LUNAR PIT EXPLORATION WITH PROBE LAUNCHING SYSTEM

*Hitoshi Arisumi[1] and Junichi Haruyama[2]

[1] *National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki, Japan, E-mail: h-arisumi@aist.go.jp*

[2] *Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Sagamihara, Kanagawa, Japan, E-mail: haruyama.junichi@jaxa.jp*

ABSTRACT

This paper discusses how to approach the lunar pit entrance in a short period of time and lower the probe to the bottom of the pit with avoiding obstacles. We propose a method of throwing a protective capsule that contains probe from a distance by a launching system to hang the capsule at the center of the pit by wires. We develop the control system for throwing capsule and feeding wire, and hardware such as a launcher, reel system, and probe release device. The effectiveness of the proposed method is verified through the experiments.

Keywords: Robotics, Planetary Exploration, Dynamic Manipulation, Launching

1 INTRODUCTION

The JAXA lunar orbiter spacecraft "SELENE (Kaguya)" discovered giant vertical pits on the surface of the moon as shown in Fig. 1. The pits are presumed to be skylights of subsurface caverns such as lava tubes or magma chambers. These pits and caverns are very significant for lunar sciences because of untouched original environment free from cosmic dust. In addition, they are promising candidates for lunar base with laboratory facilities because they are regarded as a natural shelter free from meteorite impacts, high-energy ultraviolet rays, radiation, or extreme diurnal temperature variations (more than 300K) [1, 2]. They thus could be high-priority targets of future lunar exploration. For these reasons, it is expected to develop technical method to approach this new world. We here discuss how to put the probe on the bottom of the vertical pit from the lander with robot technology.

The area around the vertical pit is considered to be fragile as the pit was formed by collapse of the roof of underlying caverns [2]. Furthermore, high precise landing techniques are still in a developmental stage. Therefore, the touchdown point of the lander must be on a flat surface and far from the vertical pit as shown in Fig. 2. Mobile robots thus are needed to carry the probe from the lander to the pit after touchdown. Following well-known technologies, a rover robot may be a dominant way to approach the pit, but it is still difficult to move through wasteland containing features such as a steep slope or a rugged/gravel /sandy surface because the system down caused by tumble or getting stuck [4] may occur there. Even if the rover manages to travel through wasteland, it cannot easily get close to the pit due to the fragility around the pit. In the first place, the main purpose of the mission is not to reach the pit entrance but to explore the pit inside. Therefore, it may not be a good idea to spend a lot of time and energy only for getting through a wasteland that induces the system down. Furthermore, it may not be necessary for robot to have several kinds of mechanism to go through wasteland because the floor of the subsurface caverns is considered flat.

We thus discuss how to pass through a place with few obstacles and reach the place as close as possible from the pit.

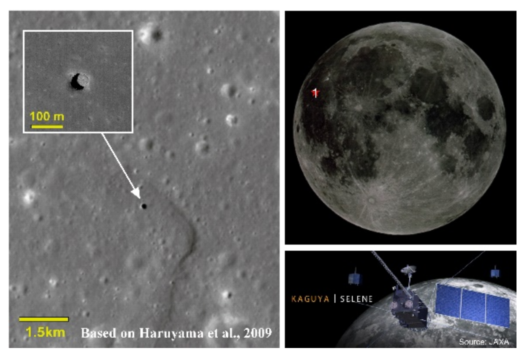

Figure 1: Lunar vertical pit (Marius Hills in Oceanus Procellarum).

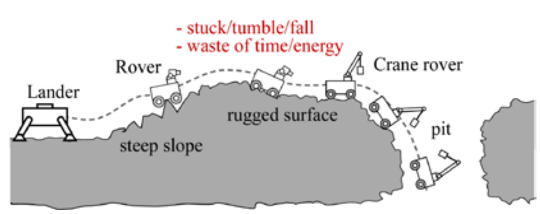

Figure 2: Example of difficulties to get through wasteland.

2 ACCESS TO BOTTOM OF PIT

To overcome the difficulties shown in Fig. 2, we apply launching system [3] to the exploration of the pits and the caverns. Figure 3 shows the scenario.

Launcher and reel system are mounted on the lander. Capsule and auxiliary weights are set at the tip of the launcher. The capsule which contains a probe vehicle is connected to the reel system via the wire, and it is also connected to each auxiliary weights. First, (a) the capsule and the auxiliary weights are thrown to the target pit together by the launcher. Then, (b) stopping the feeding wire at the suitable timing, the capsule is pulled from the appropriate directions through wires to reduce the capsule speed sufficiently. (c) After landing of the weights, the capsule is suspended in the center of the pit by the wires. Finally (d) the probe is lowered from the capsule to the bottom of the pit without touching inner side of the pit. We here discuss how to reduce the capsule speed to suspend it in midair at the center of the pit entrance at rest and develop the system to realize the motions shown in Fig. 3.

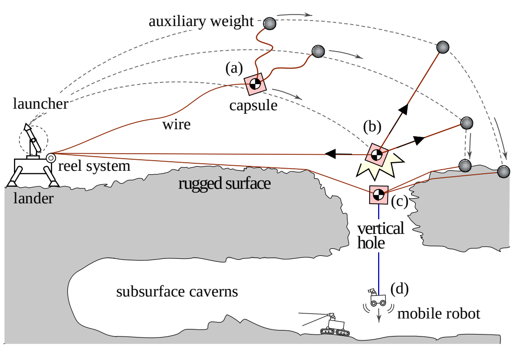

Figure 3: Scenario of delivering probe into the pit.

A key feature of the probe launching system is the ability to move the capsule quickly independent of several kinds of landforms or geological conditions. Compared to the other robots, it can be thought that the probe launching system has the advantage of reducing working time, energy consumption, and step number of operation. In addition, even if the capsule does not reach the target, the system can continue the mission by recovering the capsule and throwing it again or throwing another one.

3 DINAMICS AND PLANNER

3.1 Model

In case of launching a capsule and n auxiliary weights, wire model between a capsule and auxiliary weights is shown in Fig. 4. Points P_R, P_{r0} and P_{rk} (k = 1, 2, .., n) in the figure denote the position of reel system, release points of the capsule and auxiliary weights, respectively. L_i, T_i, K_i and C_i are length, tension, coefficients of spring and damper of wire i (i = 1, 2, .., n), respectively. Further, P_t, m_0 and m_k denote target point, mass of the capsule and k^{th} auxiliary weight, respectively. The negative direction of z axis is the direction of the gravitational force, and its value is set as 9.8m/s^2 in consideration of experiment on earth. We call the capsule and auxiliary weights together "*flying objects*" in this paper.

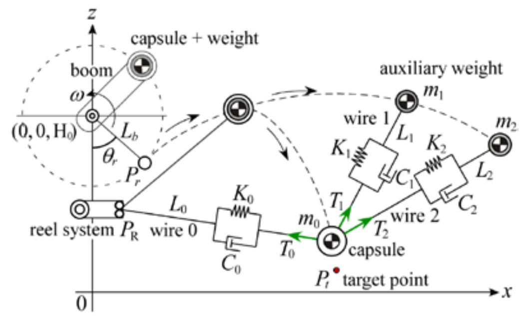

Figure 4: Model of launching system.

3.2 Dynamic Equations

Here we let the position vector of the capsule, reel system and k^{th} auxiliary weight be $\boldsymbol{X}_0 = (x_0, y_0, z_0)$, $\boldsymbol{X}_R = (x_R, y_R, z_R)$, $\boldsymbol{X}_k = (x_k, y_k, z_k)$ and $\boldsymbol{X}_k = (x_k, y_k, z_k)$. Further, letting the tension vector of wire i and gravitation vector be $\boldsymbol{T}_i = (T_{ix}, T_{iy}, T_{iz})$ and $\boldsymbol{g} = (0, 0, g)$, the dynamic equation of the system is expressed by

$$m_0 \ddot{\boldsymbol{X}}_0 = -\alpha_0 \boldsymbol{T}_0 + \sum_{j=1}^{n} \alpha_j \boldsymbol{T}_j - m_0 \boldsymbol{g} \qquad (1)$$

$$m_k \ddot{\boldsymbol{X}}_k = -\alpha_k \boldsymbol{T}_k - m_k \boldsymbol{g} \qquad (2)$$

where

$$\alpha_i = \begin{cases} 0 & if\,|\boldsymbol{T}_i| = 0 \\ 1 & if\,|\boldsymbol{T}_i| > 0. \end{cases} \qquad (3)$$

Eqs. (1), (2) and (3) express the hybrid system that can discretely switch the two states of motion: a free parabolic motion of flying objects when wire tension is zero, and flying objects' motion when they pull together via wire. Assuming that vector $\boldsymbol{d}_0 = \boldsymbol{X}_R - \boldsymbol{X}_0$ and $\boldsymbol{d}_k = \boldsymbol{X}_k - \boldsymbol{X}_0$, an expansion s_i of wire i is expressed by

$$s_i = \begin{cases} 0, & if\, L_i > d_i \\ d_i - L_i, & if\, L_i < d_i \end{cases}$$

where $d_i = |\,\boldsymbol{d}_i\,|$, and L_i is the length of unloaded wire i. Therefore the tension of wire i is expressed by

$$|\,\boldsymbol{T}_i\,| = C_i \dot{s}_i + K_i s_i$$

Since unit vector of wire i is defined by $\boldsymbol{e}_{Li} = \boldsymbol{d}_i / d_i$, the tension vector described in (1) and (2) can be expressed by $\boldsymbol{T}_i = |\boldsymbol{T}_i|\, \boldsymbol{e}_{Li}$.

3.3 Plan for launch and wire control

In order to stop the capsule temporally at the target point, a motion planning for launch and wire control should be discussed.

We let $\boldsymbol{X}_{ri} = (x_{ri}, y_{ri}, z_{ri})$, $\boldsymbol{V}_{ri} = (v_{xri}, v_{yri}, v_{zri})$, $\boldsymbol{t}_r = (t_{r0}, t_{r1}, \ldots, t_{rn})$, and $\boldsymbol{L}_i = (L_0, L_1, \ldots, L_n)$ denote the position and velocity vector of flying object i at release point, release time vector, and wire length vector. Further, we let $\boldsymbol{S}_r = (\boldsymbol{X}_{r0}, \boldsymbol{V}_{r0}, \boldsymbol{X}_{r1}, \boldsymbol{V}_{r1}, \ldots, \boldsymbol{X}_{rn}, \boldsymbol{V}_{rn})$ denote the initial state. Letting $\boldsymbol{X}_t = (x_t, y_t, z_t)$ be the target position vector, the state when the capsule reaches the target level (z_t) is defined as the final state $\boldsymbol{S}_f = (\boldsymbol{X}_{f0}, \boldsymbol{V}_{f0})$. When selecting ($\boldsymbol{S}_r$, $\boldsymbol{t}_r$, L_0) as the control parameters and giving initial values to the other parameters, the final state can be expressed by

$$\boldsymbol{S}_f = \boldsymbol{F}(\boldsymbol{u}) \tag{4}$$

where $\boldsymbol{u} = (\boldsymbol{S}_r, \boldsymbol{t}_r, L_0)$ is control vector, and $\boldsymbol{F}(*)$ is a non-linear function. Since it is ideal that the final state $\boldsymbol{S}_f$ is closer to the target state $\boldsymbol{S}_t = (\boldsymbol{X}_t, \boldsymbol{V}_t)$, we define the objective function as follows:

$$F_{obj} = \beta_0 | \boldsymbol{X}_{f0} - \boldsymbol{X}_t | + \gamma_0 | \boldsymbol{V}_{f0} - \boldsymbol{V}_t | \tag{5}$$

where β_0 and γ_0 are weighting factors. The planning of the capsule's flight motion can be regarded as the optimization problems which are solved by searching the control vector $\boldsymbol{u}$ that minimizes F_{obj}. The optimization technique based on the penalty function method is used for the search.

4 EXPERIMENTS

4.1 Experimental setup

The probe launching system is developed as shown in Fig. 5. The boom is driven by a DD motor (SGMCS-05B3C41, Yaskawa Corp.) attached at the base frame, and its angle is measured by an optical encoder (20bit). The release device equipped at the tip of the boom is driven by the solenoid. The electricity is supplied to the solenoid from outside via the slip ring. The capsule and auxiliary weights set at the release device are locked and unlocked by four fingers. Diameter and width of the capsule are 120mm and 60mm, and those of the auxiliary weight are 100mm and 70mm, respectively. The capsule and auxiliary weights are connected by wire, Super Cord "Vectran". It was developed by Kuraray Co., Ltd. and used for airbag system of an American spacecraft, "Mars Pathfinder". The wire is pay out/wound up by the reel system (driven by SGMAV-C2A3, Yaskawa Corp.). This system runs on a 1GHz CPU-based PC (Intel Pentium(R) III) under real time OS, ART-Linux 2.4.34. The sampling time is set at 1msec.

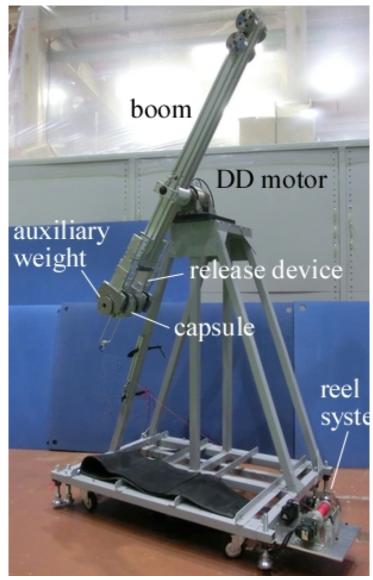

Figure 5: Experimental setup.

4.2 Launch of capsule

Figure 6 shows the experimental results. The circles in the figure show the position of the two and the circle at 01"50 (a) represents the release position of them. The capsule is pulled by the reel system through the wire at 02"00 (c), and then the capsule is separated from the weight. The green circle and the red one represent the position of the

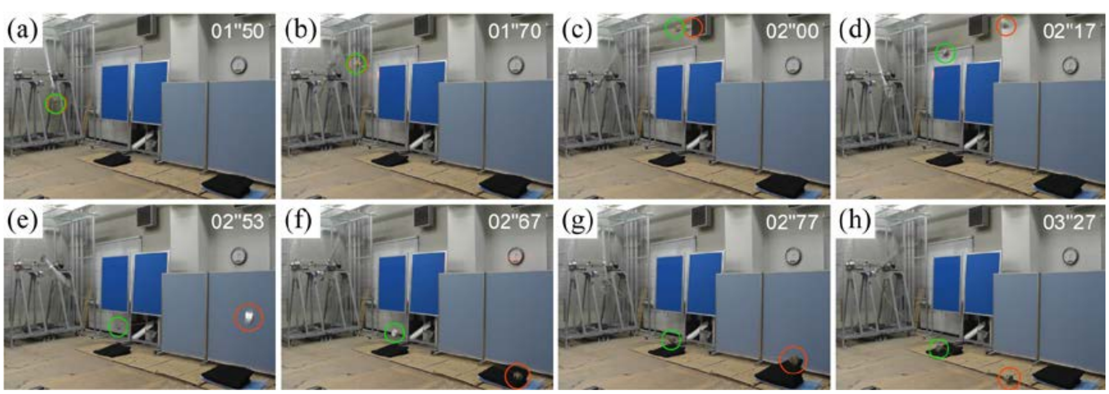

Figure 6: Flight motion of capsule and weight.

capsule and the weight, respectively. The capsule starts to fall to the target point at 02”17, while the weight continues the parabolic motion (d). The distance between the two is increasing after the separation, and then the two starts to pull each other. At 02”53 (e), the capsule is pulled by the reel system and the weight. From 02”53 to 02”77, the capsule looks floating in the air while the weight is falling vertically and bouncing on the floor. Therefore, it can be considered that the speed of the capsule in this period is greatly reduced because the tension of the two wires, inertial force, and gravitational force are balanced. That results in temporary stop of the capsule around the target position for at least 0.24s. Finally, the capsule lands at 03”27 (h). It is considered that the deceleration of the capsule is caused by partial momentum transfer from the capsule to the weight.

4.3 Release of pit probe from capsule

We conduct the test of release of probe from capsule. The release device is installed in Capsule as shown in Fig. 7(a). It mainly consists of the winch, the center of gravity (CoG) movement mechanism, the compact wireless camera, the wireless communication system and buttery. As shown in Fig. 7(b), the capsule is hanged in the middle of the ditch and the cylindrical part is freely rotatable by the bearing of the rotating shaft. If the cutout hole of cylindrical part faces downward, the camera can be lowered by the winch. If not, the weight is moved toward the cutout hole by controlling the CoG movement mechanism. Then the cutout hole faces downward as shown in Fig. 8 (1)-(3). The camera is lowered by the winch as shown in Fig. 8 (4)-(6).

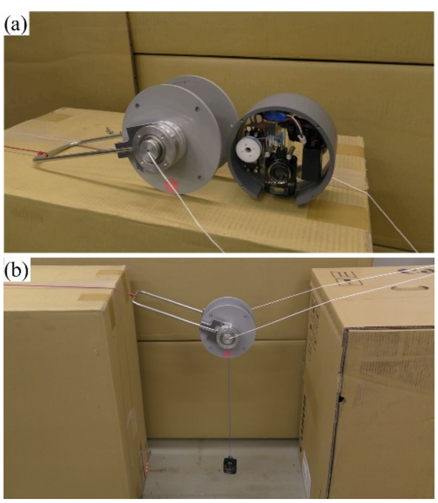

Figure 7: Contents of capsule and hanging capsule.

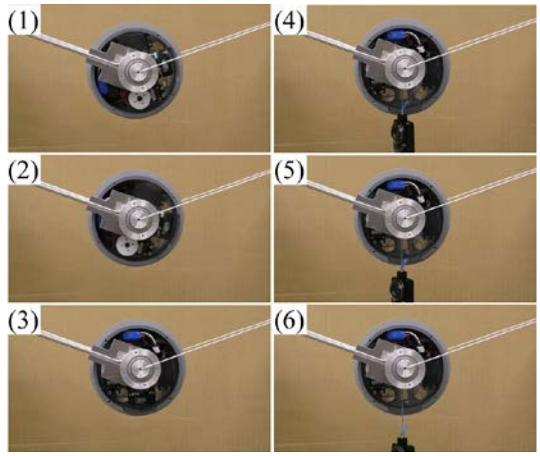

Figure 8: Flight motion of capsule and weight.

5 CONCLUSION

We discussed how to approach the lunar pit entrance and lower the probe to the bottom of the pit by using the probe launching system. Then, the control method of throwing capsule and feeding wire were proposed. The launching system, the reel system, and probe release device were developed. The effectiveness of the proposed method and developed system was verified through the experiments. We realized the motion of throwing and stopping the capsule in the air and the motion of releasing the camera as a probe from the capsule, respectively.

References

[1] Haruyama, J. et al. (2009), Possible unar lava tube skylight observed by SELENE cameras, *Geophys. Res. Lett.*, 36, L21206, doi:10.1029/2009 GL040635.

[2] Haruyama, J., et al. (2012), Lunar Holes and Lava Tubes as Resources for Lunar Science and Exploration,” Moon - Prospective Energy and Material Resources, *Springer*, pp. 139-164.

[3] H. Arisumi, et al., "Long Throw with Casting Probe System," *Proc. of the 12th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, 2014.

[4] NASA's Mars Rover has Uncertain Future as Sixth Anniversary Nears https://www.jpl.nasa.gov/news/news.php?feature=2427