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Design and Control of Thermal SMA based small crawling robot mimicking *C. elegans*

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Abstract— **This paper presents a design of a thermal SMA based simple small-sized and low-weight crawling robot, mimicking the crawling motion mechanism of *Caenorhabditis elegans* (*C. elegans*). Properties of the thermal SMA are similar to those of *C. elegans* muscle, which enables us to generate biologically relevant undulating motions. Each of 12 body segments composed of a pair of actuators is designed to be serially connected via a link that includes a motion control unit. Microcontroller is used to implement a simple sequential mode-based motion control scheme. Computer simulation and experimental results with a four segment prototype demonstrate the feasibility of the proposed robot design and control mechanism.**

I. INTRODUCTION

BIOLOGICALLY inspired robots have received much attention for last few decades in the field of intelligent robotics. Themes of biomimetic design span over a large area from biomimetic sensors and actuators to biomimetic organisms. Most of these designs, however, are based largely on traditional mechanical robot mechanisms, which are often remote from nature's design. For example, many of biologically inspired robot designs mimicking snakes [1], lamprey [2], or salamander [3] utilize electrical motors for actuation. However, such traditional actuators impose constraints on the size and weight of the robots, especially in realizing them in small size. Moreover, electrical motor-based actuation mechanism is far different from that living organism's muscle-based system. Therefore, recent efforts have been made by a number of investigators to design actuators that are not only structurally compatible to living organisms but also functionally versatile to overcome these constraints. As a result, smart materials such as shape memory alloys (SMA), electro-active polymers (EAP), and ionic polymer metal composites (IPMC) have been recently employed as promising candidate substances for actuators to engender natural motions of biologically inspired small-sized robots. Although smart materials are not yet capable of replacing traditional electrical actuators in a number of practical aspects, rigorous advancement of related technologies makes the smart material a promising option in the biologically inspired robot design. Furthermore, smart material-based actuators can be more appropriate to empirically study living organism's characteristics, which are difficult to control in actual organisms. Bio-mimetic robots that are structurally and functionally compatible to model organisms, can give clues for better understanding of the organisms.

Among biologically inspired robots, snake-like crawling robots have been widely developed due to its simplicity in motion [1][2]. These robots are actuated by rotational electric motors that receive wave patterns from the central pattern generator (CPG), resulting in complexity in implementation. Also, the electrical motor-based actuation mechanism is quite different from actual muscular system where small muscle cells coordinately work to generate motion. This type of motion can be represented better with a collection of micro-linear actuators.

This paper aims to introduce a bio-mimetic robot design with four main goals: 1) to design a small-sized and low-weighted crawling robot, 2) to mimic actual muscle and its motion, and 3) to create a motion generation algorithm that can be easily implemented in a simple hardware, and 4) to understand the dynamic characteristics of a model organism through hardware manufacturing. To meet these goals, we need a proper model organism whose structure is biologically simple and motion mechanism is well known. Among many small-sized nematodes, *C. elegans* is selected because of its far simpler structure and motion characteristics than those of snake or lamprey [4][5][6]. *C. elegans'* simple sine wave-like motion characteristics are well known and reported. Moreover, the computational modeling of its crawling motion has been reported [7]. However, very little is known about its dynamic characteristics on various surface conditions and complex motion mechanism such as a large angle turn due to inherent complexity of the biological organisms. Hence, *C. elegans'* dynamic characteristics can be investigated by the used of hardware with the help of the computational modeling of its crawling [7]. Therefore, we propose a design and control of a small crawling robot mimicking *C. elegans.*

The rest of this paper is organized as follows. In section II, several candidates of smart materials are compared to construct a muscle-like actuator to mimic *C. elegans*' motion. Section III explains the design of actuator and robot body, and their assembly. Section IV describes the motion control mechanism and controller implementation. Section V shows computational simulation results and experimental tests with

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TABLE I

List of possible smart materials for linear actuator [9][10][11][12][13]

Material	Potential Problem
Dielectric Elastomers	High voltage requirement and encapsulation issue
Relaxor Ferroelectric Polymers	Expensive material
Liquid Crystal Elastomers	Hard to make in small size, hard to control, not commercially available
Conducting Polymers	Encapsulation issue and slow response
Molecular Actuators	Expensive material and not commercially available
Carbon Nanotubes	Expensive material and too small strain rate
Ionic Polymer Metal Composites (IPMC)	Small work density
Thermally Activated Shape Memory Alloys (Thermal SMA)	Binary positioning is only possible and shorter life cycle for large strain
Ferromagnetic Shape Memory Alloys (Ferromagnetic SMA)	Coil or magnet is too bulky and heavy
Ionic Polymer Gels	Too slow response

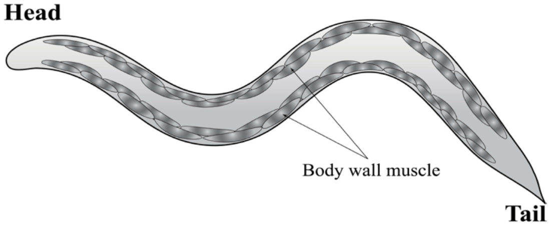

Fig. 1. Simplified illustration of *C. elegans*' anatomy: Both the dorsal and the ventral body wall muscles are organized into two rows; each of these four rows consists of 23 or 24 muscles. Only two rows are shown in the schematics

an implemented four segment prototype robot to verify our approach, which is followed by conclusions and future perspectives in Section VI.

II. ACTUATOR MATERIAL SELECTION

To design a linear actuator for a small robot of the order of centimeters, smart material is considered. There are a number of functional requirements and practical considerations to be satisfied in mimicking simple contraction-relaxation actuation scheme of *C. elegans* in a small sized robot. In practical point of view, we prefer low voltage actuation at lowest possible cost with commercial availability. To determine the detailed design specifications that mimic the body contraction mechanism of *C. elegans*, we infer from *C. elegans*' anatomy and locomotion mechanism. Movement in *C. elegans* is achieved by the contraction of muscles lining the dorsal and ventral sides of the body. Both the dorsal and the ventral body wall muscles are organized into two rows; each of these four rows consists of 23 or 24 muscles (Fig. 1). These wall muscles are able to contract at maximal strain rate of about 100% [7][8].

Therefore, our choice of smart material should have a strain property similar to that of the real worm. Through survey on various selections, we classified the smart materials and evaluated their suitability as shown in Table 1. Among these choices, dielectric elastomer, conducting polymer, IPMC, and thermal SMA are most commonly used. Dielectric elastomer is not appropriate for our purpose, however, due to high voltage requirement (over 100 V), delayed responses, complications associated with the use of electrolytes. While conducting polymer is widely used in artificial muscle applications [14][15], it is difficult to make it in small size and its fabrication process is rather complicated, thus eliminated from our selection.

IPMC is an emerging soft material for many biologically inspired robots such as worm-like robot [16]. However, because IPMC involves bending actuation, it is not appropriate for contraction-relaxation based linear actuator. Moreover, commercially available IPMC is costly and its fabrication process is complicated.

As for thermal SMA, in the linear configuration, its deformation ratio is as little as about 5% but in a coiled spring configuration, the deformation ratio can be as large as 100%, which is similar to the muscle property of *C. elegans*. Thermal SMA returns to its original shape elastically when its temperature is higher than a threshold. Therefore, binary positioning operation can be implemented easily even though sophisticated motion control is not easily doable. Since *C. elegans'* muscle produces constant force regardless of its length with simple undulations by contraction and relaxation [8], thermal SMA's binary operation property seems comparable to *C. elegans'* muscle operation. Also, its operation speed can be high if proper amount of electric current is supplied and a sequential operation of serial thermal SMA units is suitable to realize sinusoidal motion of the worm [7]. Furthermore, thermal SMA is commercially easily accessible at a reasonably low cost, and one of materials with highest work density to generate maximum possible force. Based on these considerations, thermal SMA is selected as a promising linear actuator for a small crawling robot. While thermal SMA has been demonstrated in earthworm and lamprey robots, the locomotion of these robots relies on distinct mechanism from that of *C. elegans'* [17][18].

III. ROBOT DESIGN

The robot design is explained in three steps: A. Thermal SMA based linear actuator design, B. Robot body unit design, and C. Integrated robot structural design. We seek a design of

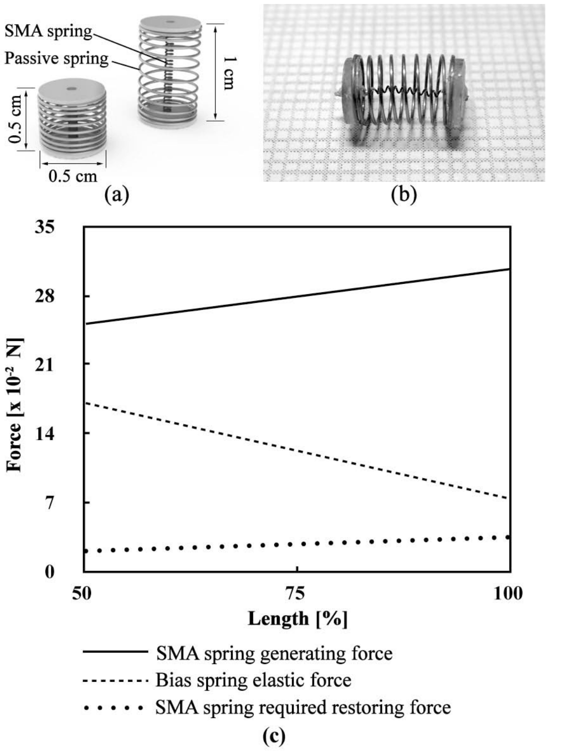

Fig. 2. Thermal SMA based linear actuator. (a) 3-D rendering of actuator which shows activated (left) and rest (right) state of linear actuator. (b) Fabricated actuator using a thermal SMA spring and a passive spring. (c) Plot for force-length relationship of linear actuator. Each line indicates the force generated by SMA spring, bias spring elastic force, and SMA spring restoring force, respectively. The x axis indicates the percentage ratio of the length of SMA spring with respect to its resting length (1 cm). Note that plot (c) is based on the specification data of SMA spring

a small robot with minimal complexity whose locomotion resembles that of the *C. elegans*.

A. *SMA based linear actuator design*

The transformation of SMA with one-way shape memory effect is an irreversible process and requires external force to recover to the original state. To resolve this issue, we place a bias passive spring in a parallel configuration to the thermal SMA spring as a single actuator unit described in Fig. 2. The bias spring restores the strained SMA to the original unstrained state. The SMA spring used here is Biometal Helix BMX150 manufactured by Mondo-Tonics Inc. The length of SMA spring is 5 mm, its diameter is 0.62 mm, and its wire diameter is 150 μm. Its kinetic displacement is 200%, producing a maximal force of about 0.3 N. The SMA spring activation shortens the actuator's length and a bias spring restores it to the resting state. The length of the relaxed SMA spring is 1cm while the fully contracted length is 0.5cm. The designed SMA based linear actuator shows the force-length relationship as shown in Fig. 2 (c). 0.1 N residual force, i.e., net force between the contraction force of the SMA spring and the elastic force of the passive bias spring, is retained at maximal contraction to provide enough force during robot locomotion.

B. *Actuator body unit design*

Fig. 3. 3-D rendering of robot assembly. Robot assembly is designed to feature 12 body segments, each of which contains two linear actuators. The detailed view of the body segment is shown on the left top corner.

Since the body wall muscles of *C. elegans* consist of 24 units longitudinally along the body length, Wakabyashi's performed a computational simulation of *C. elegans* motion for a model consisting of 24 segments of spring-damper unit [7]. However, *C. elegans*' dynamic model proposed by Suzuki [19] is constructed with 12 rigid link segments connected via rotational joints. Even though each row of its body wall muscle consists of 23 to 24 muscle cells, half of them are overlapped. Therefore, entire worm can be regarded as 12 segments like dynamic model proposed by Suzuki [19]. Based on this, we design the worm-like robot segmented in 12 units, each of which consists of two actuators one in a dorsal and the other in a ventral side, giving rise to a total of 24 actuation springs. In our robot design, rotational motion is generated by a pair of linear actuators where each actuator mimics a pair of wall muscle cells. As in Fig. 3, linear actuators are attached in a pair: when one is activated and the other is not, the body unit employs undulating motion.

C. *C. elegans robot assembly*

We design our robot to comprise of 12 body segments, containing 24 linear actuation springs, which are serially connected to each other with a rigid link in-between to form a *C. elegans* robot (Fig. 3). Inside the hollow casing that acts as a rigid link, actuator control circuitry is placed. The link, made of acryl, is laser-cut in a circular cylinder shape with a flatten bottom side to allow stability of the robot on the ground. The 12 segment robot is expected to be 25cm in length and weigh about 50g. In current stage, to evaluate the feasibility of our design and control mechanism, we made a simpler robot prototype. Initial version of the robot prototype built for demonstration purpose consists of 4 segments with 8 SMA actuators, which are sequentially assembled. Despite the reduced number of segments, it is still enough to demonstrate the feasibility of our design.

IV. MOTION CONTROL

A. *Motion control mechanism*

A number of previously reported snake-like crawling robots [1], [2], [3] execute locomotion based on CPG motor control. This kind of control mechanism requires continuous actuator operation and is inappropriate to be implemented in a small sized circuitry. Instead of CPG, this work proposes a

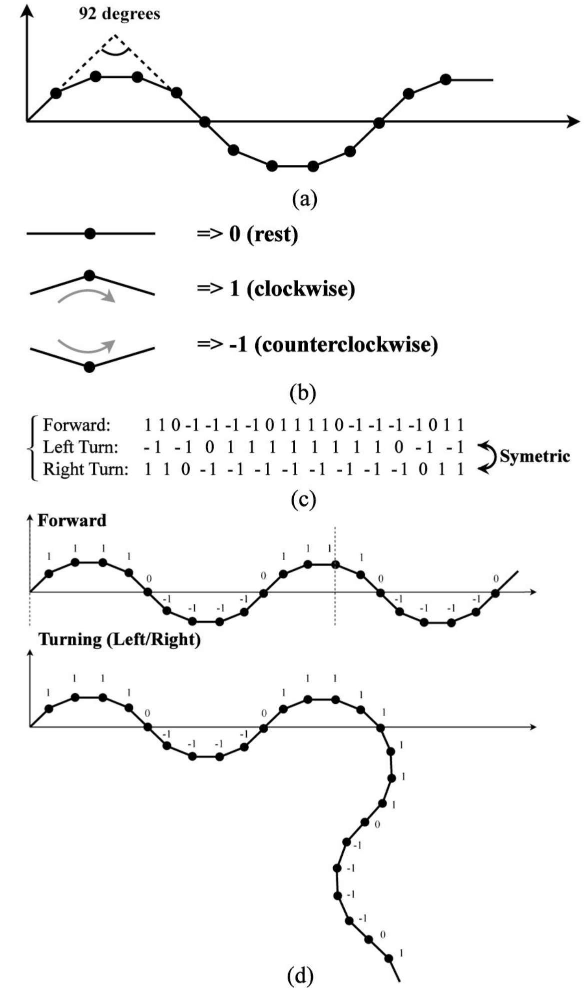

Fig. 4. (a) Sine wave formation by series connection of actuator segments. (b) Simplification of each motion modes of actuator segments. (c) Sequential code for forward and turning motion. Note that left turn and right turn are symmetric each other. (d) Whole robot's wave form for each forward motion sequence, and turning motion sequence.

sequential binary positioning mechanism to simply generate sinusoidal waveforms. A specific sequence designates a specific motion mode and its repeated cascade leads to a desired sinusoidal waveform.

Each actuator body unit is regarded as a rotational joint. A linear actuator in a pair is separately activated to bend its body by a constant angle either clockwise or counterclockwise. When both linear actuators are at rest, the body is straight. We use codes 0, 1, -1 to declare each motion mode as illustrated in Fig. 4 (b). 0, 1, -1 represent resting, clockwise bending, and counterclockwise bending modes, respectively. By assigning an appropriate code sequence, the whole robot's body shape is formulated (Fig. 4 (a)). Then, each unit's code is cyclically relayed to generate desired motion. The forward motion sequence generates the sine wave while the turning motion is established by modifying the period of the sine wave (Fig. 4 (c) and (d)). These motion modes are adopted from actual *C. elegans* movement and simplified with sequential codes.

TABLE II
ELECTRICAL CHARACTERISTICS OF ACTUATOR

Activation Current [mA]	Activation Time [sec]	Restoration Time [sec]	Note
140-150	4-5	2	Slow
170-180	2	2	.
200-210	1	2	.
220-230	1<	2	Overheated
250>	1<<	2	Burn

Note that the resistance of each actuator differs by up to one ohm and is not consistent during activation. Time is measured in the room temperature condition.

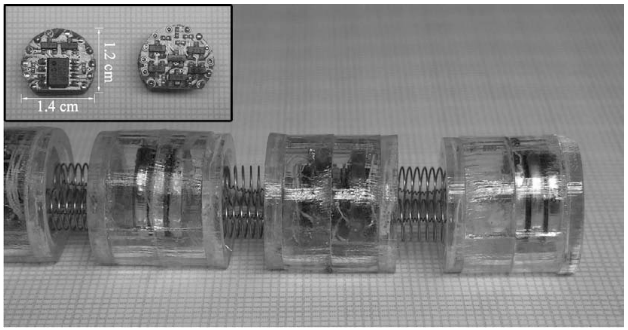

Fig. 5. Prototype (with four segments) assembly. The implemented controller is shown on the left top corner.

B. Controller implementation

The proposed motion mechanism is simple enough to be executed by a microcontroller (PIC12F675 from the Microchip, Inc). Specified signal pattern assignment and relay produce motions. Therefore, the mechanism is suitable for implementation in a compact and small-sized robot. Two external command signals are inputted into a microcontroller to represent four motion modes: 11(forward), 10(left turn), 01(right turn), 00(resting). In the case of the resting state, the microcontroller is in a sleep mode, minimizing the energy expenditure. The electric current supply of 180~200 mA turns out to be appropriate in operating the robot (Table II). The SMA based linear actuation is sensitive to the current supply, and the resistance values do not remain constant. Therefore, an extra circuit to provide a constant current of about 200mA is employed to the controller. Fig. 5 shows the implemented controller and prototype robot assembly.

V. EXPERIMENTAL RESULTS

We conduct both computer simulation and experiment to verify the feasibility of our proposed design. The robot's crawling motions are simulated to check our control scheme by Solidworks Motion (Solidworks Corp.). Based on our design, the computational robot model includes 12 body segments. Binary positioning actuation of each actuator unit is interpreted as a constant angle (22 degrees) rotation in the computational simulation. Forward and turning motions are implemented by sequential codes explained previously. As shown in Fig. 6 (a) and (b), we confirm that the motion of the simulated model adequately represents our designed motion control mechanism.

The motion generation is also tested with the developed robot prototype. The PCB controller circuit embedded in the link segment produces the command input signals described as in Fig. 6 (a) and (b) to implement forward and turning

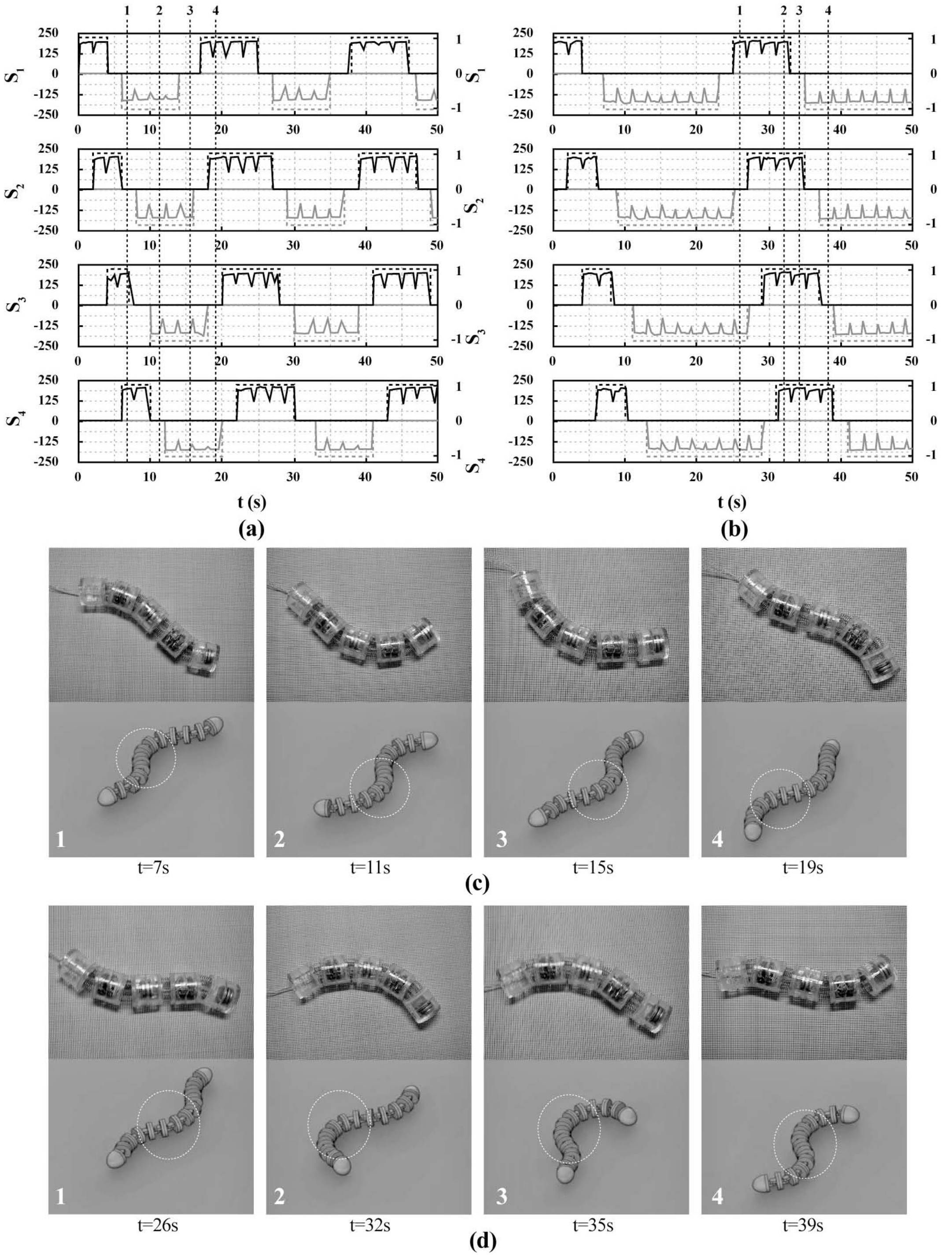

Fig. 6. (a) Forward motion (left) and (b) turning motion (right) control input signals of designed electrical controller for implemented prototype robot with four body segments. (Top to bottom) S1, S2, S3, and S4 indicate the series connected actuator unit of implemented prototype robot. Horizontal axis units are seconds; left vertical axis units are currents in mA; right vertical axis units are code for computational simulation input. Bold lines indicate electrical signal for right linear actuators and gray lines indicate electrical signals for left linear actuators. Doted lines indicate the simulation input signals. (c) and (d) are sequence of frames illustrating the computational simulation result of motion control and operation of implemented robot assembly with four actuator units. Corresponding parts in computational simulation are marked with white doted circles. (c) is forward motion and (d) is turning motion.

motions. The command input signal, given by current input, is in form of simplified sine waves that consists of sequential square pulses. The command is inputted to each body unit with a sequential delay. Small fluctuations in between subsequent square pulses are intended to prevent overheating of SMA. Although the pulse width modulation (PWM) method is generally used for the purpose [20], we do not use it because of difficulties in implementation on small-sized hardware. The command signals are illustrated with code sequence inputs in computational simulation (dotted lines). Positive and negative signals are combined to represent the operation of the linear actuators in a pair. According to experimental result, the operating frequency of a single SMA-based actuator is 250 mHz and the oscillation frequency of entire robot is about 50 mHz in the room temperature condition. Fig. 6(c) and (d) show sequential snapshots over time to compare both the computational and experimental results. Each of the numbered snapshots (1, 2, 3, and 4) in Fig. 6(c) and (d) illustrates robot motion generated by the corresponding command input marked with 1, 2, 3 and 4 shown in Fig. 6 (a) and (b), respectively. The circles on the simulation results indicate the corresponding body part in the prototype. These results confirm the suitability of the control mechanism for the implemented hardware. Each SMA based actuator consumed 0.5 W with efficiency of 0.4 %. The 12 segmented robot with 24 SMA based actuators would require 288 J/min.

VI. CONCLUSION AND FUTURE WORK

The purpose of our work is to design a small-sized crawling robot which closely mimics the crawling motion of *C. elegans*. The overall design of the robot includes two key features: 1) SMA-based actuation mimicking the body wall muscle anatomy of *C. elegans*, 2) simple binary operation-based motion control mechanism inspired by the muscular activations of *C. elegans* during locomotion. The inspirations from *C. elegans* derived a simple and easy-to-implement robot.

The actuators were designed using thermal SMA because of its property reasonably compatible with that of the wall muscle's as well as its easy accessibility. The binary operation-based control scheme was enough to generate proper motions and advantageous for the hardware implementation thanks to its simplicity. The experiments with the current prototype demonstrated the feasibility of the proposed design. On and off activations of SMA-based actuators in pair mimicked the wall muscular activation and the appropriate coordination of operation schemes successfully generated the desired forward and turning motions.

We plan to complete a crawling robot with 12 body segments of 24 actuators, comparable to *C. elegans*. Furthermore, the topological modification will be designed on the bottom side of the robot to mimic the worm's longitudinally oriented ridges which may aid the worm to increase its efficiency in forward motion by creating frictional anisotropy. We hope that this simple robot mimicking the structure and dynamics of *C. elegans* will contribute in understanding of the motion principle of the *C. elegans* as well as in the field of biologically inspired intelligent robot design.

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