Development of an Astronaut Support Robot and its Precursor REX-J, to be tested on the International Space Station

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ABSTRACT

A unique space robot is being developed by JAXA (Japan Aerospace Exploration Agency). Name of the robot is REX-J (**R**obot **Ex**periment on ISS/**J**EM) and its mission is to evaluate technologies needed to realize the Astronaut Support Robot (Astrobot) and the next generation space robots (NGSR). Uniqueness of the robot is its locomotion method which is based on tethers. The robot is floated by tethers whose ends are attached to the robot and the other ends are attached to hand rails on the space station. The robot can change its location by changing lengths of each tether. The robot can also change its area to move by changing location of the tether's end positions. Location of tether's end position can be changed using the extendable robot arm. This unique robot arm is based on the Storable Tubular Extendable Member (STEM) which is widely used for years as deployable satellite antenna and whose mechanism makes the arm compact.

At the time of the i-SAIRAS 2012 symposium, REX-J will be already launched and the initial check out will be conducted. However at the time when this paper is being prepared, REX-J is not yet launched. Therefore, this paper introduces development results and the on-orbit experiment plan.

Key words: Space robots, tether, EVA, astronaut

1. INTRODUCTION

As space exploration and its utilization by humankind expand, tasks to be conducted in space such as building, operating and maintaining satellites and space station in orbit will also increase. Some of those works will be conducted by astronauts not by robots. However from the view point of safety and economy most of works should be conducted by robots in a near future. Task allocation between astronauts and robots will be mainly decided by the capability of space robots and the capability of manned spacecraft. Safety of the astronaut and the hazardous of the work will prohibit astronauts to do such works. Space robots can be classed as follows depending on area where the robots are used and types of works required.

Orbital robots

Space robots that have already been used in space are mostly crane type robots such as the space shuttle remote manipulator system (SRMS) and the space station remote manipulator system (SSRMS).

JAXA's Engineering Test Satellite 7 (ETS-7) and the Japanese experiment module remote manipulator system (JEM-RMS) are also examples of this type of robot. These are grouped as the orbital robots.

Moon and planetary exploration robots

Exploration robots will travel on the surface of the moon or planet to investigate the moon and planets. This robot type is exemplified well by NASA's Mars Exploration Rover, Spirit and Opportunity. JAXA's Hayabusa which has collected soil samples from surface of a small asteroid named Itokawa is also grouped as this type of robot in some aspects.

Next Generation Space Robot (NGSR)

Since above mentioned "Orbital robots" and the "Exploration Robots" are already realized by some countries. Therefore, we are putting emphasis on research and development of the next generation space robots (NGSR) which will be needed soon. Tasks requested for these robots are such as assisting astronaut who is conducting Extra-Vehicular Activities (EVA) or working instead of astronauts. EVA is danger, costly and heavy workload for astronauts. Building the solar power satellites in GEO will also be tasks of NGSR to be realized in near future.

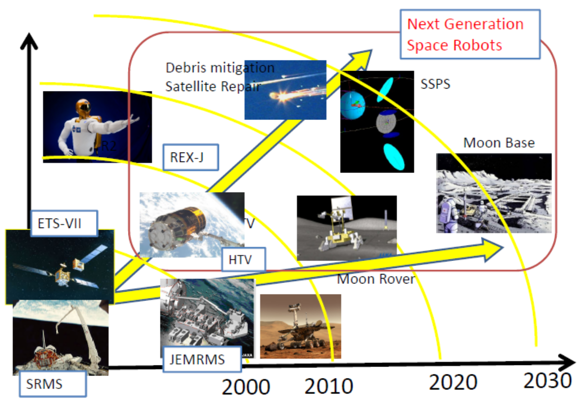

Fig. 1: JAXA's Road Map of space robots

2. NGSR Development Plan

2.1. Locomotion method of NGSR

When a space robot works inside / outside space station or on the surface of ultra-large space solar power satellite (SSPS), robot must be able to move along the surface of the space structures. There are several ways to move a robot around the space station or other space facilities such as shown in Table 1. Each method has advantage and disadvantage.

Since most of the locomotion methods have disadvantages such as limited locomotion area, complicated system, or risk of fuel shortage, we decided to use tethers to move a robot around the space facilities. If a robot is supported by three tethers, the robot can move within a triangle plane defined by three tethers' anchor points. If a robot is supported by 4 tethers, the space where robot can move is the tetrahedron. If the number of tether is more than four, one of the tethers can be released from the anchor point and the anchor point can be moved using some kind of robot arm as shown in Fig.2. We selected the STEM (Storable Tubular Extendible Member) structure as the extendable robot arm which will manipulate the tethers.

Method	Advantage/ Disadvantage
Free Flying	Risk of collision, limited life by the fuel consumption (ex. AERCam)
Transferred by RMS	Limited locomotion area by the reach of RMS (ex. Dextre)
Move on rails	Limited Locomotion area by the reach of RMS and rails (ex. SSRMS)
Inchworm move	Locomotion area is limited by location of the interface point (ex. SSRMS)
Move by multi arms on handrails	System becomes complex since number of degrees of freedom increase (ex. EUROBOT, Robonaut)
Move by tethers	Size of robot can be small while locomotion area is wide (ex. Charlotte)

Table 1: Methods of robots' locomotion in space

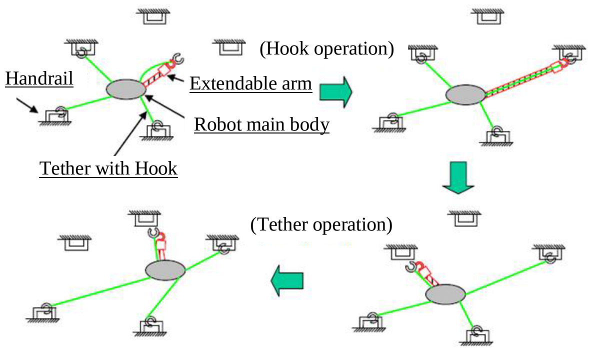

Fig. 2: Principle of the robot's locomotion

This locomotion method presents many advantages in comparison to the inchworm and flight methods. Since the robot is anchored to the space facility by several tethers, there is no danger of losing the robot. A similar experiment (Charlotte[1]) was conducted on the space shuttle (STS-63) in 1995. A major difference between the REX-J and the Charlotte is that REX-J robot can decide the area by itself in which the robot will move because of the extendable robot arm, whereas Charlotte's tethers must be attached by nearby astronauts.

2.2, Extendable Robot Arm

The key technology for this type of space robot is the deployable or extendable robot arm, which attaches or de-attaches the tethers to distant handrails. The international space station has handrails within a distance that an astronaut can reach from one to another. For that reason, the robot arm must extend at least more than a human arm's length. For more efficiency, the arm length should be much longer, but the whole arm should be sufficiently retractable to fit inside the robot. STEM mechanism was chosen to realize such high deployment capability. The STEM or Storable Tubular Extendible Member has been known as a simple and reliable deployable structure since the 1960s. However, most STEM applications are antennas and telescopes[2,3]. They are not considered to retract once they extend. Most of those STEMs are manufactured by beryllium copper (BeCu), but they are quite heavy to install in small satellites or robots

2.3: Proposal of REX-J

JAXA is to conduct the space robotics experiments named REX-J on the International Space Station Japanese Experiment Module (ISS/JEM). Aim of the REX-J is to evaluate feasibility of newly developed technology for NGSR. Technologies to be tested by the REX-J mission are robot's locomotion capability to move the robot along the surface of the space station carrying payload or conducting inspection of the space station.

The REX-J mission was proposed in 2007 in response to the announcement of opportunity (AO) to collect mission ideas to be conducted on the International Space Station Japanese Experiment Module. This mission proposal is based on an idea of tether based robot system to build and maintain the space solar power system (SSPS). However since the space which is allocated to each mission are quite limited. REX-J's experiments are not so dynamic but rather theoretical ones. The following table 2 shows milestones or events of REX-J mission.

Year	Mon	Milestones/ Events
2006	Nov	AO (Announcement of Opportunity)
2007	Feb. May Dec.	Mission proposal Pre-selected as a candidate mission Selected as a mission payload
2008	 Oct. Nov	Preparation of the project plan. System Definition Review Start of Project (phase C)
2009	Mar. Oct.	Preliminary Design Review Critical Design Review
2010	May Nov	PFM Integration & Proto-Flight-Test Integration into MCE
2011		MCE Proto Flight Test
2012	Feb. July	Integration into HTV Launch by HTV-3/H-IIB
2013	Mar.	Pre-planned mission end (Extended mission under study

Table 2: Milestones of the REX-J mission

2.4 REX-J Design Requirement

REX-J is one of the five mission equipment which is installed inside a payload unit named MCE (Multi-mission Consolidated Equipment) to be attached to the Exposed Facility of ISS/JEM. Size and mass of the unit are as follows.

<Size and Mass of MCE>

- Size: 0.8m×1.0m×1.8m
- Mass: less than 500kg

<Mission which share MCE>

- IMAP (Ionosphere, Mesosphere, upper Atmosphere and Plasma sphere mapping)
- GLIMS (Global Lightning and Sprite Measurement Mission)
- SIMPLE (Space Inflatable Membrane Pioneering Long-term Experiments)
- REX-J (Robot Experiment on JEM)
- HDTV-EF (High Definition TV Camera System)

These missions share the MCE unit as shown in Fig.3.

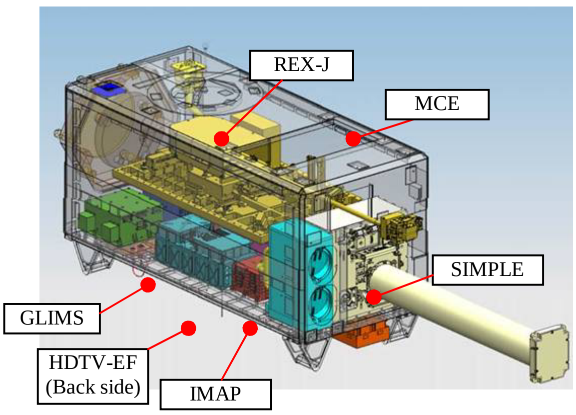

Fig.3: MCE's equipment
(IMAP, GLIMS, SIMPLE, REX-J, HDTV-EF)

3. Development of REX-J

3.1. REX-J experiment system

Since REX-J shares one MCE unit with 5 missions, space for the REX-J's experiment is limited, therefore, we decided to conduct experiment to show the correctness of the NGSR's concept and its locomotion capability within two dimension space. From this definition, REX-J experiment system is to be consisted with following major subsystems.

- Base Plate to mount REX-J's following equipment
- Robot lower section which is supported by tethers
- Robot Upper section which mount an extendable robot arm. The robot's upper section and the lower section is connected by one axes gimbal to adjust the direction which the extendable robot arm will extend
- Handrails to fix a tether.
- Electronics box

These equipment are mounted on the base plate as shown in Fig.4

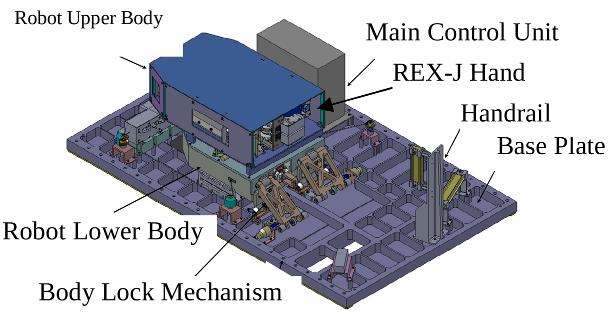

Fig.4 REX-J Experiment System

3.2 Extenable Robot Arm

The function of the extendable robot arm is to drag and hook/remove tethers to/from the handrails. To satisfy those functions, the extendable robot arm must be:

- Deployable and retractable in many times stably without hysteresis
- Controllable and maintainable of the length, even under stressed conditions.

A STEM manufactured using CFRP is used to meet the previously described requirements[4]. The Bi-STEM method is used to raise the stiffness. The maximum STEM length is 2500 [mm] in test model. The STEM reel mechanism has two sprockets; sprocket holes are on the STEM surface. The deployment and retraction mechanism is portrayed in Fig.4. It has two motors: one actuates the reels of the STEM and is used for rolling up; the other actuates the sprocket and is used for deployment. The actuated sprocket pulls out the STEM from the reels when the STEM is deployed. The STEM stiffness increases as its cross-sectional shape becomes circular. Immediately after deployment from the reel, the cross-sectional shape is flat and buckling occurs easily. To prevent this, the sprocket is set slightly distant from the reel so that the tensile stress is applied to the STEM, whereas its cross-sectional shape is too flat. The STEM reels are actuated to roll up when it is retracted. This is also efficient to prevent the STEMs from loosening in the reels. The PFM of extendable robot arm as shown in Fig. 6 was developed based on the above experimental results of prototype, BBM and EM.

3.3 Robot Hand

As described above, because of the limited resources, only the simple robot hand can be installed in this mission. However, the robot hand must still grasp at least two different objects: a hook and a handrail. Moreover, in the future, many more objects should be grasped by the same kind of hand. Therefore, we chose the human-like multi-joint fingers. The design of the finger follows the JAXA-THK hand (Fig. 7).

The same type of actuator is used in the fingers. The robot wrist has 2 degrees of freedom, which is the minimum number to grasp both a vertical and a horizontal handrail from any direction (Fig.8). The robot hand unit will be installed at the top of the arm. It is impossible to drag all cables to drive and control the unit. For this reason, the control electronics for the all the motors in the hand unit is installed not in the robot body, but in the wrist. Design concepts for the robot hand unit are listed below.

Design Concept

- The grasping targets are both the handrail and the hook of the experiment system.
- The mechanism and parts are expected to be similar to the JAXA-THK hand.
- A robot hand has two fingers.
- The wrist has 2 degrees of freedom.
- The control electronics should be set in the wrist

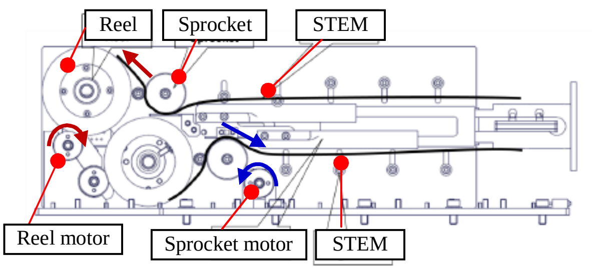

Fig.5 : Mechanism of extendable robot arm

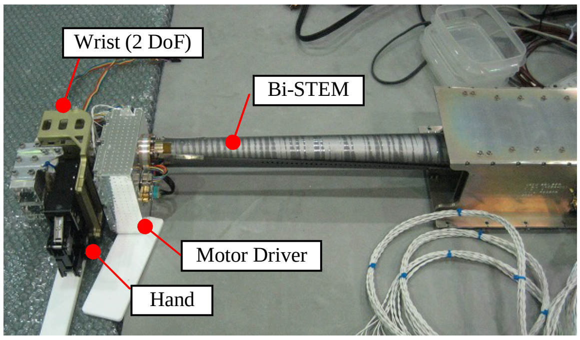

Fig.6 : PFM of extendable robot arm (the maximum length is limited to 1300mm for safety)

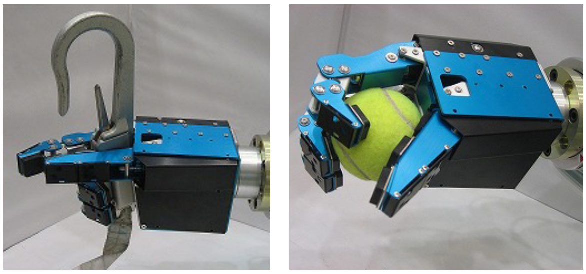

Fig. 7: JAXA/THK Hand II developed in 2009

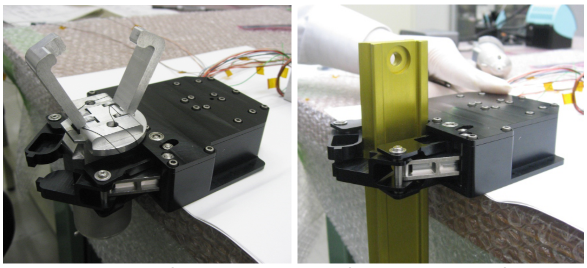

Fig. 8: PFM of robot hand (left: Grasping of Tether Hook, right: Grasping of Handrail)

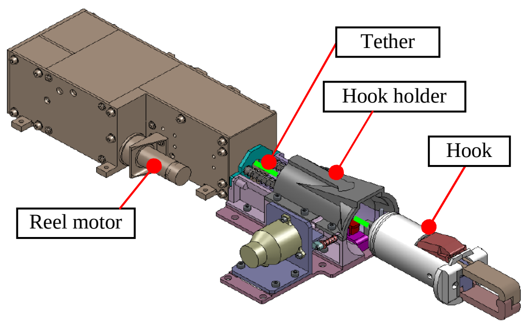

Fig. 9. 3D-CAD model of tether reel and hook

3.4 Control of Tethers

Position of the REX-J robot will be decided by the length f each robot. Therefore each tether's length must be controlled to the required length. Basic algorithm of the robot motion control by tethers is as follows.

1) Measures location of the robot body using video

image from the monitor cameras.
2) Calculate the inverse kinematics of the tethers which results the robot's location
3) Calculate the tether's inverse kinematics which will result the robot's target location
4) Calculate whether a direct path to the target location exists.
5) Control each tethers as follows.
   a) Select a tether which mainly pulls the robot to the target direction and another tether(s) will follow the motion of the robot

The tether unreeling and reeling mechanism is rather simple. Fig.9 shows a 3D-CAD model of the tether reel mechanism. A mechanical hook is attached at the end of the tether. This hook can be operated by a human or by a robot.

3.5 Tele-operation of REX-J from ground

While most of ISS/JEM's payloads are operated by onboard astronauts, REX-J will be operated from the ground. JAXA has extensive experience of tele-operation of the satellite mounted robot arm on the ETS-VII satellite from ground using a data relay satellite in the geo-stational Earth orbit. Fig.10 shows ISS/JEM's tele-operation network when REX-J experiment will be conducted.

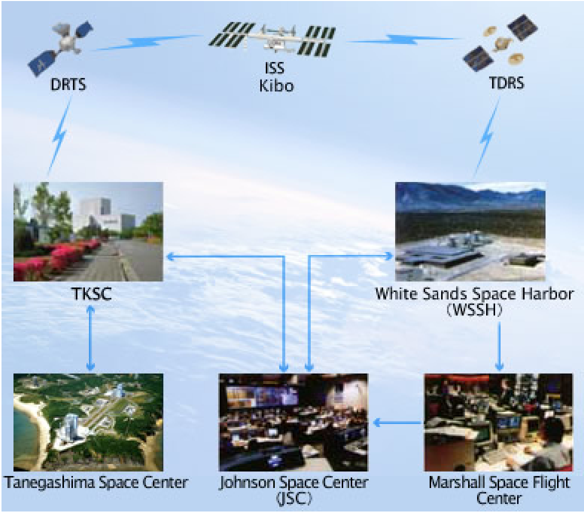

Fig.10. ISS/JEM's operation system

3.6 Ground Operational System

REX-J ground operational system consists of two laptop computers and one desktop computer as ground support equipments (GSE) as shown in Fig. 9. A laptop computer named REX-J GSE-1 is used for processing command data (CMD) to the onboard system, and the other laptop computer named REX-J GSE-2 is used for processing telemetry data from the onboard system. A desktop computer named REX-J GSE-3 is used for processing camera image data from onboard cameras.

The basic functions of each GSE are shown as follows.

(1) REX-J GSE-1 (for CMD)
- Editing CMD
- Sending CMD
- Graphic Simulation

(2) REX-J GSE-2 (for TLM)
- Receiving TLM
- Processing and Displaying TLM

(3) REX-J GSE-3 (for Vision)
- NTSC Video Processing
- Accumulating Image Data
- Image Processing

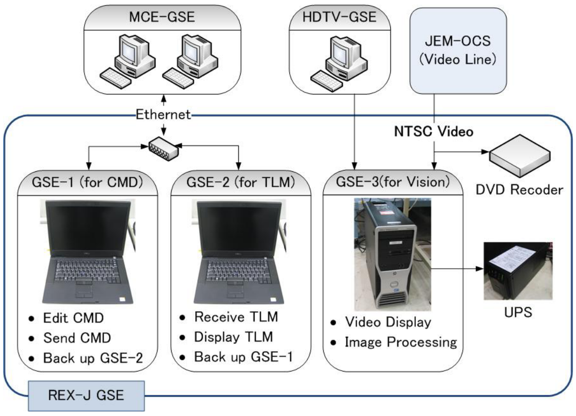

Fig.11. REX-J's on-ground tele-operation system

3.7. Proto Flight Test

Proto flight tests were conducted in 2010 after assembling experiment equipments. Proto flight tests are as follows;

- Functional test
- Environmental test (vibration test (Fig. 13), thermal vacuum test, EMC test)

Through the tests, REX-J mission equipments were successfully verified that they satisfied all the requirements.

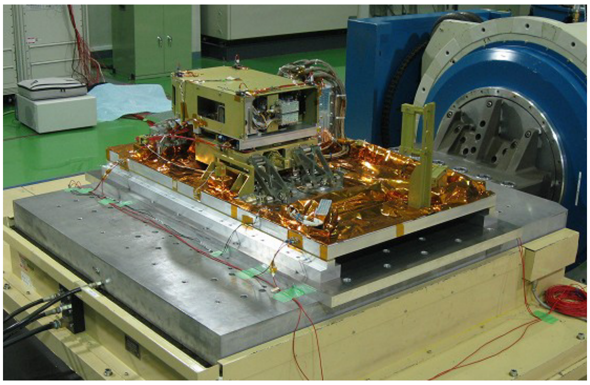
Fig. 12: REX-J PFM during Vibration test

3.8 MCE Integration Test

REX-J mission equipments were integrated into MCE with four other mission equipments (Fig. 14). After the integration, functional tests (in particular, communication function test) and environmental tests were conducted as MCE mission equipments. Then, end to end test was conducted to verify the communication function in the equivalent configuration of the actual operation including ground operation system in August, 2011. During the period of integration tests, huge earthquake hit Tohoku and Kanto region in March 11th. Some test facilities in TKSC were damaged for the disaster. MCE mission equipments did not get any direct damage to the structure but got some dusts because of wall collapse in the test room where MCE was at the earthquake. MCE mission team was forced to change their test schedule, but all the tests were finished without large delay from the original schedule. REX-J mission equipment in MCE was shipped to JAXA's Tanegashima Space Center (TNSC) in October 2011 for the launch preparation. Fig.14 shows MCE is placed on the HTV's Exposed Pallet. This Pallet will be installed into the exposed section of HTV as shown in Fig.15.

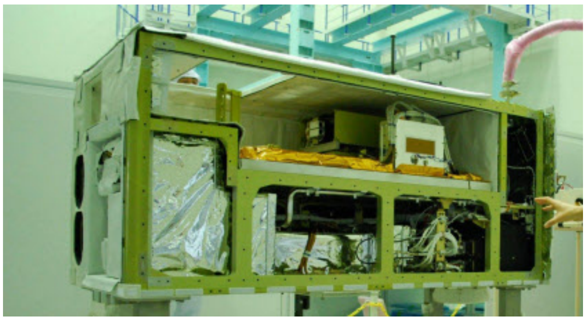

Fig. 13: Proto-Flight Model of MCE
(the REX-J robot is inside the MCE)

Fig 14. MCE and NASA's payload on HTV's payload pallet.

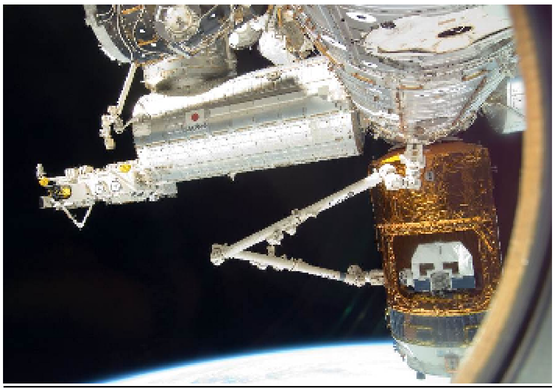

Fig. 15; Space station remote manipulator is pulling out the payload pallet from the HTV-2

HTV-3 which carries REX-J will be launched atop of the H-IIB rocket. HTV-3 will automatically conduct rendezvous with the International Space Station and then, HTV-3 will be captured by the Space Station Remote Manipulator. After HV-3 is attached to ISS, the exposed pallet will be attached to the JEM's Exposed Facility. Then the JEM Remote Manipulator will grasp MCE and attach it to the #8 port of the JEM's Exposed Facility as shown in Fig. 16.

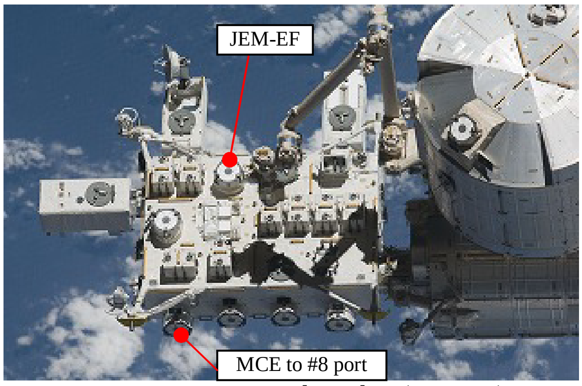

Fig. 16: JEM Exposed Facility (JEM-EF)

4. On-orbit experiments

4.1 Experiment plan

Several experiments are to be performed by the REX-J mission.

<**Minimum success level experiments**>

(1) Releasing launch locks and initial checkout of each component

(2) Evaluation of performance (ex. positioning accuracy) and property (ex. vibration property, sympathetic vibration property with tether) of the extendable robot arm during motion under micro-gravity and thermal vacuum environment

(3) Attaching the tether hook grasped by the hand to the handrail by the extendable robot arm

<**Full success level experiments**>

(4) Demonstration of tether-based locomotion method

<Extra success level experiments>

(5) Cooperative control of the extendable robot arm and tether mechanism

(6) Extending the arm to outside of MCE and checking the vibration caused by the change in the temperature and solar irradiation.

The following images, Fig. 17 and Fig. 18, show the main two experiments, "(3) attaching the tether hook to handrail" and "(4) tether based locomotion".

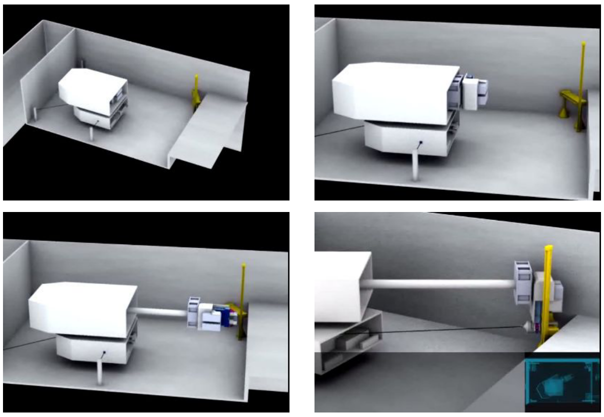

Fig.17: Experiment of attaching tether hook to handrail

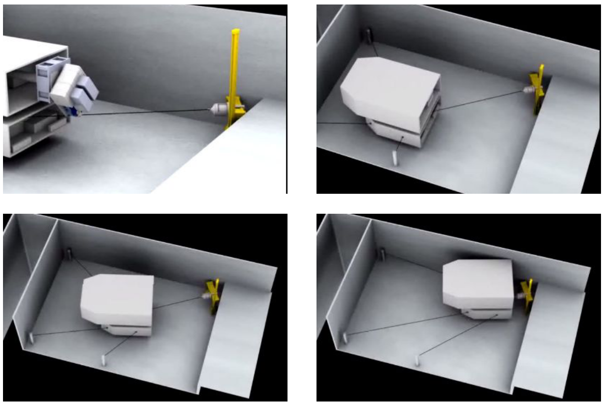

Fig. 16: Experiment of tether based locomotion

5. CONCLUSIONS

JAXA's ongoing research of the astronaut support robot, named "NGSRs" and its technology demonstration mission named REX-J are explained. Aim of the REX-J mission is to demonstrate some key technologies to realize the NGSRs. Uniqueness of the REX-J is its locomotion method which is based on tethers. The robot is floated by tethers on a wall and moves around by controlling the tether length and also changes the motion range by dislocating the attached point of tethers with an extendable robot arm. The robot mission will be conducted on the exposed facility of the Japan Experiment Module, International Space Station in 2012. This paper presented the mission, in particular, the results of proto flight tests of the on-board experimental system as ongoing development status and the preparation for the launch to the ISS and the on-board operation. The operation of the mission will be just around the corner.

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