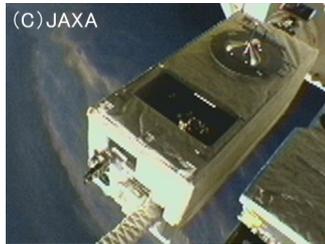


Space Demonstration of Astronaut Extravehicular Activity(EVA) Support Robot “REX-J (Robot Experiment on JEM)” Project Achieved Great Success



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“REX-J” (Robot Experiment on JEM), which was developed from 2008, was launched in July 2012 and carried out the world’s first space demonstration of robotic spatial mobility technology over a course of about one year using 4 tethers (synthetic fiber strings) and an extendable robot arm on the Exposed Facility of the Japanese Experiment Module (JEM) “KIBO” in International Space Station (ISS), and achieved a great success. This report summarizes REX-J’s development-to-operation topics including the mission outline and requirements, robotic development and achievements, and in-orbit experiments/results.

1. Introduction

In the future, it is expected that mankind’s advance into outer space will progress without end, thus, the status of robots will become increasingly important. For instance, the apparently elegant extra-vehicular activities (EVAs), so far assigned to astronauts in outer space, including maintenance operations and equipment assembly work, are not only hard work but also run various risks including space debris collision. This places a physical and mental burden on astronauts. To partially alleviate such burdens, the necessity for robots capable of shouldering some of the astronauts’ work is likely to grow with the future progress of space development.

Conventionally, space robots used in EVAs were typically manipulators on board the space shuttle, ISS, or JEM “KIBO” and their range of movement was limited. Future space robots may, however, be required to have a vast range of movements in outer space.

The astronaut EVA-support robot space demonstration project “REX-J” reported here focuses on spatial mobility technology, particularly under the microgravity environment and, specifically, that which uses tethers and an extendable robot arm-based, simple, small, and light experimental apparatus intended for demonstrations of space locomotion technology.

REX-J was, launched as 2nd-phase Exposed Facility payloads by the H-II Transfer Vehicle (HTV) “KOUNOTORI” No. 3 for ISS in July 2012, and carried out on the ISS JEM “KIBO” Exposed Facility from August to May of the following year for an approximately 9-month in-orbit space demonstration.

Mitsubishi Heavy Industries, Ltd. (MHI) participated in the development/operation of space robots and experiment systems, which were carried out by the Japan Aerospace Exploration Agency (JAXA), and took charge of robot system integration. The outline thereof is as follows:

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2. Mission Outline and Requirements

The REX-J mission was installed on the upper stage of MCE (Multi-mission Consolidated Equipment) attached to Port No. 8 of the JEM “KIIBO” Exposed Facility. **Figure 1** outlines MCE. MCE carries 5 mission equipment units including REX-J for “Ionosphere, Mesosphere, upper Atmosphere, and Plasmasphere mapping (IMAP),” “Global Lightning and sprite Measurements (GLIMS),” “Space Inflatable Membrane Pioneering Long-term Experiment (SIMPLE),” and “Commercial Off-The Shelf High Definition Television Camera System (HDTV-EF).”

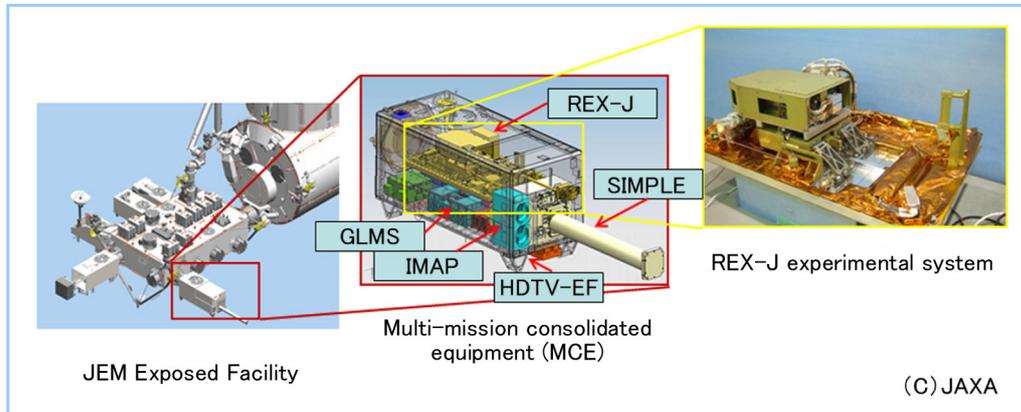


Figure 1 Outline of MCE installing REX-J

Figure 2 shows a conceptual diagram of REX-J’s locomotion in space. The principle of this mobility in space is as follows: hooks at the tip end of 4 tethers (synthetic fiber strings) are fixed to surrounding ISS handrails, from the robot main body, using an extendable robot arm. By controlling the 4 tether lengths, the robot main body moves within the space having the 4 tethers’ fixed points as apices. By shifting the tether-fixed position using an extendable robot arm, the movable range of the robot’s main body can be further changed.

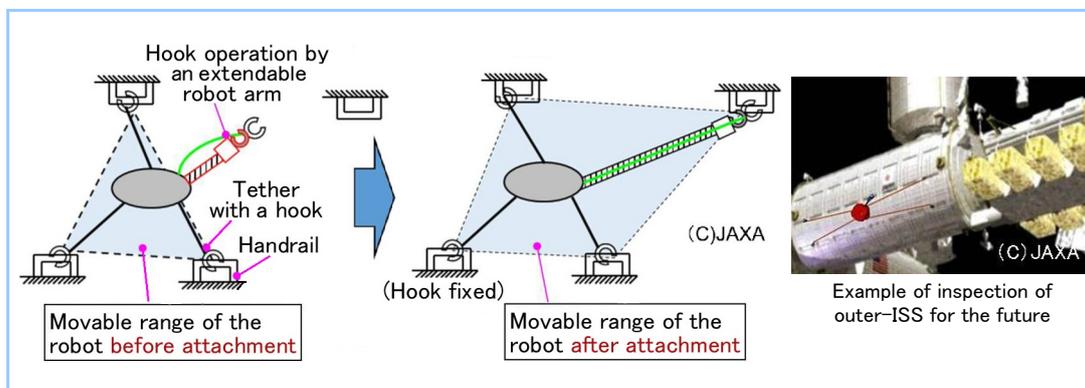


Figure 2 Robotic Space Mobility Technology

Figure 3 shows the entire schedule of REX-J mission development and operation. MHI’s participation was from the preliminary design in 2008; the development period until delivery was only 2 years of short period.

REX-J’s mission requirement is to carry out the following world’s first space demonstration, in the environmental complex of microgravity and short-time (about 90-minute frequency) hot-cold thermal cycle of outer space.

- (1) an understanding of operating characteristics including extendable robot arm vibration, tip end control accuracy, and resonance with tethers as well as:
- (2) the identification of the general functions of mobility in space based on cooperative control between an extendable robot arm and one tether, and cooperative control among multiple tethers.

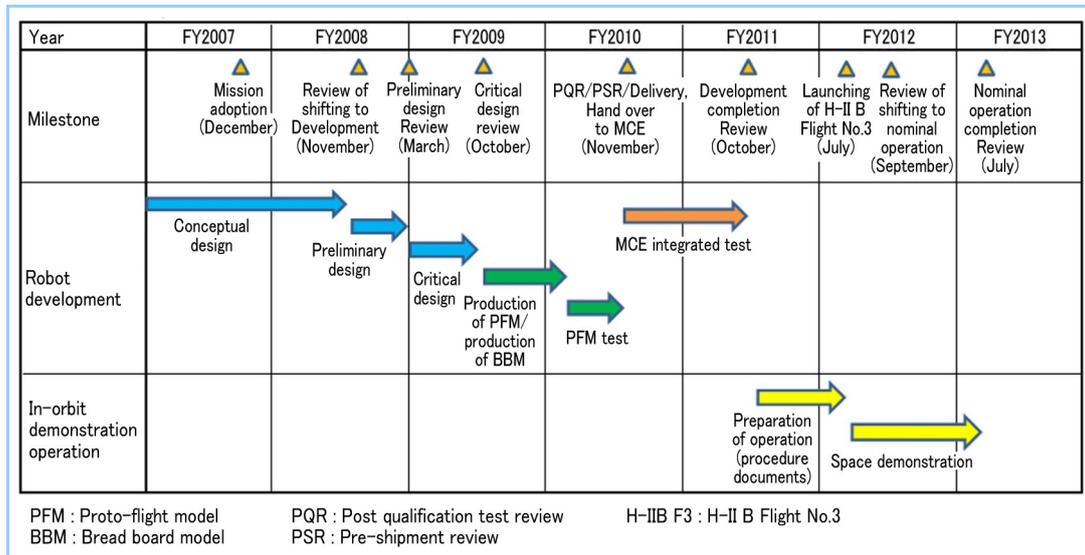


Figure 3 REX-J Mission Development and Operation Schedule

3. Robotic Development and Achievements

3.1 REX-J System

Figure 4 shows a REX-J system. REX-J is an industrial-academic-government development project carried out in a free and open atmosphere where engineers from JAXA, university research institutions, and private companies could meet and exchange innovative ideas.

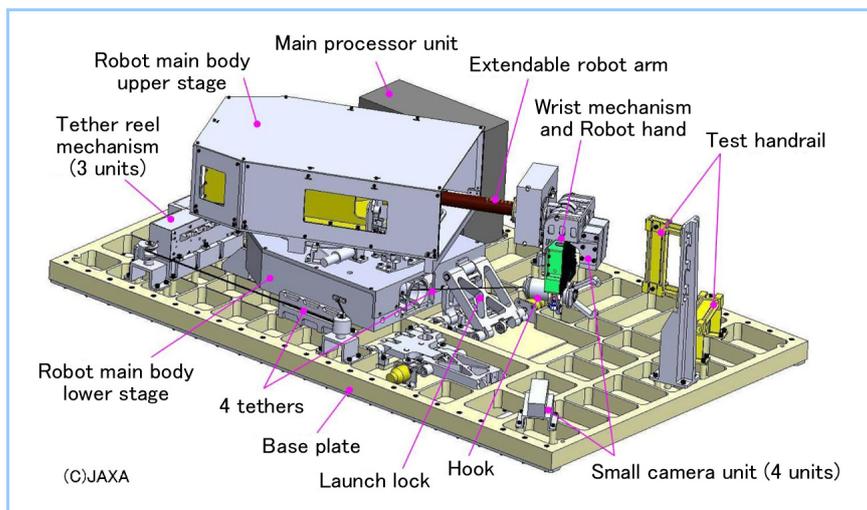


Figure 4 REX-J System

At the time of initiating the project, unprecedented demonstration tests to extend an extendable robot arm required examinations to ensure the safety of the humans in attendance. Endeavors to realize the following, which were targeted from the start, however, bore fruit and the planned targets were achieved.

- (1) Operation of element technology components including an extendable robot arm in the exposed extravehicular environment
- (2) Remote manipulation by researchers from the ground for real-time operation of the in-orbit robot
- (3) Active utilization of parts for consumer products (including SH-2:32 bit RISC processor for motor control-purpose CPU)

REX-J is composed of the robot main body and the main processor unit placed on the base plate installed within MCE, with tether reel mechanisms and cameras arranged around the outside of the robot main body.

MCE on the upstream side of the system is responsible for the supply of power to REX-J and communication with the ground.

REX-J also incorporates high-density robot demonstration-purpose functions in a limited space allocated from MCE. For example, three drivers are used to control the motors and cameras; One driver handles up to four motors, and a total of ten motors are controlled by the three drivers.

3.2 REX-J components

(1) Robot main body upper stage

The robot main body is composed of an upper and a lower stage, with both stages coupled by the rotation mechanism mounted on the lower stage. On the upper stage, an extendable robot arm, wrist mechanism, robot hand, motor driver (for the wrist and hand), and a launch lock, which supports and fixes components for camera, wrist, and hand during launch phase, are installed.

For the extendable robot arm, CFRP film is employed as the main material to help realize a light weight and necessary strength. As shown in **Figure 5**, the extension system used is called STEM (Storable Tubular Extendable Member), which is capable of rewinding two sheets of film like a tape measure; it forms a cylindrical robot arm if extended, and two motors extend or store the arm. Also, the robot hand has two fingers to tightly grasp the below-mentioned hook and, on each finger, a linear actuator is mounted, which characteristically has a relatively large gripping force for its size. This robot hand was also positioned as a target for JAXA's element technology demonstration.

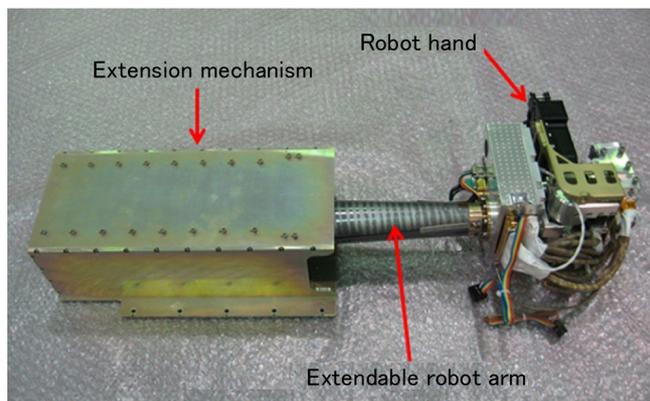


Figure 5 Extendable robot arm

(2) Robot main body lower stage

The robot main body's lower stage is equipped with a tether reel for adjusting the length of the tether attached to a hook, a main body rotation mechanism, and a driver involved in the robot main body operation.

The rotation mechanism is required to support the robot main body's upper stage under limited space and power resource conditions as well as precisely position the robot arm's extension direction and to hold a fixed position even when powered off for safety and mission possibility. Hence, the rotation mechanism was composed of worm gear and worm wheel mechanism, and used specially made-to-order bearings strong enough against loads in both radial and thrust directions for the bearing section to realize a high-accuracy, high-torque (high-rate reduction ratio) mechanism difficult to be affected by the torque conveyed in reverse from the rotational output destination, using an actuator with its torque as low as possible. In addition, bearings were coated with vacuum grease to prevent resistance increase in the sliding portion. Vacuum grease causes less abrasion and wearing in the vacuum environment and has been used in artificial satellites.

(3) Wrist mechanism

A wrist mechanism is installed at the end of the extendable robot arm as shown in **Figure 6** and is responsible for controlling the robot hand attitude. This biaxial mechanism has a pitch and a roll axis, and uses a differential mechanism due to space constraints during storage of the robot arm and for weight saving at the end of the arm.

This differential mechanism switches pitch and roll axial rotations, depending upon the combination of the two motors' rotational directions, and if both motors' directions of rotation are the same, the roll axis is put in motion while opposite directions drive the pitch axis. As two motors are driven for the operation of one axis, the motors can be downsized, thereby contributing to weight saving and miniaturization of the wrist mechanism.

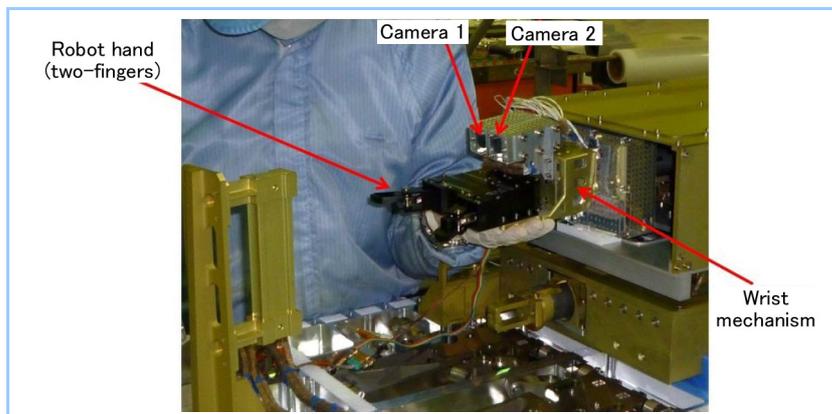


Figure 6 Hand, Camera, Wrist Mechanism

(4) Tether reel mechanism

The tether reel mechanism is composed of a reel mechanism and a tether. For the tether, high-strength synthetic fiber is adopted as the core material. Since the tether length is an important parameter to determine position of the robot main body, the reel mechanism has the function to load pre-tension for preventive collapse winding and to send out wind in a certain amount of tether. Also, worm gears were introduced into the rotational part of the reel function to keep the tether length constant even when powered off and ensures stability against external tension. Moreover, for the simultaneous operation of the robot main body and hook gripping/shifting by the robot hand, the reel mechanism is so controlled as to enable cooperative action between tether reels as well as with the extendable robot arm and the rotation mechanism.

(5) Hook

A hook is connected to the tip end of the tether installed on the lower stage of the main body, and so that the hook may not come off even if tension is loaded on the tether, with the hook remaining fixed on the handrail, the end point of the hook is a convex shape to fit the concavity of the ISS handrail.

The hook can be opened or closed by one action of the robot hand. As shown in **Figure 7**, the hook is in a closed state at normal time but, if the projection of the hook gripping section is pushed in upon the hook being gripped by the robot hand, the hook opens. If the robot hand releases the hook, the hook is closed by the spring within the hook housing.

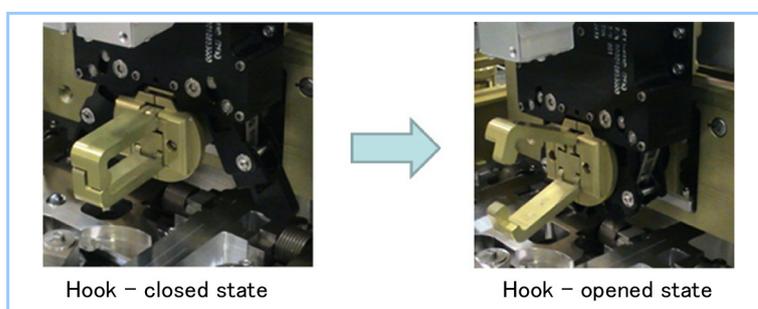


Figure 7 Hook

(6) Camera

REX-J has a total of four cameras: two near the end of the robot hand (Figure 6), one in a position where the extendable robot arm can be seen from the robot main body side, and the remaining one in a position on the base plate from where the entire robot can be observed.

The image photographed by one camera fitted to the robot hand end is digitally processed and downlinked to the ground via the JEM communications telemetry system (slow-system communication MIL-STD-1553B) or the medium speed system (Ethernet) of the same MCE-mounted HDTV-EF. The other camera images are selected into 1CH by a switcher to be downlinked via JEM's analog image system and monitored on the ground.

The hardware and software originals are based on an ultra-small CMOS camera developed by the Tokyo University of Science (Prof. Kimura).

(7) Launch lock

To fix each component on the load at the time of launching, a launch lock is installed on the main body, the rotation mechanism, and the extendable robot arm end (including the wrist mechanism and robot hand). The launch lock consists of a shape memory alloy (SMA)-based actuator called a Pin Puller, which can be compacted, and a lock mechanism. Following a command from the ground, the actuator starts operating and triggers the unlocking of the lock mechanism. The lock mechanism is so structured as to bear the load by itself to avoid the load being directly placed on the actuator. For the mechanism's sliding portions, a solid lubricant is used to prevent seizure.

The launch lock in the ISS's exposure space is an important safety control component for the safety of the crew and therefore requires a two breakdowns-acceptance design (a design that prevents any hazard from occurring even if two breakdowns occur at one time). This has been materialized by applying Design for Minimum Risk under special development control to establish risk avoidance control (main control + backup control).

(8) Main processor unit

The main processor unit (MPU) (**Figure 8**) is the crucial part managing power/control/communication of the entire REX-J. It has the function to convey received directions to each driver as well as to transmit telemetry data from each component to the upstream side for relaying the data to the ground.

For the CPU, the HR5000 (200MIPS-class 64-bit microprocessor), excellent in resistance to latch-up (a state of being out of control while powered, leaving the flow of electricity continuous), was selected to realize specifications that permit restoration by restarting to continue the mission even if the system should go out of control in orbit due to radiation. The operation was executed in such a way that the scenario program for the experiment sent from the ground was temporarily stored in the main processor unit and then commands were sent to motor drivers and other units.

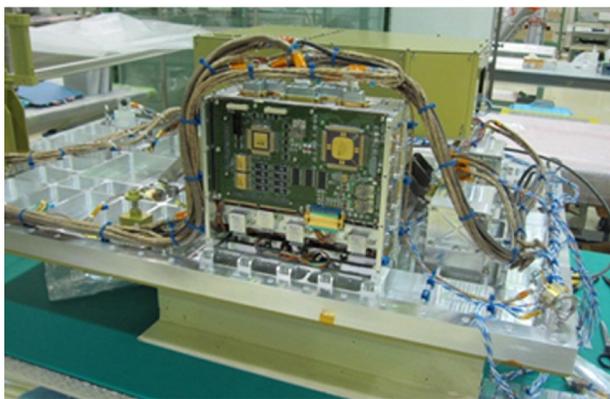


Figure 8 Main Processor Unit

(9) Motor latch driver unit

The motor latch driver (MLD) unit controls the motor, camera, and latch driver circuits of each local component, following directions from the main processor unit.

There are three MLDs, and each one carries two CPUs (SH-2) for motor control, and there are four cameras, each carrying a camera control-purpose CPU (PIC: Peripheral Interface Controller).

Of the three drivers, one is MLD1, which controls the tether reel with a hook and the rotation mechanism installed in the robot main body's lower stage as well as the extendable

robot arm mounted on the upper stage of the robot, another is MLD2 controlling two tether reels, and the remaining one is a small motor driver circuit (Dexterous Hand Motor Driver: DHMD) to control the wrist and robot hand. These three drivers, however, have a common design for the purpose of rationalization.

(10) Motor driver

Motor drivers can control the robot motion through the use of position, speed and tension control loops for flexible motion control. The features of the motor driver are as follows.

(a) Remote control of the robot by data uplinked from the ground. (See **Figure 9**)

In order to remotely control the robot motion in orbit, control command data can be uplinked from the ground to each motor driver via the main control unit. The uplinked data includes robot motion commands and the control parameters that can change the robot responsiveness characteristics.

Each motor can select the control mode from the position control, speed control or tension control.

For example, by using this function, the robot can move by combining tension control and position control. The control loop can also be switched while moving.

Likewise, it is possible to adjust gains for a change in each control loop's response as well as to change various filters' characteristics, and the servo system's dynamic characteristics can thus be fine-tuned, depending upon the situation.

(b) Realization of complex actions based on a simple combination of commands

Motor control commands roughly consist of three groups: to renew control parameters, to start/stop/change operation, and to transmit internal data.

Each command consists of a single instruction and, depending upon the combination of these commands (macro commands), complex actions can be undertaken. The main processor unit can monitor the state of its internal motor control. Therefore, autonomous motion control can be executed by judging the motion status data, and transmitting the necessary commands from the main control unit to the motor drivers.

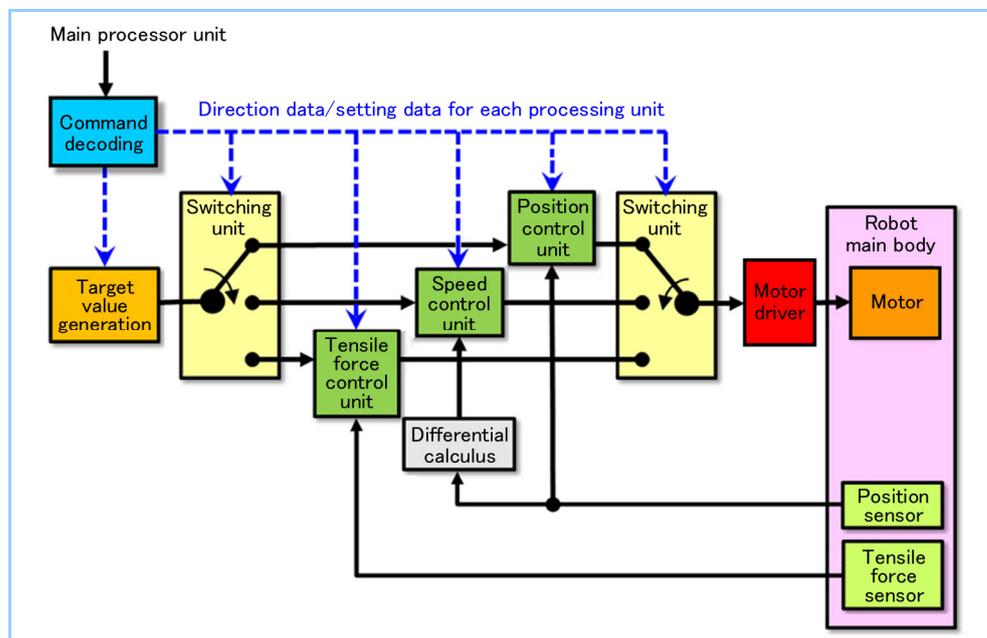


Figure 9 Schematic of motor driver

4. In-Orbit Experiments and Results

The in-orbit experimental operation sequence and mission success levels are defined as shown in **Table 1**. On August 20, REX-J was activated and the initial electric system inspection was tested. After that the checking and adjustment of the basic function of major robot sections were identified as “minimum success-level experiments.” After subsequent checking of macro command functions, the “initial operation phase” was completed at the end of August 2012.

Table 1 In-Orbit Experiment/Operation Sequence and Mission Success Level

Operation phase	Experiment level	Experiment No.	Experiment item	Date of experiment	
Initial operation phase	-	1	REX-J activation and initial checking of electric systems	August 20, 2012	
	"Minimum success"-level experiments	2	Basic function checking/ adjustment		
		2a	Small camera function checking/adjustment	August 21-22, 2012	
		2b	Unlocking of robot main body rotation unit	August 26, 2012	
		2c	Checking of robot main body rotation unit's basic operation	August 26, 2012	
		2d	Unlocking of wrist/hand unit	August 27, 2012	
		2e	Checking/adjustment of extendable robot arm's basic operation	August 28-29, 2012	
		2f	Checking/adjustment of hand's basic operation	August 29, 2012	
		2g	Checking/adjustment of wrist mechanism's basic operation	August 30, 2012	
		2h	Checking of REX-J macro command (RMC) function	August 30-31, 2012	
		3	Experiments using extendable robot arm		
		3a	Calibration of extendable robot arm (length/motor control adjustment)	October 16-17, 2012	
		3b	Assessment of extendable robot arm vibration (to be made within MCE)	October 17-19, 30, 2012	
		3c	Unlocking of tether hook (unlocking of robot main body launch lock No.2 and hook fixed)	November 1-2 2012	
		3d	Tether hook gripping by hand	November 2, 2012	
	3e	Attachment of tether hook to handrail	November 13-16, 27-29, 2012		
	4	Tether-supported experiments			
	4a	Unlocking of robot main body (Unlocking of robot main body launch lock No.1)	November 2, 2012		
	4b	Checking tether's function to suspend robot main body	November 29-30, 2012		
	4c	Understanding extendable robot arm's behavior when it operates while supporting tether	November 30, December 11, 2012		
	5	Tether-controlled robot mobility experiments			
	5a	Movement of robot main body to in-orbit standby position	December 12, 2012		
	5b	Movement of robot main body to target position	December 13, 2012, January 17, 22, February 5-7, 2013		
	Nominal operation phase	"Extra success"-level experiments	6	SSPS-applied experiments (verification and control of interference dynamics between the tether and an extendable robot arm)	
			6a	Understanding extendable robot arm's behavior to control tether when the arm extends	February 19, 2013
			6b	Gripping handrail by hand under tether-supporting robot main body	February 20-21, 2013
			7	Experiments of extending extendable robot arm out of MCE	
			7a	Extension of extendable robot arm out of MCE and assessment of vibration characteristics	March 5, 2013
7b			Acquisition of peripheral video with small cameras	March 6, 22, 2013	
Developmental experiments		8	[Tohoku University] Developmental experiments to understand vibration characteristics of extendable robot arm	April 9-11, 2013	
		9a	[Tokyo University of Science] Acquisition of camera imaging conditions in the in-orbit optical environment	April 23-24, 2013	
		9b	[Tokyo University of Science] Experiments of shape recognition and position attitude measurement	April 25, 2013	
		10a	[Tokyo Institute of Technology] Developmental experiments of mobility of robot main body	May 8, 2013	
		10b	[MHI] Experiments for reattachment of hook to handrail	May 9, 10, 21, 23-24, 2013	

The period following the September 2012 review meeting to check the shift to nominal operations was defined as the “nominal operation phase.” Experiments using the extendable robot arm, the tether-supported experiments and the tether-controlled robotic mobility experiments were defined as “full success-level experiments.” SSPS (space solar power system)-applied experiments (verification and control of interference dynamics between the tether and an extendable robot arm) and experiments of an extendable robot arm’s extension out of MCE were concluded at the end of March 2013 as the most challenging “extra success-level experiments.”

As additional experiments, applications for space experiments using REX-J were requested for proposal from university research institutions and private companies. As a result, those were proposed by Tohoku University, Tokyo University of Science, Tokyo Institute of Technology, and MHI were adopted and carried out as “developmental experiments” from April to the end of May 2013.

How closely each success (judgment) criteria was met is explained as follows:

First, basic robotic functions of a stand-alone operation were checked for cameras and each mechanism, finding that the “minimum success level” had been reached on August 30, 2012.

Next, the vibration and positioning characteristics of an extendable robot arm under the microgravity environment were understood. Also, using the robot hand mounted on the extendable robot arm, the tether hook was operated for gripping and fitted to the handrail. Furthermore, the robotic locomotion function in space by way of cooperative control of 3 tethers (**Figure 10**) was checked, finding that the “full success level” had been reached on February 7, 2013. Under a microgravity environment, it was proved that, only with three tethers, an approximate 30-kg robot main body could remain stably suspended and move in space.

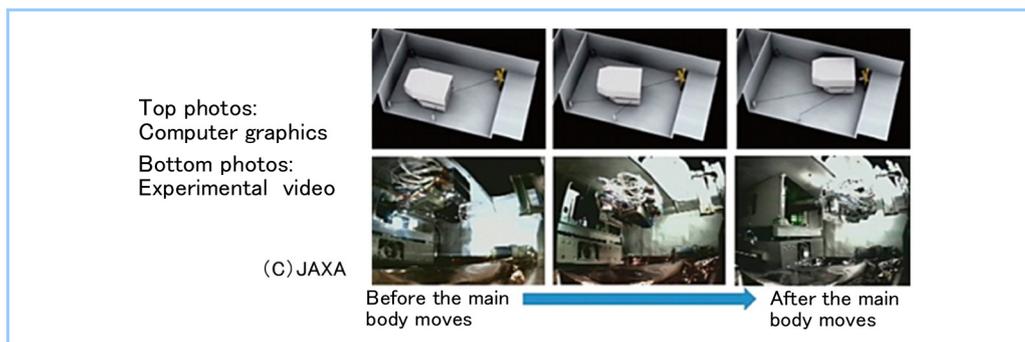


Figure 10 3-Tethers Cooperative Control-Based Space Locomotion of Robot Main Body

Finally, the working function based on cooperative control of the tether and an extendable robot arm was checked. The vibration characteristics were also understood, with the robot hand and the camera at the end of the extendable robot arm remaining extended out of MCE. Further, using the robot hand camera, JEM “KIBO’s” surrounding ISS space and the earth were monitored (**Figure 11**) and the “extra success level” was reached on March 22, 2013.

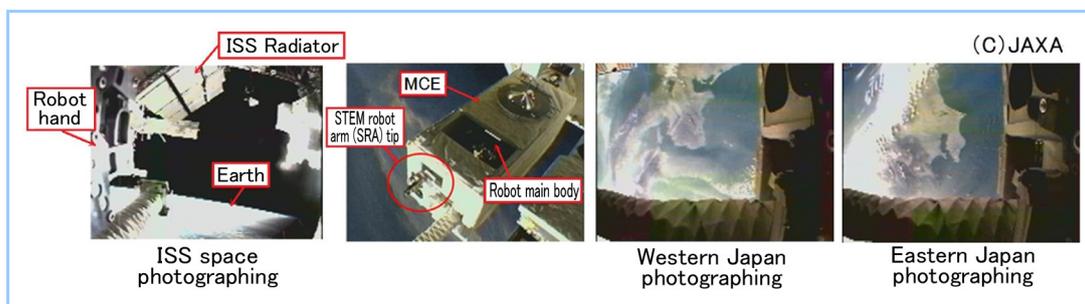


Figure 11 ISS Space and Earth Monitor

As mentioned above, upon finding zero serious nonconformities likely to affect the mission in in-orbit experimental operations, the most challenging “extra success” in the mission success criteria of Table 1, was achieved. Furthermore, in an additional development experiment, MHI’s experimental proposal was adopted and could be successfully implemented.

The following results were obtained from this mission:

- (1) World-first space demonstration of an extendable robot arm in an exposed space environment
- (2) World-first space demonstration of robotic space locomotion function based on cooperative control between an extendable robot arm and one tether.
- (3) World-first space demonstration of robot main body's space locomotion function based on cooperative control among multiple tethers.

5. Lessons Learned from Demonstration

- (1) The development project was very challenging; despite a short development period of only two years from the preliminary design to flight model delivery, and being the first development of exposed facility-experiment equipment, a proto flight model (PFM) had to be made without the engineering model (EM) for whole system due to reduced total development costs, although there were bread-board models (BBMs) for the main processor unit. Since nonconformities at the time of development are to be concentrated on a flight model, it is important henceforth to secure pre-study through entrance management of the project for well-prepared visualization of the identification of development risks.
- (2) During development, concern was raised over the concentration of nonconformities in flight models while, in in-orbit experimental operations, no major nonconformities were found, thus, obtaining results favorable enough to surprise customers. We believe this was due to our quality-first concept implemented by having securely corrected and solved developmental nonconformity cases one by one. If the correction of nonconformities that occurred in ground tests is insufficient, they will always reoccur in in-orbit operations as well. Accordingly, it is important for later in-orbit operations to have securely verified all procedures for in-orbit use in ground tests without fail.

6. Conclusion

The world's first space demonstration of robotic space mobility technology based on multiple tethers and an extendable robot arm was carried out and achieved "great success." For this in-orbit demonstration, the JAXA department in charge was awarded a space engineering division prize, "Space Frontier," by the Japan Society of Mechanical Engineers (JSME) on March 28, 2014 and then a JAXA General Director Prize on January 29, 2014, while enjoying a high reputation with the general public, and we understand that the customers are satisfied.

Toward the future, we will apply or further develop the achievements of REX-J as well as continue our support to JAXA, aiming at practicalizing astronaut support robots (Astrobots) that contribute to the improvement of safety and work efficiency for astronauts assigned to extravehicular activities.

We would like to express our gratitude to JAXA Robotics Research Group's Manager, Dr. Oda (professor at Tokyo Institute of Technology Graduate School of Science and Engineering from April 2012) for his creation of a free and open atmosphere during our joining JAXA's REX-J project, as well as for his kind instructions regarding development. We would also like to thank the Robotics Research Group for their advice concerning the preparation of this technical paper.