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A Mole-Type Drilling Robot for Lunar Subsurface Exploration

Keisuke WATANABE (The Univ. of Tokyo), Shingo SHIMODA (The Univ. of Tokyo),
Takashi KUBOTA (ISAS), Ichiro NAKATANI(ISAS)

3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan
E-mail:{*keisuke, shimoda, kubota, nakatani*}@nnl.isas.ac.jp

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Abstract

This paper proposes a new mole-like robot for the lunar subsurface exploration in the near future and the mechanism for forward movement. The mole robots have to carry the excavated regolith backward because of its high density. Therefore a new scheme is proposed, to move forward under the soil by making use of reactive force caused by pushing the discharged regolith. Simple experiments demonstrate the effectiveness of the proposed method.

1. Introduction

Unmanned deep space explorations have received a lot of attention again in recent years. Some missions to land safely and explore on the surface of the moon or other planets are proposed. As regards the moon, some lander-rover missions are planned such as Japan's SELENE-B[1]. In these missions, in order to conduct in-situ analysis of geological samples or deploy devices for measurement, it is required to excavate the regolith layer, which covers the lunar surface, in depth of several meters. Some suggestions for drilling on the lunar surface have already been made[2][3][4]. However, there are no schemes that satisfy the requirement. This paper, to begin with, proposes a mole-like robot which is small and maneuverable in regolith. Then, a scheme is also proposed, for the robot to move forward in the soil. Finally, the moving mechanism is studied by powder mechanical analyses and some experiments. The experimental results show the feasibility of the proposed method.

2. Excavation on the surface of the moon

2·1 Problems in excavation

This paper deals with the regolith layer that is said to cover the lunar surface at least 10[m] in depth[5]. Because of its extremely high filling factor, it is hard to make space by compressing. In addition, the characteristic environment such as small gravitation and vacuum need to be considered. There are also constraints on system's weight and energy consumption like the other space probes.

2·2 Drilling robot

Considering the problems mentioned above, for drilling regolith layer, a novel mole-like robot is proposed. The proposed robot system has the following features.

1. The robot can drill and move forward in the soil, when the whole body is buried.
2. The robot is so small and light that rovers can carry it.
3. The robot has enough autonomy to explore by itself.

As to 1., a boring scheme, which is generally used as means of drilling on the earth and also planed to use in space[2], needs shafts as long as the depth of hole that is to be excavated. In addition, the friction force is getting larger as a hole becomes deeper. Therefore, it means that this feature can suppress increasing system's weight and power consumption comparing with boring. Yoshida et al.[3] also suggest a mole-type drilling robot. Because the robot needs mechanism that carries excavated regolith to the surface of the moon or planets, the problems come up with increasing hole's depth is the same as boring. In contrast to this, the proposed robot is buried. Meanwhile, it is assumed that the robot does not come back to the surface. As regards 2., a rover will be used to explore on the surface. Therefore, if the drilling robot can be carried by the rover, the robot need not to be able to move all by itself. As to 3., it is desirable for the drilling robot to excavate alone, in order to make

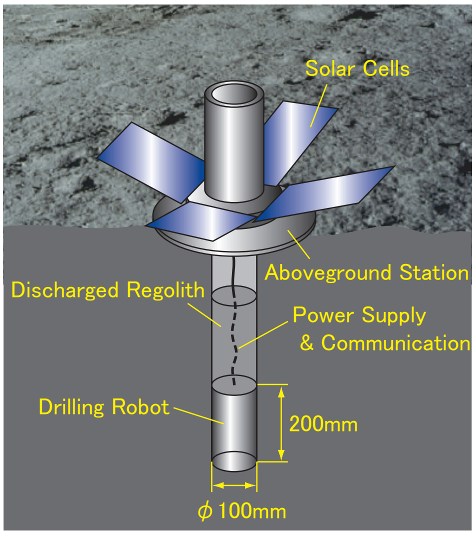

Fig.1 Proposed drilling robot system.

use of resources for exploration such as a lander and rover.

It is assumed that electrical power is supplied by a wire from the robot ground station on the surface.

3. Proposal of mole-type robot

Figure 1 shows the concept of the proposed robot system. The system consists of a drilling robot and aboveground part. The whole body of drilling robot is to be buried as mentioned above. The aboveground part is connected with the drilling robot by a wire in order to supply electric power and communicate. The ground station has not only power generator(solar cells), but also communication system between the robot and the lander or the mother rover, and relays the commands and data between the drilling robot and lander or rover.

3·1 Forward movement in the soil

When the subsurface exploration is carried out, the activity of the robot can be divided into three phases.

1. Moving to the drilling point and deploying.
2. Starting to drill (half-buried).
3. Moving in the soil (full-buried).

As to phase 1, the robot can move through cooperation with a rover (i.e. a rover carries the robot to the drilling exploration point). Therefore, the robot need not to move all by itself. In phase 2, also, the aboveground station (see Fig.1) can help the robot to start drilling. Thus, the problem on phase 3 is especially discussed in this paper.

In order to move forward in the soil, the following two mechanisms are required.

(a)Making space forward.
(b)Moving toward that space.

As regards (a), because the filling factor of regolith on the moon is known to be very high, the robot must carry the excavated regolith backward and discharge. In addition to this, as for (b), the gravitation on the lunar surface is the one sixth times as much as that on the earth's surface. Therefore it is difficult for the robot to keep moving downwards only by the gravitation. Thus, some mechanisms that make the robot move by itself are needed.

Therefore, the following functions are needed for subsurface exploration robots.

1. Excavation.
2. Carrying.
3. Discharging.
4. Forward Movement.
5. Direction Control.

This paper focuses on the discharging function and forward movement. This paper proposes a novel forward-movement method that makes use of reactive force caused by pushing the discharged regolith above the robot. Figure 2 shows the proposed method to move forward in the soil. First, the robot excavates the regolith and lets them into the robot's body(Fig.2(a)). Secondly, the robot carries the excavated regolith upward through the body, and discharges from the top of the robot(Fig.2(b)). Finally, by pushing the discharged regolith, the robot moves forward(Fig.2(c)).

4. Feasibility study on forward movement

The performance of the proposed method depends on the following points.

- Whether discharged regolith can support enough reactive force required for the robot's moving forward.
- Whether the drilling robot can discharge regolith inside with being other regolith that has already discharged on the robot.

As to the former, the analyses are performed, based on a model using powder mechanics, and

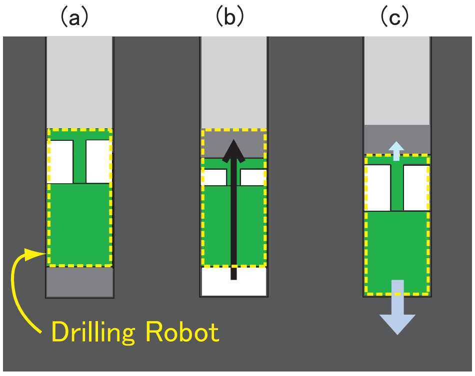

Fig.2 Forward movement method.
(a)Excavation. (b)Carrying regolith backward through the robot and discharge. (c)Forward movement by pushing discharged regolith.

some experiments are conducted, by measuring maximum load that discharged regolith can support. As regards to the latter, a novel discharging mechanism is devised, and the function of the mechanism is evaluated through simple experiments.

4·1 Regolith discharge

4·1.1 Analyses by the powder mechanical model

A shaft in dry sand is known to be comparably stable [6] . Thus, regarding the shaft formed by drilling as a cylindrical tube, some analyses are made by using a model of powder in the tube.

Set z-axis downwards from the surface. When the external force F applies upwards at $z = h$, the vertical stress distribution is expressed by the following equation.

$$P = \frac{\rho g D}{4\mu K}\left(1-\exp\left(-\frac{4\mu K z}{D}\right)\right)-\frac{4F}{\pi D^2}\exp\frac{4\mu K}{D}(z-h) \tag{1}$$

Where D is the diameter of the cylinder, μ is the friction coefficient between the powder and the wall of the cylinder, g is gravitational acceleration. It is assumed that the horizontal stress is proportional to vertical stress, and K is the ratio. The share stress at the wall is proportional to P and the direction is inverse, therefore, the condition that whole powder moves upwards is $P \le 0$ with $0 \le z \le h$. Define as $F = F_{max}$ at this moment, when F_{max} satisfies the following equation, the drilling robot can move forward by pushing discharged regolith.

$$F_{max} > F_r - F_g \tag{2}$$

Where F_g and F_r is gravitational and frictional force affecting on the robot respectively. In the next section, F_{max} is measured though some experiments.

4·1.2 Measuring experiments

In order to measure maximum sustainable load of discharged regolith, a load measuring apparatus are developed. Its shape is cylindrical and the diameter is 100[mm]. It has a piston whose stroke is 70[mm], maximum output and measurable load are both 100[kgf].

Experiments are conducted as follows. First, to compare the result from analyses based on the model with that from the experiments, some parameters (friction coefficient μ and ratio of vertical to horizontal stress K) must be estimated. As shown in Fig.3 (a), an acrylic pipe is set, where regolith simulant has been glued on the internal surface, in order to make surface condition correspond with actual situation, on the top of the measuring apparatus. Then, regolith simulant is put into it without moving the piston and the load is measured. And then the relation between depth of the simulant and load is studied. As a result of this experiment, $\mu K = 0.2$ is obtained as an estimated value (μ and K always appear as a pair in equation(1), their product is regarded as a constant here). Secondly, as shown in Fig.3 (a), the load is measured at the moment when the upper surface of the simulant start to move, by having the piston move upwards with the simulant being put in the pipe. Furthermore, as shown in Fig.3 (b), other measurements are performed by forming a shaft in simulant and on the same way as mentioned above.

However, it is difficult to form a shaft completely for more than 100[mm] in depth. Therefore, as shown in Fig.3 (b), a weight is put on the simulant and stress distribution in the deeper area is simulated. This simulation is conducted as following. First, the piston is moved upwards without the weight, load and displacement of the piston when the surface of regolith starts to move is measured.

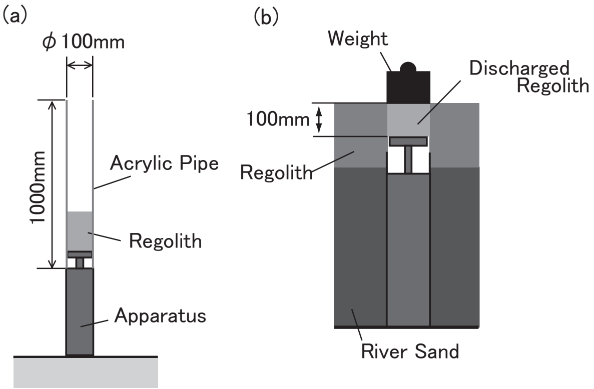

Fig.3 (a)Experimental configuration with acrylic pipe. (b)Experimental configuration with regolith.

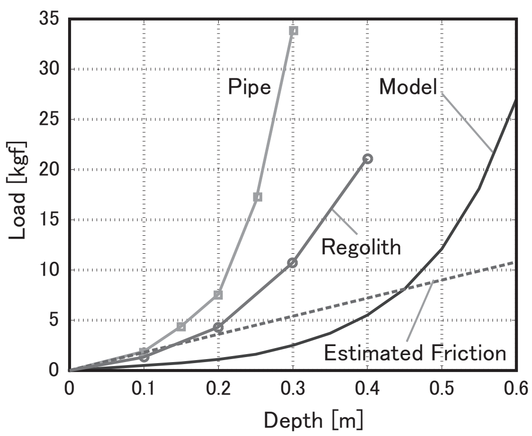

Fig.4 Results of measuring maximum sustainable load.

Then, the weight, whose mass generates equal load to the measured value, is put on regolith and next measurement is conducted. This time, there are following rules to be kept.

- When the displacement of regolith's surface is equal to that of the former measurement, the load is measured.
- If the load becomes maximum before reaching above state, the maximum load is regarded as measured value.

By repeating this procedure, the stress distribution of every 100[mm] in depth can be simulated.

These experimental results are shown in Fig.4. It is assumed that the earth pressure follows Rankine's theory. The estimated friction by the earth pressure under 1[G] condition is shown as dotted line in Fig.4. When the sustainable load of discharged regolith is larger than the friction force, the drilling robot is able to move forward. Therefore, it can be concluded that the forward movement by the proposed method is feasible when the position of the robot is more than 0.2[m] in depth, by the experiment, or 0.5[m] in depth, by the analysis from the model.

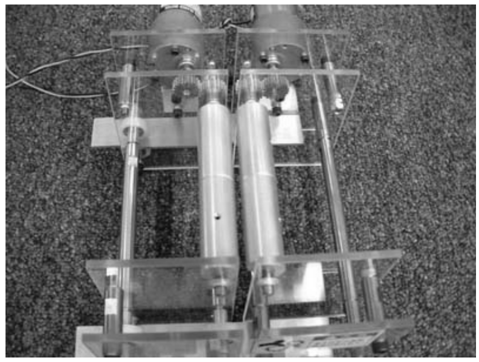

Fig.5 Experimental model of the regolith discharging mechanism.

4·2 Discharging mechanism

A discharging mechanism is required to discharge inside regolith with preventing outside regolith from entering into the robot. The authors devised novel discharging mechanism considering this requirement.The mechanism has two rollers which rotate to the opposite direction of each other(i.e. right roller rotates clockwise, left one rotates counterclockwise). Figure 5 shows the test model of discharging mechanism. This test model consists of two parallel rollers whose length is 100[mm] and diameter is 20[mm], and made of aluminum alloy(A5052). The rollers rotate at 2.5[rpm](approx.). The interval between them can be fixed arbitrarily with being kept parallel. In addition, it is possible to affect tension between rollers by using springs.

To evaluate whether this mechanism satisfies the requirement, some simple experiments are conducted. First, supplying regolith from bottom side of rollers and see whether regolith can be discharged upwards through the gap between rollers. A rectangular table, whose size is

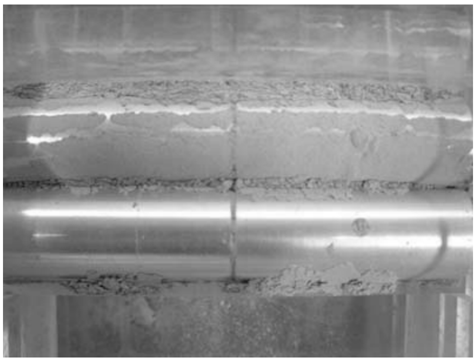

Fig.6 After driving the roller mechanism for 60[s] with tension affected between the rollers.

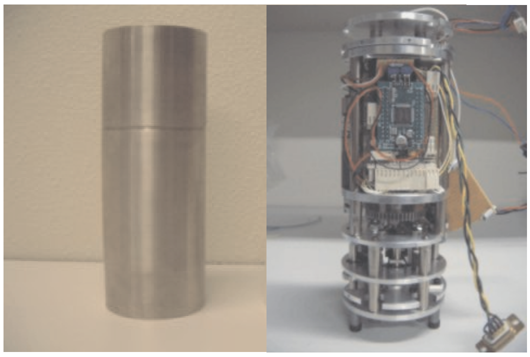

Fig.7 Trial integrated system's external appearance(left) and internal mechanism.

100[mm]×40[mm], is made by acrylic plate and set right below the rollers. Then push the table toward the rollers by four springs(pushing force is approximately 0.12[kgf] when the table touches the rollers). After being charged regolith on the table, the rollers are driven for 60[s] in following three cases. (1)Interval fixed at 0.1[mm]. (2)Interval fixed at 0.2[mm]. (3)Tension affected by two springs(spring constant is 0.13[kgf/mm], initial tension is 2.8[kgf]). As a result, it is confirmed that regolith can be discharged when the interval is 0.1[mm] and tension affected. Figure 6 shows appearance of the rollers after the experiment with being tension affected.

Secondly, put regolith on the rollers and affected load(approx. 5[kgf]) on whole of them. In this circumstances, drive the rollers for 60[s] and observe whether regolith falls through the gap. Though, no falling regolith is seen.

These results lead to the conclusion that the discharging mechanism satisfies the requirement.

5. Integrated robot system

To investigate the validity of the proposed robot system, the integrated robot with the proposed mechanisms was developed. External appearance and internal mechanism of the integrated robot is shown in Fig.7.

The integrated robot is cylindrical shape, whose diameter is 100[mm] and length is 270[mm], and has drilling, carrying, discharging, compressing and moving mechanisms. Sensors for measuring pushing load and drilling resistance are also equipped. On the occation of implementation of the system, specifications, such as output of actuators, are determined based on the studies so far. By using the developed system, some check tests were performed. The check tests suggested that some improvement were clear and the design will be changed minorly.

6. Conclusions and future works

This paper proposed a mole-type robot for lunar subsurface exploration and the mechanism for forward movement by making use of discharged regolith. The feasibility of the proposed method was confirmed by the analyses and some experiments on each component part.

The construction of the completed system and demonstration of the proposed method by drilling experiment are under going as future works.

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