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Locomotive Mechanism Design and Fabrication of Biomimetic Micro Robot Using Shape Memory Alloy

Young Pyo Lee, Byungkyu Kim*, Moon Gu Lee and Jong-Oh Park
Microsystem Research Center
Korea Institute of Science and Technology, KIST
P.O.Box 131, CheongRyang, Seoul 130-650, Korea
{yplee93, bkim, crystalship}@kist.re.kr, jop@microsystemt.re.kr

** The author to whom all correspondence should be addressed.*

***Abstract*— Recently, micro robots have been applied in various industrial areas. Some of them are requested to be able to move in small space or rough environment that people can not reach. It is necessary to have a capability to move at even overturned and adapt simple mechanism to fabricate it easily with small size. In this paper, a novel bio-mimetic micro robot with simple mechanism using shape memory alloy (SMA) is introduced to generate earthworm-like locomotive motion. There have been many kinds of mobile micro robot using the SMA. However, these actuators generally require electric cable for power supply, which might have an adverse effect on the mobility of the micro robot. The proposed micro robot system is composed of an actuator with SMA spring and silicone bellows, wireless control system, wireless power supply (battery) and body frames. The robot is also analyzed to customize required specifications. After the design and experiment, we find out that the micro robot can move a wireless free motion and be fabricated easily. Like an earthworm, the robot can travel on uneven, slippery and flexible environment.**

Keywords-locomotion; bio-mimetic; earthworm; shape memory alloy; micro robot

I. INTRODUCTION

Currently, millimeter or micrometer scale robots have been widely studied. From the literatures, robot's mobility is essential functions. To propose and design effective moving robots, various locomotive mechanisms have been were investigated. Rotating wheel has been the most conventional method for the robot's locomotion. In this case, the mobility is not sufficient when the robot moves on uneven, slippery or flexible environments [1]. Some of legged robot has been studied, but the mechanism is complex and hard to control [2][3]. In addition, the miniaturization of robots does not mean downsizing the existing macro technologies. It is often necessary to use new principle for actuation and fabrication. In the prior technologies, meso or micro scale robots have needed cable wire for power supply or control. The cable causes limitation of working area and mobility. Therefore, it is necessary to integrate robot with its own control system and power sources. It is also required that the robot moves on the rough environment.

In this paper, a bio-mimetic micro robot is proposed in order to create an autonomous free mobility. A two-way linear actuator using shape memory alloy (SMA) spring and silicone bellows is applied to the micro robot. A simple passive clamping mechanism is mounted on the surface of the micro robot. All of locomotive and clamping mechanism is mimicked from earthworm.

II. SHAPE MEMORY ALLOY ACTUATOR

Generally, SMAs return to their original shape after they are heated even if they undergo shape. That is called shape memory effect. Shape memory effect occurs as the result of a change in the atomic crystal structure of the alloys by a temperature change: austenite phase at a high temperature and the martensite phase at a low temperature.

This kind of simple actuation principle is easy to be realized. Also SMA has the advantage of low driving voltage. However, straight SMA wire has some problems with small displacement and difficulty to provide bias force, so called deformation force. Therefore, we make use of SMA spring to compensate the disadvantages. To achieve the two-way linear actuator which moves back and forth, the deformation force is needed because the SMA memorizes the only one shape at the high temperature. A bias spring (steel spring) can be used to provide the deformation force as depicted in Fig.1. The bias spring is stretched when the left SMA spring is heated. At the same time, deformation energy is stored in the steel spring. Then, the energy deforms the SMA spring to its initial length when it cools. Instead of the bias spring, one more SMA spring

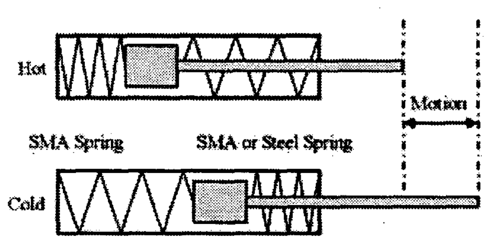

Figure 1. Two-way linear actuator using SMA spring

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can be used to provide the deformation force. However, it requires additional power to operate. Therefore, the actuator with a bias steel spring has advantages of low power consumption and simple structure. In this paper, we chose the bias spring method in order to embody a two-way actuation.

III. LOCOMOTIVE MECHANISM DESIGN

A. Driving Principle

An earthworm's body is made up of segments. On each segment, except the first and the last, there are pairs of tiny bristles called setae that help the worm move on the ground. The worm crawls by elongating to push the fore and by contracting to pull the hind part. The worm has two kinds of muscles used to crawl. Circular muscles, surrounding the body, can make the body shrink or expand radially. Longitudinal muscles, mounted along the length of the body, can shorten and spread out the length of the worm. If the circular muscle expands, the setae are erected and then they prevent the body from slipping [4]. Fig.2 shows structure and locomotive mechanism of the earthworm. The longitudinal muscles play a two-way linear actuator role and the setae play a clamping device role. This mechanism is simple but effective. Such mechanism enables the earthworm to move on any environments.

Fig.3 shows the locomotive principle of the proposed micro robot. Silicone bellows acts as a bias spring to provide deformation force. The front needles clamp a contact surface and the rear body slides forward when SMA spring is contracted by heating. After the contraction of the SMA spring, the deformation energy of the silicone bellows makes the SMA spring elongate when it cools. At that time, the rear needles clamp the contact surface and the front body slides forward. Finally, the bellows' spring force is equal to that of SMA spring as initial equilibrium state. As the step from (a) to (d) in Fig.3 is repeated, the micro robot can move forward.

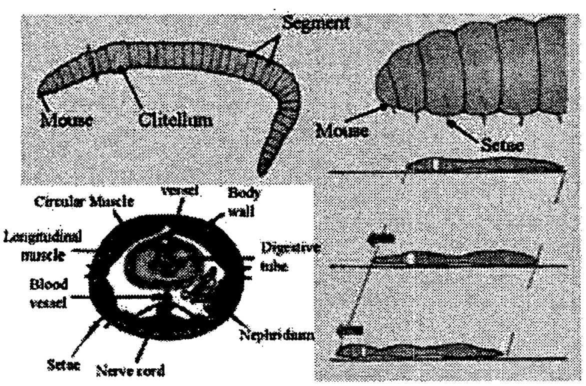


Figure 2. Structure & Locomotive mechanism of earthworm

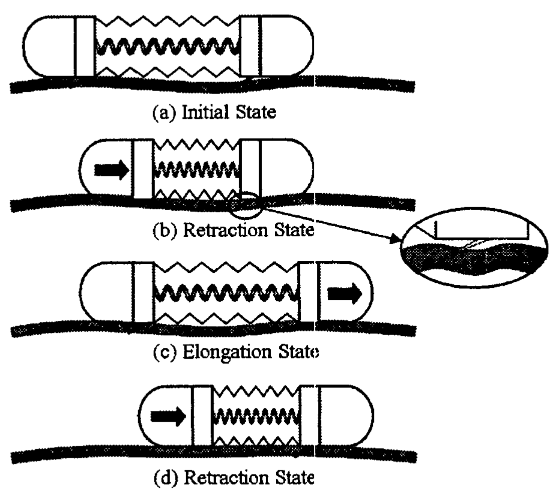


Figure 3. Principle of locomotion

B. Two-Way Linear SMA Actuator Design

Fig.4 is the schematic analysis of the two-way linear actuator. The SMA spring has an original length of L_{S0} and the silicone bellows has an original length of L_{B0}. The silicone bellows spring rate is K_B, nearly independent of temperature change. When the two springs are assembled at low temperature, the SMA spring which has low spring rate, K_L, is elongated by L_E-L_{S0} and bellows are compressed by L_{B0}-L_E. And then, the potential state is in equilibrium at the point of P_L. When the temperature of the SMA spring rises due to current, the SMA spring rate is changed into high spring rate of K_H. Therefore, the SMA spring's elongation is changed into L_R-L_{S0} and the bellows' compression into L_{B0}-L_R, too.

At high temperature, the potential state is in equilibrium at the point of P_H. The actuator reciprocates between the point of P_L and the point of P_H by heating and cooling. As this process is repeated, it generates the two-way linear motion [5].

To design the two-way linear actuator, we calculate and analyze the maximum stroke of proposed actuator. We assume that the relation between force and deformation is linear.

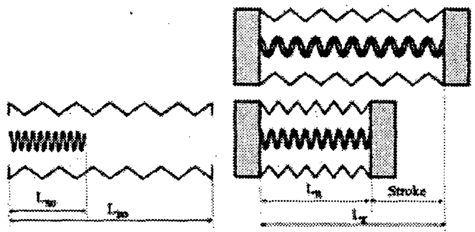
$$L_E = \left(\frac{K_B}{K_B + K_L}\right)\cdot L_{B0} + \left(\frac{K_L}{K_B + K_L}\right)\cdot L_{S0} \qquad (1)$$

$$L_R = \left(\frac{K_B}{K_B + K_H}\right)\cdot L_{B0} + \left(\frac{K_H}{K_B + K_H}\right)\cdot L_{S0} \qquad (2)$$

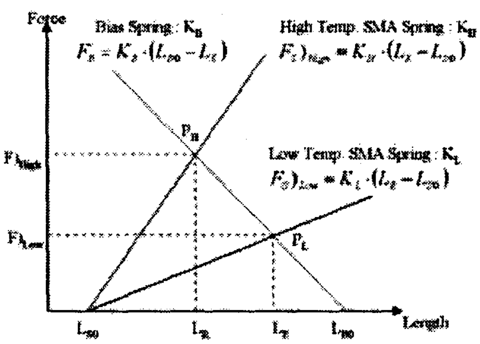
From the equations (1) and (2), the theoretical stroke of the two-way linear actuator is;

$$Stroke = \left[\left(\frac{K_B}{K_B+K_L}\right) - \left(\frac{K_B}{K_B+K_H}\right)\right]\cdot L_{B0} + \left[\left(\frac{K_L}{K_B+K_L}\right) - \left(\frac{K_H}{K_B+K_H}\right)\right]\cdot L_{S0} \qquad (3)$$

K_B: spring rate of silicone bellows
K_L: spring rate of SMA at low temp. K_H: spring rate of SMA at high temp.
L_{B0}: initial length of silicone bellows L_{S0}: initial length of SMA Spring
L_E: system length at elongation state L_R: system length at retraction state



(a) Modeling of SMA actuator



(b) Force-Displacement relation diagram

Figure 4. Analysis of bais steel spring type actuator

From the equation of stroke, we derive a relation between each spring's initial length and actuator's stroke [6][7]. The proposed micro robot size is required to be smaller than Φ9.5mmX50mm for special purpose. Therefore, the length of the actuator should be limited to 20mm considering the space of other components. A battery occupies 15mm and a control system module needs 15mm in length. In addition, SMA spring's strain at low temperature has to be lower then 200% to prevent the loss of shape memory effect due to permanent deformation.

From the analytical modeling with the specified spring rates, the initial length of each spring can be chosen after the desired stroke is determined. Fig.5 indicates the change of stroke with respect to the initial length of each spring. We can obtain that L_{S0} is 10mm and L_{B0} is 20mm when the desired stroke is 3.4mm.

C. Clamping Device

The clamping device also plays important role in the locomotion. It is difficult to include separated actuators for each clamping device. Therefore, we design and fabricate passive clamping devices with micro-size and simple structure,

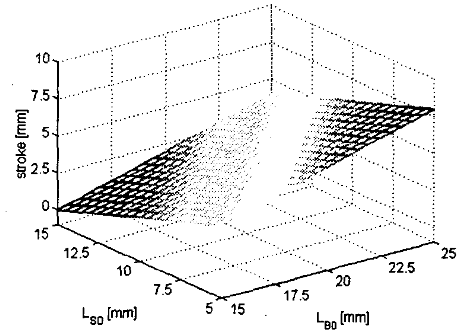
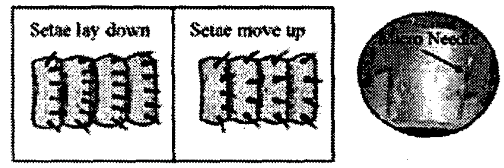


Figure 5. Analysis results of relation between initial length and stroke



(a) Schematic view of the earthworm's setae (b) Fabrication

Figure 6. Experiment of locomotive performance

mimicking earthworm's setae [5][8]. Fig.6 (a) shows the clamping mechanism of earthworm. The setae prevent slip by increasing friction when it tends to move backward while they do not work in moving forward. Fig.6 (b) shows the fabricated passive clamping device using a micro needle whose diameter is 180μm.

D. Spring rates of SMA spring and bellows

We assumed that the springs are deformed linearly according to the applied force. The SMA spring rate is measured at a low and high temperature. We get SMA spring rate, K_L of 0.95gf/mm at low temperature and K_H of 5.90gf/mm at high temperature. The spring rate of the silicone bellows is measured at low temperature. It is coated by parylene to adjust the spring rate precisely to the designed value. The spring rate, K_B is 0.95gf/mm.

IV. Control Systems and Battery

A. Control Systems

It is difficult to control the two way linear actuator because the shape memory effect is dependent on temperature. In this paper, the control law is simplified as an On/Off control. The simplified control law is better than a complex control law in order to verify feasibility and repeatability. To meet the requirements of size, we reduce power consumption and size of the control system module. The On/Off control signal is generated by PIC (Programmable Interrupt Controller), 12C508A, periodically. The signal switches transistors and then amplified current flows in the SMA spring. At that time, the current generates heat in the SMA because of its resistance.

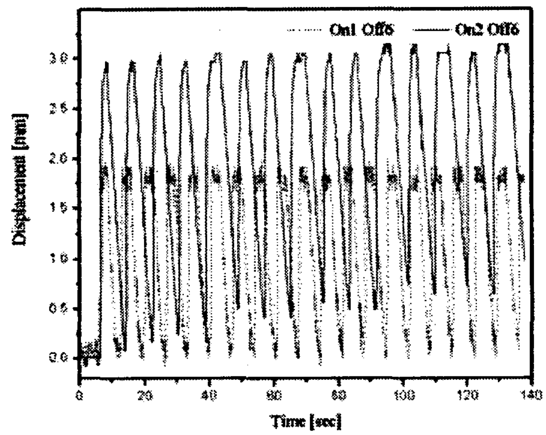


Figure 7. Actuation characteristic of fabricated actuator

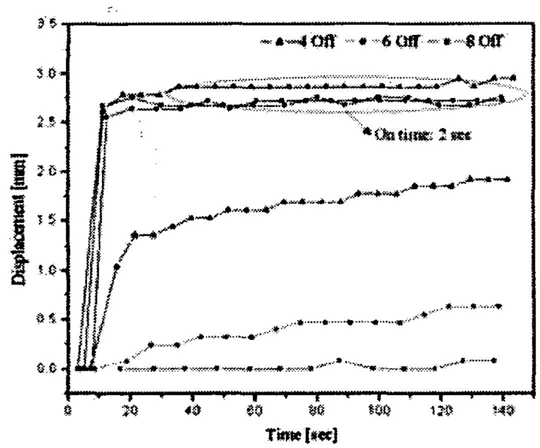


Figure 8. Coolinf characteristic of fabricated actuator

B. Experiments for Optimizing Actuation time

When the rear part of an actuator is fixed, the front part is displaced if the current flows into the actuator by the On/Off signals. The current is supplied by a power supply (Advanteck, P303PD). The displacement is shown in Fig.7. For each cycle, there are maximum and minimum displacements. The difference between the two values is stroke. The initial stroke is about 3mm when "on-time" is 2sec. and "off-time" is 6sec. The value is similar to the calculated result as in section III. B. At steady state, the stroke is about 2.6mm. The on-time of 1sec is not enough to heat up the SMA spring to obtain the sufficient stroke.

The minimum displacement deviates from zero because heat is accumulated in SMA actuators with increasing operation time, which causes less stroke. Therefore, we also study the stroke changes with variation of cooling time from 4 sec to 8 sec. In Fig. 8, top 3 graphs are the maximum elongation while bottom 3 graphs are the deviation from zero. Based on the results, we could find most effective cycle time in consideration of speed was 2 sec of "on-time" and 6 sec of "off-time." Then, the optimized speed, about 0.375 mm/sec is obtained. With 8 sec of off-time, the speed of micro robot is limited to about 0.27 mm/sec because it requires more cycle time even if it makes more stoke.

C. Battery

Instead of using the power supply, commercial batteries were applied to realize a wireless micro robot system. To estimate performance of batteries, we carry out experiments and then investigate lifetime and voltage drop.

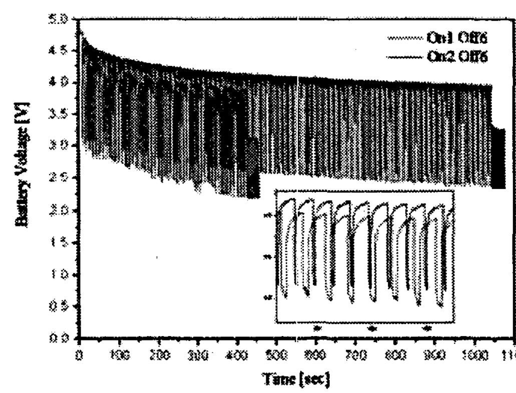
Three kinds of battery were tested under consideration of the size limitation; lithium, silver oxide and alkaline battery.

A lithium battery is CR1025 model of Panasonic co. Its nominal voltage, 3V is higher but nominal capacity, 30mAh is lower than the others. Lithium battery's lifetime is significantly shortened when used over designed standard current.

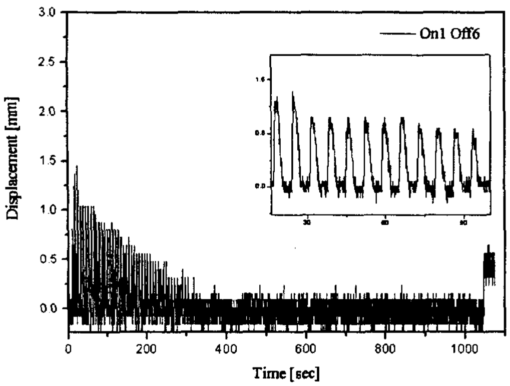
Silver oxide batteries are S736 model of VINNIC co. and SR726 model of Maxwell co. Their nominal voltage is 1.55V, nominal capacity is 30~40mAh and standard current is 0.07mA. The batteries can supply more stable power and constant voltage than the others. However, lifetime is significantly shortened when used over designed standard current, too.

An alkaline battery is L736 model of VINNIC co. Its nominal voltage is 1.55V, nominal capacity is 33mAh and standard current is 0.07mA. Its lifetime is longer than the others even when used over designed standard current because it has high energy density. We find out that the alkaline battery is better than the others for micro robot performance, so it was introduced for power source of the fabricated micro robot.

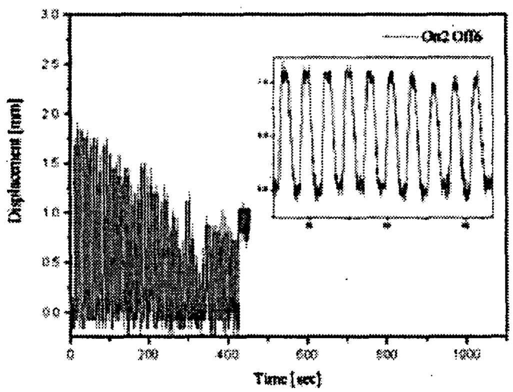
Based on the above results, three of L736 alkaline batteries were mounted on the micro robot. The relation between driving time and supplied voltage is measured to investigate the battery lifetime.



(a) Battery voltage drop



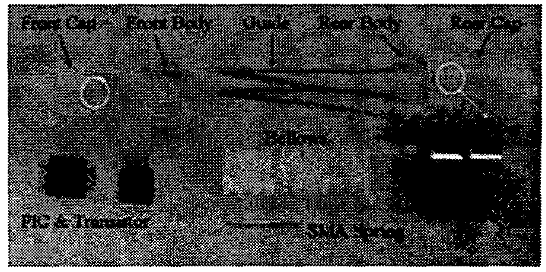
(b) Displacement characteristics on time: 1sec



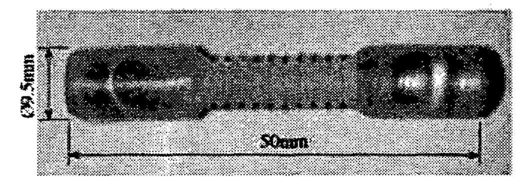
(c) Displacement characteristics on time: 2sec

Figure 9. Experiment of locomotive performance

The voltage drop causes the micro robot to stop after 8 and 18 minutes for each duty ratio On1/Off6 and On2/Off6, respectively, as shown in Fig. 9(a) even when all of the power of battery is not consumed. It is because the PIC stops due to battery voltage drop below its working voltage. In consideration of the battery lifetime, on-time of 1 sec is better. However, the on-time is worse concerning displacement and travel length as shown in Fig. 9 (b) and (c) because it is not enough to heat and deform the actuator. Therefore, we choose 2sec. of on-time (heating) and 6sec. of off-time (cooling) for the optimal locomotive performance. When we use the batteries and the duty ratio, the stroke becomes 30% shorter than that of the micro robot which adopts the power supply, comparing Fig.7 with Fig.9 (c). As the operating time goes by, the stroke per cycle is significantly shortened due to shortage of battery energy density. For the same reason, the heat accumulation does not appear. Consequently, it is essential to improve the battery performance to enhance the micro robot's operating time and displacement. If the restriction of diameter is relaxed so that we can adopt a bigger alkaline battery, L936 which has more capacity than L736, the operating time can be extended up to 40 min.



(a) Components of locomotive robot



(b) Assembled locomotive robot

Figure 10. Experimental setup

V. Robot Fabrication and Experiments

A. Robot Fabrication

A prototype micro robot was fabricated and experimented in order to verify the feasibility and performance of the proposed driving mechanism. The prototype consists of three parts; one is front body module where the control system module is mounted in. Another is the two-way linear actuator which connects the front and rear body module. The other is rear body module where the batteries are located in. Each component is presented in Fig.10 (a). And Fig. 10 (b) shows the assembled locomotive micro robot. Its body is made of acryl. The outer diameter is set to 9.5mm. The total length of micro robot is 50mm in initial elongation state. The weight of the prototype is minimized up to 4.0g, considering integrations of additional components including 1.8g of batteries.

B. Experiments

To validate the performance of locomotive micro robot, we carry out the experiments on slippery and flexible silicone rubber pad, acryl and paper pipes. Fig.11 shows experimental setup. To measure displacement, LB-60/01 laser sensor of Keyence co. and PCI-MIO-16E-4 data acquisition board of National Instrument co. are used.

Fig.12 shows the measured displacement for each contact materials. The on-time is 2sec., the off-time is 6sec., so the total time per cycle is 8sec. The theoretical speed of the micro robot is approximately 3.5mm/cycle. The locomotion on the silicone rubber pad and paper pipe is satisfactory. The measured maximum speed of the micro robot is about 2mm/cycle using power source of battery. The main difference of between theoretical speed and the measured value comes form

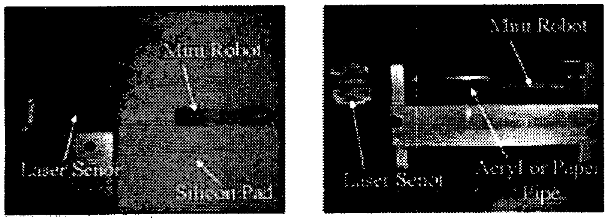


Figure 11. Experiment of locomotive performance

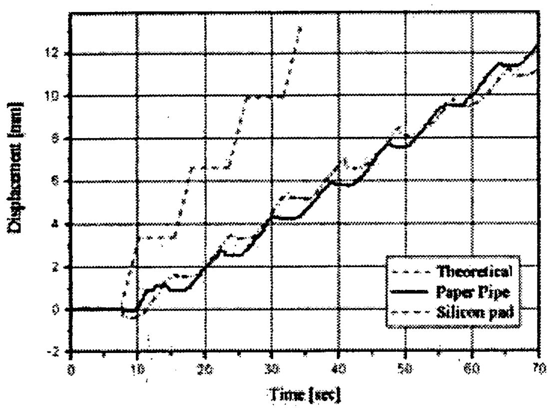


Figure 12. Experiment of locomotive performance

shortage of battery energy.

In addition, the micro robot's clamping mechanism does not work immediately. It takes a few hundreds of milliseconds to clamp after the retraction and elongation of the micro robot. During the time, a little backward motion occurs. That is why there is the difference between the theoretical and the measured speed.

VI. CONCLUSIONS

In this paper, we designed and fabricated a novel locomotive mechanism in order to realize a wireless micro robot. To acquire proper locomotive mechanism, we analyze motion of natural insect and worm. It turns out that earthworm's moving principle is simple and effective to design and fabricate. We find out that a two-way linear actuator using SMA spring and silicone bellows is suitable for fabrication. Then, clamping device using micro needles is proper for the micro robot because it can clamp and release the surface simply but effectively.

The fabricated micro robot can moves with the velocity of 10mm/min for 10 minutes. The stroke per cycle is 2.0mm if the every cycle has driving time, 2sec and cooling time, 6sec when the micro robot moves on silicone surface. After simple modification, the operating time can be extended up to 40min.The proposed mechanism is simple but effective to travel in narrow and rough environment such as human digestive organs, bended long pipeline and so on. If one makes a comparison with micro robots have been studied, the proposed micro robot has an advantage of traveling without cable wire from the outside. It is possible due to integrating a control system and batteries in the micro robot's body.

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