Deep Drilling Robot for Subsurface Exploration

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Abstract - **This paper presents a mobile robotic system designed to perform deep soil sampling for lunar subsurface exploration in the near future. Drilling 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.**

I. INTRODUCTION

Unmanned deep space explorations have received a lot of attention in recent years. Some missions[1][2] to land safely and explore on the surface of the moon or other planets are proposed and planned in the world. In Japan, lunar lander-rover mission is also planned, which is called SELENE-B[3]. In these missions, it is required to perform sampling, conduct in-situ analysis of geological samples and deploy devices for measurement and observation. Many researchers have studied and developed sample acquisition systems[4][5][6] and driller or corer systems[7][8]. Recently deep drillers or penetrating systems have been required to obtain deep data for subsurface exploration. In lunar mission, it is needed 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[9][10][11][12]. However, there are no schemes that satisfy the requirement. This paper, to begin with, proposes a mole-like robot which is 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 robot.

This paper is structured as follows. Section 2 describes the requirements, the problems, and the concept of mole-type robot for lunar subsurface drilling. In Section 3, a new mechanism for forward movement in the soil is proposed. Section 4 discusses the feasibility of the proposed scheme by investigating the regolith property. In Section 5, a discharging mechanism is proposed. For discharging regolith, two rollers are used. In Section 6, a regolith carrying mechanism is developed based on the torsion vibration method. Finally, Section 7 is for discussions, conclusions, and future work of the research.

II. LUNAR SUBSURFACE DRILLING

A. Problem in Excavation

This paper deals with the regolith layer that is said to cover the lunar surface at least 10[m] in depth[13]. 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 the system weight and energy consumption like the other space probes.

B. Requirements for Drilling

Considering the problems mentioned above, for drilling regolith layer, the authors proposed subsurface exploration concept by mole-like robot[14]. The proposed exploration 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 the mother rover can carry it.

3. The robot has enough autonomy to explore by itself.

If a boring scheme[15] is used in planetary mission, which is generally used as a means of drilling on the earth, longer shaft is needed according to the depth of the hole that is to be excavated. In addition, the friction force is getting larger as a hole becomes deeper. Therefore, it means that the proposed mole-typed robot can suppress increasing system weight and power consumption comparing with boring. Yoshida[10] also proposed another type of drilling robot. However, the same problems come up with increasing hole's depth as boring systems, because the robot needs mechanism that carries excavated regolith to the surface of the moon or planets. In contrast to these, the proposed robot is buried. Meanwhile, it is assumed that the robot does not come back to the surface.

Scientists would like to explore wide areas on the planetary surface. So it is reasonable that the mother rover carries a drilling robot and so small drilling robot has to be developed. It is desirable for the drilling robot to excavate alone, in order to make 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.

C. Lunar Drilling Robot Concept

Figure 1 shows the concept of the proposed robot system. The robotic system consists of a drilling robot and aboveground parts. 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.

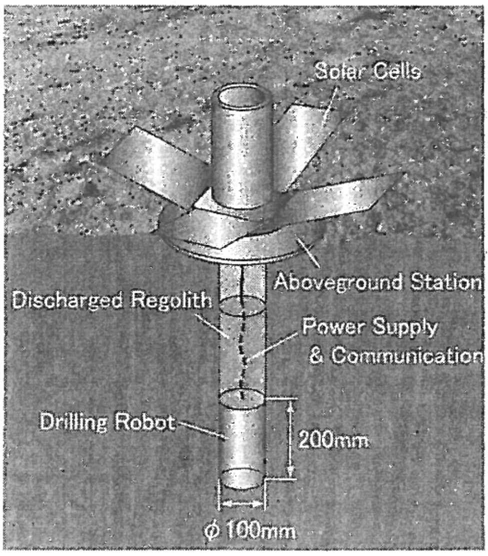

Fig.1. Concept of drilling robot system

III. FORWARD MOVEMENT MECHANISM

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 the phase 1, the robot can move through cooperation with the mother rover (i.e. the mother rover carries the robot to the drilling exploration point). Therefore, the robot need not to move all by itself. In the phase 2, also, the aboveground station as shown in Fig.1, can help the robot to start drilling. Thus, the problem on the 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), the robot has to carry the excavated regolith backward and discharge, because the filling factor of regolith on the moon is known to be very high. 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 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. Firstly, 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)).

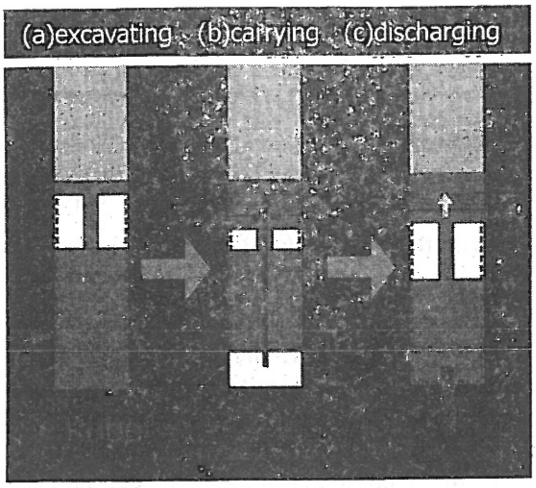

Fig.2. Forward movement method

IV. REGOLITH PROPERTY TEST

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

(1) whether the discharged regolith can support enough reactive force required for the robot's moving forward,

(2) whether the drilling robot can discharge regolith inside where already discharged regolith has been above the robot.

As to (1), the analyses are performed, based on the model using powder mechanics, and some experiments are performed by measuring the maximum load that discharged regolith can support. As regards to (2), a novel discharging mechanism is devised, and the function of the mechanism is evaluated through simple experiments.

A. Analysis by Powder Mechanical Model

A shaft in dry sand is known to be comparably stable[15]. 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.

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

, 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.

Here, it is assumed that the horizontal stress is proportional to the 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 the whole powder moves upwards is $P \leq 0$ with $0 \leq z \leq h$. Define as $F = F\max$ at this moment, when $F\max$ satisfies the following equation, then the drilling robot can move forward by pushing the discharged regolith.

$$F\max > Fr - Fg \qquad (2)$$

,where Fg and Fr are gravitational and frictional force affecting on the robot respectively. In the next section, $F\max$ is measured though some experiments.

B. Measuring Experiments

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

Experiments are conducted as followed. Firstly, to compare the result from analyses based on the model with the result from the experiments, some parameters, the friction coefficient μ and the ratio of the vertical to the horizontal stress K, need to 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 these experiments, $\mu K = 0.2$ is obtained as an estimated value. Because, μ and K always appear as a pair in equation(1), and 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 starts 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 performed as followed. Firstly, the piston is moved upwards without the weight, load and displacement of the piston when the surface of regolith starts to move is measured. Then, the weight, whose mass generates the equal load to the measured value, is put on regolith and the next measurement is conducted. At this time, there are the following rules to be kept. By repeating these procedures, the stress distribution of every 100[mm] in depth can be simulated.

<R1> When the displacement of regolith surface is equal to that of the former measurement, the load is measured.

<R2> If the load becomes maximum before reaching the above state, the maximum load is regarded as measured value.

Figure 4 shows the experimental results. Here it is assumed that the earth pressure follows Rankine's theory.

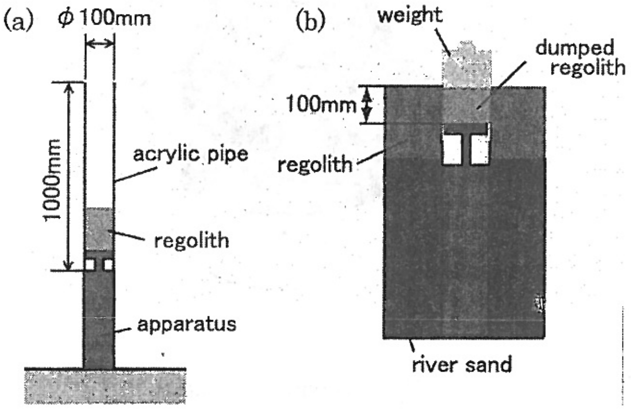

Fig.3. Experimental configuration

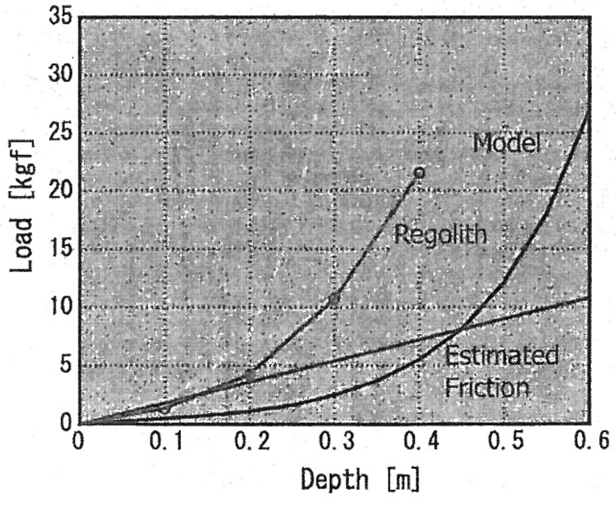

Fig.4. Results of measuring sustainable load

The estimated friction by the earth pressure under 1[G] condition is shown as a red 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.

V. DISCHARGING MECHANISM

A discharging mechanism is required to get out the inside regolith with preventing outside regolith from entering into the robot. A novel discharging mechanism is developed considering the above requirement. The proposed mechanism has two rollers which rotate to the opposite direction of each other. The right roller rotates clockwise and the left one rotates counterclockwise. Figure 5 shows the test model of discharging mechanism. The test model consists of two parallel rollers, whose length is 100[mm] and diameter is 20[mm]. These are made of aluminum alloy (A5052). The rollers rotate at 2.5[rpm]. 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 the proposed mechanism satisfies the requirement, some simple experiments are conducted. Firstly, supplying regolith from the bottom side of rollers, it is checked whether regolith can be discharged upwards through the gap between rollers or not. A rectangular table, whose size is 100[mm]*40[mm], is developed by acrylic plate and set right below the rollers. Then the table is pushed toward the rollers by four springs. Here the 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 the following three cases.

(1) Interval fixed at 0.1[mm]

(2) Interval fixed at 0.2[mm]

(3) Tension affected by two springs

(4) The spring constant is 0.13[kgf/mm]

(5) Initial tension is 2.8[kgf]

As a result, it is confirmed that the regolith can be discharged when the interval is 0.1[mm] and tension affected. Figure 6 shows the appearance of the rollers after the experiment with being tension affected.

Secondly, the regolith is put on the rollers and about 5[kgf] load is affected on the whole of them. In this circumstances, the rollers are driven for 60[s] and it is checked whether regolith falls through the gap or not. In these experiments, though, no falling regolith is seen. These results lead to the conclusion that the proposed discharging mechanism is effective to satisfy the requirement.

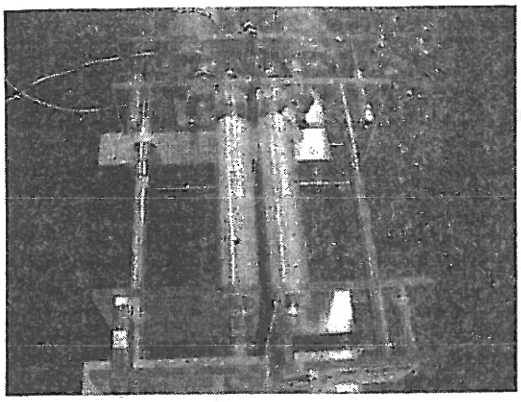

Fig.5. Experimental model of discharging mechanism

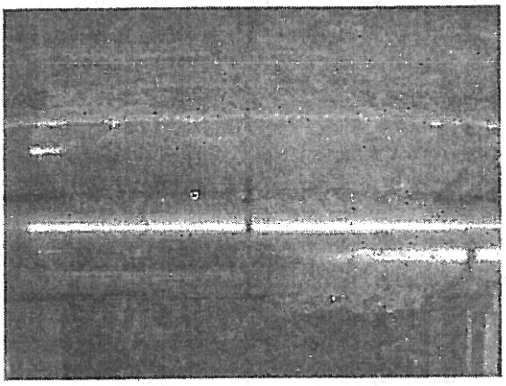

Fig.6. Experimental result after driving the rollers

VI. CARRYING MECHANISM

A carrying mechanism is required to move the drilled regolith to the upper part for forward movement. Some carrying mechanisms are developed. One is the bucket elevator method[10] to use the principle of a belt conveyer. Another one is the vibration based transportation method[11]. The mechanism based on the bucket elevator method is complex and need a lot of parts and space. So the vibration based transportation method is modified to carry the regolith. Figure 7 shows the mechanism of the torsion vabration. Figure 8 shows the principle of the vibration based transportation method. By vibration, the acceleration a is generated. The force of particles in the horizontal direction is expressed as follows.

$$g\cos\theta - a\sin(\phi - \theta) \tag{2}$$

Therefore, the condition that particles can hop and move is described as follows.

$$a > g\frac{\cos\theta}{\sin(\phi - \theta)} \tag{3}$$

By giving vibration to the plate trough, particles can have upper velocity along the trough.

To confirm the effectiveness of the carrying mechanism, the experimental model is developed as shown in Fig.9. The developed system has two DC motors and two weights to generate torsion vibration. By rotating the weights at about 12[rps], the width of vabration was about 0.003[m]. It was observed that regolith on helocal trough was moved. By the experimental results, it is confirmed that the regolith can move upward along the trough.

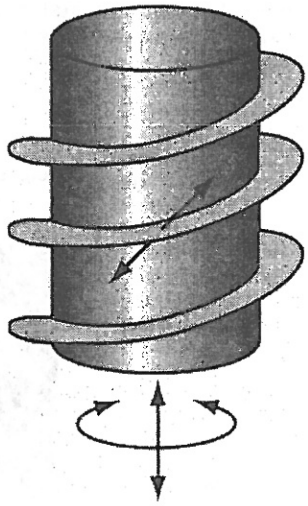

Fig.7. Torsion vibration

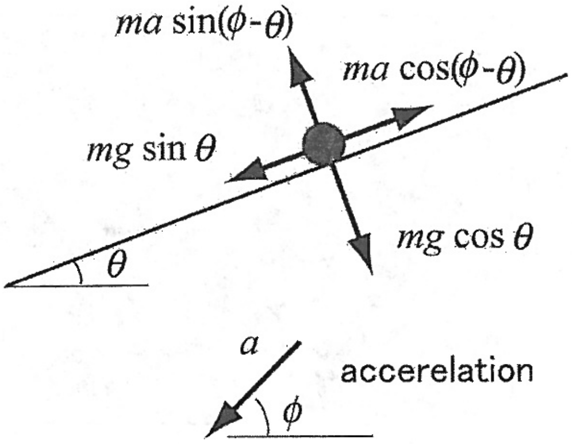

Fig.8. Principle of torsion vibration

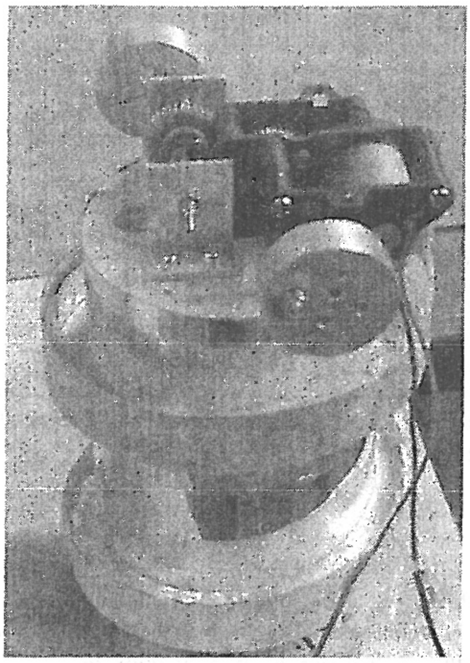

Fig.9. Experimental model of carrying mechanism

VII. CONCLUSIONS

This paper has presented a mole-type robot for lunar subsurface exploration. This paper proposed the mechanism for forward movement by making use of discharged regolith. The discharging mechanism and the carrying mechanism were also developed and tested. The feasibility of the proposed method was confirmed by the analyses and some experiments on each component part. The integrated construction and the demonstration of the proposed method by drilling experiment are under going. This research was partially supported by JSPS, Grant-in-Aid for Scientific Research (C), 2004, 15560230.

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