Study on Excavation Mechanism for Lunar Subsurface Exploration by Burrowing Robot

*Kenji NAGAOKA, Grad. Univ. Advanced Studies,

Satoshi TANAKA, JAXA/ISAS, Takashi KUBOTA, JAXA/ISAS

Abstract－The authors have studied the strategies for subsurface excavation and propulsion for the development of a lunar subsurface explorer. This paper focuses on an excavation mechanism of a burrowing robot system for a future lunar subsurface exploration. The main objective of the proposed robot is to bury a long-period seismometer under the lunar land which is covered with lunar regolith, and then an efficient excavation mechanism is required. In this paper, the authors propose a new screw drilling system with double rotation, which is called N-RDM (Non-Reaction Drilling Mechanism). This paper discusses the feasibility and availability for the proposal of a burrowing robot system.

埋没型月面地中探査ロボットの掘削機構検討

〇永岡 健司（総合研究大学院大学）

田中 智（JAXA/ISAS）　久保田 孝（JAXA/ISAS）

概要ー本研究において，次期月探査のための埋没型地中探査ロボットによる探査ミッションの実現へ向けたシステム戦略，および地中での掘削・推進に関する検討を行っている．筆者らは月面を覆うレゴリス層内へ長周期地震計を埋没設置させることによって月の大域的情報の取得を行うシステムの提案を行っている．本稿では，埋没型ロボットのための掘削機構に焦点を当て，高充填率を有する月レゴリス層を高効率で掘削するような新たな掘削機構として，無反動力機構を備えたスクリュ式ドリルを提案する．本稿では，基礎検討によって得られた知見より，掘削機構としての有用性についてまとめる．

1. Introduction

Even now, the Moon is a one of interesting celestial bodies for exploration or investigation in space development. The Moon has a lot of unclear questions as the origin, the chemical components, and the internal structure. Thus, according to these remarks, it is required to obtain the global information about the Moon for future lunar exploration missions. Therefore the authors propose a robotic system for burying a long-period seismometer under the lunar surface. In general, the lunar regolith has high adiabatic property, and the temperature is constantly -20 degree even if at night. This consequently enables the seismometer to measure for a long term. Also, the buried seismometer can realize better contact with surrounding regolith. This paper firstly describes the strategies of subsurface propulsion of the burrowing robotic system and required mechanisms. Then, this paper especially discusses an excavation mechanism which is very important for the system, and proposes a novel excavating mechanism.

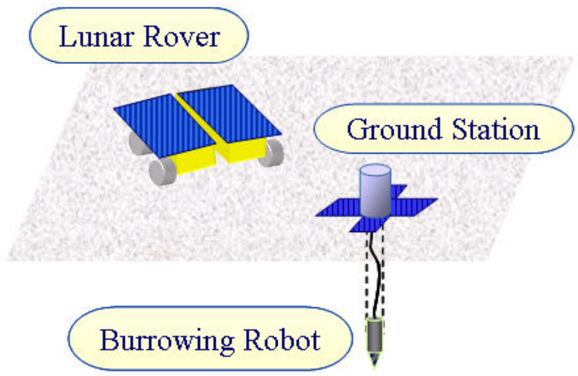


Fig. 1　Schematic of lunar subsurface exploration

Table 1 Planetary excavation systems

	Mechanism	Size	Weight	Robustness	Purpose
Bucket Wheel	*simple*	*large*	*heavy*	×	*sampling*
Penetrator	*simple*	*middle long*	*middle*	×	*investigation*
Drill	*simple*	*narrow long*	*light*	○	*sampling*
Burrowing Robot	*complex*	*compact*	*light*	△	*investigation*

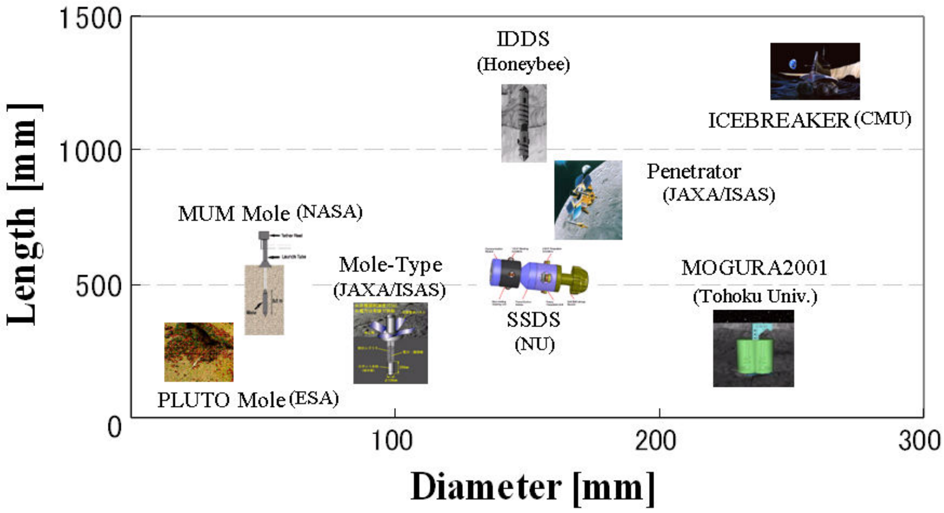


Fig. 2 Overview of planetary excavation robots

2. Burrowing Robot System

2.1. Conventional Robots

Planetary exploration with excavation of soil has received a lot of attention in the world. The comparison on planetary excavation systems is shown in Table 1, where the robustness means a capability to have some excavating points. So far, there have been proposed burrowing robots for planetary subsurface exploration [1]-[5]. However, those robots do not meet the scientific requirements. The overview of some proposed ideas which are classified in the length and the diameter is shown in Fig.2. ICEBREAKER and the Lunar-A penetrators of JAXA are not actually burrowing robot, but these are robotic systems for subsurface investigation or the similar objective. Therefore these two different methods are shown in Fig.2 for a comparison.

2.2. Strategies for subsurface propulsion

Based on the past researches, the authors set the following assumptions:

- The burrowing robot is carried by the rover
- Power is supplied by a cable from the ground station
- Target depth is several meters from the surface
- Target soil-layer is lunar regolith
- The robot diameter is about 0.1 m

Next, the authors define the strategies for subsurface propulsion by the burrowing robot, and consider the following two phases. Several concrete methods are shown in Fig.3.

(1) Make space
- Compress fore-regolith
- Remove and back transport fore-regolith

(2) Advance forward
- Utilize a contact with surrounding regolith
- Utilize an excavated regolith
- Self generation unrelated to regolith

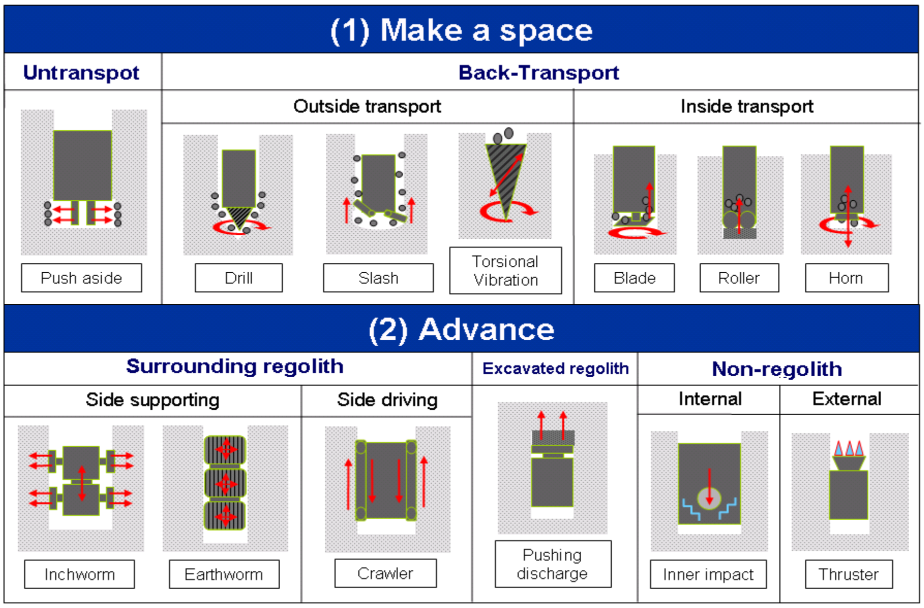


Fig. 3 Strategies of subsurface propulsion

3. Propulsion Limit Depth

Before considering the active generation of propulsion force as shown in Fig.3, this paper discusses the propulsion limit depth by only its weight. The main resistances for propulsion are lateral friction and excavating resistance by applying the simplified dynamics model as shown in Fig.4. For subsurface propulsion, the lateral friction is universal resistance. Firstly the soil pressure underground is calculated by the following equation.

$$\sigma = (p_0 + \rho g h)K \pm 2c\sqrt{K} \tag{1}$$

where, the notations used in this paper are as followings.

σ : lateral soil pressure [kPa],
p_0 : external stress on the surface [kPa],
ρ : soil bulk density [kg/m^3],
g : gravity acceleration [m/s^2],
h : depth from surface [m]
c : cohesion of soil [kPa],
K : Rankine's soil pressure coefficient,
H : robot length [m],
D : robot diameter [m],
A : robot cross-section [m^2] ($:= \pi (D/2)^2$),
μ : friction coefficient (soil – robot),
F_L : soil friction resistance [N],
M : robot mass [kg],

Also, the robot shape assumes to be cylindrical. When p_0 and c are zero, and the total lateral friction resistance F_L is calculated by the integrating through total lateral surface as following.

$$\begin{aligned} F_L &= A\mu K \int_{h-H}^{h} \rho g h \cdot dh \\ &= \frac{A\mu K \rho g \left(2hH - H^2\right)}{2} \end{aligned} \tag{2}$$

Thus the propulsion limit depth is estimated for the burrowing robot which mass is M from the following equation (3).

$$F - Mg = 0 \tag{3}$$

As the above consideration, the propulsion limit depth respect to the robot mass is shown in Fig.5 where ρ is 1600 [kg/m^3], D is 0.1 [m] and H is 0.2 [m]. Thus, given the strict weight limits of space mission, the burrowing robot needs to generate the propulsive forces subsurface.

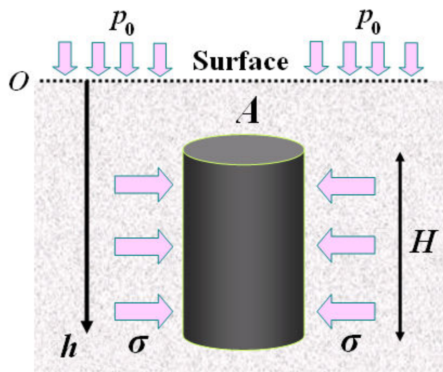


Fig. 4 Simplified dynamics model of soil friction

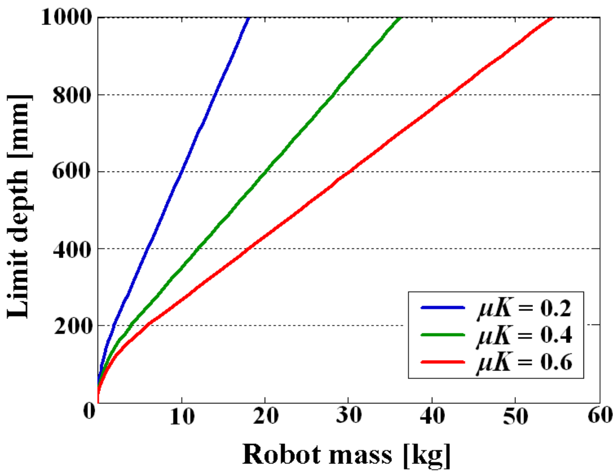


Fig. 5 Advancing limit depth by its weight

4. Compression Limit

This paper considers the capability of compression fore-soil method as an excavation mechanism. The relationship at an extreme state between vertical compressing stress σ and shear stress τ by applying Mohr-Coulomb's failure criterion theory is shown in following equations (4) and (5).

$$\sigma = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \sin\phi \tag{4}$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \cos\phi = \sigma \tan\phi + c \tag{5}$$

Here the following new notations are defined.

τ : shear stress [kPa],
σ_0 : initial stress [kPa],
σ_1 : maximum soil pressure [kPa],
σ_3 : minimum soil pressure [kPa],
ϕ : internal friction angle [rad],
e : void ratio,
e_0 : initial void ratio,
C_C : compression index,
B : generated space distance [m],
x : effect compressing range [m],

The compression index C_C is introduced, which denotes the relationship between void ratio and compressing pressure as described in the following equation (6).

$$C_C = -\frac{\Delta e}{\Delta \log_{10}\sigma} = -\frac{de}{d\log_{10}\sigma} \tag{6}$$

Therefore, by integrating the above equation (6), the following equation is obtained.

$$e = -C_C \log_{10}\left(\frac{\sigma}{\sigma_0}\right) + e_0 \tag{7}$$

Then, the effect range is assumed by the following equation (8). This means that compression force affects to distance X from the body's center line as the same force, and this can indicate the best condition about the compression to make space.

$$B = xD \cdot \left(\frac{e_0}{1+e_0} - \frac{e}{1+e}\right) \tag{8}$$

The simulation result is shown in Fig.7. In the simulation, the parameters are $1 \le x \le 10$ and e_0=1.2, and D is 0.1 [m]. The simulation result shows that it can be too hard to make space. Thus it is concluded that because the lunar soil layer has high-filling state under the surface, a method to compress fore-soil is an unrealistic to make space and the robot has to remove and transport fore-soil to backward.

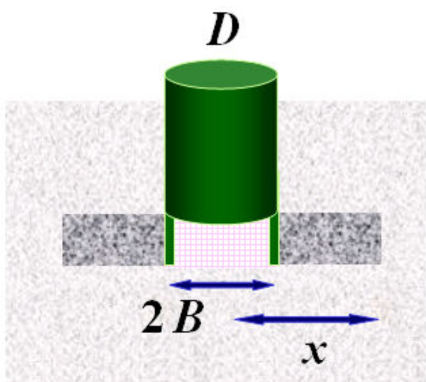


Fig. 6 State model of compression method

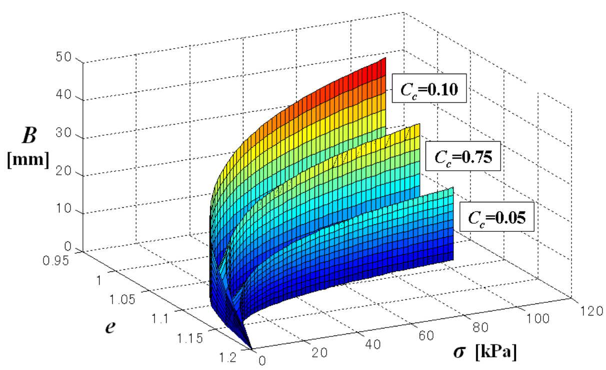


Fig. 7 Compression limit by Mohr-Coulomb's failure criterion with C_C

5. Non-Reaction Mechanism

5.1 Proposal of Double Rotation System

From the above considerations, the required properties for robotic excavation mechanism are following:

- Fore- soil removal and transportation backward
- Contribution of propulsion force
- Dust prevention mechanism

Therefore, a screw drill is one of candidates, which has a series of spiral wing. However, there is a problem that a single spin drill has reaction to the body. This reaction can be friction as reducing the efficiency as well as leading to a wobbling of propulsion axis. So this paper proposes a new type spiral screw drill unit as a kind of novel excavation mechanisms to improve the problem.

The double rotation screw is developed with N-RDM (Non-Reaction Drilling Mechanism). The double rotation methods are classified into three types as shown in Fig.8. The contra-rotor type (a) has one drilling unit which has the contra-rotation axis at the same of another rotation axis. The twin-rotor type (b) consists of two drilling units which have regular and contra rotation axis each other at binary positions. The dual-spin type (c) has one drilling unit which has dual different spin axis. Each type has two rotation axes, so it is possible to cancel the reaction. On the other hand, firstly the contra-rotor type is compact size, and it can be estimated that it has an equivalent excavating performance with the single screw drilling. Secondly the twin-rotor type has unexcavating space compared with the contra-rotor type because the shape of an excavated hole is anomalous. It is impossible to make one circular hole, and there is constraint for the body shape. Thus it can be estimated that it can be lower efficiency. Thirdly the dual-spin type has some external driving parts, and the efficiency is getting lower. According to these considerations, the authors firstly adopt contra-rotor type and will do some experiments in the near future.

5.2 SSD

The schematic of the basic model, where it is call SSD (Single Screw Drilling Unit) unit, is shown in Fig.9(a), and also the prototype model is shown in Fig.9(b). The developed SSD is a conceptual model of the contra-rotor type screw. And it is a basic dynamics model for the theoretical analysis.

The SSD unit consists of a body-part and an excavation-part. Furthermore, the excavation-part has an inner cone, called CONE, and a helical screw wing which wind around the CONE, called SCREW. From Fig.9(a), a parameter θ denotes the volubile angle from that central axis along the SCREW upper surface through from the top to end of the SSD. Then α_{SC} [deg] denotes the angle of inclination of the SCREW's center position and p denotes the SCREW pitch, where these parameters are a function which is defined by θ.

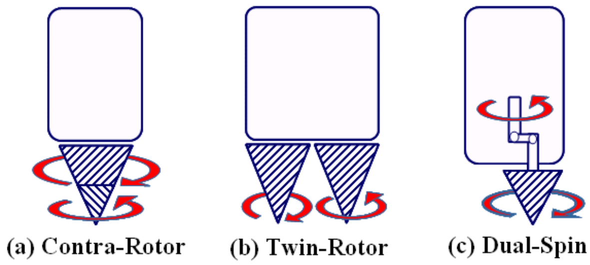
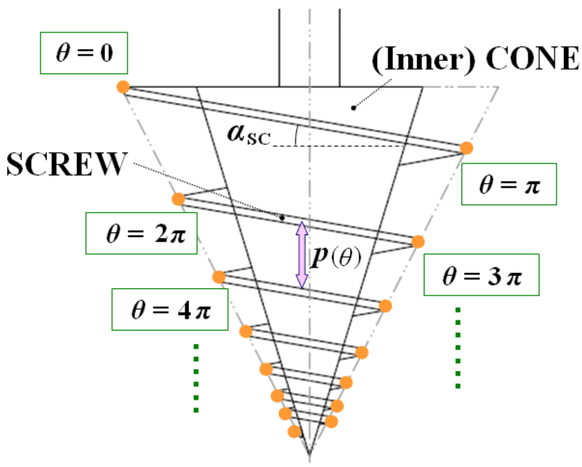


Fig.8 Schematic of N-RDM systems



(a) Drawing


(b) Picture

Fig. 9 Model of SSD unit

6. Conclusion

In this paper, the authors discuss a novel robotic burying seismometer system. And firstly this paper describes the limit of compression method for making space in subsurface and need of generation of a propulsive force for advancement. Then the authors propose a new excavating screw mechanism with N-RDM. Some experiments are under going for the validation of the proposed excavating method as future works.

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