

# Omegabot: Crawling Robot Inspired by *Ascotis Selenaria*

Je-Sung Koh, Kyu-Jin Cho

**Abstract**—In this paper, we describe the design, fabrication processes, and control of a new biomimetic robot inspired by the inchworm, *Ascotis Selenaria*. The robot, called Omegabot, is named after the omega ( $\Omega$ ) shape of the crawling motion of the inchworm. This type of inchworm can travel approximately its body length per stroke along rough surfaces, leaf edges, and boughs of trees. The robot is built with smart composite microstructures (SCM), a fabrication method that uses laser micromachining to cut composites and assemble them into micro structures. We suggest a special pattern design for SCM to generate a two-dimensional turning motion, crawling motion, and a proleg design for climbing a tree. The robot is actuated with a shape memory alloy coil actuator activated by a PWM (pulse-width modulation) signal control electric current. As a result, Omegabot can crawl, turn, and grip a tree bough. This robot can be used for search and rescue or gathering useful information in an area where only small-scale robots can penetrate.

## I. INTRODUCTION

MANY researchers have developed various robots with novel gaits that can travel on rough terrains that conventional vehicles or other robots cannot traverse. Most of them are inspired by animals in nature. One of the animals that have novel gaits for propelling themselves in various environments is the worm.

For instance, in biology, earthworms have been studied with regard to their locomotive and control patterns [1]. A few robots based on earthworm-like motion have been developed. Some of them have used a polymer in the body and a shape memory alloy (SMA) coil actuator [2], [3], metal-based body and motor [4], [5], and piezoelectric actuator [5].

In this paper, we imitate an inchworm that can generate bending motion that is similar to the letter, omega ( $\Omega$ ). Several robots have been inspired by this motion and actuated through piezo actuators [7], pneumatic [8], and electric motors [9].

The robot is fabricated using smart composite microstructures (SCM) [10] and actuated using SMA (Shape Memory Alloy) coil spring actuators. SMA coil spring actuators and SCM are advantageous for building meso-scale robots. SMA has high energy density and a unique, two-phase (martensite/austenite) property. Using these characteristics, SMA has actuated robotic hands [11], several robotic fish fins [12], [13], and crawling micro robots [2], [3]. SCM is used to build micro linkage structures that are fabricated from the 2D pattern cutting of composites using micro laser machining.

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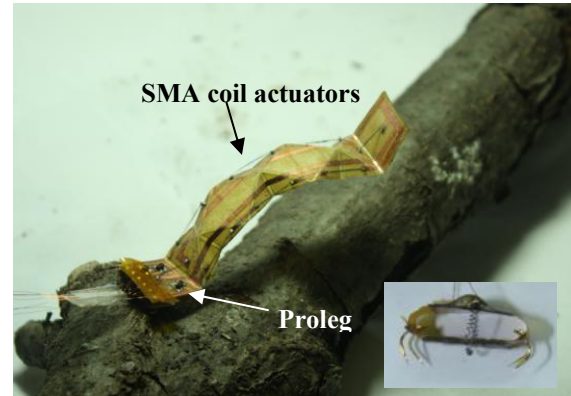


Fig. 1. Omegabot, a biomimetic inchworm robot, grasps the branch of a wood, raises its head, and turns right. Bottom right: Proleg of Omegabot.

Flexible polymer films and composites replace metal-based pins and link joints that cause large friction losses at the micro scale. 3D micro robot structures, e.g., micro flying insect robots [10], are made from the 2D pattern.

## II. THE BIOLOGICAL MODEL: INCHWORM

This section describes features of the motion of the inchworm (*Ascotis Selenaria*) as well as various motions and parts that are to be applied for Omegabot.

### A. Characteristics of Inchworm Motion

There are two types of worm-like motion. One is the peristalsis type (e.g., earthworms, sea cucumbers, caterpillars, and snails). A representative worm of the peristalsis type is the earthworm. An earthworm is composed of many segments, and can expand and contract its body with circumferential and longitudinal muscles [1]. These segments create a traveling wave by sequential activation. The other is an inchworm-type motion. An inchworm moves forward by alternating two kinds of stroke motion: longitudinal extension and omega ( $\Omega$ )-shaped bending. Fig. 2 shows the difference in motion between a peristaltic worm and an inchworm.

In this paper, we present a robot that mimics the omega ( $\Omega$ )-shaped bending motion of *Ascotis Selenaria*. The omega ( $\Omega$ ) motion is a simple means of crawling on a rough terrain and climbing on a wall. It does not involve sequential motions unlike the case of earthworms. It consists of multiple segments where the first and last segments touch the ground, while the segments in the middle create an omega shape when the muscle is activated and extend when the muscle is deactivated. Through grips of the ground with the prolegs that exist at the first and last segments, repetitive generations of this omega shape create forward movement. The middle part

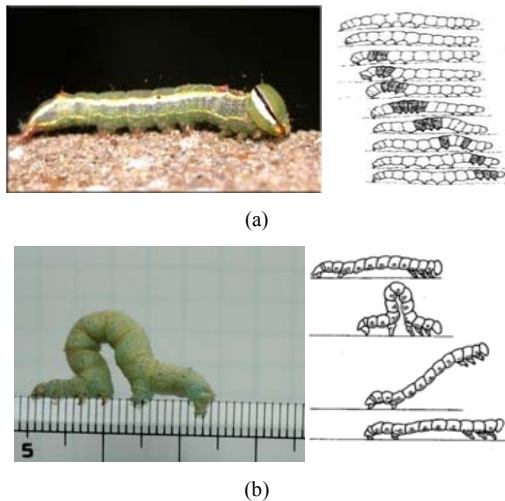


Fig. 2. Differing motions between peristaltic worms and the inchworm. (a) Sequential motion of a multi-segment normal caterpillar. (b) Omega ( $\Omega$ )-shaped motion of an inchworm.

of the body does not need to touch the ground and the robot moves forward by alternating between the two motions.

Inchworms that exhibit omega ( $\Omega$ )-shaped motion move approximately one body length per stroke. Omega motion can be implemented with a simple control and actuation architecture. Hence it is suitable for miniaturization and passive adaptation to the environment.

### B. Representative Motions of *Ascotis Selenaria*

Even though the inchworm has a simple movement mechanism, as mentioned in the previous section, it employs

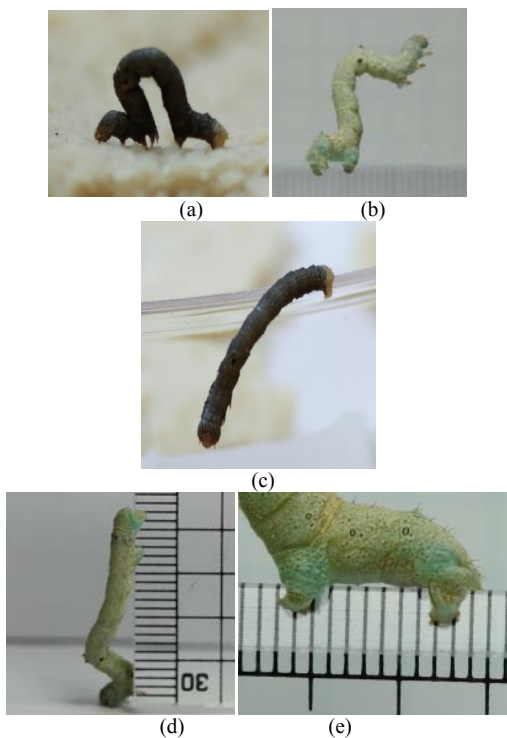


Fig. 3. Various motions and the proleg part of *Ascotis Selenaria*. (a) Crawling motion (Omega motion). (b) Bending to change the direction. (c) Standing. (d) Climbing the wall. (e) The proleg of the last segment.

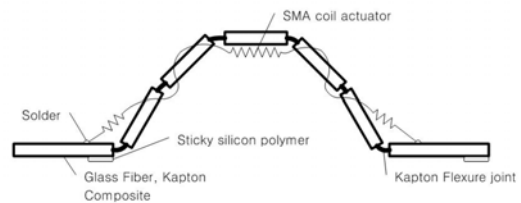


Fig. 4. Schematic diagram of the Inchworm Robot.

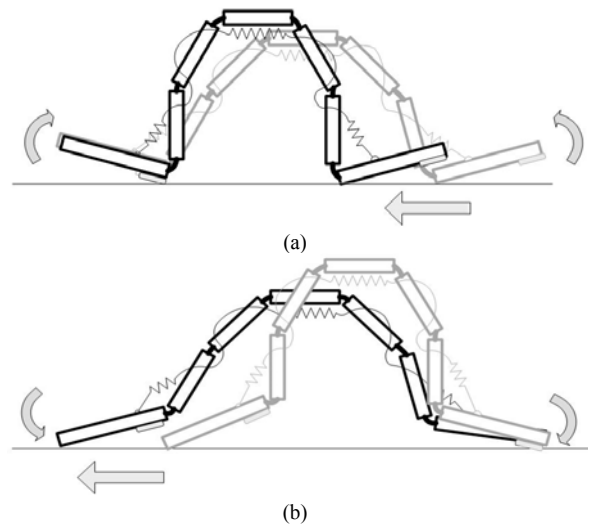


Fig. 5. The mechanism of crawling. (a) Actuator contraction. (b) Actuator release.

various amazing motions to live and survive in nature when surrounded by a harsh environment. To imitate the inchworm's behavior in nature, we observed what motions could be generated by *Ascotis Selenaria* and chose four representative motions as shown in Fig. 3.

The omega ( $\Omega$ ) bending motion is the main motion. Combined with the proleg at the first and last segments as shown in Fig. 3(f), it can produce the motions of crawling (a), turning (b), standing (c), and climbing (d). The proleg is a very important part for the worm-like motions of not only the inchworm but also various caterpillars. It functions as an anchor to generate friction and contributes stability of movement. In this work, a major goal is the development of the proleg mechanism.

Through the fabrication of a body that can produce omega-shaped motions and lateral bending motion and prolegs that can grip the ground or trees, Omegabot can move in a similar manner to that of a real inchworm.

## III. DESIGN

### A. Crawling Structure

As described earlier, inchworms can crawl on various terrains using a simple omega-shaped motion. This motion is realized through multiple rigid segments that are connected with flexible joints. An SMA coil spring actuator is attached to the structure in a way that makes the structure bend and form an omega shape when activated. Directional friction is used to allow the robot to move forward, but not backward.

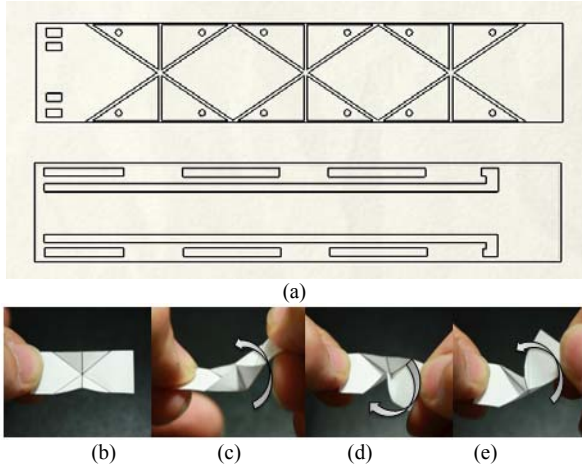


Fig. 6. (a) 2D pattern of a universal joint for the SCM. (b) Paper origami trial version of (a). (c) Pitch bending motion. (d)-(e) Yaw bending motion.

Fig. 4 shows a schematic diagram of an inchworm robot that can generate the omega motion based on an SCM structure and a SMA coil actuator. White squares denote glass fiber composites, which are used as the rigid components of linkages. The black connecting lines are Kapton films that are used as flexure joints. The electric circuit for wiring the SMA coil actuators is fabricated on a copper-laminated Kapton film. As shown in the diagram, a single SMA coil actuator exists that is composed of three serially connected coils. The line of the SMA passes through particular holes in the composites, as shown in the diagram. Omega motion can be generated by this arrangement of the actuator.

The crawling mechanism has two steps. The first is the actuator contraction, as shown in Fig. 5(a). The inner tips of the first and last segments touch the ground. The polymer attached to the inner tip of the first segment generates a frictional force that fixes the first segment while the last segment slips forward. The second step is the actuator release, as shown in Fig. 5(b). A SMA coil is extended and the outer tips of the first and last segments touch the ground. Then, the sticky polymer at the last segment has friction while the first segment slips forward. The robot moves forward by alternating between those two steps.

### B. Universal Joint for Turning

The SCM structure is based on a 2D pattern; hence, it is hard to create a multi-degree joint similar to universal joints. For the inchworm robot to turn while crawling forward, a two-dimensional bending motion is required. Both bending motions are orthogonal to the direction of forward movement. Pitch-axis bending generates a forward movement while yaw-axis bending generates a turning motion. We propose a structure similar to origami that enables turning motion.

Fig. 6(a) shows the 2D pattern of an SCM joint structure that can create a two-degrees-of-freedom joint when folded. The lower pictures in Fig. 6 are a series that demonstrates the two-dimensional bending motion of the structure. The small circles in triangles are the spots for soldering for connecting the actuators. The lower figure in (a) is the circuit pattern. The

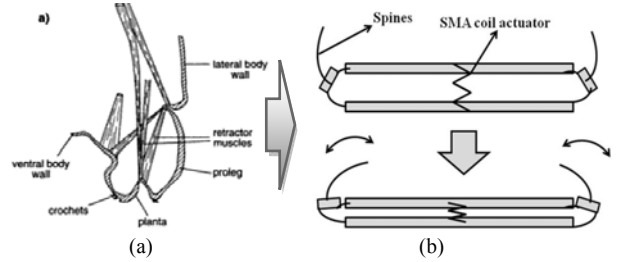


Fig. 7. (a) Transverse section through part of an abdominal segment of a caterpillar showing a proleg [14]. (b) Conceptual design of Omegabot's proleg.

circuit connects the circle holes to two actuation lines. The two actuation lines are actuated separately. When both lines are actuated, the structure is bent forward, as shown in Fig. 6(c). When one of those lines is actuated, the structure is bent to one side where the actuation is generated, as shown in Fig. 6(d) and (e). By separately actuating two actuator lines, this structure can generate a crawling motion and a turning motion.

### C. Proleg

As seen in Fig. 7(a), a proleg of a caterpillar has a muscle inside of a soft body wall. There are no rigid parts in the proleg except for the spiny crochets. The crochets are directly attached to the soft body tissue, allowing the proleg to be compliant. This compliance along with a greater number of crochets increases the statistical probability of the success of gripping. Inspired by this caterpillar's proleg, we suggest the design of the Omegabot's proleg, as shown in Fig. 7(b). Spines are attached to the flexure joint. The rigid sheets made of glass fiber composite are actuated by a short SMA coil actuator. When the sheet is actuated, spines at the flexure close up and grip something that exists at the gap between them. The flexures render the spines similar to real caterpillar prolegs.

## IV. FLEXURE JOINT ANALYSIS

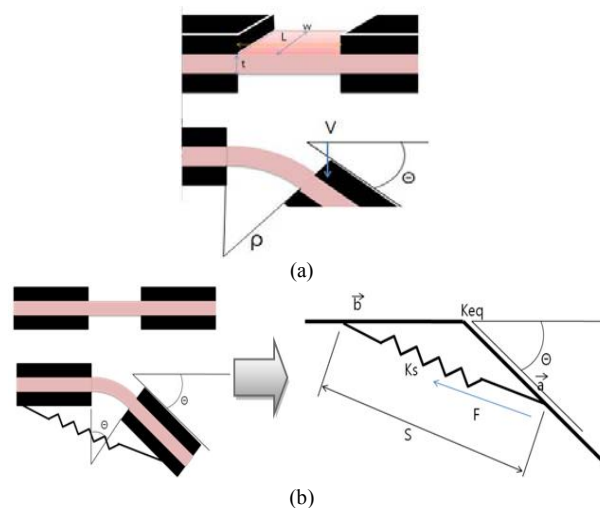


Fig. 8. Schematic diagram of the flexure joint. (a) Flexure component. (b) Entire joint.

Flexure joint modeling is required to determine the

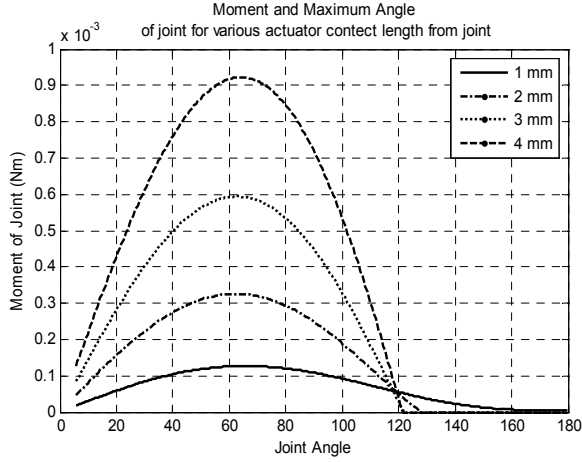


Fig. 9. Graph of the relationship between the joint angle and the total joint moment.

appropriate SMA coil actuators, the thickness of the flexure joints, and the values of several design parameters. Through the estimation of the stiffness of the flexure joints, the required torque and the resultant bending angle can be computed.

The joint of the smart composite microstructures (SCM) is composed of a flexible sheet component and a rigid composite component. The joint is assumed to be a thin film flexure, as shown in Fig. 8(a). The joint stiffness and moments are derived from linearized beam bending formulas, where  $v$  is the vertical length of the bend,  $\theta$  is the angle of the bend,  $\rho$  is the radius of curvature,  $M$  is the moment,  $E$  is the Young's modulus,  $I$  is the area moment of inertia,  $L$  is the width, and  $S$  is the length of the coil actuator.

$$\frac{dv}{dx} = \sin \theta \quad (1)$$

$$dx = \rho d\theta \quad (2)$$

$$\frac{1}{\rho} = \frac{d^2v}{dx^2} \quad (3)$$

$$\frac{1}{\rho} = \frac{M}{EI} \left( I = \frac{wt^3}{12} \right) \quad (4)$$

$$M(\text{Flexure}) = \frac{EI}{L} \theta \quad (5)$$

Fig. 8(b) shows a schematic diagram of the combination of a flexure joint and a SMA coil actuator.  $K_s$  is the SMA spring coefficient and is computed as 200N/m.

The total moments are:

$$M_{(SMA)} = \vec{a} \times \vec{F} \quad (\vec{F} = K_s \bullet \Delta S) \quad (6)$$

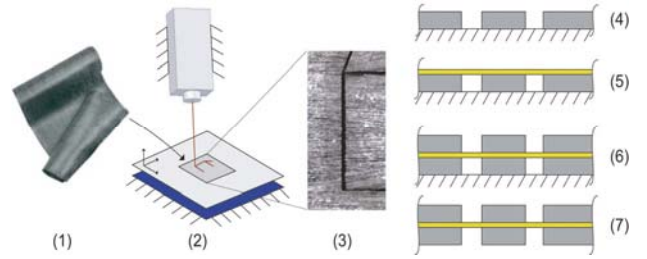


Fig. 10. Overview of the laser micromachining step of the SCM process. (1) Composite prepreg. (2) Thin-film polymer laminae are laser cut. (3) The desired platform geometry. (4-6) Alignment and stacking of the laminae. (7) Curing of the laminae to form the spine segments [12].

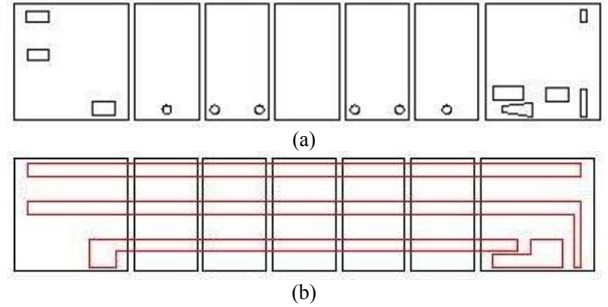


Fig. 11. (a) 2D pattern of an inchworm robot platform for SCM. (b) Flexible-circuit pattern for laser machining.

$$M_{(total)} = M_{(SMA)} + M_{(flexure)} \quad (7)$$

where  $\vec{a}$  is a position vector of the soldering spots for the actuator and  $\vec{F}$  is the force generated by the coil actuator.

The maximum torque and bending angle are related to the point where the SMA coil actuator is soldered. Fig. 9 shows a graph of the moments on the joint. Four different graphs are plotted for varying lengths of the position vector,  $\vec{a}$ . Each graph shows the moment as the bending angle changes from 0 to 180° after the actuator is activated. As the joint bending angle increases, the moment arm becomes larger. But at the same time, the stiffness of the joint increases and the actuator force decreases. Therefore, the moment reaches a maximum value and starts dropping beyond a certain point. The joint angle when the moment becomes zero represents the equilibrium point. As shown in the figure, the maximum moment and the equilibrium point vary with the length of the vector,  $\vec{a}$ . This means that the joint angle and torque are controlled by the point where the actuator is soldered.

## V. FABRICATION

### A. Body

The SCM is fabricated by the following procedure, as shown in Fig. 10. A glass fiber prepreg is used as the rigid part link. Two single-layered glass fiber laminae are joined orthogonally and cut with a laser. The flexible part is made of copper - laminated Kapton (polyimide) film. Copper - laminated film is used because it can be used as a flexible circuit. Fig. 6(a) and Fig. 11 show the 2D pattern for the glass fiber prepreg and the copper-laminated Kapton film.

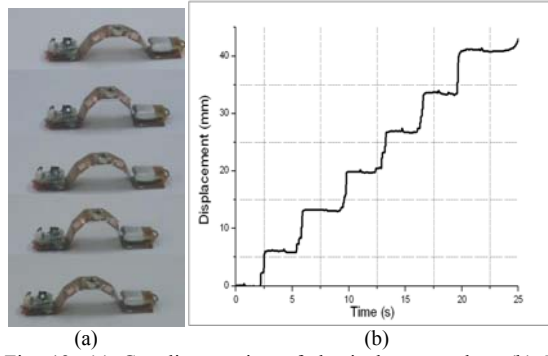


Fig. 12. (a) Crawling motion of the inchworm robot. (b) The displacement graph of Omegabot for crawling motion.

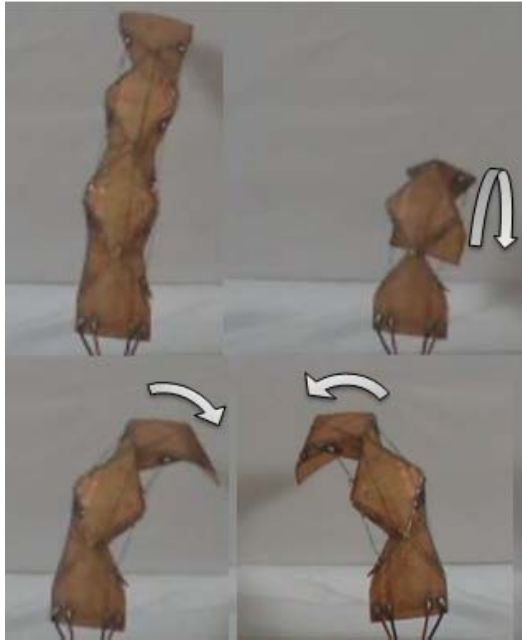


Fig. 13. Two-degrees-of-freedom bending motion of the SCM universal joint.

The circular holes shown in Fig. 11(a) are where the SMA actuator passes through to the opposite side, and the square holes are where the electric devices and SMA actuators are soldered. The red line in Fig. 11(b) denotes the copper film that remains on the Kapton film. It is used as a circuit.

### B. Electric Circuit

The flexible circuit is made of copper-laminated Kapton film. First, a masking film such as Kapton tape covers the entire copper area of the copper-laminated Kapton. The masking film is cut using laser machining and causes a circuit pattern on the copper film. The superfluous Kapton tape is removed except for the circuit pattern. The copper area is etched by Ferric chloride solution. After etching, only the masked copper part remains upon the Kapton film.

### C. Actuator

The SMA coil actuator generates a force when heated above the phase transformation temperature. The SMA phase transformation from Martensite to Austenite occurs at the phase transition temperature of 90°C.

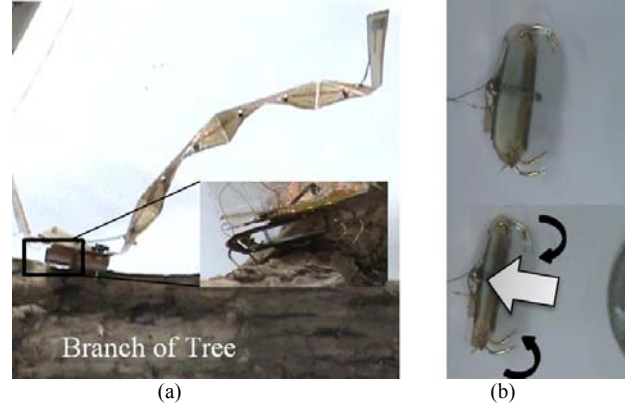


Fig. 14. Standing motion of Omegabot. (a) Gripping a tree with the proleg. (b) Gripping motion of the proleg.

The diameter of the wire ( $d$ ) is 100 $\mu$ m and the coil spring diameter ( $D$ ) is 380 $\mu$ m. The spring index  $C$  is 3.8.

$$\delta = \frac{8PD^3n}{Gd^4} \quad (8)$$

$$k = \frac{Gd^4}{8D^3n} \quad (9)$$

According to the formulas, (8) and (9), the coil spring constant in the austenite phase when the coil is actuated is about 200N/m (where the shear modulus,  $G$ , of Ni-Ti in the austenite phase is 23000Mpa and the number of active coils,  $n$ , is 60) [15].

In order to change the shape of SMA wire, the wire needs to be annealed at a high temperature, i.e., 500°C~600°C. After annealing, the austenite-phase shape of the SMA changes to the desired shape [12].

## VI. RESULT

### A. Crawling Structure

The inchworm robot, Omegabot, which employs an omega motion for crawling, is tested. The inchworm robot is manually controlled by an IR remote controller.

The crawling Omegabot has a battery of 3.7V and 40mAh. The SMA coil actuator consumes a current of 200mA for activation. In light of the computed energy consumption, the robot can operate 1440 cycles of the omega motion stroke. According to the characteristics of the SMA coil actuator, a 1Hz period of operation can be achieved. The maximum velocity of the robot is 5mm/s. Fig. 12(a) shows a video grab of the crawling motion. As seen in Fig. 12(b), the robot travels a distance of 5mm per stroke.

### B. Universal Joint for Turning Motion

The two-degrees-of-freedom motion of the SCM universal joint can be seen in Fig. 13. It has three joints connected serially. The SMA coil actuators are attached to each side of the joint and can be actuated separately. To perform a turning

motion, the actuator on a single side is activated as in the lower part of Fig. 13; for bending forward, actuators on both sides should be activated. Using this control mechanism, a two-degrees-of-freedom bending joint is realized.

### C. Standing with Proleg

Given the development of the proleg, Omegabot can grip and stand on a branch of a tree. Fig. 14(a) shows the standing motion of Omegabot that grips a branch of a tree by a proleg that is designed as per Section III. The proleg's gripping function can be achieved through spines that are attached at the flexure, as shown in Fig. 14(b).

## VII. CONCLUSION

The present paper reports the first step for establishing an inchworm-like robot that can crawl on various terrains where conventional robots cannot travel. We have chosen the inchworm as the model. An inchworm has simple crawling motion that we have named Omega motion. It does not need sequential control but the generation of a single stroke. Because of this simple mechanism, the crawling motion can be accomplished by a simple structure and control method.

The SCM (Smart Composite Microstructures) makes it possible to build a micro-scale linkage structure. There are a lot of design parameters in the design of the SCM 2D-pattern. For example, the positions of soldering for the SMA coil actuators can change the bending angle of the flexure joint, and various geometric parameters exist regarding the 2D pattern of a universal SCM joint such as the angle of each triangular shape and the length of the square. These parameters affect the final performance of the robot and the energy consumption.

## ACKNOWLEDGMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF); the program was funded by the Ministry of Education, Science, and Technology (Grant No. 2009-0087640, 2009-0070058)

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