

**BIO-INSPIRED BURROWING MECHANISM
FOR UNDERGROUND LOCOMOTION CONTROL**

S. M. Moon, S. W. Hwang, S. M. Yoon, J. HUH and *D. Hong

Department of Mechanical Engineering

Korea University

Seoul, Korea

(*Corresponding author: dhong@korea.ac.kr)

BIO-INSPIRED BURROWING MECHANISM FOR UNDERGROUND LOCOMOTION CONTROL

ABSTRACT

Today, underground exploration is spotlighted as an infinitely developable area. For this purpose, many tunneling technologies were created. And until this very day, many techniques are being developed for more efficient underground movement. Although previous technologies have been developed and now being used in various forms like TMB, struck propulsion method and hydraulic propulsion method, it is hard to find a robot type exploring in small scale. But development of small scale underground exploration robot is a promising research subject for its usage in examination of soil, mineral, and subterranean resources, investigation of hazardous regions, and the military. So we developed a robot that can dig and move underground, inspired from the motion of earthworm and mole cricket. Earthworm and mole cricket dig the soil in the front and draw it off backward, so that they can move forward.

We developed a mechanism that uses 2 rotating solid of revolution (bits) for pulverizing the firmly united soil in the front and put it inside the body. The bits rotate in the opposite direction of each other. While moving forward, the soil in the front moves along the spiral on the bit and is saved inside the body. The soil saved inside is taken out through an outlet in the back by a ventilation system. The ventilation system on the ground blows through a hosepipe connected to inner part of the robot and the air blows off the soil. The moving mechanism of exploring underground can be classified into 2 parts. One is to fix the blade link on the soil in a form of 4-bar link. The other one is to move forward rotating the whole link. When the blade link system for movement rotates a certain degree, one blade link is fixed, while the other one is folded in. When 2 blade links of different length rotate as it is, different torque is applied on each link. By the law of action and reaction, the link that has larger torque leads the rotation and movement.

KEYWORDS

Burrowing robot, Underground locomotion, Bio-inspired robot

INTRODUCTION

At present, there are advanced boring machines developed for the purpose of tunneling such as the Tunnel Boring Machine (TBM) but a small scale exploration robot system is yet an unfamiliar field of study. Development of small scale underground exploration robot is a promising research subject for its usage in examination of soil, mineral, and subterranean resources, investigation of hazardous regions, and the military.

The types of boring equipment that have been used so far are cable tool drilling (percussion drilling) type, where a heavy string falls freely to dig ground underneath, hydraulic percussion drilling which applies impact using a pneumatic hammer, jetting drilling which sprays a jet of water, and the rotary drilling which rotates a bit to dig. There are several methods the TBM uses to drill large size tunnels but the main conformation is the rotary drilling method of rotating bits to dig. Such methods are certified methods of tunneling, but are unsuitable for a small scale exploration robot considering matters of size and mobility.

A tunneling system designed for the purpose of exploration has been in study recently but progress is so far incomplete. Thus, we have developed a mobile subsurface exploration robot that derives its motive from earthworms and mole crickets. The robot requires excavation, carry, discharge, forward movement, direction control functions in order to move under the ground. (Takashi et al., 2005) A mechanism was developed for our robot system to implement the specified functions. This mechanism mimics mole cricket's movement of burrowing and moving a unit to a certain direction, and the earthworm's movement of relocating dug soil to the back of the unit.

DESIGN OF BURROWING MECHANISMS

Excavation Mechanism

Excavation method of burrowing robot

Existing burrowing exploration robots mostly use screws to burrow. In Figure 1 shows some screw type burrowing robot. (a) is the Prototype of autonomous burrowing screw robot (Kenji et al. 2008), (b) & (c) is the Earthworm type drilling robot.(Takashi et al., 2008)

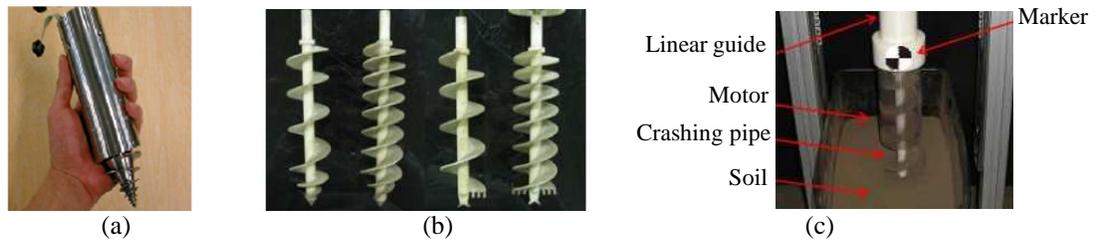


Figure 1 – Existing burrowing exploration robots using screws

However, the most developed method is the bit type used by TBM and other boring equipment. Therefore we use a simplified version of the bit type while copying mole cricket's technique of using its fore feet to tunnel as shown in Figure 2. (a) is the Diamond rotary bits, (b) is the Tri-cone rotary bits (Kim et al., 2010) and (c) is the sketch of mole cricket's fore feet (Retrieved from website: <http://www.bumblebee.org/invertebrates/Orthoptera.htm>)

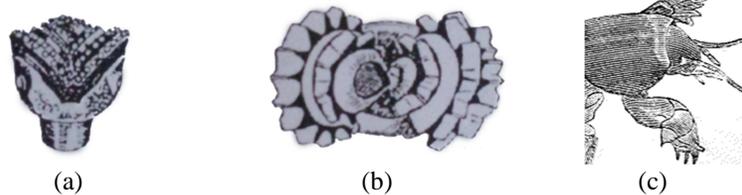


Figure 2 –Boring equipment's bits and mole cricket's fore feet

Design

Figure 3 shows that the bit design was simplified and modified to provide space for a motor to be located inside the bit. This removed the need for allocation of additional space for the motor. A motor with small radius and large torque was required to fit inside the bit. A small motor but having 2.4 N·m torque through large gear ratio was selected and inserted inside the bit. A motor housing was designed to prevent infiltration of sand into the motor, and in order to remove friction between housing and the bit, a design provision was made to insert a bushing. Also the bit installation space shapes like excavator's bucket for crushing soil.

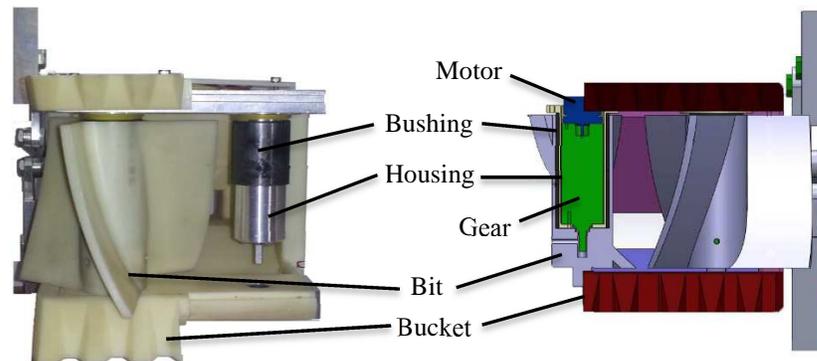


Figure 3 - Configuration of excavation system

Carrying & Discharging Mechanism

Carrying & Discharging method

Crushed soil must be transferred to the back of the unit in order for the unit to move forward. The robot's design implements earthworm's method of absorbing soil into the body and emitting it out the back. The benefit to this method lies in conservation of space. Transferring soil through the body conserves additional space on the outside which otherwise would be used to transfer soil out and also minimizes power supply for friction occurring during that process.

Design

Earthworms use peristalsis to transfer soil. We selected a method involving an air blower to minimize scale, expedite transfer, and minimize power. As shown in Figure 4, drawn-in soil by the bit is collected naturally inside the unit by gravitational force and passes over a slope inside the unit by air pressure from an externally supplied blower. Slope inside the unit prevents soil from flowing backwards. Also an air divider was designed for dividing 1 hose into 2 hoses which supplies the nozzle. It makes that air may come out evenly from a long area of the nozzle.

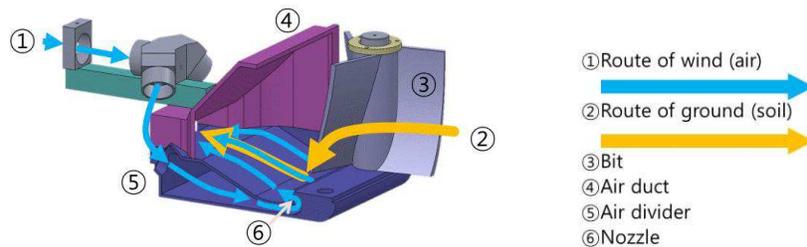


Figure 4 - Air-blowing carrying & discharging system

Forward locomotion Mechanism

Forward locomotion method

Using a universal single wheel to embody movement creates rotation rather than movement of the unit due to friction that exist on top and bottom of the wheel. Instead, we mimicked mole cricket's movement for our unit's movement. A 4-bar link locomotion mechanism was designed based on blade link and base link's movement. Figure 5 shows the sequence of links motion. Motor rotation causes blade link to bury itself into the soil (a), (c) and with a certain angle of rotation this buried link and the base link which supports it rotates together, moving the unit forward (b). Two blade links in opposite directions of each other is connected to one base link so that two forward motions may be possible in one cycle, increasing effectiveness. The base link stays still when a blade link is inserted into the ground and an effective movement is made when the blade and base link rotate together as blade link is rotated. Through link's movement the unit rises and falls, which assists the unit's bucket to crush soil and move forward.

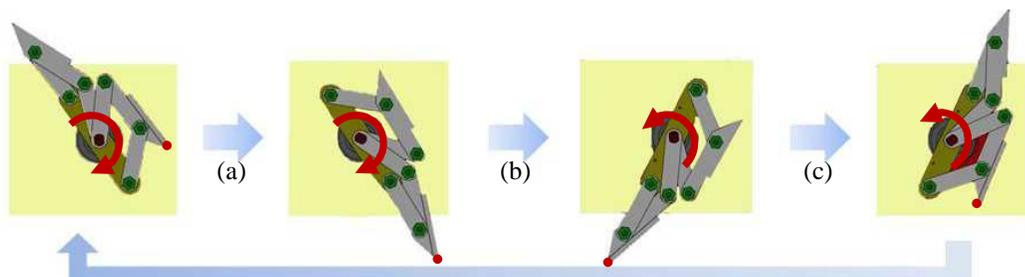


Figure 5 – Sequence of links motion for underground locomotion

Design

Displacement analysis of a 4-bar link mechanism was carried out to design a 4-bar link mechanism. Displacement analysis of a 4-bar link mechanism is made possible by Figure 6 and the following formula.

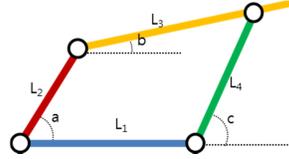


Figure 6 – Simple sketch of 4-bar link

$$L_2 \cos a + L_3 \cos b = L_1 + L_4 \cos c \quad (1a)$$

$$L_2 \sin a + L_3 \sin b = L_4 \sin c \quad (1b)$$

By the rearrangement of formula

$$c = \cos^{-1}(-PR - \sigma\sqrt{P^2 + Q^2 - R^2}/P^2 + Q^2), \quad b = \sin^{-1}(L_4 \sin c - L_2 \sin a/L_4) \quad (2a)$$

$$P = 2L_4(L_1 - L_2 \cos a), \quad Q = (-2L_4L_2 \sin a), \quad R = L_1^2 + L_2^2 + L_4^2 - L_3^2 \quad (2b)$$

Link length was designed to produce efficient movement with entry angle is limited to $60^\circ \sim 120^\circ$. Afterwards, base link L_1 was designed to rotate at entry angle $a = 60^\circ$.

This method can be realized by different mechanisms but this mechanism was designed to consider miniaturization and protection against dust, along with durability. As shown in Figure7, one motor controls two axes but by adding lock & release mechanism the links can be controlled through mechanical control. The trigger connected to motor's axis rotates and control lock & release between base link and locker. By spring's restoring force the locker attempts to approach locking bump on the base link side and thus attempting to control base link movement. However locker moves away from the base link as trigger rotates and the base link rotates along with the trigger.

Therefore, when base link, fixed by the locker, rotates by a certain angle, the trigger lifts locker and allows base link to be rotated as well. This method saves the trouble of having to design complicated control for movement.

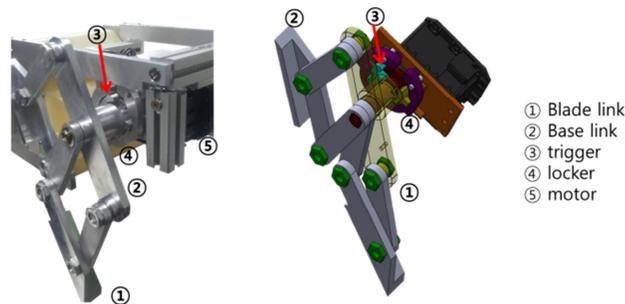


Figure 7 - Configuration of locomotion system

The motor is capable of 2.8 Nm of torque and angle control through an encoder. Numerical calculation shows that approximately 10 N of force is able to be exerted at the end of a link. The robot is designed to have 2links exerting approximately 20 N of force and lift its weight of 1.8 kg during movement.

System & Algorithm design

Figure 8 shows the configuration of the total system. MCU controls four motor drivers each of which are connected to a motor. Two motors drive the bits and the rest drive the locomotion linkage. Also, MCU controls activation of the external air-blowing device which is connected to the discharging system.

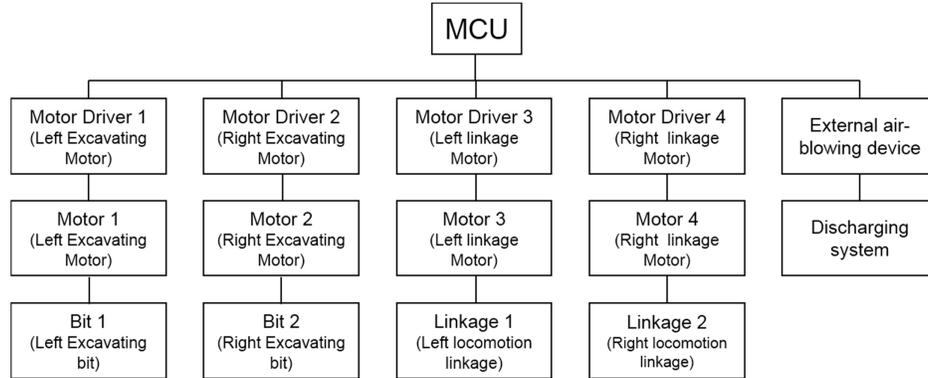


Figure 8 - Configuration of total system.

The algorithm for the underground locomotion system is shown in Figure 9. The underground locomotion system's motor driver senses a change in current when the bit is under load and through comparison to a reference current the system determines whether to activate the air blower or not. Once the system starts, the excavation bits rotate continuously and when the bits contact soil, $I_{E,M}$ (current of Excavating Motor) will rise higher than $I_{R,E,M}$ (Reference current of Excavating Motor). The Reference current of Excavating Motor ($I_{R,E,M}$) is current during in which the bits do not have any resistance. If $I_{E,M}$ is higher than $I_{R,E,M}$, the air blower turns on and locomotion linkages drive very slowly in order to synchronize with excavating speed. If $I_{E,M}$ is lower than $I_{R,E,M}$, the air blower turns off and locomotion linkages drive to the desired direction. Two linkages move synchronously during forward locomotion. On the other hand, turning is accomplished by asynchronous movement of the linkages. For example, if it moves to the right, the right linkage sticks itself into the soil and only the left linkage drives.

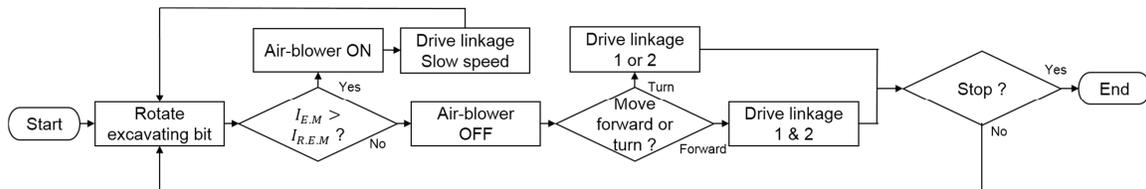


Figure 9 – Algorithm for underground locomotion system

Experiments

Excavation experiment

We created a hypothetical environment of the following dimensions to experiment the robot's digging: 300 mm length, width, and depth. Culture soil was put inside this environment and a dirt wall was formed by applying approximately 2 atm. A constant force of 5 kgf was applied to the bit unit for experiment excavation capability. Figure 8 shows the results of excavation experiment. After 3 repetitive experiments the average displacement of the mechanism in culture soil and sand was 10 cm, and 17 cm respectively, average speed in culture soil and sand was 3.3 cm/min and 5.7 cm/min respectively. Total amount of excavated culture soil was 1.82 m³. In the case of sand, large amounts of sand caved in and reduced accuracy bit and calculating volume was challenging.

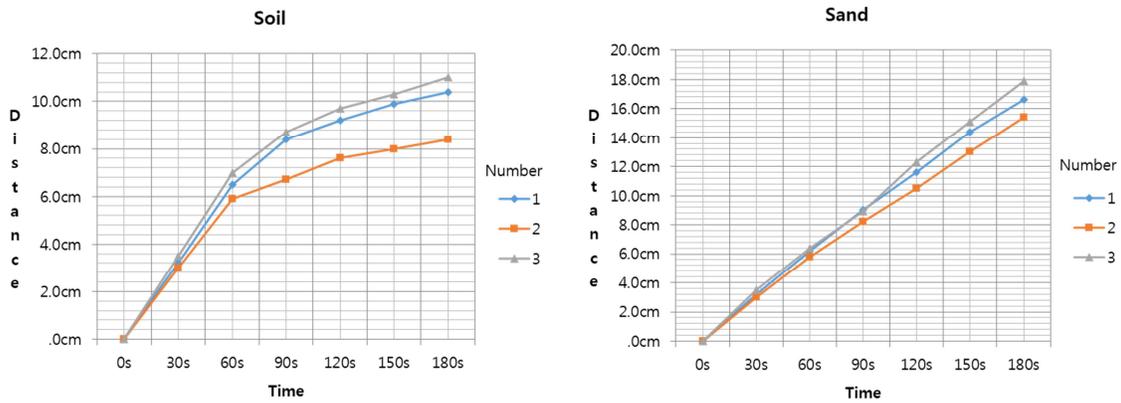


Figure 10 – Experimental results of excavation

The unit's front cross-sectional area is 120 mm × 120 mm but due to excavation and disintegration of soil, the actual area of excavation turned out to be approximately 130 mm × 140 mm. This is enough space for the unit to pass. However the bucket requires a large amount of force in order to pulverize soil above and below the bit. This is a part which requires some improvement.

Carrying & Discharging experiment

To transfer crushed soil drawn in by the bit the unit requires appropriate pneumatic pressure and flow rate. An experiment was carried out using an air compressor to create optimum pneumatic pressure. However an air compressor did not effectively remove soil due to low flow rate. An air-blower was selected to replace the air compressor. The air-blower that was applied to the robot system has volume flow rate of 4.5 m³/min, maximum pressure of 72 mbar, which is used to remove soil in industrial settings. The maximum power of blowing increases power consumption and it decreases robot durability due to fatigue from vibration.

Therefore we experimented carrying & discharging efficiency and applicability in relation to supply pressure to find optimum blowing value. For the experiment 50 g of sand and 10 g of culture soil were used and maintained equal volumes of sand and soil throughout the experiment.

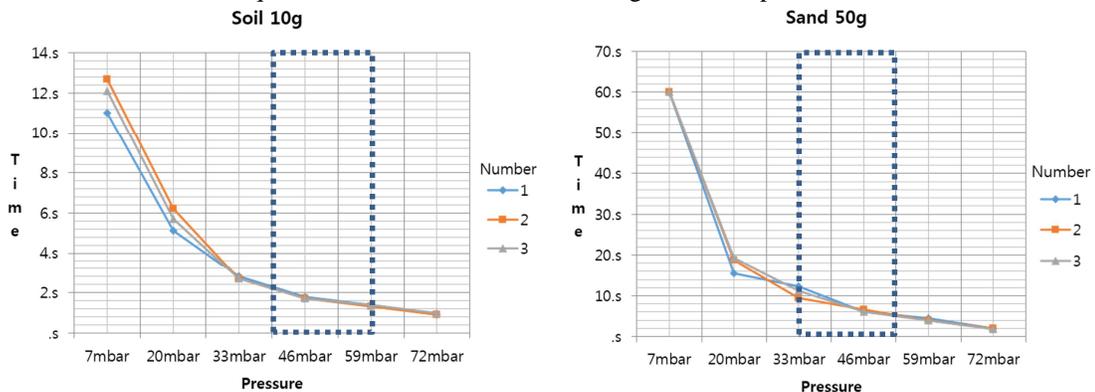


Figure 12 – Experimental results of air-blowing carrying & discharging

Figure 12 shows the results of excavation experiment and the results show optimum supply pressure in relation to various excavation amount and shows optimum capacity at approximately 33 mbar ~ 59 mbar.

Forward locomotion experiment



Figure 13 – Moving process of forward locomotion

This experiment was carried out to verify operation of forward locomotion. As shown in Figure 13, a forward distance from locomotion link's half cycle movement was approximately 11 cm. Due to excavation speed, forward locomotion is predicted to be much lower in a real subterranean environment.

CONCLUSIONS

Unlike vast research carried out on large boring machines, we have designed a very small and mobile bio-inspired burrowing robot that incorporates movement of an earthworm and a mole cricket. In addition, through experimentation of our burrowing robot, we have verified credibility and potential of our design model. We predict the burrowing robot's application to wide fields such as exploring hazardous regions and the military.

ACKNOWLEDGMENT

The work presented in this paper was funded by BMRC(Building-Façade Maintenance Robot Research Center), supported by Korea Institute of Construction and Transportation Technology Evaluation and Planning(KICTEP) under the Ministry of Land, Transport and Maritime Affairs(MLTM).

This work was supported by the Human Resources Development program(No. 20124010203250) of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES

Takashi Kubota, Ichiro Nakatani, Keisuke Watanabe, & Shingo Shimoda (2005). *Study on Mole-Typed Deep Driller Robot for Subsurface Exploration*. International Conference on Robotics and Automation. Barcelona, Spain.

Kenji Nagaoka, Takashi Kubota, Masatsugu Otsuki, & Satoshi Tanaka (2008). *Experimental Study on Autonomous Burrowing Screw Robot for Subsurface Exploration on the Moon*. International Conference on Intelligent Robots and Systems. Acropolis Convention Center. Nice, France.

Takashi Kubota, Kenji Nagaoka, Satoru Tanaka, & Taro Nakamura (2007). *Earth-worm typed Drilling Robot for Subsurface Planetary Exploration*. International Conference on Robotics and Biomimetics.

K.B Kim, & K.M. Ahn (2010). *Technology for groundwater well drilling and construction* (pp. 34-36). Korea

Mole cricket, *Gryllotalpa gryllotalpa*. Retrieved from website:
<http://www.bumblebee.org/invertebrates/Orthoptera.htm> Mole cricket, *Gryllotalpa gryllotalpa*