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Smart Manipulator Actuated by Ultra-Sonic Motors for Lunar Exploration

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***Abstract*— A new lunar exploration mission including a lander and rovers is under studying in Japan. The main mission for lunar robotics exploration is to demonstrate the technologies for lunar or planetary surface exploration. They will cover pin-point landing technology, reliable landing scheme with obstacle avoidance, landing mechanism on rough terrain, exploration rover and tele-science technology. Lunar geologic survey will be also performed to investigate the underground materials. The working group has been conducting the feasibility study of advanced technologies for lunar robotics exploration. In the rover mission, a robotic manipulator plays an important role as scientific observation tools for geological exploration. This paper proposes a light-weight manipulator with low-power consumption function. To investigate the effectiveness of the proposed design, a manipulator was developed. This paper describes a proposed smart manipulator system. This paper also presents the environment test results on Ultra-Sonic Motor. The performance of the developed smart manipulator is discussed.**

I. Introduction

A new lunar exploration mission including lander and rovers is under studying in Japan. The mission will follow up SELENE (SELenoligical Engineering Explorer), a lunar global remote sensing mission scheduled in 2007. The main mission for lunar robotics exploration in post SELENE [1] is to demonstrate the technologies for lunar or planetary surface exploration. They will cover pin-point landing, reliable landing scheme with obstacle avoidance [2], safe landing mechanism on rough terrain, exploration rover and tele-science technology. The following top science will also be conducted in the robotics mission[3]. Lunar geologic survey will be performed to investigate the underground materials. In-situ analyses of the surface rocks and soils are also conducted with a special emphasis on the investigation into the organization, structures, and composition by cutting or grinding the collected samples. The characterization of the site can be observed by multi-band imaging X-ray spectroscopy and Gamma-ray spectrometer. These are the key information to study the lunar inner structure and to understand the origin and evolution of the moon, as well as to investigate the evolution of magma ocean and later igneous processes [4][5][6][7][8].

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Fig.1 Lander-Rover Exploration

For geological exploration on the moon, the lander and rover cooperative exploration is under studying as shown in Fig.1. The working group has been conducting the feasibility study of advanced technologies for lunar robotics exploration. Unmanned mobile robots[9] are expected for the detailed surface exploration of the moon, because rovers can travel safely over a long distance and observe what to see by some scientific instruments. Therefore the rover R&D group has studied an innovative science micro rover with a new mobility system and a lightweight manipulator.

This paper describes a lunar robotics exploration by rover [10]. In the rover mission, a robotic manipulator plays an important role as scientific observation tools for geological exploration. This paper proposes a light-weight micro manipulator with low-power consumption function. To investigate the effectiveness of the proposed design, a novel manipulator was developed. The developed smart manipulator has five degrees of freedoms and each joint is driven by an Ultra-Sonic Motor (USM). The developed manipulator needs no electrical power to keep the posture of the manipulator. This paper presents the environment test results on Ultra-Sonic Motor. This paper also presents the performance of the developed micro-manipulator.

II. SMART MANIPULATOR

To perform the in-situ analysis or direct observation on lunar surface, manipulation is required. Here the science requirements and the design for lunar exploration manipulator are discussed.

A. *Requirments for Lunar Manipulator*

Requirements for a manipulator in the rover mission are as follows:

(1) Observation of remote place (by a camera, etc.)
(2) Observation of environment surrounding a rover (including itself)
(3) Collecting samples for scientific observations
(4) Approaching and touching to soils and rocks with scientific instruments such as spectrum cameras
(5) Digging the ground or breaking samples into pieces
(6) Removal of dust from the surface of samples
(7) Functions as maintenance tools such as the cleaning tool for the solar panels etc.
(8) 3D space measurement sensor, etc.

On the other hand, to use manipulators in space environment, various kinds of conditions should be considered as follows:

(1) Down sizing and weight reduction
(2) Low electric power consumption
(3) Long links for large work space and observation of remote place
(4) Enough degree of freedom for missions
(5) Installation of sensors such as cameras
(6) Installation of end-effectors

B. *Design of Lunar Manipulator*

Considering the mentioned demands and requirements, the authors propose a smart manipulator for lunar rover. The proposed manipulator has five degrees of freedom (5DOFs) as shown in Fig.2, because of some operations, for example, picking up samples and inserting a scientific equipment into topsoil.

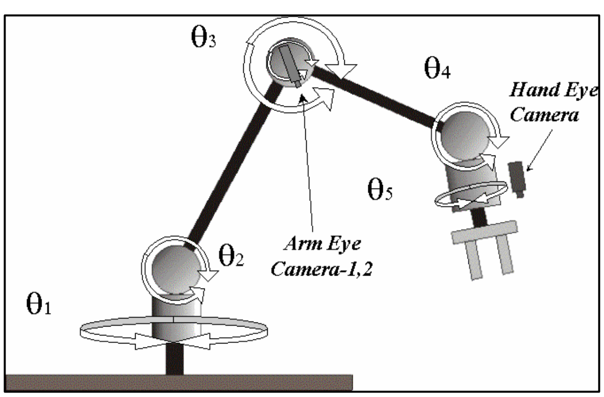


Fig.2 Structure of Smart Manipulator

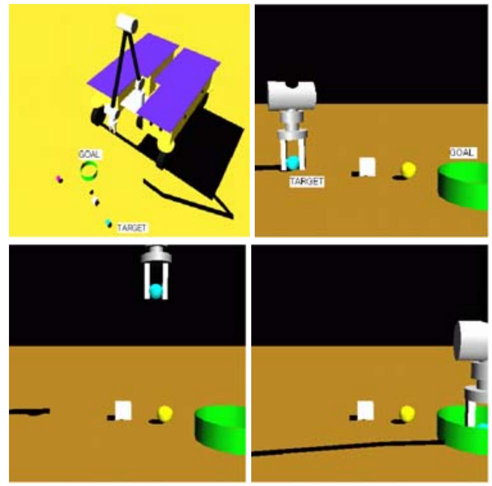


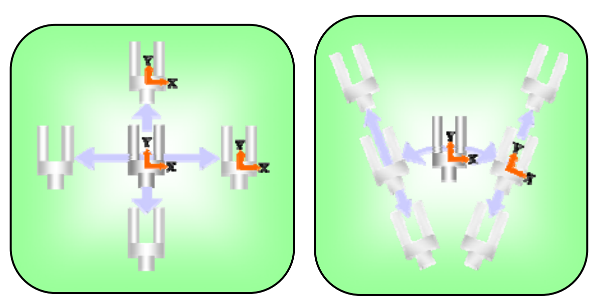
Fig.3 Tele-sampling Simulation

C. *Joint Driving Rate*

In general, a manipulator spends almost of working times on maintaining the posture. So it is considered how long the manipulator keeps the posture and how much the manipulator spends waiting time by each command.

First of all, let us consider the task of a planetary manipulator, grasping samples and putting them into a bucket by tele-operation control. The computer simulation study is performed for these operations as shown in Fig.3. The operator uses a joystick to control the manipulator during operations. In the first step of the approach phase, where a manipulator comes upon a sample, a manipulator is constrained into a parallel plane to the ground.

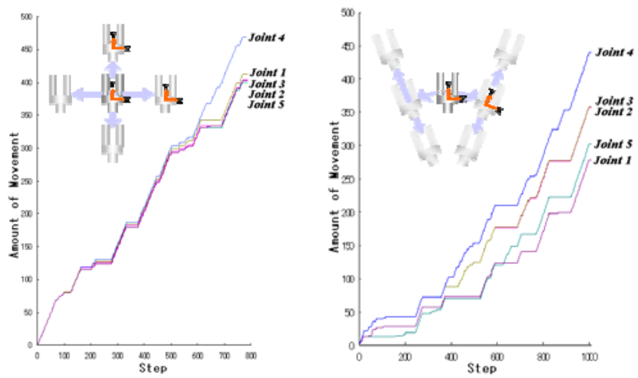
The operator can approach to an upper point of a target sample by two operational methods, namely, the orthogonal mode (mode1) and the polar mode (mode2) as shown in Fig.4. At the second step, when a manipulator arrives at the upper point of a target sample, it will go down to and grasp the target sample. After grasping the sample, the manipulator will be moved to toward the bucket and the grasped sample will be input into the bucket.



(a) orthogonal mode (b) polar mode

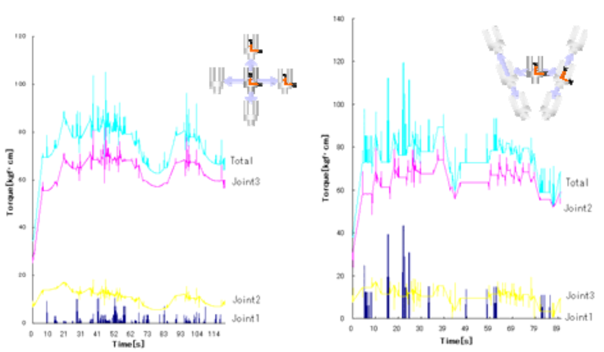
Fig.4 Structure of Smart Manipulator

Here, let us check stopping time of a manipulator during the operation. The transition of joint angles and torques are shown in Fig.5 and Fig.6 respectively. Figure 5 shows the integral summation of each joint motion. Those even parts of each transition indicate that the joints stop. It is easy to find even parts on each operational mode in this operation. Drive rate of actuators is shown in Fig.7. Each joint does not work for more than half of operational time. In that time, however, each actuator produces a torque by using electrical power and also CPU power. This idle time might be increased more and more in actual science operations. That means the huge energy loss for the very severe energy environment like planetary environment. So it is needed to have some countermeasure on this problem.



(a) orthogonal mode (b) polar mode

Fig.5 Joint Movement



(a) orthogonal mode (b) polar mode

Fig.6 Joint Torque

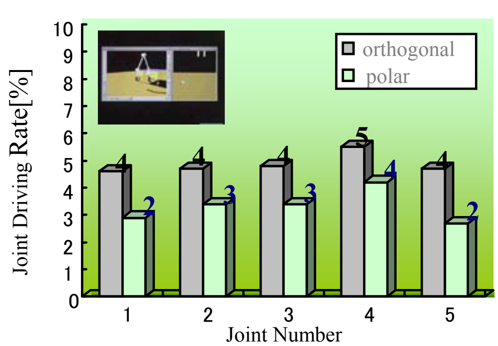


Fig.7 Driving Rate of Actuators

III. Actuator

A. Ultra-Sonic Motor

One of solutions to reduce the power consumption might be a clutch put on a joint. However the clutch mechanism increases the weight of each joint and makes complexity of joint structures. High gear ratio is also one solution, but it is difficult to guarantee to keep joint angles without control. The authors strongly believe that the best solution of this problem is to apply Ultra-Sonic Motor (USM) to the smart manipulator[11]. The actuation principle of USM is an ultra sonic wave, which makes a traveling wave on the surface of a stator. This traveling wave makes an elliptical orbital motion on a contact surface to a rotor, and a rotor is carried to the opposite direction of the traveling wave. It works like a wave, which can carry garbage to somewhere, in the sea. To make a torque on a rotor, it should have a large friction on an interface between a stator and a rotor. It means that USM can have a large static friction during an idle state, so that USM works like a clutch. Furthermore, USM does not need any electrical and CPU power to stop a rotation of a joint. USM and its specification are shown in Fig.8 and Table 1 respectively. The specification shows that USM is the best solution on the point of low electrical power consumption and its weight.

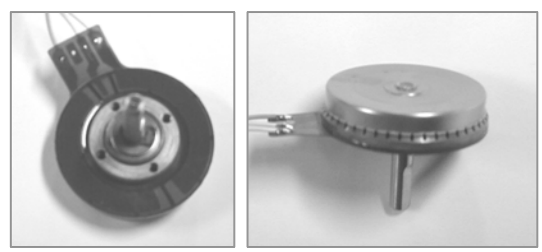


Fig.8 Ultra Sonic Motor (USM)

Table 1. Specification of USM

Rated Speed	250[rpm]
Rated Torque	0.5[Kgf-cm]
Rated Power	1.3[w]
Max. Torque	1[Kgf-cm]
Hold Torque	1[Kgf-cm]
Weight	20[g]

B. Environment Tests

As mentioned before , by using USM as an actuator of a drive part, a big advantage is expected. However, there is no actual use of USM in space mission until now. Therefore, the durability test to the space environment for USM is required, and also space specification will be considered.

First of all as a space specific environment condition, the durability of USM is tested. As early stages of research, the performance is measured by using a consumer product motor. As a motor characteristic, T-N characteristic and the T-I characteristic are measured in the test. As a method of measurement of the characteristic, the USM is rotated at 300[rpm], which condition is no-load and maximum speed. And torque and current and rotation of the motor are measured by using a hysteresis brake.

Furthermore, in order to avoid the influence of self-generation of heat of the motor at the time of rotation, the rotation time of a motor was limited only during measurement.

C. Durability Test for Launch Vibration

Artificial satellites, spacecrafts and rovers are launched with a rocket in the universe. So, a big vibration is added at the time of a launch, and it maybe becomes the cause of failure at USM used for an actuator. Therefore, first of all, the durability on the structure of USM to the vibration at the time is checked.

In an oscillating test, the equipment which carries out the seal of approval of the special vibration at the time of a rocket launch is needed. So, in this test, the launch oscillating simulation equipment of H2A rocket in Japan Aerospace Exploration Agency is used. As vibration at the time of a launch of H2A, the sine wave with a periodic vibration and the random wave which vibrates with random amplitude are used.

In the environment test, the sample motors with the load of 10[g], 20[g], 30[g], and 50[g] which are supposed as the gear of a gear unit hung at the tip of a motor are equipped on the oscillating simulation equipment. In Fig.9, USM with loads are attached on the oscillating simulation equipment. As a result, the characteristic change in oscillating environment test was immeasurable by all 12 motors as shown in Fig.10. However, it is expected that vibration given to sample motor changes with methods and attachment positions, etc. to the equipment. Therefore, it is difficult to guarantee the durability over all the situations of vibration emitted at the time of employment of artificial satellites, spacecrafts and rover only by the result of this environment test.

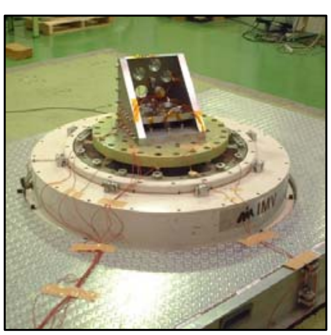
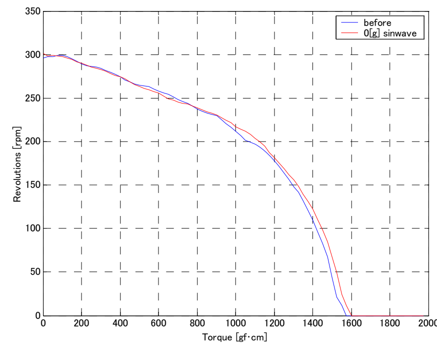


Fig.9 Vibration Test Facility

However, it is rare that a motor is used independently. Usually, sufficient reinforcement is carried out in order to avoid that big load is applied to an axis, in case a motor is used as an actuator. Therefore, from the result of these tests with a motor simple substance, it is shown that USM has excellent durability for the launch vibration.

(a) T-N Curve (Sine Wave)



(b) T-N Curve (Random Wave)

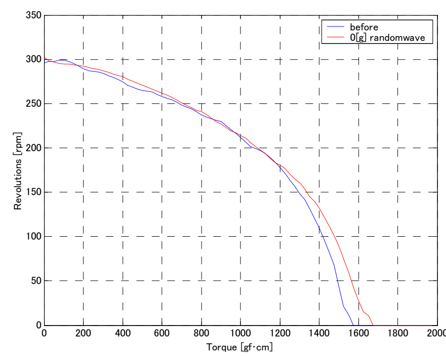


Fig.10 Vibration TestResults

D. Durability Test for Vacuum and Heat Vacuum

First of all, the characteristic change of USM is investigated by change of the degree of vacuum from the T-N characteristic and the T-I characteristic. In that case, temperature was maintained at 20 degrees and the degree of vacuum was changed from 10^{-1} [Torr] to 10^{-6} [Torr]. The motors are rotated only at the time of measurement, and aimed at characteristic measurement of the short period of a vacuum state. Figure 11 shows the experimental equipment.

Figure 12 shows the result of the T-N characteristic. In Fig.11, the horizontal axis indicates time and the vertical axis indicates the number of rotations in each torque. From the graph, even over 12 hours, there are not big characteristic changes.

Next, the degree of vacuum was carried out to more than 10^{-6}[Torr], and the temperature around a motor was changed from -20 degrees to 80 degrees as a heat vacuum environmental test. Figure 13 shows the environment test results. In Fig.12, the horizontal axis indicates temperature and the vertical axis indicates the number of rotations in each torque.

From these test results, the fall of the T-N characteristic was observed at the time of the high temperature environment over 60 degrees. Moreover, not only the fall of this characteristic but the increase in power consumption was observed. Then, when motor rotation at the temperature of over 80 degrees is maintained, rotation became slow gradually and rotation has stopped. And, the rotation stop of this motor is checked in the environment of over 90 degrees also in the normal pressure environment by the present. About the investigation of the cause of failure of this motor, it is under going as a future subject.

However, it is usually artificial satellites and the systems of rovers are equipped with the mechanism of thermal control system. For this reason, in case of USM usage as an actuator by the mechanism of thermal control, it is thought that sufficient temperature adjustment is possible. Therefore, it is possible to carry out improvement to space specification from these results, without carrying out large-scale change for the present USM.

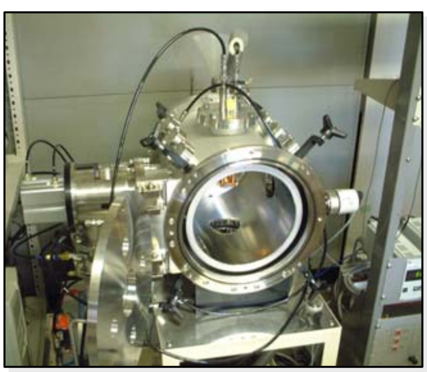


Fig.11 Heat Vacuum Test Facility

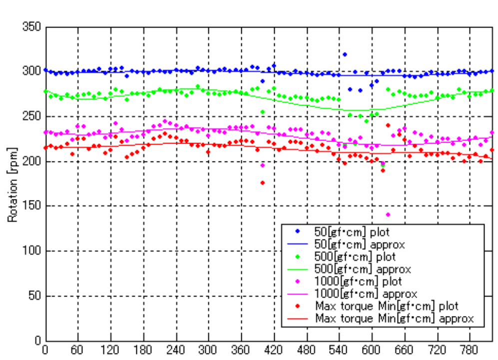


Fig.12 Vacuum Test Results

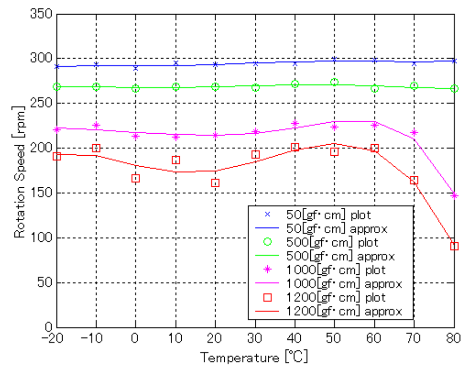


Fig.13 Heat Vacuum Test Results

IV. Development of Smart Manipulator

A. Manipulator

The authors developed a smart manipulator with USM as shown in Fig.14. The feature of the manipulator is described in Table.2. Ultra-Sonic Motor (USM) drives each joint with Harmonic Drive gear, and almost all of links are made of carbon fiber plastics (CFRP). Power consumption for USM and DC motor is compared as shown in Fig.15. Figure 15 shows that USM has better performance than DC motor.

The manipulator is automatically operated between the closed mode and the opened mode. When the manipulator is in the closed mode, the direction of a hand eye camera is into the forward of rover. Therefore it is possible to obtain the front view image by sending from rover. On the other hand, the workspace is mainly to be at the back of rover, when it is in the opened mode. It can also touch solar panel side. It is possible to clean up dusts on panels.

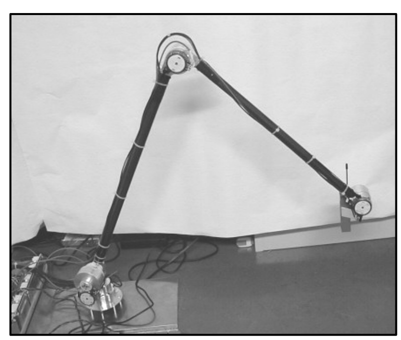


Fig.14 Developed Manipulator

Table 2. Specification of Smart Manipulator

Total Length	920[mm]
Total Weight	1.45[Kg]
Conveyable weight	300[g](on the earth)
Actuator	Ultra-Sonic Motor
Reducer	Harmonic Gear

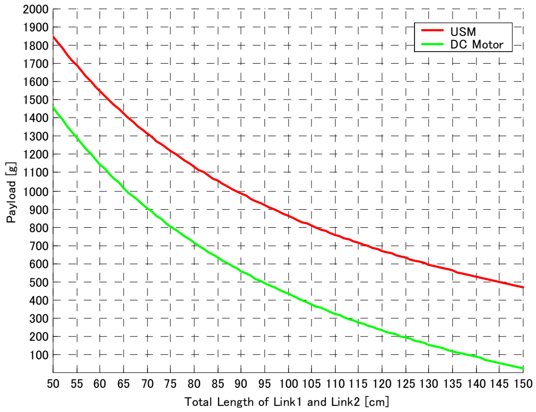


Fig.15 Performance of Manipulator

B. End-effecter

For sample collection, a new end-effecter was developed as shown in Fig.16. The developed end-effecter has two kinds of functions, gripping and scooping. The experimental results for sample collection show the effectiveness of the developed end-effecter as shown in Fig.17.

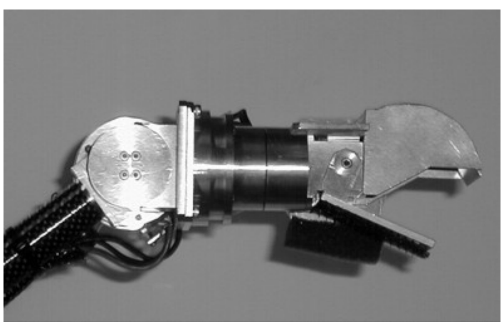


Fig.16 Developed End-Effecter

V. CONCLUSION

This paper presented a new design concept on the small lightweight manipulator for lunar rover mission. This paper has presented scientific mission requirements of a manipulator, an evaluation of its joint driving rates, and developed a micro manipulator for rover. The developed smart manipulator has five degrees of freedoms and each joint is driven by an Ultra-Sonic Motor (USM), which needs no electrical power to keep a posture of a manipulator. And this paper has presented the durability of USM in huge vibration environment and heat-vacuum environment. This paper studied end-effecter and experimental study was performed. A lot of tests about the lifetime of USM will be conducted as a future work.

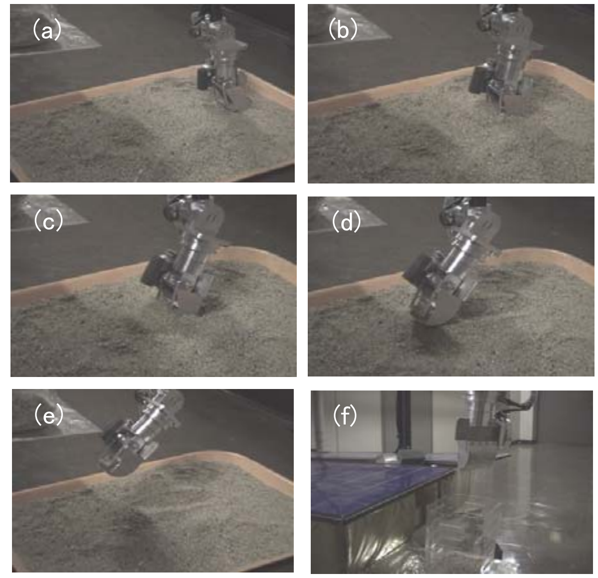


Fig.17 Experimental Results

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