembly. If connection and grasping of a segment are performed according to the local internal force generated at the connection mechanism part, it is not necessary to generate a large torque at the arm joints. Efficient assembly is achieved by allocation of the grapple fixture on the structure corresponding to inchworm movement with a short arm relative to the average size. Assembly segments are packed into a container which is carried near the work place and temporarily attached to a grapple fixture on the work site to eliminate the need for frequent replenishment.

3.2 Composition of Assembly Task

By combination, use of the local internal force to the grasping, and use of a palette, the reflector assembly in the task flow shown in Fig.2 becomes possible. The result of having analyzed the contents of each work task by this method is shown in the first face. Compliant operation of the arm is required, and since each task causes the closed link state through a structure, the force/torque depended statically indeterminate generate it without a compliant. An artist’s conception of on-orbit assembly is shown in Fig.3.

3.3 Grasping and Connecting Task

Grappling the reflector segments and attaching them to the work site are the basic operations of assembly. A position gap is corrected by the following four steps, and the mating of an attaching mechanism is attained.

Step 1: Positioning based on a coordinates value
Step 2: Position error correction by visual feedback from the target
Step 3: Forcing in alignment with a guide
Step 4: Pulling in by a finger mechanism

A compliant function to have a virtual compliance center in along-to forcing work at a guide is required for an arm.

3.4 Switching on Mobile Motion

During a walk, end effectors will grapple the structure alternately, and so the signaling system needs to be switched simultaneously. Since switching the hardware line could result in signal interruption, both effectors need to be connected to the communications network at the same time. Although the method of giving two IP addresses to one computer has also been considered, the software required for this can become complicated. Thus, two computers, each with a different IP address, were placed on the arm side-by-side to provide redundancy as well, and the method which switches the signaling system by switching authority between computers in the arm was devised. Therefore, in a closed link state, it will once be in the state where two computers were connected to the network, and authority is switched, and after confirming that, communicating normally.

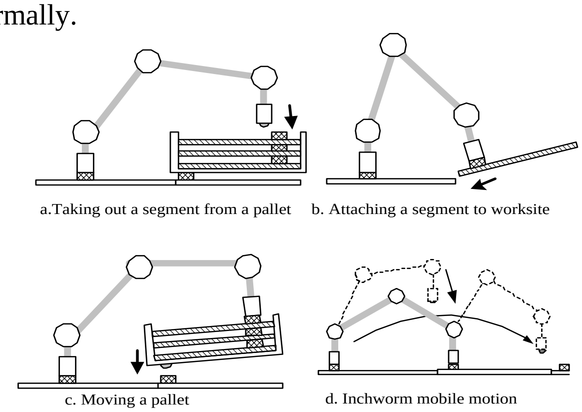


Fig.2 Reflector assembly tasks

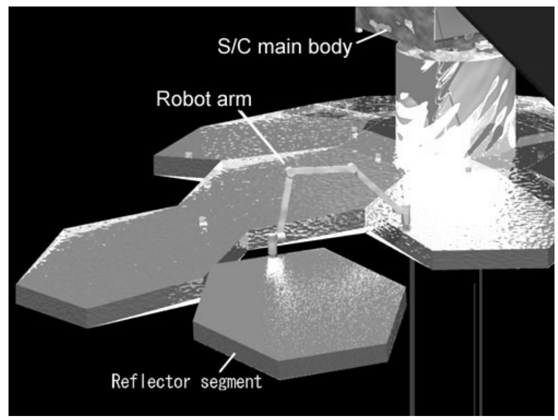


Fig.3 Artist concept of on-orbit assembly of a reflector

4 - COMPOSITION OF ASSEMBLY TYPE STRUCTURE

4.1 Composition of Reflector Segment

A viable system for the inter-connection of hexagonal reflector elements is one which makes use of attachments at the edge of each element. Grapple fixtures are also required for the robot arm to perform its work; these are located on the reverse side of each element, so as not to affect the reflector characteristics on the front face. Moreover, electrical connecters enabling the flow of electrical current and signals between elements are required. The fundamental composition of a reflector segment is shown in Fig.4.

4.2 Power Line & Signal Network

A robot arm is transferred to the reflector structure in the middle of an assembly, walks along it and carries the pallet out, and assembly work is done. For this reason, a power supply and a communication network are critical elements, which must be supplied to the grapple fixture on the structure during construction.

4.3 Connection Mechanism

The segment connection mechanism should have three desirable properties: it should not require the application of a large force by the robot arm, it should be of a simple design and it should be as light as possible. For this reason, a method which operates a mechanism using the driving force of the socket wrench of the arm end-effecter is chosen. Thereby, connection action is realizable even if it does not set a drive in each element. To increase the work efficiency, an electric connector is built in to the connection mechanism, and it is constructed such that mechanical connection and electric connection may be performed simultaneously. Reflector segments are combined in two steps. Thereby, segments can be combined, without making the surface structure of reflector segments collide. A prototype of the connection mechanism is shown in Fig.5.

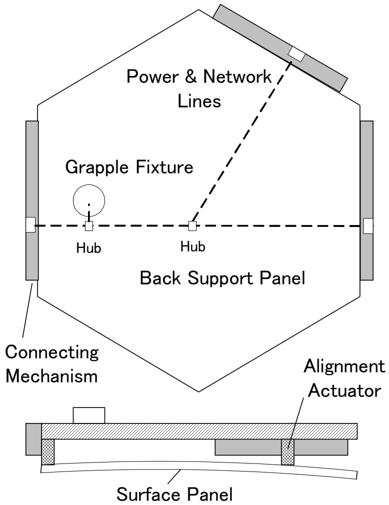


Fig.4 Fundamental composition of a reflector segment

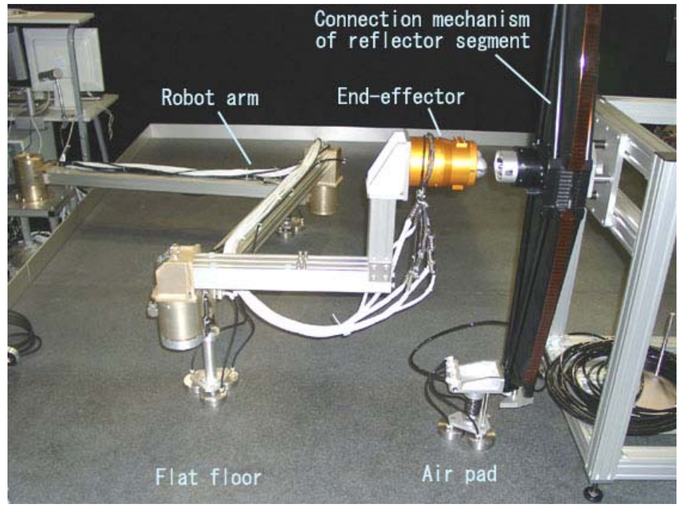


Fig.5 Prototype of connection mechanism of reflector segment

5 - END-EFFECTOR MECHANISMS

In order to secure holding and stiffness to high load, a clip type mechanism is proposed as a new grasping mechanism method. This is a method which holds by inserting the housing of an end-effector and grapple-fixture structure with finger structure, and has the following features.

a. Since the load path in a holding state passes only along the inside of a rigid member and does not pass along the hinges of fingers, holding tolerance is high (Fig.6).
b. Since the wide contact surface between an end-effector and a grapple fixture can be taken, allowance is small and stiffness is high (Fig.7, Fig.8).

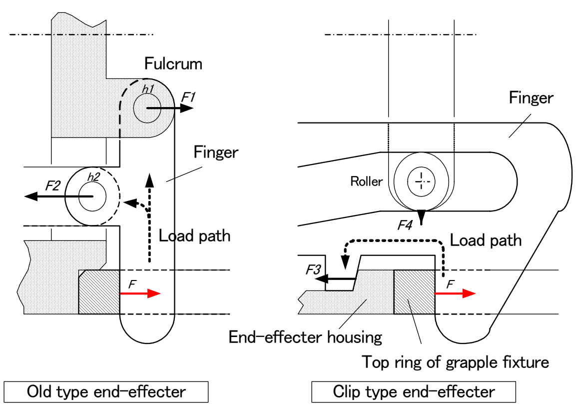


Fig.6 Path of drawing force applied to the grapple fixture

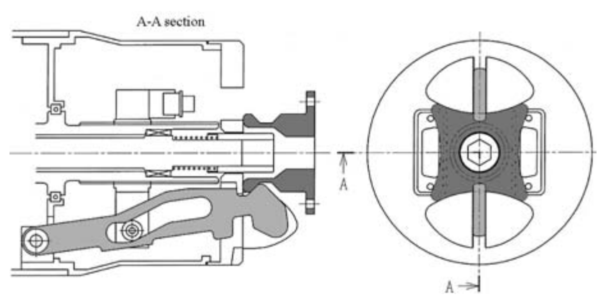
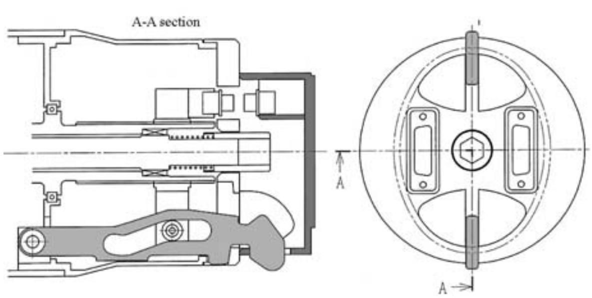
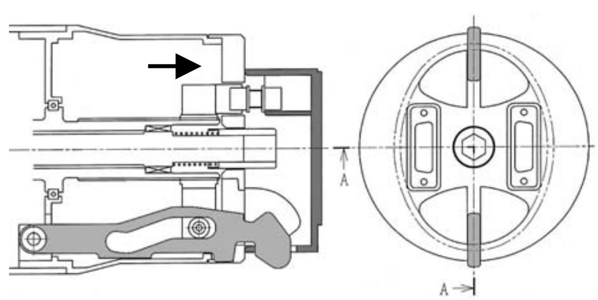


Fig.7 Configuration of grasping the small fixture



a. Grasping of the large grapple fixture



b. Mating of electrical connectors

Fig.8 Configuration of grasping of the large fixture and mating of its electrical connector

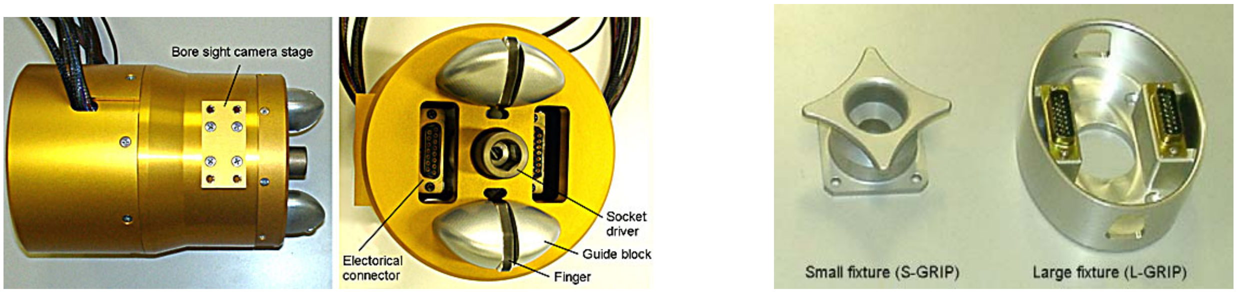


Fig.9 Prototype of the new end-effector and grapple fixtures

6 - TESTING OF NEW END-EFFECTOR

6.1 Static insertion testing

6.1.1 Testing method

Testing of the position gap allowed in insertion of the end effector to the grapple fixture of each size was carried out. The relative position gap of the lateral direction of the end effector to a grapple fixture was set up by the optical stage, the end effector which hung with gravity compensation equipment on the transverse direction and the grapple fixture which was supported by the rotational compliance mechanism, and reduced gravity was inserted statically (insertion force: 18N), and insertion nature was investigated. The composition of prototype end-effector and testing equipment are shown in Fig. 9 and Fig.10, respectively.

6.1.2 Testing results   The testing results about each grapple fixture are shown in Fig. 11.

It was confirmed that the position gap of 10mm or more in insertion was allowed for both grapple fixtures.

6.2 Dynamic insertion testing

6.2.1 Testing Method

The grapple fixture was attached at the tip of a two-dimensional robot arm, and insertion operation testing to the fixed end effector was carried out. The composition of testing equipment is shown in Fig.10. The handle and the end effector were considered as reverse arrangement because of the carriable weight limit of the two-dimensional robot arm. However, satisfactory composition is considered by the check of the insertion characteristic by arm operation. The initial position gap in the transverse direction of the insertion in the testing was 5mm and insertion speed was 5mm /s.

6.2.2 Control System

The Joint virtual compliance control of a joint unit was performed. The virtual rotation rigidity of a wrist joint was set as the level equivalent to the target rotation rigidity at a tip. And the virtual torsional rigidity of the shoulder and the elbow joint was set as the value computed from the target translation rigidity in the arm tip.

In the testing, the virtual compliance center was set up in the center of the front end of the grapple fixture, and the following virtual impedance was used.

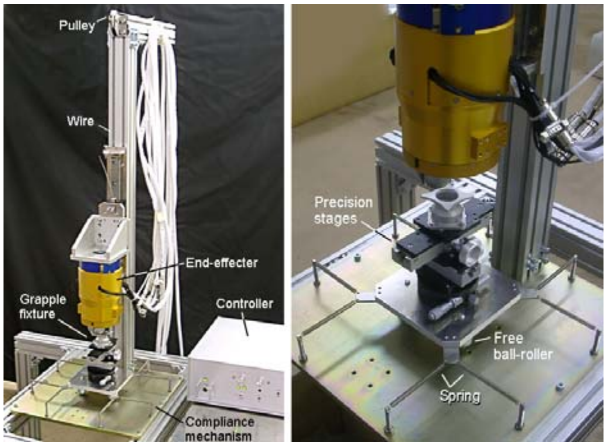
- Virtual rigidity : 500 N/m, 5Nm
- Virtual viscosity : 475 Ns/m, 5Nms
- Virtual mass / inertia : 10kg, 0.1kgm^2

For position control of the arm, the rotary encoder information on each joint motor axis was used.

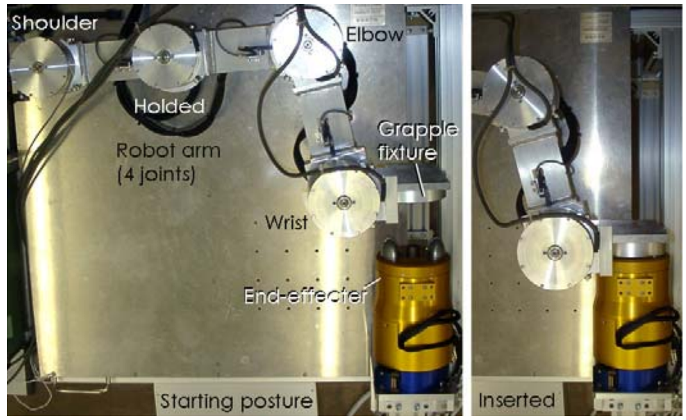
Moreover, the control cycle of position control and joint virtual compliance control was set to 2msec.

6.3 Testing results

The tip of the end-effecter was inserted into the grapple fixture normally. An average final gap from the mating position after insertion was about 0.8mm. It is sufficiently smaller than the allowable gap for the finger motion on mating operation. Mating was actually confirmed by this testing by pulling-in motion of the finger for the joint active limp controlled arm. The history (the transverse direction position X, the transverse direction force Fx, pushing force Fy) of insertion operation is shown in Fig.12. Contact was caused in about 10 seconds after the start of operation, insertion was performed by the smooth guide, and insertion was completed after about 16 seconds. The force at the time of completion was about 9N.(Also after that according to the increase in virtual intrusion, pushing force is increasing.) Thereby, it was confirmed that insertion on the cup type grapple fixture could be accomplished smoothly by the hemisphere formed guide of end-effecter and the joint virtual impedance control. Since the connection mechanism of reflector segments is also at the same form, joint virtual impedance control is effective also in the insertion.

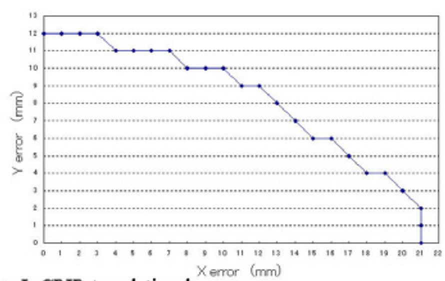


a. Static insertion testing

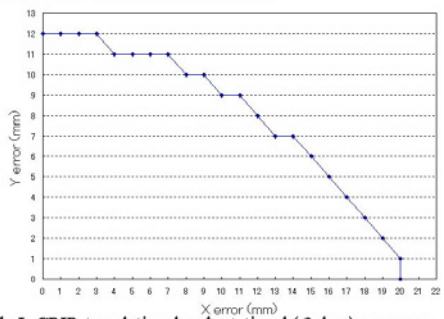


b. Dynamic insertion testing by using 2 dimensional robot arm

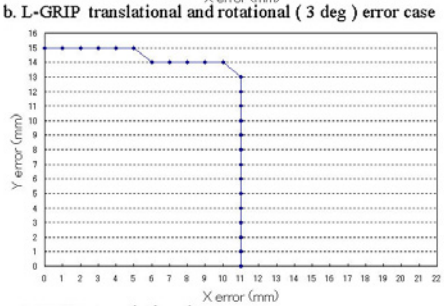
Fig.10 Configurations of end-effector insertion testing



a. L-GRIP translational error case



b. L-GRIP translational and rotational (3 deg) error case



c. S-GRIP translational error case

Fig.11 Results of static insertion testing

X :E/E position, Fx :Lateral force, Fy :Axial force

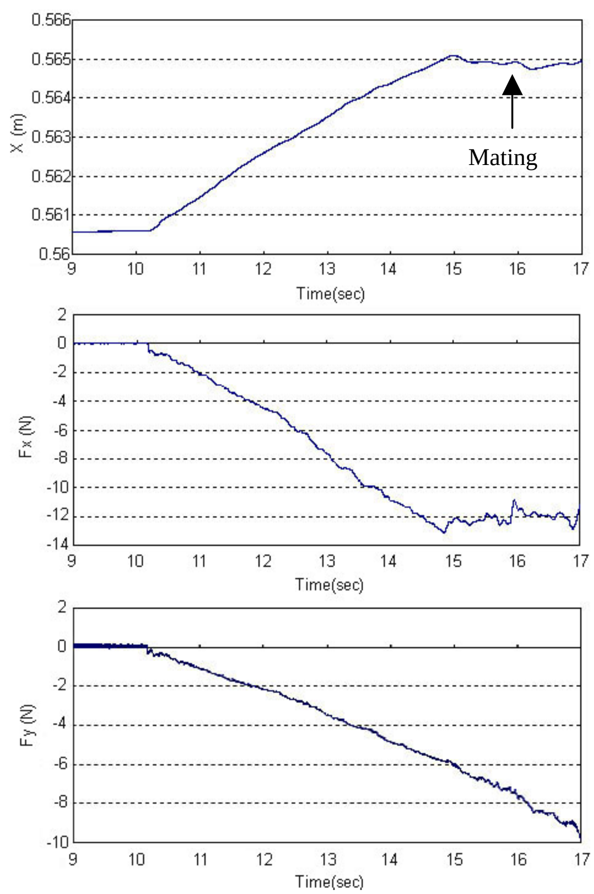


Fig.12 Results of dynamic insertion testing

7- ROAD MAP

On-orbit demonstrations of new components and assembly tasks by the new robot arm and end-effector are planned towards realization of an on-orbit autonomous assembly and a high precision radio telescope reflector. A possible development road map for the on-orbit assembly technology is shown in Fig.13.

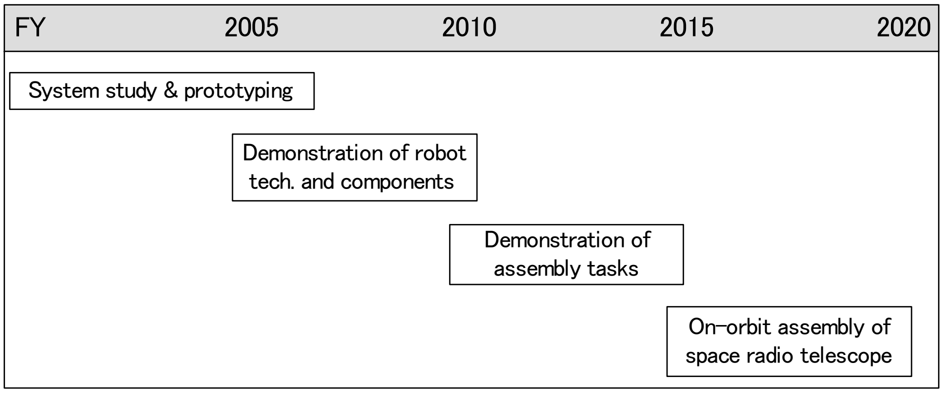


Fig.13 Possible road map of research and development for on-orbit reflector assembly

8 - CONCLUSION

On-orbit assembly of a radio telescope reflector has been analyzed. A reflector made up of hexagonal elements, which incorporates a conducting network for power distribution has been studied. A space robot arm and end-effector for assembling it were also considered. An end-effector which has electric connectors and a socket driver, clip type fingers and spherical insertion guides was proposed. Moreover, by testing a prototype end-effector, its functions and characteristics were evaluated and validated.

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