Crawling robot design mimicking *C. elegans*

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Abstract – This paper describes a design of a simple small-sized crawling robot based on thermal SMA actuators, mimicking the the motion mechanism and biological structure of *Caenorgabditis elegans* (*C. elegans*). Thermal SMA is selected as an actuator due to the similarities in the properties to those of *C. elegans* muscle. A 12 body segment robot is designed to generate undulating motion based on *C.elegans* motion mechanism and anatomy. Each body unit consists of a pair of SMA actuators and serially connected by rigid links with the embedded motion control circuit. Simple binary operation-based motion control mechanism is developed and implemented using microcontroller. The feasibility of proposed robot design and control is evaluated through experiment with a three segment prototype.

Keywords – Biomimetic Robot, *C. elegans*, Thermal SMA, Crawling Robot

1. Introduction

Biomimetic or bio-inspired robots have widely been developed and investigated. Many of them are operated through traditional actuators such as rotational or linear electrical motors. For example, crawling robot designs inspired by snake [1] or lamprey [2] use electrical motors. However, electrical motor-based actuation mechanism is far from living organism's actuation mechanism based on contraction of muscles. Therefore, researchers attempt to design actuators not only functionally similar to living organisms but also structurally compatible with them. Smart materials such as shape memory allow (SMA) and electro-active polymer (EAP) have interested investigators due to their properties comparable with actual model organisms [3]. Soft actuators based on those smart materials have demonstrated large potential on development of biomimetic robot applications. Living organism's muscular system is based on contraction of a number of small muscle cells, which can be more appropriately represented by a collection of micro-linear actuators. Smart material-based actuator is promising to mimic each micro-linear actuator unit.

This work was supported in part by the Korean National Research Foundation (NRF 2009-0073354), KAIST KI for Design of Complex Systems and the Korea Ministry of Knowledge Economy under Human Resources Development Program for Convergence Robot Specialists.

In this paper, we introduce a design of a small crawling robot mimicking actual muscular actuation and its motion. Moreover, we develop a motion generation algorithm that can be easily implemented in simple hardware. As a model organism for robot, a living organism with biologically simple structure and well-known motion mechanism is sought. Among several small-sized nematodes, *C. elegans* is selected due to its much simpler structure and motion mechanism than those of snake and lamprey [4-6]. *C.elegans'* simple sine wave-like motion is well-known and reported by several investigators and computational simulation of its motion is also studied [7].

The rest of paper is organized as follows. In section 2, describes design of actuator and robot body. Section 3 introduces motion control mechanism and its hardware implementation. Section 4 shows the experimental result with preliminary two segments robot prototype to verify our approach. Finally, conclusions and future works are presented in section 5.

2. Robot Design

2.1 Thermal SMA based Linear Actuator Design

C. elegans' motion is achieved by contraction of body wall muscle lining dorsal and ventral sides of body. According to literature, these body wall muscles are able to contract nearly half of its rest length [7, 8]. Therefore, we choose the spring type thermal SMA which retains similar strain property to that of real *C. elegans*.

Thermal SMA returns to its original configuration when its temperature exceeds a threshold. Hence, binary positioning operation can be easily implemented even though complicated control method such as pulse width modulation (PWM) [9] is employed. Moreover, according to reported computational motion simulation of *C. elegans* [7], sequential operation of serial binary positioning actuator is suitable to realize sinusoidal motion of the worm. Thermal SMA has been used in small crawling robots such as earthworm robot [10], but the locomotion control mechanism of the robots is distinctly different from the *C. elegans*'.

The thermal SMA with one-way shape memory effect requires external force to restore its original state. Therefore, in the actuator design, a passive spring is placed in parallel configuration to thermal SMA as described in Fig 1. (a). Biometal Helix 150 SMA spring manufactured by Mondo-Tronics Inc is used in this work. The spring diameter is 0.62 mm, wire diameter is 150 µm, kinetic displacement is 200%, and maximum producing force is about 0.3 N. A pair of SMA actuators forms an actuator unit as shown in Fig 1. (b).

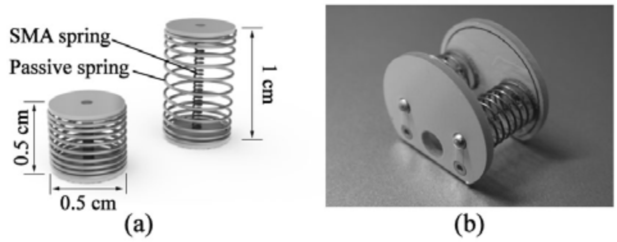

Fig. 1. (a) Rendering of actuator that shows contracted (left) and rest (right) state of actuator. (b) A fabricated actuator unit.

2.2 Robot Body Design

C. elegans has 23~24 body wall muscle cells in each row at dorsal or ventral side. Therefore, Wakabyashi's computational simulation of *C. elegans* motion uses a model consisting of 24 segments of spring-damper unit [7]. On the other hand, a dynamic model of *C. elegans* proposed by Suzuki [11] consists of 12 rigid links connected by rotating joints. Although actual *C. elegans* has 23~24 body wall muscle cells at each row, half of them are overlapped with each other. Therefore, a model with 12 body segments is reasonable for robot design as in a dynamic model proposed by Suzuki [11]. Based on this approach, we design a robot with 12 body segments. Bending motion of each actuator unit is generated by a pair of thermal SMA actuators where each of actuators mimics dorsal and ventral sides of body wall muscle respectively.

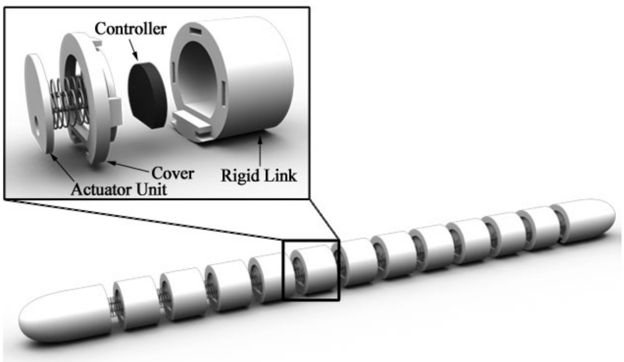

Fig. 2. Rendering of robot assembly.

As a result, a designed robot consists of 12 actuator units, containing 24 thermal SMA actuators, which are serially connected to each other with rigid links as described in Fig 2. Each actuator unit is fixed to the cover part attached to a rigid link as shown in the upper left corner of Fig 2. Inside the rigid link, control circulatory is placed. Robot body parts are fabricated by the rapid prototyping. The length of the entire worm-like robot is expected to be about 30 cm, and its weight about 100 g. In a current stage, to verify the feasibility of our design, we build a simpler hardware prototype. In this paper, the feasibility test is performed with a two segment prototype before completing the whole robot manufacturing.

3. Motion Control

3.1 Motion Control Mechanism

Previously reported snake-like crawling robots performed their locomotion mostly based on the CPG motor control methods [1, 2]. The control methods require the continuous operation of actuators. Therefore, the CPG based control methods are inappropriate for binary positioning actuation based on thermal SMA. Instead, we propose a simple sequential binary positioning mechanism to generate a sinusoidal waveform.

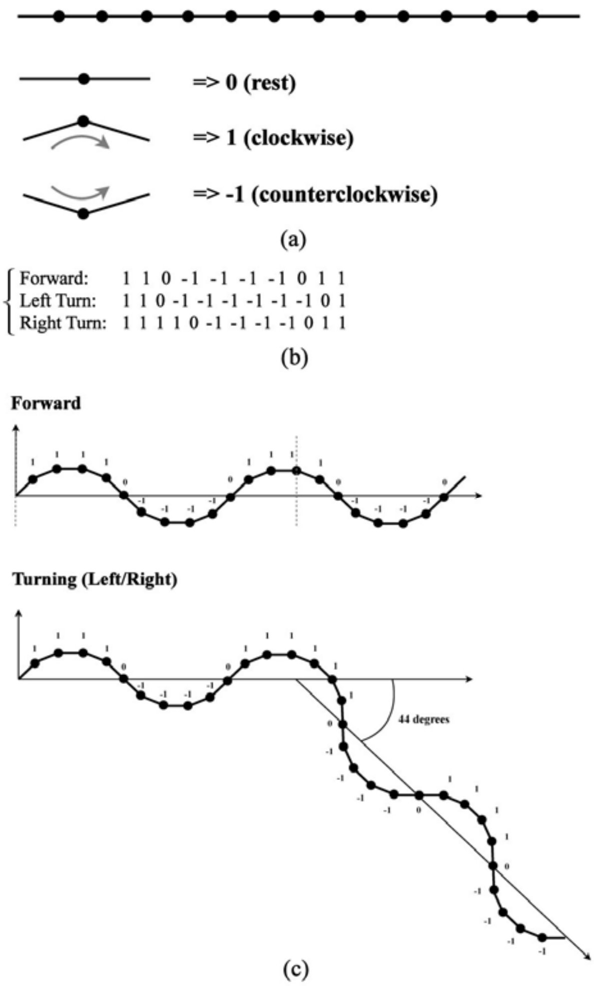

Fig. 3. (a) Simplification of each motion modes of actuator segments. (b) Sequential codes for forward and turning motions. (c) Wave form for each forward and turning motion sequences.

Each actuator unit is considered as rotating joint. Since each pair of SMA actuators operate with binary positioning, each actuator unit bends its body by a constant angle either clockwise or counterclockwise. Three possible configurations are coded as illustrated in Fig 3. (a). Therefore, by assigning an appropirate sequence, forward and turning motions can be coded (Fig 3. (b)), and a resultent wave form for each motion is formulated as illustrated in Fig 3. (c). The forward motion code forms a simple sine wave while the turning motion code is created by modifying the period of a sine wave. The motion modes are adopted from *C. elegans*' and mimic the actual worm's motion.

3.2 Implementation of Control Method

The motion control mechanism is simple enough to be operated in a simple circuiatory with microcontroller (PIC12F675 from the Microchip, Inc.). Two external command signals are fed into a microcontroller to represent one among four motion modes: 11(forward), 10 (left turn), 01 (right turn), and 00 (rest). Each thermal SMA actuator requires about 350 mA to operate appropirately. The resistance of thermal SMA do not remain constant and changes in a small range during activation. Therefore, an extra constant current circuit is included in the controller circuiratory. Fig 4. shows a two segment prototype with the implemented conroller.

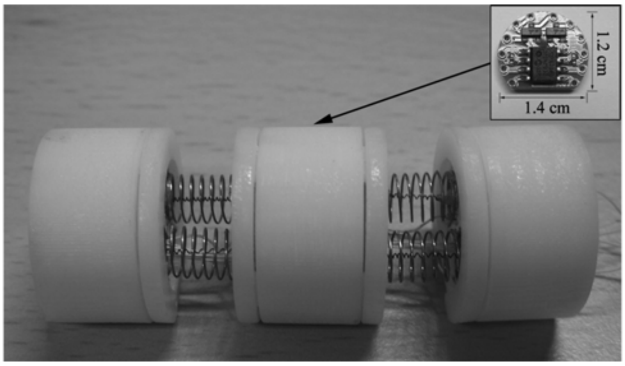

Fig. 4. Prototype with two segments. Implemented controller is shown on the upper right corner.

4. Experimental Results

The PCB controller circuits embeded inside the rigid links are designed to produce the command input signal as described in Fig 5. (a). The commend input signal, in discrete current inputs, produces sequential square swaves which approximates sine waves. Positive and negative signals are combined to represent the operation of the linear actuator in a pair. Corresponding bending movement of each actuator unit is also represented in dashed-line in Fig 5. (a). Repeated contraction and relaxation of actuator unit generate a sine wave-like motion. According to experimental results, the operating freqency of a single thermal SMA-based actuator is 0.5 Hz and the oscillation frequency of an entire worm-like robot is about 0.2 Hz in room temperature condition without any forced cooling. The oscillation frequency of actual *C. elegans* is about 0.5 Hz on typical agarose substrate. The faster or slower oscillation is possible conditioned on drag level of agarose substrate. Therefore, the oscillation frequency of the fabricated robot is comparable to the actual speed of the worm. Figure 5. (b) illustrates the operation of implemented two segment robot prototype. The test result supports the suitability of the proposed robot design and control mechanism .

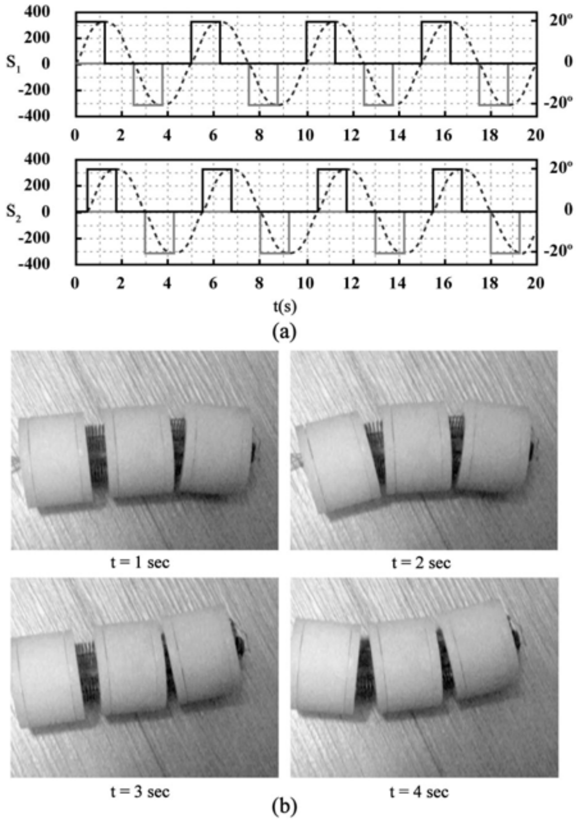

Fig. 5. (a) Designed forward motion signal input and motion of each actuator unit for fabricated two segment prototype. S1, S2 indicate series connected actuator units of the implemented prototype. The horizontal axis unit is time in seconds; the left vertical axis unit is current in mA; the right vertical axis unit is angle in degrees. Bold lines indicate electric input signal for a pair of SMA actuator and dashed line is estimated bending angle of actuator unit. (b) is a sequence of image frames which illustrates the operation of the implemented prototype.

5. Conclusion and Future Works

In this paper, we introduce the design of a small-sized crawling robot which closely mimics the crawling motion and biological structure of nematode *C. elegans*. The overall design of the robot includes two key design feature: 1) thermal SMA-based actuation mimicking the body wall muscle anatomy of *C. elegans*, and 2) simple binary positioning-based motion control mechanism inspired by the muscular activation of *C. elegans*.

The designed thermal SMA-based actuator has properties resonably compatible with that of the actual worm's body wall muscle. The binary positioning-based control scheme is appropriate to generate sinusoidal motions and has advantages in implementation because of its simplicity. The experiment with the current hardware prototype demonstrated the feasibility of the proposed robot design and control method.

We plan to complete a whole robot assembly with 12 body segments which is structurally comparable to the actual worm. Moreover, external adjustments on the bottom environment will be attempted for the purpose of increasing its propultion efficiency. We expect the proposed simple robot mimicking the motion and structure of *C. elegans* will contribute in better understanding of the motion principle of the *C. elegans* as well as in the field of biologically inspired robot design.

Acknowledgement

Authors thank Mr. Daeyeon Kim for insightfull discussion and advice in robot design and manuscriapt preparation.

References

[1] S. Hirose, Biologically Inspired Robots (Snake-like Locomotor and Manipulator), London, U.K.: Oxford Univ. Press, 1993.

[2] Crespi A. and Ijspeert A. J., “Online optimization of swimming and crawling in an amphibious snake robot,” IEEE Transaction on Robotics, vol. 24, no. 1, pp. 75-97, 2008.

[3] J. Madden, et al., “Artificial muscle technology: physical principles and naval prospects”, IEEE Journal of Oceanic Engineering, vol. 29, no. 3, pp. 706-716, 2004.

[4] J. Bryden, and N. Cohen, “A simulation Model of the Locomotion Controller for the Nematode *C. elegans*,” From animals to animals 8 (Proc. Of the eighth International Conference on the Simulation of Adaptive Behavior), pp. 183-192, 2004.

[5] J. G. White, E. Southgate, J. N. Thomson, and S. Brenner, “The Structure of the Nervous System of Nematode *Caenorhabditis elegans*,” Phil. Trans. Royal Soc. London, series B, Boil. Scien. vol. 314, Issue 1165, pp.1-340, 1986.

[6] N. A. Croll, “Components and Patterns in the Behaviour of the Nematode *Caenorhabditis elegans*,” Journal of Zoology, London, vol. 176, pp. 159-176, 1975.

[7] Mark Wakabayashi, “Computational Plausibility of Stretch Receptors as the Basis for Motor Control in *C. elegans*,” B.A. Thesis, School of Information Technology & Electrical Engineering, Univ. of Queensland, Australia, October 2006.

[8] Toida N., Kuriyama H., Tashiro N., and Ito Y., “Obliquely striated muscle,” Physiological Reviews, 55:7000-756, 1975.

[9] N. Ma and G. Song, “Control of shape memory alloy actuator using pulse width modulation” Smart Material Structures, vol.12, no.5, pp. 712-719, 2003.

[10] A. Menciassi, S. Gorini, G. Pernorio, and P. Dario, “A SMA actuated artificial earthworm,” in Proc. IEEE ICRA, New Orleans, LA, pp. 3282-3287, 2004.

[11] Michiyo Suzuki, Takeshi Goto, Toshio Tsuji, and Hisao Ohtake, “Dynamic Body Model of the Nematode *C. elegtans* with Neural Oscillators,” Journal of Robotics and Mechatronics, vol. 17, no.3, pp. 318-326, 2005.