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Robotic hand developed for both space missions on the International Space Station and commercial applications on the ground

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Abstract— **It is readily apparent that a more dexterous and practical robot hand will be needed both in space and for commercial applications. However, although robots can succeed in many fields, highly advanced robotic hand have not been used.**

In our laboratory, robot hands that are useful for both in space and in commercial use are developed. The robot hand for space is designated as the *REXJ Hand*. It has been developed by remodeling another robot hand designed for ground use. The *REXJ Hand* will be launched to the International Space Station in 2011 as a part of the REXJ Project. Remodeling of a normal robot hand to a space robot hand is described herein.

I. Introduction

ALTHOUGH astronauts and space tourists are expected to become more numerous in the near future, the cost of sending them to space and returning them safely to Earth will not decline sharply during that time. These circumstances demand the utilization of space robots to support manned space activities. Robots are expected to play an increasingly important role in space development.

Benefits of using space robots for space missions include reduction of mission costs related to astronauts and reducing risks of accidents involving astronauts. Reducing astronauts' work hours will also justify the use of space robots. Those spared work hours of astronauts might then be used for other useful and worthy tasks.

Robots that support or work in place of astronauts are therefore anticipated. We define this new type of robot as an Astronaut Supporting Robot (Astrobot) [1]. Science Astrobots are expected to handle many tasks such as those that astronauts do in space, they should have hands that are small, dexterous, and sufficiently powerful to perform astronauts' work.

Not only for space applications, but also for commercial applications, more dexterous and powerful robot hands are also anticipated. During mass production processes, industrial robots are designed to grasp only one or a very few shapes, and the general mode of using robots in factory lines is for "pick and place" tasks. However, many processes require high-mix low-volume production: factory lines need a more generally useful robot hand to respond to such demands for tasks. In addition, robots, such as nursing robots or artificial hands for people with disabilities, require more dexterous and powerful hands [2]. Many robots have been suggested for use in society, but the tasks those robots can accommodate are practically limited to roles such as security verification or giving directions because many tasks and functions that humans must do in everyday life require the use of hands: as stated earlier, those robots did not have adequate hands. Their hand shape and dexterity should resemble those of human hands to work in human society. A more dexterous and powerful robotic hand is a necessary technology.

As described in this paper, two robot hands are introduced. The first hand is designated as *JAXA-THK Hand*, which was developed for both commercial and advanced space applications. Another robot hand is called *REXJ Hand*, which was designed for the Astrobot to be used in the *REXJ* project. In fact, *REXJ Hand* was developed by remodeling the *JAXA-THK Hand*. This paper describes the process of adaptation for space application of a robot hand originally designed for ground applications.

II. Former robot hands and requirements for a new robot hand

Many dexterous hands have been designed to resemble human hands [3]–[5]. Nevertheless, they have very limited grasping power because of the actuators' capability to drive fingers. Most hands include rotary actuators in the finger joints, but human hands are too small to contain sufficiently powerful actuators. Most powerful robot hands are gripper-type robot hands, but those hands are insufficiently dexterous to perform many tasks. Two famous robot hands—the Stanford–JPL hand [6] and the Utah/MIT hand [7] developed in the 1980s—had large actuators inside of the robot's body to increase grasping power, but the actuators

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made the hand impossible to use depending on the situation and payload. Moreover, this method complicates mechanisms and maintenance. The SARAH Hand [8] developed by LAVLA University is a very advanced dexterous robot hand designed for use in space. It has a good command of holding, but it is not designed to operate tools.

These prior analyses indicate that a new robot hand for astronaut-supportive activities or as a general industrial robot should have the following functions.

1. The robot hand must have sufficient dexterity to grasp or handle payloads and tools with high grasping power; it should be sufficiently small to be installed in many arms and must handle objects a human could usually handle.
2. The robot hand should be removable or exchangeable from its wrist so that it can be maintained easily or exchanged depending on the mission.

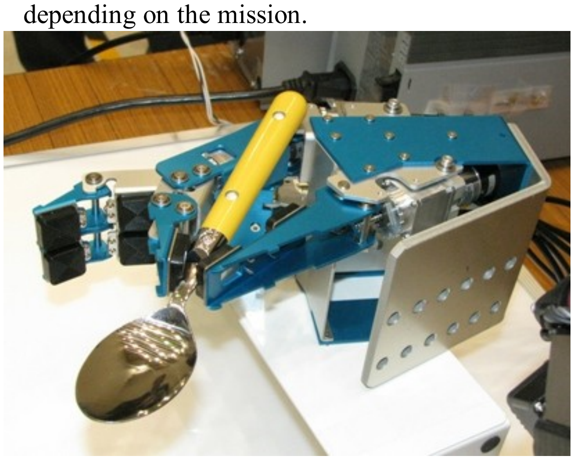

Fig. 1 *JAXA-THK Hand*

III. JAXA-THK HAND

According to the functions listed above, a team of members from *JAXA-THK*, Keio University, and the Tokyo Institute of Technology developed a *JAXA-THK Hand* for advanced space and ground application (Fig. 1).

FUNCTIONS

The salient feature of this hand is that it can produce high grasping power without large actuators. The grasping power of this hand is about 200 N. Also this hand is designed to have almost same capability as the suited astronauts. The actual functions required to the hand are listed in TABLE I.

Basically, the EVA is classified into three phases. Moving, Working, and Inspection. The crew's hands perform different role in each phase. In the Moving Phase, the crew must hang to the handrail and move around the ISS or Space Shuttle. The handrail is grasped tightly and the safety hook, which prevents the crew from flying away, is used. The crew also must drug and bring the equipments and module to the worksite. After the crew reaches the worksite, he/she works by using their hands and EVA tools. D. L. Akin et. al. categorized the EVA tools used in Space Shuttle mission [9]. The categories are according to the taxonomy developed by Cutkosky and Wright [10]. It is reported that 53 percent of the EVA tools can be handle just by cylindrical holding. Other EVA tools must be grasped by pinching and some have levers, dials, and buttons to be operated, so it is obvious that just grasping is not enough. However, it is true that the dexterity of the robotic hand can be limited comparison to the one on the ground. On the other hand, quite high grasping force is needed. In the document, "*Extravehicular Activity (EVA) Hardware Generic Design Requirements Document*" [11], a maximum force of 20 lbs and torque of 30 in-lbs are required to remove and install EVA orbital replaceable units (ORUs). In the inspection phase, the crew inspects the outside of the facility or watches other crew's safety. Almost same functions as in the moving phase are required to the hands.

The *JAXA-THK Hand* is designed to perform every required function in the EVA. Furthermore, all the actuators and control electronics to drive this hand are installed inside

TABLE I
EVA PHASE AND THE TASKS THAT THE ASTRONAUTS' HANDS CONDUCT

phases	Hand's Tasks		Grasping Modes
Moving	Moving with holding/hanging to the handrails		Power Grasping
Moving	Carrying Object to the Work Area		Power Grasping
Moving	Handling tethered-hook		Power Grasping, Fitting Movement
Working	Operation by the hand		Power Grasping, Pinching, Push With Finger
Working	Operation by the tool	Simple Tool	Power Grasping
		Pulling Lever	Power Grasping, Fitting Movement
		Pushing Button	Fitting Movement, Push with the Finger
		Operate Dial	Pinching
Working	Sampling Approach		Power Grasping, Pinching
Inspection	Moving with holding/hanging to the handrails		Power Grasping

the hand. This hand needs only the CAN signal and 24 V power supply to be driven.

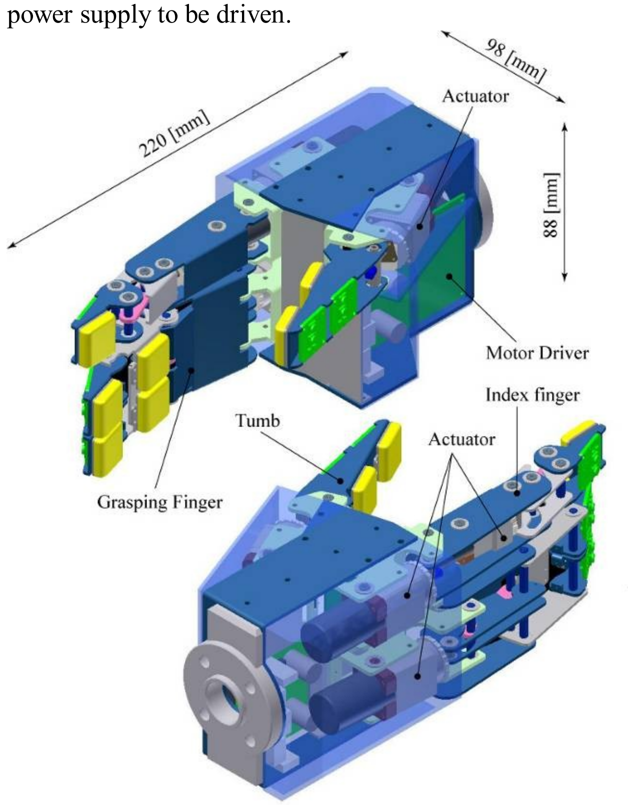

Fig. 2 Architecture of the *JAXA-THK Hand*

ARCHITECTURE

JAXA-THK Hand has three fingers, one thumb, one index finger, and one grasping finger. The thumb has one *metacarpophalangeal joint* (MP) facing to the index finger to support pinching. The index finger has three joints. Two actuators are installed inside. One at the bottom of the finger drives only the MP joint. Another in the first link drives both *the proximal interphalangeal joint* (PIP) and *the distal interphalangeal joint* (DIP) joint simultaneously. This finger is used mainly for handling or operating tools or for pinching. The grasping finger also has three joints, but it has only one actuator at the bottom. This finger's width is almost double that of the index finger. A spring is installed in the distal joint; using it, the distal finger can fit to the object. This mechanism is also efficient to prevent sprained fingers. Rotary actuators are usually used for robot hands. However a linear actuator is selected for our *JAXA-THK Hand* because the linear actuator can apply more power than rotary actuators. A small brushless linear actuator (Fig.3) is developed for our hand. It can produce up to 500 N even though it is sufficiently small to install inside the finger. A brushless motor, the harmonic gear, and a ball screw are assembled in the actuator.

Small control electronics are developed for our hand, with approximate size of 54 [mm] × 45 [mm]. It can drive two actuators, so two boards are mounted in one hand. It has a CAN interface to reduce the wiring.

Using the *JAXA-THK Hand*, several holding experiments were conducted. The objects are grasped using three grasping modes: power grasping, pinching, and operation (Fig.4).

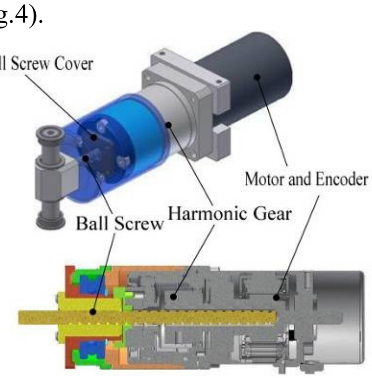

Fig. 3 The blushless linear actuator

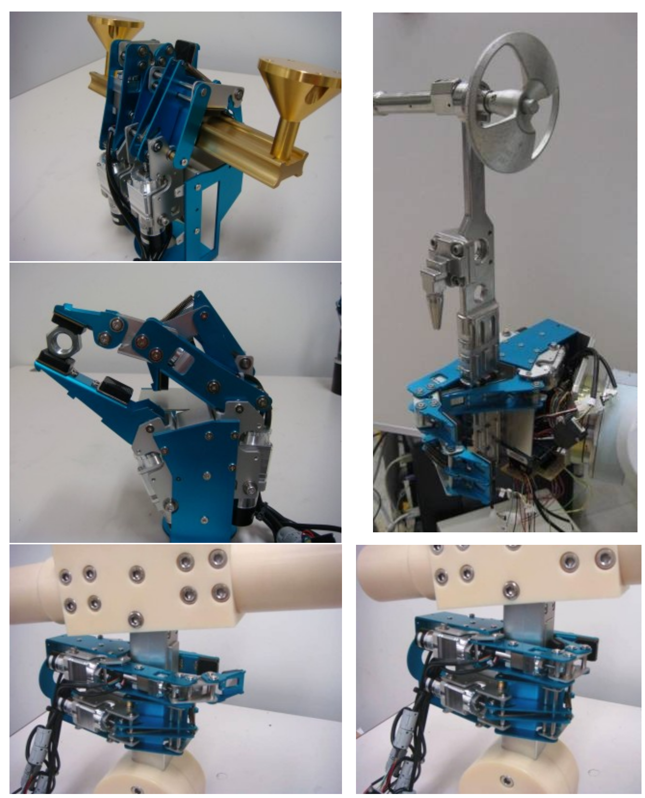

Fig. 4 *JAXA-THK Hand* holding handrail and demonstrating pinching and operation some EVA tools

IV. REXJ PROJECT

In our laboratory, an Astrobot is being developed with the Japan Aerospace Exploration Agency (JAXA). This project is called the REXJ project, which stands for "Robot Experiment on JEM" (Fig. 5). It will be demonstrated on the International Space Station (ISS) in 2011. Our *JAXA-THK Hand* is used to develop the robot hand for this robot. This new Astrobot robot hand is designated as the *REXJ Hand*.

Because the volume of the space that is allocated for the REXJ mission is limited, a robotic hand with two fingers is developed for this mission. This robotic hand is developed to be a proving test model of *JAXA-THK Hand*. The *JAXA-THK Hand* is designed to grasp a wide range of objects of various sizes. In stark contrast, only a few objects must be grasped in REXJ Project. Consequently, *REXJ Hand* can be much simpler than the *JAXA-THK Hand*. This is an important point because a simpler design greatly reduces the risk of trouble. Before developing an Astrobot hand, we must clarify the mission and actual tasks in REXJ Mission.

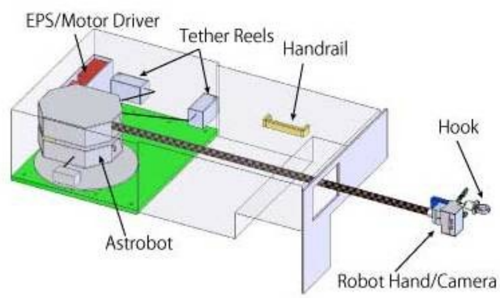

Fig. 5 The system of REXJ project

REXJ MISSION

The REXJ project's purpose is to demonstrate the fundamental functions and key technologies to realize the Astrobot. Because initial conditions allowed for the mission are strictly limited, we specifically examine the following necessary capabilities for the Astrobot.

(a) Capability of moving around the space structure using infrastructure prepared for the astronaut's work.
(b) Capability of holding equipment or tools designed for astronauts.

For the REXJ project, we suggest a new type of the locomotion using several tethers and an extendable robot arm. It is called *tether-based walking*. This new method enables the robot to move quickly and safely. The robot's locomotion principle is the following.

(1) The robot has several tethers wound in reels inside the robot body. Each tether has a hook-like mechanism to attach it to a structure, such as a handrail, prepared for astronauts.
(2) Robots have an extendable robot arm. The robot arm has a robot hand at its end.
(3) The extendable robot arm will grasp the tether hook and extend the tether.
(4) The robot attaches the tether hook to a handrail or secures itself by some other method.
(5) It retracts the robot arm and grasps the other tether hook.
(6) Connect other tethers to other points.
(7) Adjust the length of each tether. Then the location of the robot will change.
(8) The area in which the robot can move depends on the number of tethers attached to the structure and the location of each tether anchoring point. Using three tethers, the area in which the robot can move is a triangular plane defined by the three tether-anchoring points. The area in which the robot can move becomes a three-dimensional space if the number of tether-anchoring points is four or greater.
(9) If necessary, the robot can change the locations of the tethers' hooks using the extendable robot arm. Then the area or space in which the robot can move can be changed.

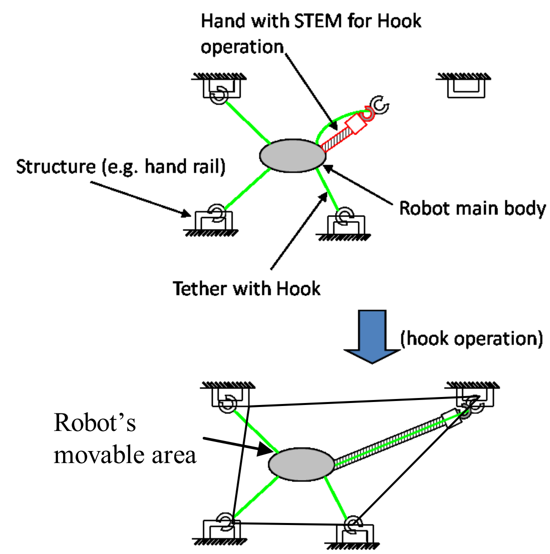

Fig. 6 Principle of the tether based walking

V. REMODELING DEXTEROUS HAND TO *REXJ HAND*

To realize the tasks and moving method described above, the major requirements for *REXJ Hand* are set as the following;

(a) *REXJ Hand* must be able to manipulate tether's hook so that the robot can move.
(b) *REXJ Hand* must have sufficient power so that the robot

hand can convey a tether's hook or even apply some tensile force to the tether. To open the hook used in the mission, more than 20 [N] of the finger tip force is required.

(c) Because the *REXJ Hand* is a demonstration model of the *JAXA-THK Hand*, almost same architecture must apply.

The robot hand in space must also consider the space environment. TABLE II shows a specific problem caused by the space environment.

Considering the REXJ's missions and space environment, the *REXJ Hand* is developed. Fig.7 portrays the CAD model of the *REXJ Hand* and Fig.8 shows the whole *REXJ Hand* system.

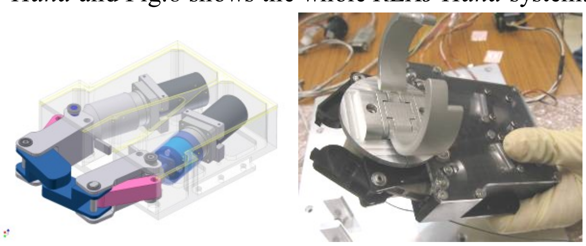

Fig. 7 The CAD model and the Engineering Model of*REXJ Hand*

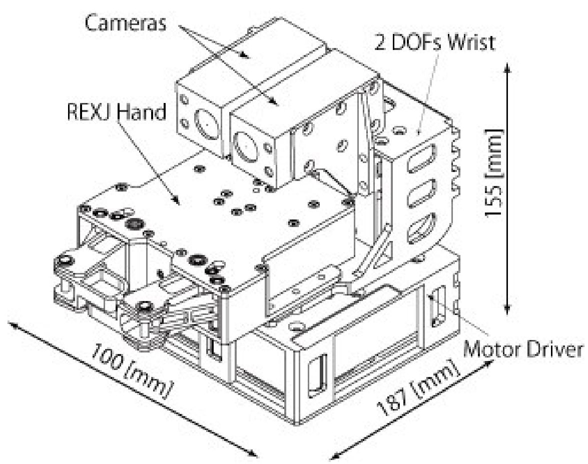

Fig. 8 The Whole View of *REXJ Hand* System

(1) Architecture and Mechanism

Considering these circumstances and the hand requirements, two fingers with two joints in each finger are necessary for the *REXJ Hand*. Each finger has an actuator: they are mutually independent. Consequently, the hand can hold or release grasping objects even if either finger of the two has trouble. Two fingers are opposing each other. When it is launched, their finger tips bunt to each other for launch lock. The hand surface is treated with black-alumite to prevent the hand from oxidization caused by Atomic Oxygen.

(2) Control Electronics

TABLE II
SPACE ENVIRONMENT

Radiation	High radiation causes SEE damage to the control electronics. Elemental radiation-tolerant devices must be used.
Atomic Oxygen	In lower orbit, atomic oxygen oxidizes structures.
Temperature	Temperatures extends from less than -100°C to more than 100°C. Therefore, appropriate thermal management is needed.
Vacuum Atmosphere	Under vacuum circumstances, most lubricants are vaporized.
Vibration	The robot is launched by the rocket. Every moving part should be locked.

Radiation is the biggest hazard to the control electronics. Because most space elements are too large to install in the hand, many commercial-off-the-shelf (COTS) items are used after radiologic examination. Consequently, the control electronics are enlarged to 100 [mm] × 100 [mm]; one controller has two CPUs and it can drive four motors.

(3) Lubricant

The *REXJ Hand* uses space lubricant for all bearings and inside the actuators. To prevent contamination by vaporized lubricant, the actuator's ball screw is covered and all bearings are shielded.

(4) Temperature

Because of the vacuum circumstances, the temperature of the actuator rises easily. The actuators used in this hand are not space devices. It is impossible to drive actuators continuously for a long time because of the fear of burning. To avoid this problem, we limited its operation and mission time. The hand is designed to keep holding even during power-off so the actuators need not be driven for a long time.

VI. *REXJ HAND* SIMULATION AND EXPERIMENT

Motion analysis of grasping a hook by the *REXJ Hand* was conducted. It was done using software (dynamic simulation, Autodesk Inventor; Autodesk Inc.). The simulation confirmed that the hand can push the button of the hook even if the hook doesn't face to the hand properly on some level (Fig.9).

Also, simple operation check has done. The tethere's hook is opened by the *REXJ Hand* and as the result, the it is confirm that the hand can open the hook used in the REXJ mission. Fig.10 (left) shows the *REXJ Hand* open the hook.

Fingertip force is measured and the result is shown in the following matrix. TABLE III shows that this hand has sufficient power to grasp handrail and handle hooks. The fingertip force is maintained after turning the power off. The force is measured by the force gauge like that shown in Fig.10 (right).

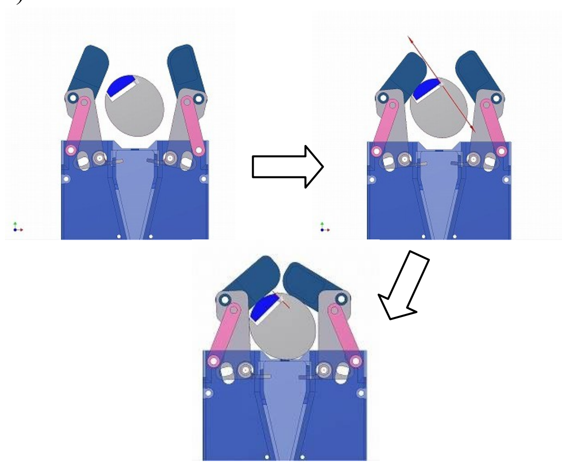

Fig. 9 An example of the simulation results. The figure shows the hand can push the button that opens the hook even the hook posture doesn't face to the hand properly.

Fig. 10 The picture of*REXJ Hand* opens the hook (left) and measuring the fingertip force (right).

VII. CONCLUSION

As described in this paper, two models of dexterous hands are introduced. One is a robot hand designed for commercial applications; another is for space. It is readily apparent that more dexterous and practically useful robot hands will be needed in both space and commercial applications. However, although robots can succeed in many fields, highly advanced robotics have not been brought to space. One reason is that developing space robots is costly. Another reason is that robots specialized to space environments can only be used in space. It is difficult to apply them for commercial applications. Regarding these facts, we decided to develop a space robot hand by remodeling a robot hand for commercial applications. The developed space robot hand, called *REXJ Hand*, will be launched to the ISS in 2011 as a part of the REXJ project, which is a demonstration of an Astrobot. The mission of this project is to demonstrate the capability of new movement methods and handling by the *REXJ Hand*. Requirements for the *REXJ Hand* to realize those missions are inspected and *JAXA-THK Hand* is remodeled to satisfy those requirements.

TABLE III
FINGERTIP FORCE

Current to actuator [mA]	Power Consumption at actuator [W]	Fingertip Force [N]
600	1.08	31.3
700	1.56	39.2
800	1.92	44.7

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