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Subterranean locomotion of half-inch diameter soft earthworm robot with bellows segments

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***Abstract*— Moving through the ground with a soft robot is a difficult task. Soft locomotion can move without damaging the environment, such as tree roots, but even in just a few centimeters of soil, high friction and resistance forces occur. Differences in soil topography and moisture content also affect the motion. We therefore developed a small, bellows-shaped earthworm robot with an outer diameter of 12 mm. The robot consists of silicone rubber and shape memory alloy wire, and the inside of the bellows is filled with air. When electric current is applied to the shape memory alloy wire, the convex part of the bellows contracts and stretches in the axial direction, generating a force for movement. When no current is applied, it is used as an anchoring segment. We have experimented with 16 different patterns of soil topography and moisture content, and succeeded in realizing soft-robotic subterranean locomotion.**

I. INTRODUCTION

Robots for soil exploration and environmental monitoring require efficient movement in the soil. Soft robots have the advantage of not damaging tree roots or the environment within the soil due to their flexibility. On the other hand, the high frictional and drag forces in the soil make it a particularly difficult environment in which to move. [1] Among living organisms, earthworms are well known for their ability to live freely in the soil. The earthworm moves through the soil using a hydrostatic skeleton, a soft body that moves through the soil by alternately contracting two different muscle groups. The earthworm can move forward by contracting from the leading segment to the trailing segment. [2] In soil movement, differences in soil topography and the moisture content of the soil, such as dry soil or mud, can affect the performance of the robot's movement. However, to the best of my knowledge, there have been no mobility experiments conducted with different soil moisture content and soil topography, so it is important to conduct such experiments.

Several earthworm robots have been studied. An earthworm robot with a diameter of less than one inch that moves on a horizontal surface has also been developed. Among them are a study on reproducing the locomotion of earthworms, which showed that a combination of braided mesh tubing and shape memory alloy wire can move smoothly on a horizontal surface, and an earthworm robot made of shape memory alloy wire and silicone material. [3] [4]A robot that mimics the hydrostatic skeleton of an earthworm using silicone rubber of two different shore hardnesse and a wire-driven robot using braided mesh tubing and a DC motor have also been reported. [5] [6]

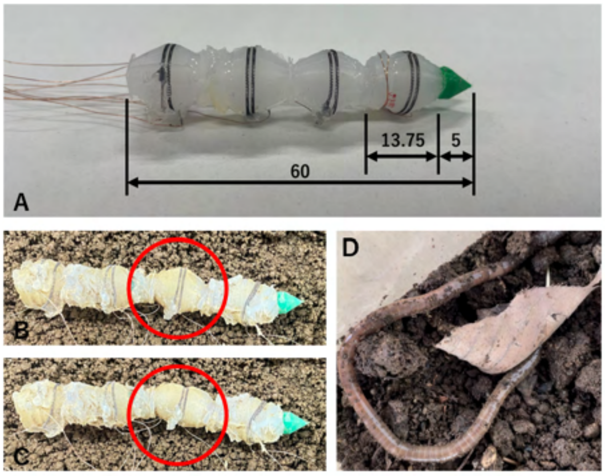

Fig. 1. Bellows-shaped earthworm robot (A):Overview of Bellows-shaped earthworm robot (B):Bellows state before driving (C):Bellows state during operation (D):Earthworms observed in the laboratory

There have also been several studies on earthworm robots that move in granular media or in soil. Experiments have shown that the peristaltic wave characteristics required for an earthworm robot to move in granular media and on a horizontal surface are different, and that controlling the stiffness of the robot tip is important for effective movement in granular media. [7] [8] Earthworm bristles are known to be used to generate anisotropic friction in soil. Focusing on this function, a robot was fitted with bristles fabricated from polyester plastic sheets, which were shown to increase the speed of movement in a trench. [9] Another approach mimics the hydrostatic skeleton of an earthworm. There is a study of an earthworm robot with a hydrostatic skeleton made of low-hardness rubber resin and shape memory alloy wires that actually moves in the soil. [10]A pneumatically driven actuator based on the antagonistic contraction of the earthworm's muscles and the hydrostatic skeleton was developed and shown to be able to move in multiple environments, including granular media, based on this actuator. [11]

The purpose of this study was to conduct mobility experiments in a soil environment and to clarify how changes in soil topography and water content affect the locomotion of an earthworm robot.

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II. BELLOWS-SHAPE EARTHWORM ROBOT

A. *Manufacturing Method*

To fabricate the body of the earthworm robot, a mold was first created using a 3D printer (Bambu Lab X1, PLA Basic Bambu Green). The mold was coated with a mold release agent, allowed to dry naturally, and then injected with silicone rubber (Ecoflex 00-50 Smooth-On) to cure. After curing, the interior was sealed and polyurethane conductors and shape memory alloy wires (Biometal BMX150, Toki Corp., Japan) were soldered in 60 mm lengths. 3D printed conical parts were attached to the robot's head. The completed earthworm robot is shown in Figure 1-A, and its internal dimensions are shown in Figure 2.

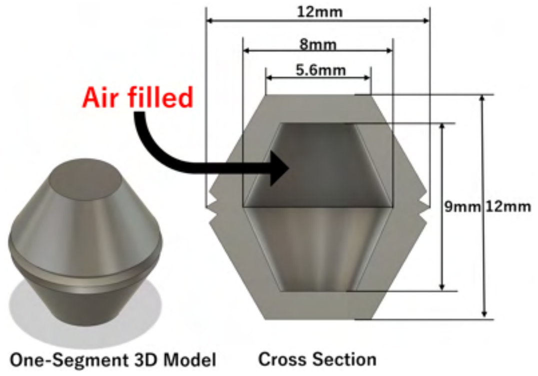

Fig. 2. 3D representation and external and internal dimensions of one segment of the bellows-shape earthworm robot

B. *Working Principal*

As shown in Figure 3, when an electric current is applied to the coiled shape memory alloy wire, the contraction of the shape memory alloy wire causes the bellows-shaped bulges to collapse, extending the robot body. During this process, a force is generated along the axial direction. When the current to the shape memory alloy wire is stopped, the silicone rubber body returns to its original shape, which functions as an anchoring segment. Figures 1-B and 1-C show the actual movement and extension of the earthworm robot in action.

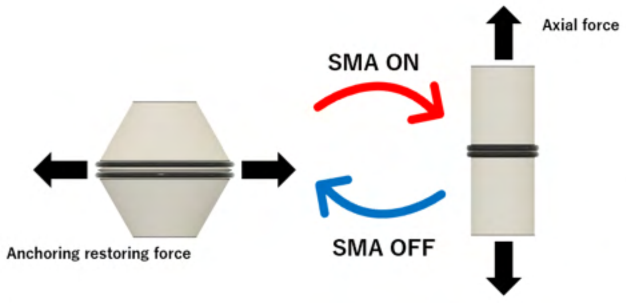

Fig. 3. One-segment working principal

C. *One-Segment Experiment*

An experiment was conducted to measure the elongation rate of one segment of a bellows-type earthworm robot to determine the drive time of the motion experiment. Figure 4 shows the elongation of one segment of the worm robot when 6 V-0.3 A was applied from the stabilized power supply (Matusada P4K18-2). The measurement was made by attaching a color marker to the end face of one segment of the bellows type and color tracking it with a color camera (web camera mini web camera 8 MEGA PIXEL PC CAMERA). The amount of elongation of one segment of the worm robot is shown in Figure 5. The experimental results show that the change occurs within 3 seconds and then there is no change. Based on the results of this experiment, the drive time was set to 3 seconds.

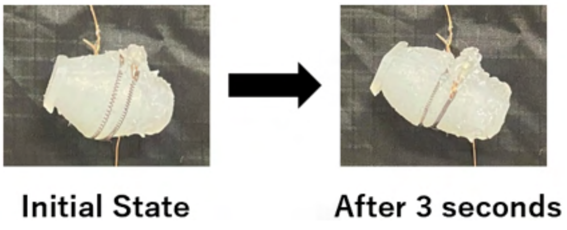

Fig. 4. Displacement of one segment

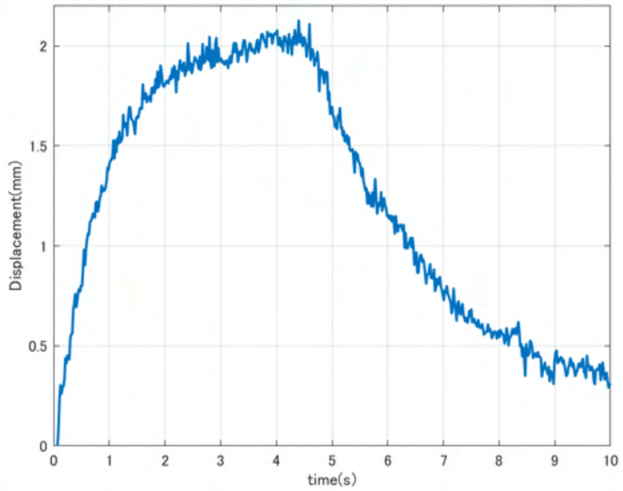

Fig. 5. One-segment elongation

Since the shape memory alloy wire is a thermal actuator, we measured the temperature changes using a thermographic camera (KG-500 Thermographic Camera, KAISE Co.) under the same conditions as in the extension measurement experiment. As shown in Fig. 6, the ambient temperature of the shape memory alloy wire after 3 seconds of activation was 46.7°C, and it took 60 seconds from the start of driving to return to the ambient temperature. This measurement marks the first instance of temperature monitoring for an earthworm robot utilizing a shape memory alloy wire.

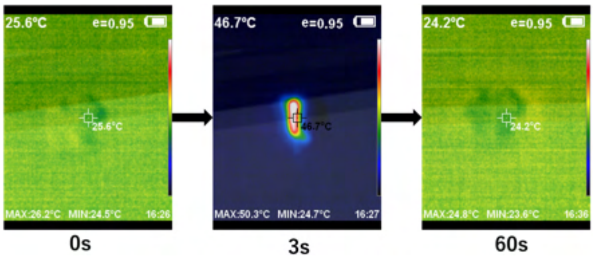

Fig. 6. Temperature change due to Joule heat on shape memory alloy wire

III. LOCOMOTION EXPERIMENT

A. *Experiment Preparation*

The control of the worm robot fabricated in this study is performed by an Arduino Uno R3 and a switching circuit. The switching circuit controls whether or not the current is given to each segment of the worm robot, allowing for precise timing and control during the motion experiment. As shown in Figure 7-A, the experiment consisted of activating each segment for 3 seconds, followed by a 10-second cool-down after all segments were activated. This sequence was considered one cycle, and a maximum of 10 cycles were measured. Displacement during locomotion was tracked by color markers attached to the head of the worm robot. Based on the experimental results of displacement of one segment, the voltage and current applied to the shape memory alloy wires of each segment of the earthworm robot were 6 V and 0.3 A, respectively. The experiments were conducted under four conditions: on the ground surface, in a trench, in soil 3 mm deep, and in soil 10 mm deep. In addition, the soil moisture content was adjusted to four levels: dry soil, 10%, 30%, and 50%, as shown in Figures 7-B and 8. One kg of heat-treated gardening soil (No. 050952, Tachikawa Heiwa Noen Co., Ltd.) was used in the experiments.

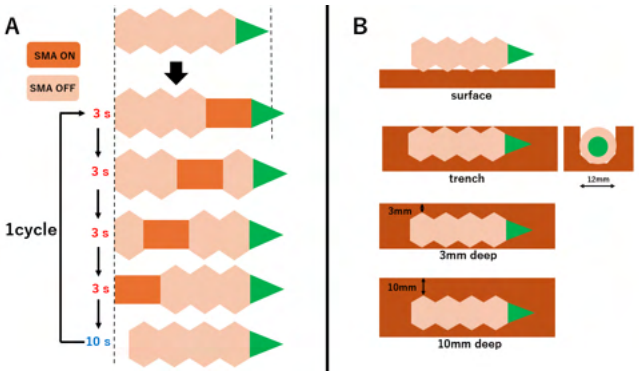

Fig. 7. Experiments overview (A):Driving sequence of the earthworm robot (B):Overview of the moving environment

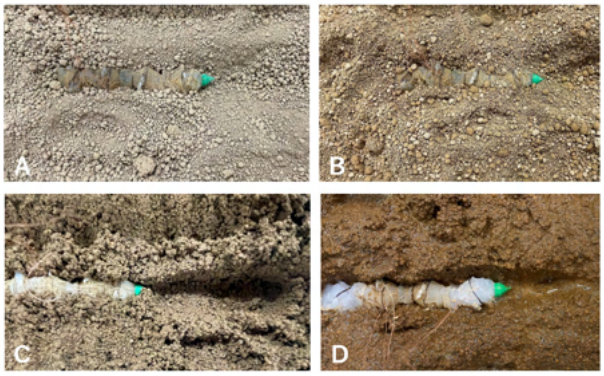

Fig. 8. Experiments on soil trench (A):On the dry soil (B):10% water content (C):30% water content (D):50% water content

B. *Experimental Result*

The results of the experiment are shown in Figures 9 through 12. The environments with the highest velocities were on soil, in a trench, in soil 3 mm deep, and in soil 10 mm deep, in that order. In the experiment on soil (Figure 9), there was no significant difference in the results of the displacement of movement at the 10th cycle in any of the soil conditions. In the experiment on the soil trench (Figure 10), dry soil had the highest velocity, 10% soil and 30% soil had about the same velocity, and 50% soil did not advance as far as the other conditions. In the experiment with the robot buried in soil (Figures 11 and 12), the speed was fastest in the 30% moisture condition. Similar to the experiment in the trench, the robot did not move in the soil at 50% moisture content. The deeper the soil, the slower the migration speed. The soil at 50% moisture content was mud as the experimental environment.

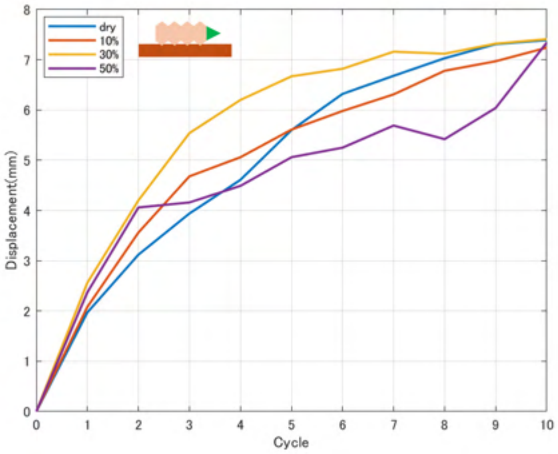

Fig. 9. On the soil

TABLE I

COMPARISON EARTHWORM ROBOT SPEED IN THE GRANULAR MEDIA

Actuator	Diameter(mm) x Length (mm)	Speed (mm/min)	Environment
Shape memory alloy(proposed)	12 x 60	1.58	3 mm depth in the soil(30% water content)
Shape memory alloy(proposed)	12 x 60	0.84	10 mm depth in the soil(30% water content)
Shape memory alloy[10]	10 x 132	0.46	semi buried in the soil
Shape memory alloy[10]	10 x 132	1.5	fully buried in the soil(5 mm depth)
Pneumatic Actuator[7]	35 x 330	262.8	in a plastic granular medium 25 mm depth
Pneumatic Actuator[11]	40 x 250	15.6	in a granular medium at depths of 20 mm
Pneumatic Actuator[11]	40 x 250	21.6	in a granular medium at depths of 40 mm

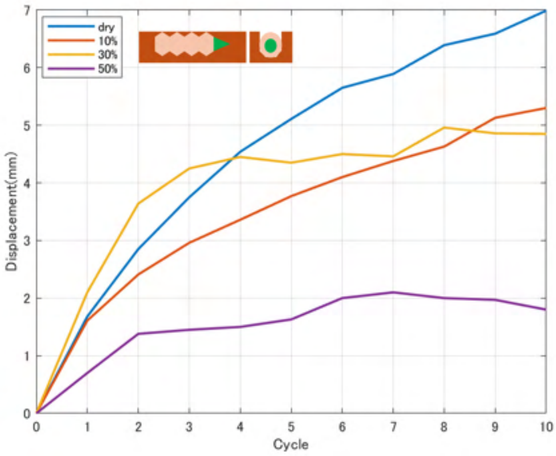

Fig. 10. Soil trench

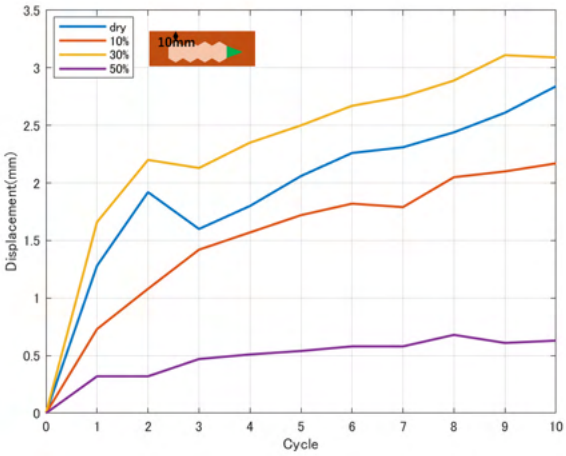

Fig. 12. 10mm depth in the soil

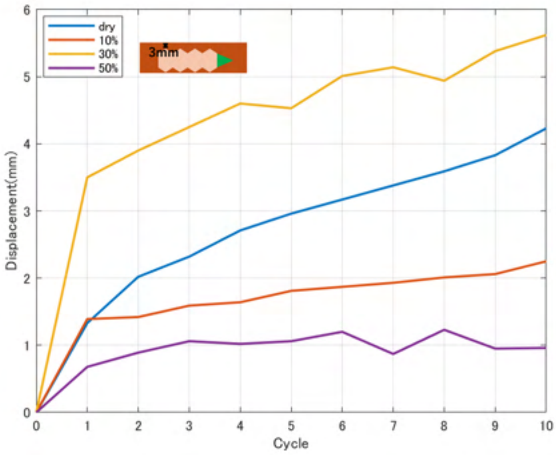

Fig. 11. 3mm depth in the soil

IV. DISCUSSION

A. Effect of Differences in Soil Conditions on Movement Speed

Regarding the variations in soil conditions, no significant differences in locomotion performance were observed on the ground surface. However, in the trench environment, the locomotion speed was higher in dry soil, whereas almost no forward movement was observed in muddy soil with a water content of 50%. This can be attributed to the fact that, in dry soil, the low cohesion between soil particles hindered anchoring. Nevertheless, forward movement was achievable as the propulsion force exceeded the frictional resistance. In contrast, in muddy soil, the slippery surface and the inadequate restorative force for anchoring significantly impeded locomotion.

In the experiments conducted within the soil, the locomotion distance over 10 cycles was shorter compared to the results observed on the ground surface or in the trench. However, in all experimental conditions, the environment with 30% water content yielded the highest locomotion speed, while forward movement was nearly impossible in muddy soil with 50% water content. In dry soil, the weak cohesion between particles and the smooth surface reduced locomotion efficiency. Conversely, in muddy environments, the heightened fluidity diminished frictional resistance, further reducing locomotion efficiency. On the other hand, an intermediate water content improved soil cohesion and structural integrity, enabling the earthworm robot to establish a secure grip on the soil and effectively transmit propulsion forces. This facilitated the most efficient locomotion.

B. Comparison with Previous Studies

The mobility performance of the bellows-shaped earthworm robot developed in this study is presented in Table 1, which lists the actuators, mobility environments, and movement speeds in soil and granular media. While numerous studies have explored earthworm robots utilizing pneumatic actuators, there is little research on robots capable of moving through granular media, let alone actual soil environments. For subterranean locomotion, the small diameter of the robot is crucial for reducing drag within the soil. Among various actuators, shape memory alloy wires, made of nickel-titanium alloy, exhibit excellent corrosion resistance and durability. Moreover, their lightweight and compact nature makes them particularly suitable for thin earthworm robots. When comparing mobility speeds, although the movement environments and robot sizes differ, robots using pneumatic actuators generally achieve faster speeds. However, despite its compact size, the robot employing shape memory alloy wires does not match the speed of pneumatic robots. Nevertheless, in terms of mobility performance, this robot demonstrated superior results in energy efficiency and speed compared to previous studies [10]. Furthermore, it is anticipated that the locomotion capability can be further enhanced by incorporating anisotropic bristles onto the convex parts of the current bellows structure and increasing the number of segments.

V. CONCLUSION

In this study, we developed a small bellows-shaped earthworm robot with an outer diameter of less than half an inch. We measured the extension of a single segment and the temperature changes in the shape memory alloy during operation. Additionally, we conducted movement experiments in 16 different soil environments to evaluate its locomotion performance. The results demonstrated that the earthworm robot is capable of moving in soil, and certain experimental conditions provided insights into the optimal environment for its operation.

Future challenges and prospects include designing a more anisotropic body, developing a method to optimize the operation of the thermal actuator, and achieving wireless control of the robot by incorporating a battery, eliminating the need for wired connections currently used.

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