Control and Mobility of a Novel Wired Explotarion Robot for Vertical Hole on the Moon

Shuhei Shigeto*, Sayuri Sugimura*, Masatsugu Otsuki**, Takashi Kubota**

*Department of Electrical Engineering and Information systems, The University of Tokyo, JAPAN
e-mail: shigeto.shuhei@jaxa.jp s.sugimura@ac.jaxa.jp

**ISAS,JAXA,JAPAN
e-mail: otsuki.masatsugu@jaxa.jp kubota@isas.jaxa.jp

Abstract

Moon holes were discovered by JAXA in 2009. It is believed that moon holes are helpful to know the formation of the moon because bedding plane is exposed. In addition, because inner hole is sealed from solar wind, a moon hole is also important as a candidate site for base camp in the future. However, exploration of vertical hole is difficult with the conventional exploration robots. A new robot is required to go down and explore a moon hole. In this study, a vertical hole exploration system with a small robot into a moon hole with wire is proposed. The proposed exploration system will use wireless power transfer for supply energy. Wireless power transfer is a method of power transfer using a microwave or laser to send energy for distant area. When the robot goes into underground space, solar ray will not reach. Wireless power transfer is a suitable method for underground exploration. There are a lot of rocks in the bottom of a vertical hole as a result of collapse of hole entrance. When an exploration robot arrives at the bottom of a hole, the robot has to avoid these rocks. In the landing phase, the robot searches a plane site for landing. Then, the proposed robot swings the wire and releases itself for the landing site. This paper describes a modeling and attitude control scheme of the proposed robot, and a power supply method.

1 Introduction

In 2009, Japanese Moon explorer “Kaguya” (SELENE) found a vertical hole on Marius Hill in Oceanus Procellarumas shown in Fig. 1. Kaguya also found two other holes. These holes are called Marius Hills Hole(MHH), Mare Tranquillitatis Hole(MTH), and Mare Ingenii Hole(MIH) respectively. Scientists made a conjecture that these holes spread out underground, and were originated as either lava tubes where once lava flowed, or magma chambers. It is believed that the meteorites strike on the ceiling of underground space made vertical holes[1].

Vertical holes are also found on Mars. Life exploration in underground space on Mars is one of the most important goals of Mars exploration. Because there exist volcanoes on Mars and hence there is enough energy for life to evolve underground of Mars, and ultraviolet rays do not reach underground. A possibility of having suitable conditions for life to survive is also pointed out [2]. And moreover, the vertical hole and underground space of the moon or Mars has stable temperature, and is protected from a meteorite, radiation, and ultraviolet rays. Therefore these holes are suitable for future bases for human activities.

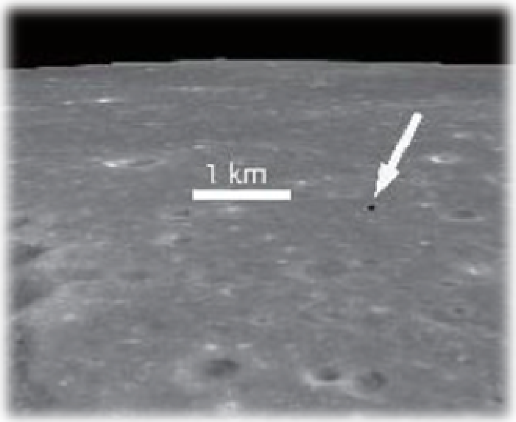


Figure 1. Image of moon vertical hole by SELENE (Haruyama et al,2008)[7]

Despite these advantages, structures and scientific characters of underground space and vertical holes are unknown. To obtain new knowledge, underground exploration is one of the most important missions.

In the past lunar or planetary rover exploration missions, exploration robots are commonly used. Conventional rovers have high mobility to traverse rough terrain, but it is limited. Different from conventional explore missions which were conducted on surface of the moon or planets, vertical hole exploration requires a robot to descend vertically into a hole. Therefore a new exploration robot is required.

The authors have proposed a exploration robot for Moon hole [3]. The proposed robot descends with wire, and runs around with wheels. While descending, the robot is controlled using wheels like a reaction wheel.

In this paper, three dimentional motion of the proposed robot, and power supply of exploration system are discussed.

2 Moon Hole

2.1 Moon hole size

Lunar exploration orbiter of NASA took a lot of pictures of Moon holes. Scientists estimate two cases for the structure of moon holes with those pictures[6].

The sizes of three holes which "Kaguya" discovered are estimated that: the diameter is 59[m], deapth is 48[m] in MHH case,the diameter is 98[m], deapth is 107[m] in MTH case, and the diameter is 118[m], deapth is 45[m] in MIH case[7].

2.2 Requirements for exploration robot

Hole exploration is expected to obtain the following data:[3]

- Image of wall
- Temparatre
- Structure of hole
- Amount of radiation
- Chemical composition

Exploration robots are required to have the following ability to achieve exploration.

- No big load to the hole ceiling
- Take pictures while descending
- Perform attitude control while descending
- Carry many sensors
- High mobility in the hole

2.3 Exploration system

To meet these requirements, an exploration robot with wire is proposed. Figure 2 shows the concept of the proposed system. The proposed exploration plan is separated in 3 phases: descending phase, swing phase, and landing phase. First, a small rover moves to a hole from the lunar lander. Then, the rover descends from the hole with wire. When the robot approach to a moon hole, throwing system is effective for this mission[4][5]. In this phase, a motion control is necessary for the robot to start exploring: taking pictures, measuring the structure of a hole, etc. Finally, the robot lands on the bottom of the vertical hole, though there are a lot of rocks on the bottom.The robot moves like a swing and releases the wire to land to appropriate area for landing.

When the robot stays underground, the sunlight would not reach. The robot uses Wireless Power Transfer (WPT) for supply energy. The mother lander has Solar Array Panels (SAP) to supply WPT transmitter, and supplies energy for a robot.

2.4 An exploration robot

Figure 3 shows a concept image of a robot in the proposed exploration system. The robot has two wheels and runs around with these wheels. When descending, the robot uses the wheels as reaction wheels. Wheels have camber angle. And the robot also has thermal sensors, cameras, light, and radiation detector for scientific missions. Power supply depends on WPT, and internal small battery.

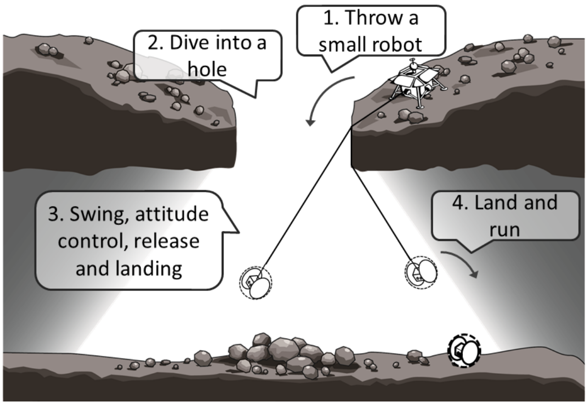


Figure 2. Image of the proplosed method for exploration with throwing robot

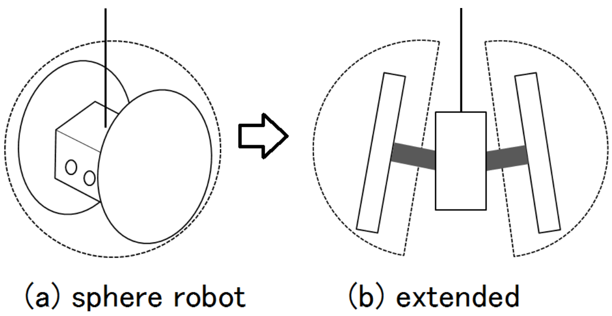


Figure 3. Proposed exploration robot

3 Power Supply for Robot

3.1 Whole system

The common method for power supply to exploration rovers is using solar photovoltaic generation. However, the sunlight does not reach the space under the holes. Therefore, Wireless Power Transfer (WPT) by electromagnetic wave is used as a way of power supply. The principle of WPT is the same as telecommunication[8]. Figure 4 shows the image of whole system. Electricity is transmitted to the robot by the sending system in the cave, and is received by the antenna on the exploration robot.

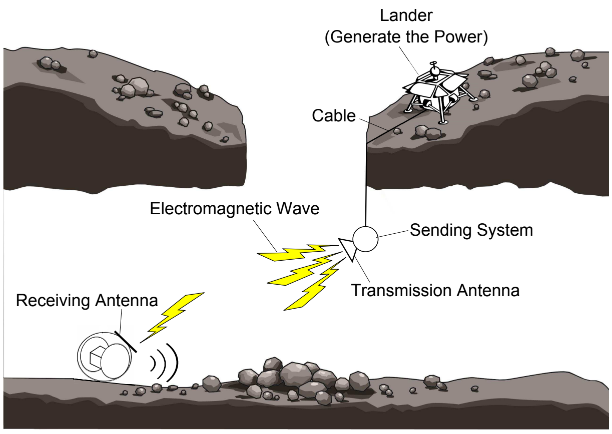


Figure 4. Image of the proposed method for transmitting electricity

3.2 Transmission system

In the proposed method, a transmission system is hung in the hole connected via an electrical cable to the electrical generator put near the hole (ex. Lander). Electricity generated by the generator on the ground is sent via the cable to the transmission system, and is converted into electromagnetic waves. After conversion, the waves are transmitted in the cave toward the receiving antenna on the robot.

As a transmission antenna of the system, it is thought to use Phased Array Antennaas shown in Fig. 5. The antenna can change directivity and the direction of emitted electromagnetic waves by electronic control without changing a direction of the antenna itself[9].

And the proposed transmission system is used not only the power supply device but also the repeater for radio communication with the earth or satellites around the moon.

3.3 Receiving system

Receiving antennas differ depending on kinds of electromagnetic waves. If microwave is used for WPT, rectifying antenna,which is called Rectenna for short, is used as a receiving system. If laser is used for WPT, a solar panel is used as a receiving system.

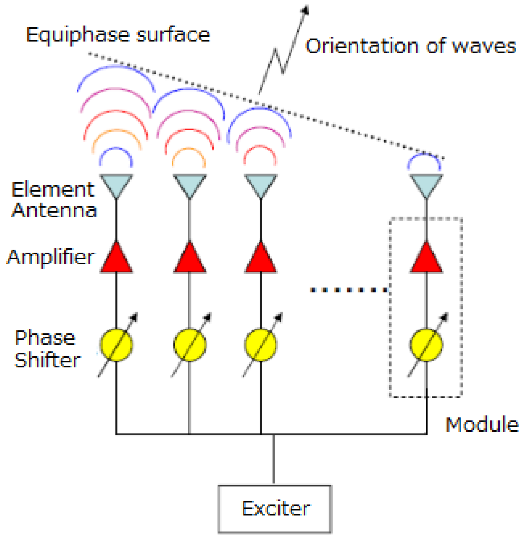


Figure 5. Image of Phased Array Antenna

4 Motion Control of Wired Robot

The exploration robot need to control its motion when descending with tether wire. When taking pictures or measuring the structure of hole, the robot has to stop its motion and control the position. Damping vibration control is needed to stop swing motion. And when a robot releases the wire and lands, the robot has to land on appropriate area for landing. In this purpose, the proposed robot moves like a swing and releases a tether to fall to aimed area.

In this section, a modeling and control scheme is described.

4.1 Modeling of a robot

Figure 6 shows a reaction torque model of the robot. α denotes a camber angle. By controlling left and right wheels simultaneously, pitch and yaw direction reaction torque are generated. Pitch and yaw direction reaction torque are described below.

$$\tau_{yaw} = \sin\alpha(\tau_l + \tau_r) \quad (1)$$

$$\tau_{pitch} = \cos\alpha(\tau_l + \tau_r) \quad (2)$$

, when

$$\tau_l : leftmotortorque \quad (3)$$

$$\tau_r : rightmotortorque \quad (4)$$

The robot performs three-dimensional pendular motion in descending phase at first. It is necessary to suppress movement to start exploration. Figure 7 shows a 3D motion model. Yaw rotation denotes the rotation around a tether wire, and roll axis denotes a forward direction of a robot. Movement of a robot can be described as follows from a conservation-of-angular-momentum rule.

The equation of motion is described in Eq.(6).

$$\frac{\partial \boldsymbol{L}}{\partial t} = \boldsymbol{R}\boldsymbol{N} + \dot{\boldsymbol{\theta}} \times \boldsymbol{L} \tag{5}$$

$$\dot{\boldsymbol{\theta}} \cdot \boldsymbol{I} = \boldsymbol{\theta} \times (\boldsymbol{\theta} \cdot \boldsymbol{I}) + \begin{pmatrix} \dot{\theta}_p \omega_y J_w - \dot{\theta}_y \omega_p J_w \\ -\dot{\theta}_r \omega_y J_w \\ \dot{\theta}_r \omega_p J_w \end{pmatrix} - \begin{pmatrix} 0 \\ \dot{\omega}_p J_w \\ \dot{\omega}_y J_w \end{pmatrix} + \boldsymbol{R}\boldsymbol{N} \tag{6}$$

$$U = \begin{pmatrix} 0 \\ \omega_p J_w \\ \omega_y J_w \end{pmatrix} \tag{7}$$

,where $\boldsymbol{\theta} = (\theta_y, \theta_p, \theta_r)^T$: Attitude angle of a robot
$\boldsymbol{\omega} = (\omega_y, \omega_p, \omega_r)^T$: Angluar velocity of wheels
$\boldsymbol{I}$: Inertia moment of robot body
$\boldsymbol{J}$: Inertia moment of wheels
J_w : Inertia moment of each wheels
$\boldsymbol{N}$: Gravity torque
$\boldsymbol{R}$: Rotation Matrix
$\boldsymbol{L}$: Angular momentum of all system
$\boldsymbol{U} = \boldsymbol{J} \cdot \boldsymbol{\omega}$: Motor input torque(controllable)

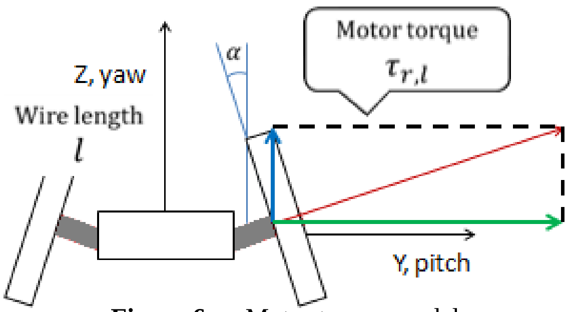


Figure 6. Motor torque model

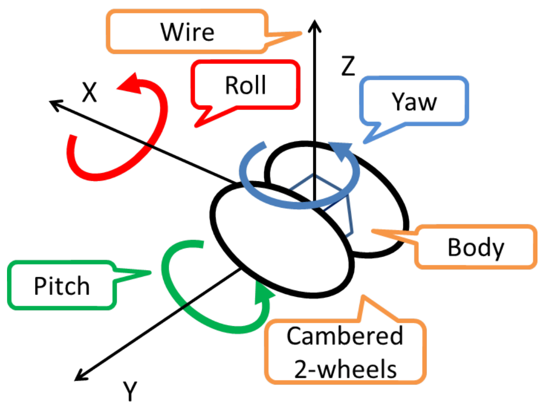


Figure 7. Axis define of a robot

4.2 Design of damping control

At the first of descending phase, the proposed robot would jump into a hole. The robot has to damp its vibration occurred by jumping into a hole when taking pictures or measuring the hole structure. In this paper, the first vibration is regarded as vibration as shown in Fig. 8. Roll and pitch vibration is the main vibration, and there is no rotation in the yaw direction.

By the way, Eq.(6) shows that appropriate input will damp the vibration of the robot and tether. Here, input $\boldsymbol{U_1}$ and $\boldsymbol{U_2}$ are described below to stop the vibration. $\boldsymbol{U_1}$ denotes damp the roll and pitch motion, and $\boldsymbol{U_2}$ denotes damp pitch angle vibration and stop yaw rotation.

$$\boldsymbol{U_1} = (0, -D_p\dot{\theta}_p, -D_r\theta_r)^T \tag{8}$$

$$\boldsymbol{U_2} = (0, -D_p\dot{\theta}_p, -D_y\theta_y)^T \tag{9}$$

To confirm the 3D motion, damping simulation is conducted. Table. 1 shows the conditions of simulation. Here, think of a small size experimental model. Figure 8 shows initial vibration, and initial value is 0.08 rad. Simulation result of each axis motion is shown in Fig. 9. (a) shows a pitch motion, (b) shows a roll motion, and (c) shows a yaw rotation respectively. The simulation results that 3D pendlum motion is damped by two independent wheels.

Table 1. Simulation conditions

variable	name	value
l	wire length	$1.6m$
h	lowest height	$0.4m$
M	robot mass	$2.3kg$
g	Earth gravity	$9.8m/s^2$
$\tau_m ax$	maximum torque	$0.5N/m$
C_{wire}	damping coefficient of the wire	$0.05N/m/rad/sec$

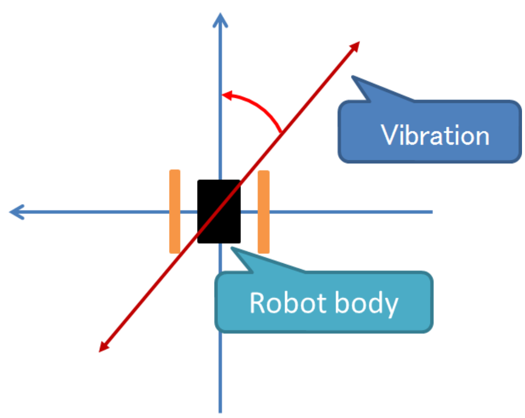
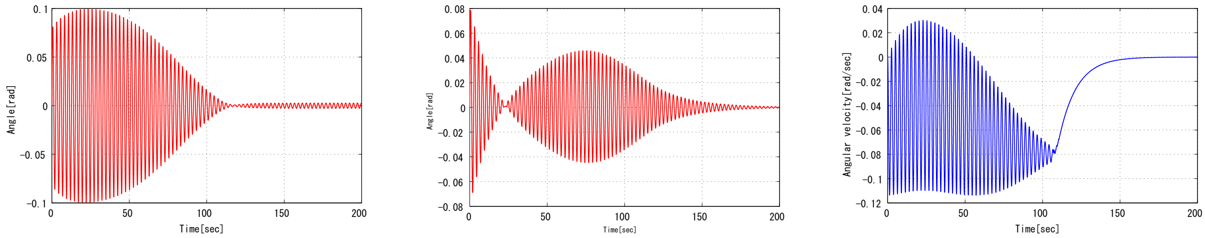


Figure 8. Assuming the initial vibration direction



(a) Roll angle vibration damping (b) Pitch angle vibration damping (c) Yaw angular velocity damping

Figure 9. The result of 3D motion simulation

4.3 Design of landing control

When a robot releases the wire and lands, the robot has to land on appropriate area for landing. In this purpose, the robot moves like a swing and releases a tether to fall to aimed area. The effectiveness of the landing phase scheme is confirmed and also the accuracy of landing position is evaluated by experiments.

For the accurate landing, it is necessary to release a tether at intended timing. Relationship between release timing and landing position is shown in Fig. 10. A circle is the plot of state of pendulum. θ_p and $\dot{\theta_p}$ are plotted in Fig. 10. When a robot releases a tether on the line, the proposed robot lands on titled position. After releasing a tether, the robot draws a parabola and falls.

Here, the robot is thought as a 2-dimension pendulum. Pitch torque is outputted only to swing in 2-dimension simple pendulum. Yaw torque is outputted if a robot needs to rotate around the wire.

By removing the yaw and roll motion from Eq.(6), the equation of motion of 2-dimension pendulum is obtained by the following equation.

$$Ml^2\ddot{\theta} + C_{wire}\dot{\theta} + Mlg\sin\theta + \tau_{pitch} = 0 \qquad (10)$$

,where C_{wire} : Coefficient of tether wire

Eq.(10) shows the relation between vibration of pitch swing and motor torque τ_{pitch}. Here, $A\dot{\theta}$ is inputed to the motor torque τ_{pitch}. If θ_p is enough small, Eq.(10) shows a simple vibration. If A is larger than $-C_{wire}$, Eq.(10) is damping vibration, and if not, diverge vibration. The variable A is controlled to control the pendulum amplitude [10][11].

Figure 11 shows a block diagram of control. The control system refers internal energy of a pendulum, because a size of pendulum state circle depends on energy of a pendulum. When a motion state reaches on a intended state, a robot releases a tether.

Figure 12 shows a picture of a experimental settings. A tether is fixed on the ceiling. Robot position is measured by OptiTrack system. Error of the measuring system is 0.8mm in this condition. An experimental robot is wired from a controller set on the ground. Experimental conditions are shown in Table. 2.

Figure 13 shows the result of landing experiment. Grey line and red points show a ideal line and the results respectively. Experimental result has an offset because of settings of a OptiTrack. Considering the offset, the dispersion of landed position is 3.0[cm]

There are large rocks on the bottom of the hole. The size of them is estimated almost 7[m]. Error of the landing position is 0.21[m] when jump to avoid bottom rocks. The size of a robot is about 0.3[m], exceeds the position error. Therefore the accuracy is enough to land aimed area. The proposed landing system is available for the lunar hole exploration.

Table 2. Experimental conditions

name	value
wire length	$1.6m$
lowest height	$0.4m$
robot mass	$2.3kg$
maximum torque	$0.5N/m$
damping coefficient of the wire	$0.05N/m/rad/sec$

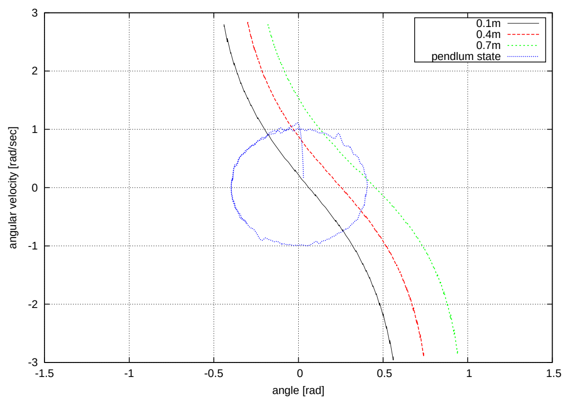


Figure 10. Result of release and land on the ground; reference and pendulum state

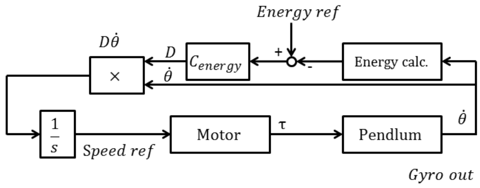


Figure 11. A block diagram of control system for experimental robot

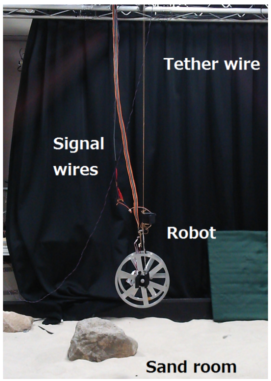


Figure 12. Experimental equipments

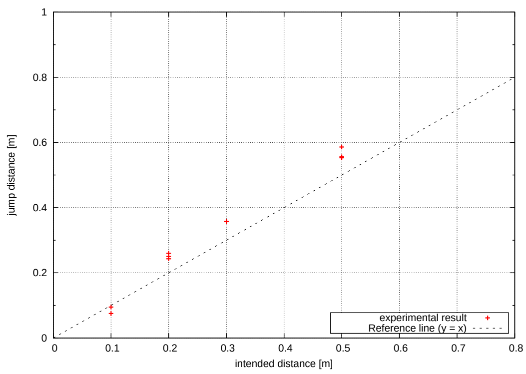


Figure 13. The result of jump experiment: distance; purpose distance vs. actual distance

5 Conclusions

A vertical hole is a candidate for future exploration missions. In this study, the moon hole exploration system and the exploration robot with wire considering power supply are proposed. This study focuses on exploration robot motion control. The robot uses its wheels as a flywheel to control its attitude. When the robot is suspended in the vertical hole, the robot moves like a swing. An attitude control and a landing control are proposed. Its motion is confirmed by simulation and experimental study. Locomotion mechanism on the ground and moon surface landing system are required to achieve moon hole exploration as the future work.

References

[1] Junichi Haruyama, et al, "Possible lunar lava tube skylight observed by SELENE cameras", Geophys.Res.Letters.Vol.36, 2009.

[2] Junichi Haruyama, Takashi Kubota, Isao Kawano, Masatsugu Otsuki, Ryunosuke Imaeda, "Exploration of lunar and planetary holes and subsurface caverns: The significance of explorations", 57th Symposium on Space Science and Technology, 2013.(in Japanese)

[3] Shuhei Shigeto, Masatsugu Otsuki, Takashi Kubota, "A Proposal of Exploration Robot with Wire for Vertical Holes in the Moon or Planet", International Conference on Robot Intelligence Technology and Applications, 2013.

[4] Hitoshi Arisumi, Osamu Matsumoto, "Casting manipulator system for a lunar exploration-Mid-air control of the end-effecter by tension of wire-" JSME ROBOMEC, 2012.

[5] Hitoshi Arisumi, Masatsugu Otsuki, Shinichiro Nishida, "Exploration of lunar and planetary holes and subsurface caverns: A long throw and soft landing with a casting probe system" 57th Symposium on Space Science and Technology, 2013.

[6] M.S. Robinson, J.W.Ashley, A.K.Boyd, R.V.Wagner, E.J.Speyerer, B.RayHawke, H. Hiesinger, C.H. van der Bogert, " Confirmation of sub lunar eanvoids and thin layering in mare de posits, " Planetary and Space Science 69, 2012.

[7] Junichi Haruyama, Tomokatsu Morota, Shingo Kobayashi, Shujiro Sawai, Paul G.Lucey, Motomaro Shirao, Masaki N.Nishino: "Moon(chapter name: Lunar Holes and Lava Tubes as Resources for Lunar Science and Exploration)", Springer Berlin Heidelberg, pp.139–163(Chapter 6) , 2012

[8] Naoki Shinohara: " Power Without Wires " , Microwave Magazine, IEEE, Volume:12, Issue:7, S64-S73, December 2011

[9] Robert C. Hansen: " Phased Array Antennas " , Wiley-Interscience, 2009

[10] Toshiaki Tsuji, Kouhei Ohnishi, "Oscillation Control of Suspended Load with Flywheels," Transactions of IEEJ-D Vol.125, 2005.(in Japanese)

[11] Toshiaki Tsuji, Kouhei Ohnishi, "Oscillation Control of Suspended Load with Flywheels," Transactions of IEEJ-D Vol.125, 2005.(in Japanses)