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Finger-Sized Climbing Robot using Artificial Proleg

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***Abstract*—Climbing is one of the major subjects in robotics research. We present a finger-sized wood climbing robot with a spine-based gripper. This robot is inspired by the inchworm (*Ascotis Selenaria*) which can crawl and climb on trees with a simple omega-shaped bending motion. This simple locomotion enables the robot to be smaller and more easily controlled. The robot is built with smart composite microstructures (SCM) and shape memory alloy spring actuators. We suggest a special pattern design for the SCM to generate a two-dimensional turning motion and climb a vertical wood surface. Compared with crawling on the ground, climbing a wall against gravity requires larger actuation force. This paper describes the design and fabrication of "Climbing Omegabot," and a proper selection of SMA spring actuators with a method for improving actuation performance. Our results demonstrate that Omegabot can crawl, turn, and climb on a tree. This robot can be used for search and rescue, or gathering useful information in areas where only small-scale robots can penetrate.**

I. Introduction

IN the woods, there are many kinds of animals that have high mobility for propelling through the trees and bushes. Big animals such as the Cheetah and small caterpillars such as the inchworm can penetrate rough terrain and climb trees with their own devices and methods.

The inchworm (*Ascotis Selenaria*) is a caterpillar that can climb and crawl on trees and leaves with simple locomotion. It can make forward movement with just four steps using an omega (Ω)-shaped bending motion. Its body length is just within 5 cm. Its simple locomotion enables a system to be small. With these advantages of simple locomotion, many climbing robots have been inspired by the inchworm [1]-[6]. D. Rus *et al*. [3] presented an inchworm robot that can climb complicated metal structures like the Eiffel Tower. This robot has electromagnets on its two feet to attach to arbitrarily-oriented surfaces. K. Kawamura *et al*. [4] described the design and control of an inchworm-shaped inspection robot that employs two vacuum fixtures to attach to a wall and McKibben-type pneumatic muscles for motion. W. Wang *et al*. [5] proposed a servomotor-based caterpillar robot that can make omega-shaped bending motion and used passive suckers for adhesion. A small crawling inchworm robot has also been developed using piezoelectric technology [6]. A crawling robot inspired by an inchworm, a.k.a Omegabot, was fabricated using smart composite microstructures (SCM) and was actuated by shape memory alloy (SMA) spring actuators [7], [2]. A SMA spring actuator

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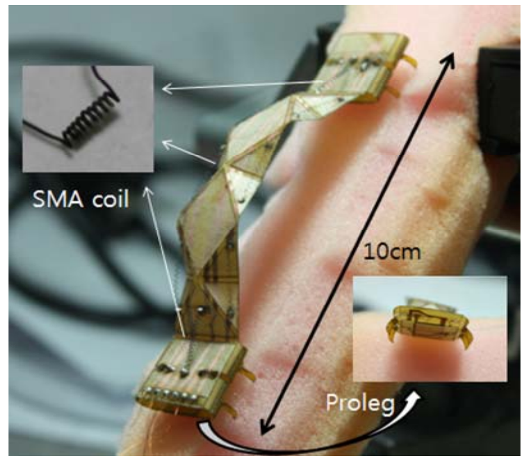


Fig. 1. Omegabot, a biomimetic inchworm robot that can climb vertical wood.

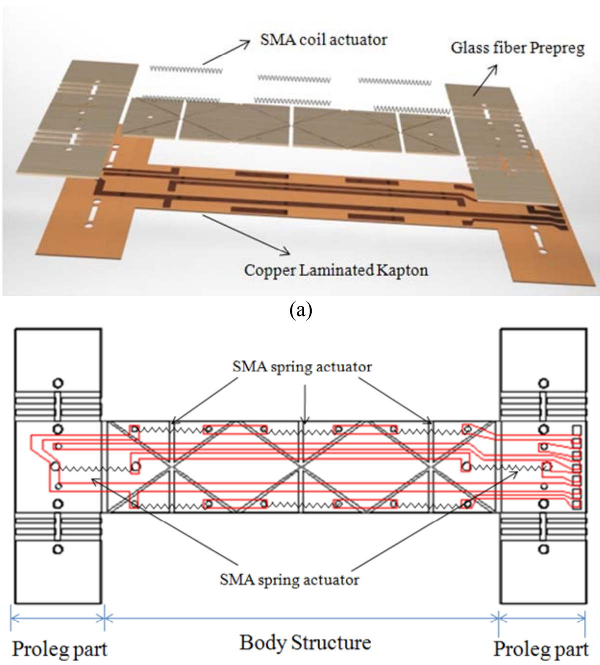
has high energy density and a unique two-phase (martensite/ austenite) property. Using proper thermal and mechanical treatments, performance of the SMA spring actuator can be improved. SCM processes and SMA actuators have been used to build robotic fish fins [8] and crawling micro-robots [9].

Composite based mechanical element with two-dimensional (2-D) pattern designs replaced conventional joint elements such as the universal joint [1]. This element was used for steering of the robot.

In this paper, climbing version of the previously developed crawling robot called Omegabot [1]-[2], is presented. K. Cho *et al.*[1]-[2] showed the inchworm robot based on composites and SMA spring actuators. The robot crawls and grips a rough surface. We integrate all components which are developed before in a one structure and improve actuator performance.

When climbing trees, most animals use claws to maintain gripping force. Although some animals such as the Gecko and many kinds of caterpillars can climb a smooth surface using micro-hairs Van der Waals force or fluid capillary force, they use claws for climbing a rough surface. We developed a gripping device inspired by an inchworm proleg. Prolegs are small legs of the caterpillar. The gripping device should be designed small enough to fit in finger sized climbing Omegabot. The small scale gripping devices were built using composite prepreg and polymer film based on the concept of the proleg. These grippers enable Omegabot to climb up a rough surface.

Furthermore, we describe how to design a proper SMA spring actuator. Improving the performance of an SMA spring actuator by inversion of the actuator was introduced in



(a)

(b)

Fig. 2. (a) Exploded diagram of Omegabot. (b) 2-D pattern design of Omegabot. Black line: glass fiber composite prepreg cutting pattern. Red line: copper-laminated Kapton circuit.

[10],[11], and an inversion method was suggested. A large diameter spring is comparatively easy to invert, but a small diameter spring is hard to invert. Using the previous methods, undesired large deformation occurs during inversion of a small diameter spring which causes degradation in the spring performance. Thus, we propose a novel manufacturing process which can invert SMA spring actuators with a small diameter without causing undesired deformation

Finally, a 10 cm finger-sized Omegabot prototype is built. It consists of a body capable of steering and small climbing grippers.

Small robots have many advantages when performing tasks in areas where conventional robots cannot reach because of their body size and rigid components. In applications such as search and rescue at a disaster site or inspection of a hazard area, the use of many small robots may be faster and more efficient than one large robot.

II. Mechanical Design

A. Design Overview

Fig.2 shows the 2-D pattern design of the climbing Omegabot. The structure consists of two parts. One is a fiber-reinforced composite part that becomes a rigid link in the robot frame. The other is a polymer film that functions as a flexure joint. The black line in the fig. 2 (b) represents a composite and polymer film cutting line. Composites are cut along the whole black line, while the polymer film is cut along the outer line and a square hole to make proleg spines separated. Fig.2 (a) shows the exploded diagram of two layers, glass fiber prepreg and copper laminated Kapton. After vacuum curing at 140°C these two layers are bonded together. And SMA coil actuator is attached by soldering process. Detail design and fabrication methods are described in following.

Two major mechanical elements are developed for the climbing Omegabot. First, using the concept of Origami, a structure that is capable of a yawing motion and a pitching motion is created. A diamond-shaped pattern is designed on a flat composite and folded into a structure that can generate the two motions. Fig. 4 shows the pattern design of the structure. Second, a artificial proleg mechanism is developed for the robot to attach to a wall. In Fig. 2, the patterns that are folded into gripper mechanisms are shown on the both ends of the planar figure. The detailed mechanism design is described in the following.

B. Body Frame Capable of Steering and Crawling

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

Fig. 3 shows the 2-D bending motion of the structure. Two series of actuators are attached on the structure. They are placed on left and right side of the planar structure. In Fig. 2 (b), the small circles inside the triangles represent locations for soldering the actuators. Single actuator consists of multiple SMA spring actuators that are connected in series using electrical wiring embedded in the structure. Two actuators are controlled to create pitching motion for crawling and yawing motion for steering of the robot. When both actuators are turned on, the structure is bent forward, as shown in Fig. 3 (b). When one of the actuators is turned on, the structure is bent to the side where the actuation is generated, as shown in Fig. 3 (c) and (d). By separately actuating two actuators, this structure can generate the crawling motion and the turning motion.

C. Artificial Prolegs

As seen in Fig. 4 (a), a proleg of a caterpillar has a muscle inside of a soft body tissue. There are no rigid parts in the proleg except for the spines. The spines are directly attached to the soft body tissue, allowing the proleg to be compliant. This compliance along with a greater number of spines 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. 4 (b). spines are attached to the flexure joint. The rigid sheets made of glass


(a) (b) (c) (d)

Fig. 3. Paper origami trial version of SCM universal joint. (a) Neutral state. (b) Pitch bending motion. (c)-(d) Yaw bending motions [2].

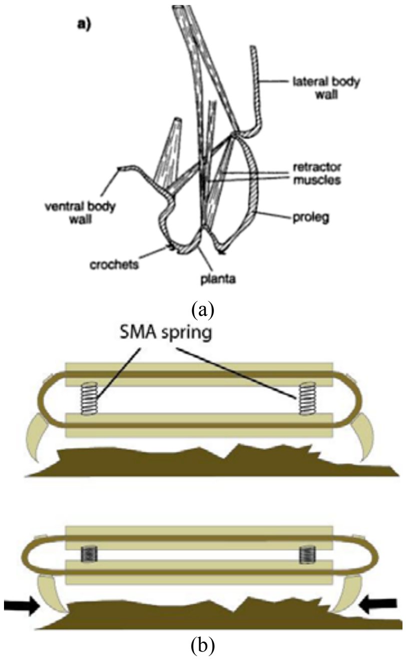


Fig. 4. (a) Transverse section through part of an abdominal segment of a caterpillar showing a proleg [14]. (b) Conceptual design of Omegabot's proleg.

fiber composite are actuated by a short SMA coil actuator. When the sheet is actuated, claws at the flexure close up and grip at the gap between them. The flexures produce motion similar to real caterpillar prolegs, and the claws on the flexure configuration make the spines more compliant. Thus, the gripper can attach to the rough surface adaptively.

D. Generation of Climbing Motion

Two parts of the robot described in the previous sections enable the robot to climb up. Fig. 5 shows procedures of climbing motion. Similar to a real inchworm climbing motion, the climbing Omegabot grips the surface with two artificial prolegs alternately. While one proleg grip the surface, the other moves upward. Body frame becomes Omega shape at the period between two gripping steps. The climbing Omegabot moves upward by repeating this cycle. And precise control is needed for transition between each step.

III. SMA Spring Actuator

A. Design of SMA Spring Actuator

In considering the design of actuators in a micro-robot, it is necessary to achieve certain characteristics such as a large stroke length/weight ratio, a large force output per unit weight, and miniaturization. To satisfy all of these requirements, an SMA spring actuator was designed. SMA spring is an actuator that can generate stroke as temperature change between austenite and martensite finish temperature.

The important parameters in designing an SMA spring actuator are the deflection of the spring δ, and the spring constant k, which are given as follows [13] :

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

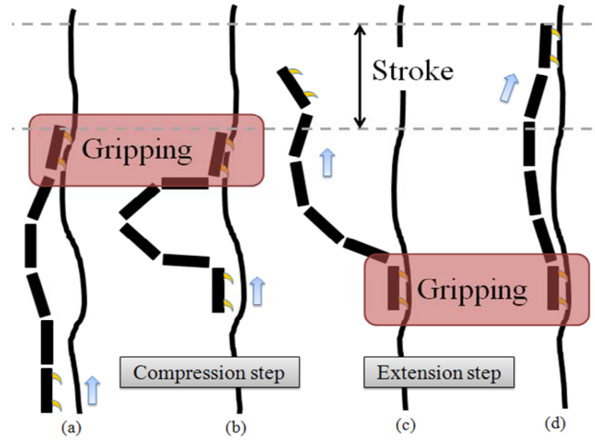


Fig. 5. Climbing procedure of The climbing Omegabot. (a)Head proleg gripping (b)Compression of body frame (c)Tail proleg gripping (d)Extension of body frame.

$$k = \frac{Gd^4}{8D^3 n}$$

where d is the wire diameter, D is the spring diameter, P is the load, n is the number of active coils, and G is the shear modulus of the wire.

Spring index C(=D/d) was chosen to be between 2.5~3.8. Although spring index is normally chosen based on the stiffness requirements, it was chosen based on the size requirements. The small area in the micro-robot where the spring is attached restricted our selection of spring diameter and wire diameter. In general, a spring constant below 3 is avoided due to difficulty of production.

The number of active coils, *n*, needs to be minimized for spring SMA actuators. Uneven cooling is more likely to occur in a spring with large number of active coils that are closely spaced. If the active coils are closely spaced, the coils in the center of the spring are likely to cool slower than the coils at the end of the spring. This uneven cooling causes large deformation of certain coils due to the time difference in the martensitic transformation. This drawback can result in degradation.(see Fig. 6.) Therefore, the number of active coils was chosen to be about 12.

Load factor P is a load that pulls both ends of the SMA spring actuator. It can be calculated by considering the reaction forces where SMA spring actuator is attached.

The value of shear modulus G is a crucial issue in designing a SMA spring actuator. The SMA spring actuator is heat treated by annealing to memorize its shape. In the annealing process, the value of G is decided by changing temperature and time [8]. This is characteristic of SMA. The annealing temperature chosen in this work was 500 °C for one hour.

Fig. 6. The drawback of uneven cooling in martensitic transformation.

There is another important factor in designing a SMA spring actuator. It is the critical shear stress; i.e., the maximum stress that induces martensite [13]. If the stress exceeds the critical stress that induces martensite, martensite variants would emerge and not allow the desired stroke in the design stage. This phenomena was named stress induced martensite (SIM).

In order to reduce the undesired SIM effect, the springs are inversed after annealing. The detailed method of spring inversion is explained in the next section. This fabrication method increases the critical stress level needed to induce the martensite phase. Therefore, perfect recovery in the high temperature actuation stage is achieved. This work also contributes to the performance of micro-robots.

B. Inverting the SMA spring actuator

To improve the SMA spring actuator, the application of initial tension by spring inversion was described in [10], and useful methods for the fabrication of an inversion SMA spring actuator such as flipping over, the wrapping method, and the central tube method are proposed in [11]. However, these methods have the limitation in the spring diameter. A small diameter spring is harder than a large one. And it is easy to cause undesirable deformation for fabrication methods.

We propose a recoiling method to invert an SMA coil that can be applied to a small diameter and small index spring with a diameter of smaller than 400µm and index number of 3~4. The method is shown in Fig. 7 Using this method, we succeeded in making an inversion spring with a spring index of 4, 400µm spring diameter, 100µm wire diameter with a minimum of undesirable deformation.

C. Fabrication

To attain a suitable actuation force from an SMA spring actuator for a micro-robot, certain process steps are needed. Commercial Ti-50 at% Ni wires with diameters of 0.08 in and 0.04 in (Austenite start temperature=90 °C) (Dynalloy Inc., California, USA) were prepared. To acquire a spring geometry from the SMA wire, the prepared 0.08 in and 0.04 in SMA wires were wound around a 0.020 in and 0.015 in rod. The SMA spring actuator was designed to have 12 active coils and the pitch length of zero. The calculated stroke length in each joint of the micro robot was below 6 mm. To achieve a memory effect in the SMA spring actuator, an annealing process was carried out. In this work, the springs were annealed at 500 °C for one hour to attain an adequate shear modulus G. After the annealing, an inverse spring process was carried out to increase the maximum stress level that can induce SIM.

D. Performance of Inverted SMA springs

Experiments were carried out to verify the improvements in performance of the inverted SMA spring. Inverted and non-inverted SMA springs were prepared. Tensile tests were conducted for each sample under the same conditions. Force-displacement data were acquired at room temperature, martensite phase, high temperature, and austenite phase. In martensite phase, inverted and non inverted SMA spring was extended until the deflection of the sample spring is 5mm to acquire a force level. It is the similar length in actuation of micro-robots. And in austenite state the samples were extended with 800mN force to compare the performance of each sample.

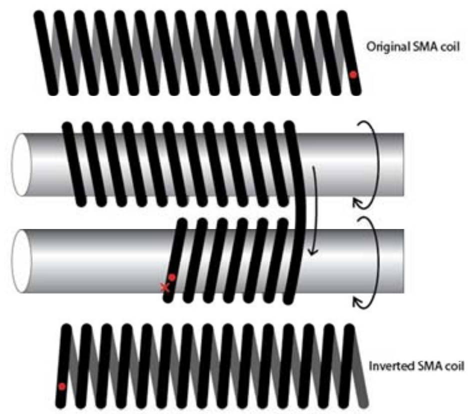
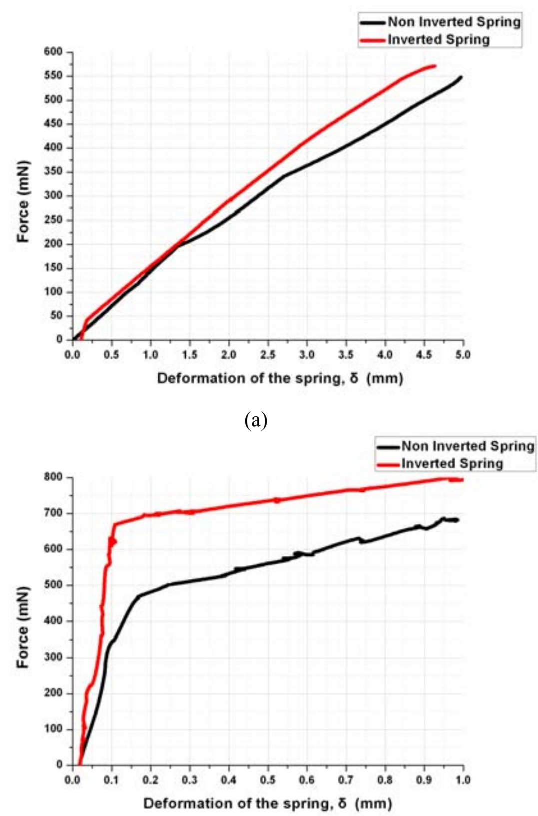


Fig. 7. Inversion of SMA coil actuator by recoiling in the opposite direction.

In room temperature, the martensite phase, the SMA spring had a lower spring constant, which is given by the slope of the graph.(see Fig. 8(a)) Although there is a slight difference between a non-inverted and inverted spring, it was not significant in this experiment. From this data the force that is needed to extend the SMA spring to 5.0 mm is about 550mN.

The tensile data of SMA spring actuator in austenite phase is divided into two sections. (see Fig. 8(b)) The first section is



(b)

Fig. 8. Force-the deflection curves of Non-inverted and inverted SMA spring Actuator at (a) Martensite and (b) austenite state.

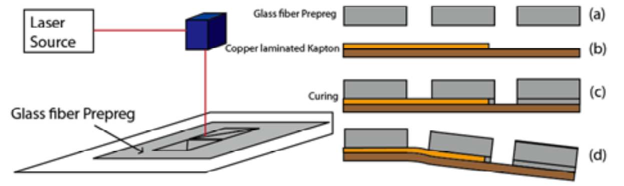


Fig. 9. Overview of the laser micro machining step of the SCM process. (a) Composite prepreg. (b) Thin-film copper laminated polymer are laser cut and etched to make circuit. (c)Curing of the laminae to form segments. (d)finally, circuit embedding structure capable of bending.

fully austenite. The second section is a region of detwinned martensite, also named a region of SIM. Before the stress increases up to the critical stress that induces martensite, SMA spring actuator can recover its perfect shape, generating much higher force than in region of SIM. But after that point, the spring constant is decreased and imperfect recovery occurs.

Result in martensite state shows that the critical force that spring can resist should be above 550mN to achieve a perfect recovery. Therefore Non inverted spring is not suitable for our design constraint. This is reason why we use inversion spring method.

IV. Fabrication

A. Body Frame Integrated Electric Wire

The body frame of the climbing Omegabot was fabricated using the following procedure, as shown in Fig. 9. A glass fiber prepreg was used as the rigid part link. Two single-layered glass fiber laminae were joined and cut with a laser (VersaLaser). The flexible part is made of copper-laminated Kapton (polyimide) film. Copper-laminated film was used because it can be used as a flexible circuit [8].

The circular holes shown in Fig. 2 (b) are where the electric devices and SMA actuators are soldered. The red line in Fig. 2 (b) denotes the copper film that remains on the Kapton film. It is used as a circuit.

B. Artificial Prolegs with Spines

Artificial prolegs pattern design is the both ends of robot design shown in Fig. 2. A front view is shown in Fig. 4(b). This pattern design is different from common grippers. It is based on two rigid glass composite layers and it is connected by polymer flexures. Layer based design enable to use precision laser cutting process. Only 2D cutting process can be performed by Laser machining. And this artificial proleg design allows scalability for small structures. It has just one continuous composite layer after assembly.

Fabrication procedure is demonstrated in Fig. 10. Composites that have design pattern is bent and bonded by epoxy. Spines that also made of glass composite are attached to both flexure's beneath surface with epoxy. Finally SMA spring actuators are soldered on copper layer of circuit pattern laminated on Kapton film.

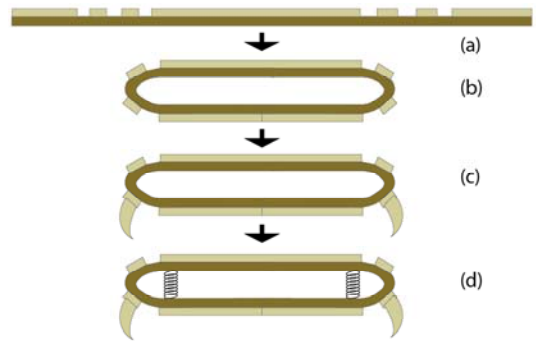


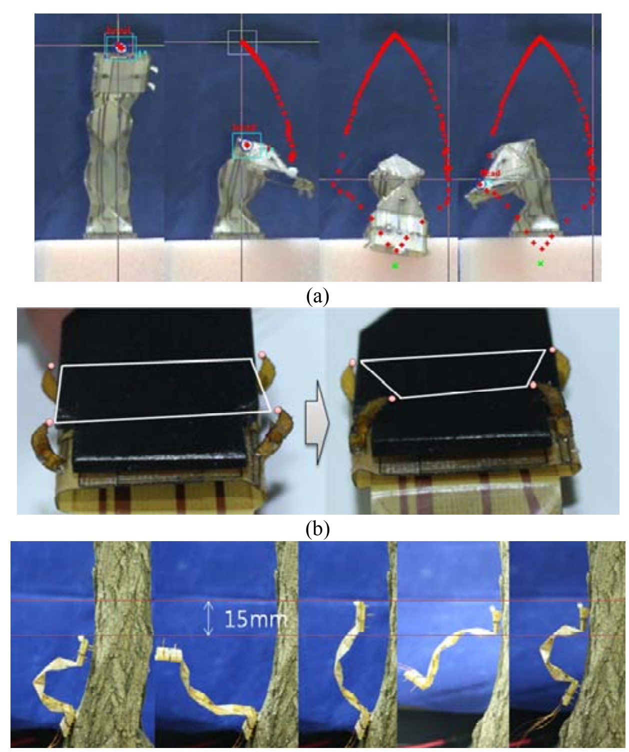
Fig. 10. Artificial proleg fabrication procedure. (a) Cured film of Glass fiber prepreg and Kapton (poly imide) film (b) Bend and make two layer structure (c) Attach the claws (d) Soldering the SMA spring actuator.

V. Results

Omegabot was developed with the following dimensions: 10 cm length, 1.5 cm width, 0.5 cm thickness, and 0.6 g weight. The robot operates under electric power supplied by an electric wire connection and requires about 5 V and 1 A. The robot has mobile abilities of crawling, climbing, and steering on a tree. PWM digital signals are used to control the electric currents using MOSFET. This signal controls each SMA spring temperature and actuation sequence.

A. Steering

A universal joint body has a specific 2-D pattern that allows the robot to turn to find the proper position for the next step. Fig. 11(a) shows Omegabot's steering ability. A turning angle of about 40° in the forward direction is achieved. The angular velocity is about 10°/sec. The steering angle



(a)

(b)

(c)

Fig. 11. (a)Steering motion (b)Gripping motion, white shows the compliant gripping area (c)Two anchor climbing motion.

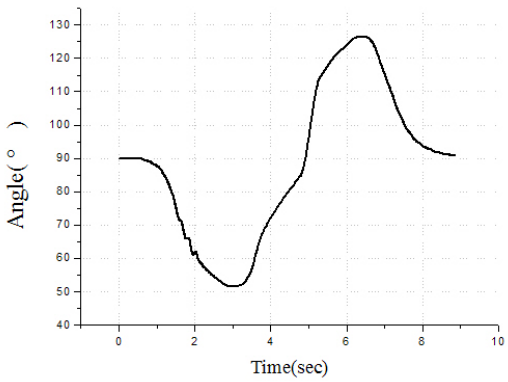


Fig. 12. Steering angle-Time curves of the climbing Omegabot.

trajectory is shown in Fig. 12.

B. Compliance in artificial prolegs

Omegabot has two small grippers on the first and last segments. Fig. 11(b) shows the gripping motion of Omegabot's proleg. It can change its claws angle by about 45°, and this angle is changeable depending on the object's size to grip. Rough terrains have local surface variation. To grip the surface reliably, the claws adapt to surface variations. The composite claws are attached to flexible film. This flexure allows the claws to be more compliant when gripping a surface. These flexures can move independently and allow the claws to adapt to the surface variation. Fig. 11 (b) shows the compliant gripping motion of the Omegabot's artificial prolegs.

C. Climbing vertical wood

Proper sequential signals to the robot's body and two prolegs generated the robot's motion. Fig. 11 (c) shows each step for climbing vertical wood. It has stroke length of about 15mm per cycle. Proper control method for transition of each steps is needed to increase climbing speed.

Our results show that using an inverted SMA spring actuator is very effective and can increase the performance of a micro-robot.

VI. Conclusion and Future works

This paper presents a climbing version of the Omegabot, a robot inspired by Inchworm. In order to climb up a wall and turn to the proper direction, the Omegabot consists of two main body parts. One is the diamond shaped body frame pattern capable of steering and crawling. The other is the artificial proleg. Artificial prolegs grip the wall adaptively with compliant flexure.

Shape memory alloy (SMA) springs are used as actuator for the climbing Omegabot. Compared with the previous crawling Omegabot, the climbing robot requires larger force to overcome the weight of the whole body frame. To improve the performance of SMA spring actuators, thermal and mechanical treatment are processed. Some experiments verify that inversion method of SMA spring actuator can increase actuation force of SMA spring.

Finally, a 10 cm finger-sized Omegabot prototype is built. This robot crawls, turns and climbs on the rough surface such as trees.

For integrating a battery, microprocessors and sensors for gathering useful information in a field, it is required to increase actuation force and robustness of structures. To achieve high mobility of small crawling robot, the gripper need more reliable gripping ability and gripping force for maintaining stability of crawling and climbing motion.

Acknowledgment

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References

[1] J. Koh and K. Cho, "Omegabot: Biomimetic Inchworm Robot using SMA coil actuator and Smart Composite Microstructures(SCM)", *Proceedings of the 2009 IEEE International Conference on Robotics and Biomimetics(RoBio 2009)*, 2009, pp.1154-1159.

[2] J. Koh and K. Cho, "Omegabot: Crawling Robot Inspired by Ascotis Selenaria", *2010 IEEE International Conference on Robotics and Automation, 2010. Proceedings.*, 2010. to be published.

[3] K. Kotay and D. Rus, "The Inchworm Robot: A Multi-Functional System," *Autonomous Robots*, vol. 8, Jan. 2000, pp. 53-69.

[4] R.T. Pack, J.L. Christopher Jr, and K. Kawamura, "A rubbertuator-based structure-climbing inspection robot," *1997 IEEE International Conference on Robotics and Automation, 1997. Proceedings.*, 1997.

[5] W. Wang, Y. Wang, K. Wang, H. Zhang, and J. Zhang, "Analysis of the kinematics of module climbing caterpillar robots," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, 2008, pp. 84-89.

[6] N. Lobontiu, M. Goldfarb, and E. Garcia, "A piezoelectric-driven inchworm locomotion device," *Mechanism and Machine Theory*, vol. 36, Apr. 2001, pp. 425-443.

[7] R.J. Wood, S. Avadhanula, R. Sahai, E. Steltz, and R.S. Fearing, "Microrobot design using fiber reinforced composites," *Journal of Mechanical Design*, vol. 130, 2008, p. 052304.

[8] K.J. Cho, E. Hawkes, C. Quinn, and R.J. Wood, "Design, fabrication and analysis of a body-caudal fin propulsion system for a microrobotic fish," 2008, pp. 706-711.

[9] A.M. Hoover, E. Steltz, and R.S. Fearing, "RoACH: An autonomous 2.4 g crawling hexapod robot," 2008, pp. 26–33.

[10] K.K. Jee, J.H. Han, Y.B. Kim, D.H. Lee, and W.Y. Jang, "New method for improving properties of SMA coil springs," *The European Physical Journal - Special Topics*, vol. 158, May. 2008, pp. 261-266.

[11] S. Kim, E. Hawkes, K. Cho, M. Joldaz, J. Foleyz, and R. Wood, "Micro artificial muscle fiber using NiTi spring for soft robotics," *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009. IROS 2009*, 2009, pp. 2228–2234.

[12] K. Quillin, "Kinematic scaling of locomotion by hydrostatic animals: Ontogeny of peristaltic crawling by the earthworm Lumbricus terrestris," *Journal of Experimental Biology*, vol. 202, 1999, pp. 661-674.

[13] K. Otsuka and C. M. Wayman, "Shape memory materials," Cambridge University Press, 1998.

[14] R. F. Chapman, *The Insects: Structure and Function*, 4th ed., Cambridge Universit Press, 1998, p. 175.