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An Adaptive Decentralized Control of a Serpentine Robot Based on the Discrepancy between Body, Brain and Environment

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Abstract— **Despite its appealing concept, a systematic way of designing autonomous decentralized control system is still lacking. In order to alleviate this, we have so far proposed a design scheme for local sensory feedback control leading to adaptive behaviors from the entire system, based on a so-called discrepancy function that extracts the discrepancies between body (*i.e.*, mechanical system), brain (*i.e.*, control system) and environments. This paper intensively investigates the validity of this design scheme under the real world constraints by taking a two-dimensional serpentine robot exhibiting undulatory slithering locomotion as a practical example. The experimental results show that the robot exhibits adaptive behavior against environmental changes as well as the robustness against malfunctions of body segments due to the local sensory feedback control. The results obtained are expected to shed a new light on methodology for autonomous decentralized control system.**

I. INTRODUCTION

Living organisms exhibit astoundingly adaptive, supple and versatile locomotion in real time under unpredictable real world constraints. In order to endow robots with similar capabilities, their bodies must have significantly many degrees of freedom equivalent to living organisms. For successfully taming many degrees of freedom according to the situation encountered, the concept of *autonomous decentralized control* plays a pivotal role, and then has attracted considerable attention in the recent past. In fact, living organisms nicely orchestrate and maneuver their many degrees of freedom in their bodies by distributed neural networks called *central pattern generators* (CPGs), which are responsible for generating rhythmic movements, particularly locomotion [1]. Based on this knowledge, thus far various studies have been conducted for implementing decentralized control schemes into robots to generate adaptive locomotion, focusing in particular on legged locomotion [2]-[6]. Obviously from these observations, autonomous decentralized control method is expected to become an attractive tool for designing highly adaptive robots.

Despite its appealing concept, a systematic way of designing such autonomous decentralized controllers is still lacking. This is because the methodology connecting the local behavior to the global behavior that induces useful functionalities, *e.g.*, adaptability and fault tolerance, has not yet been established. In order to alleviate this, we have to intensively consider the following issues that can be summarized as:

(1) Dynamics of an individual component to be implemented, *i.e., intra-modular dynamics*.
(2) Interaction between the components to be implemented, *i.e., inter-modular dynamics*.
(3) The way of interaction between body and brain.

As the pioneering works done by Taga *et al.* [4]-[6] indicate, issues (1) and (2) are often modeled as coupled (nonlinear) oscillator systems. In contrast to this, with regard to issue (3), the way of interaction between body and brain has been designed completely on ad-hoc and tailor-made basis for specific applications. In sum, presently an undeniable lack of a consistent methodology for designing the way of interaction between body and brain still exists.

In light of these facts, we have employed a so-called "back-to-basic" approach. More specifically, we have focused on *true slime mold* (*Physarum polycephalum*) which employs purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPG [7]. The body of true slime mold is highly soft and deformable and there is an explicit conserved quantity, *i.e.*, mass of protoplasm. Owing to these properties, the long-distant physical interaction between the body parts is induced inside true slime mold, similar to that observed in waterbeds, which guarantees to connect the local behavior with the global behavior. Due to these intrinsic properties, slime mold is a good biological organism that allows us to extract the design methodology of how the control and mechanical systems should be coupled in a systematic way. By studying the slime mold, in our earlier works we have introduced a systematic design methodology for the interaction between control and mechanical systems based on *discrepancy function* that extracts the discrepancies between body (*i.e.*, mechanical system), brain (*i.e.*, control system) and environments [8][9]. Now a question arises: to what extent the decentralized control scheme extracted from true slime mold is applicable to different types of locomotion?

In order to discuss a common principle that underlies various types of locomotion, in this paper, we implement the design scheme to the control of a real physical two-dimensional serpentine robot that exhibits undulatory slithering locomotion. The experimental results show that remarkable adaptability to environmental changes as well as robustness against local malfunctions can be successfully achieved by implementing the decentralized control scheme extracted from true slime mold.

In what follows, section II mainly illustrates our proposed

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decentralized control method by taking a two-dimensional serpentine robot. Then section III presents how we built a real physical serpentine robot and implemented our proposed decentralized control method into the robot. Section IV subsequently introduces some experimental results in terms of exhibition of adaptability and fault tolerance obtained by employing our design scheme, finally followed by conclusions of this paper together with future works.

II. THE MODEL

A. Mechanical System

A schematic of the robot employed in this research is shown in Fig. 1. The robot consists of multiple homogeneous body segments that are attached one dimensionally at the joints, and each joint is driven by a motor positioned there. The robot advances on a two-dimensional surface by lateral undulation, in which waves of lateral bending of the body are propagated from its head to tail, thus generating a travelling wave. For effectively generating a propulsion force, we assume that the friction between each body segment and the ground is relatively low along the longitudinal direction compared to the latitudinal direction.

B. Control System

In this section, we introduce a way of designing autonomous decentralized control under the conditions of the above-mentioned mechanical structure. For generating undulatory slithering locomotion, each joint should rotate itself periodically, and it is necessary to set a certain fixed phase difference between adjacent joints. To this end, we have focused on oscillators [10][11]. As shown in Fig. 1, a phase oscillator is implemented at each motor and controlled autonomously. The dynamics of each phase oscillator is shown in the following equation:

$$\frac{d\theta_i}{dt} = \omega + f(\theta_{i+1}, \theta_i, \theta_{i-1}) + g(\phi_i, \phi_{n,i}, \theta_i). \tag{1}$$

Here, θ_i is the phase of the i-th oscillator, ω is the angular frequency, $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ is the phase difference set term between adjacent oscillators, and $g(\phi_i, \phi_{n,i}, \theta_i)$ is the local sensory feedback term based on the discrepancy function. In addition, ϕ_i, $\phi_{n,i}$ represent the i-th joint angle and desired joint angle, respectively. This robot is controlled by setting each of the desired joint values responding to the corresponding oscillator's output to drive the motor so as to reach the desired value. The equation for the desired joint angle $\phi_{n,i}$ is given by:

$$\phi_{n,i} = \phi_0 \sin\theta_i, \tag{2}$$

Here, ϕ_0 is the constant defining the desired joint angle amplitude. In order to generate undulatory slithering locomotion, it is important to create a travelling wave from its head to tail by rotating each joint with appropriate timing (phase). Note that this travelling wave should be flexibly modified according to the situation encountered so as to generate adaptability and fault tolerance from the entire system. In order to meet this requirement, the terms of (1), *i.e.*, $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ and $g(\phi_i, \phi_{n,i}, \theta_i)$ are vitally important. In the following, we explain how we design these terms.

1) Phase Difference Set Term $f(\theta_{i+1}, \theta_i, \theta_{i-1})$: In order to propagate the lateral bending of the body from its head to tail and create a travelling wave, it is necessary to set a certain fixed phase difference between adjacent joints. For simplicity, we define $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ by introducing the phase difference ψ as:

$$\begin{aligned} f(\theta_{i+1}, \theta_i, \theta_{i-1}) =& \varepsilon \sin(\theta_{i+1} - \theta_i + \psi) \\ &+ \varepsilon \sin(\theta_{i-1} - \theta_i - \psi). \end{aligned} \tag{3}$$

ε is a constant defining the strength of the interaction between the coupled oscillators.

2) Local Sensory Feedback Term $g(\phi_i, \phi_{n,i}, \theta_i)$ Based on the Discrepancy Function: Now, let we consider how to design local sensory feedback term, which allows each oscillator to modify its behavior so as to emerge useful functionalities from the entire system. To this end, we introduce the concept of discrepancy function. The discrepancy function plays an important role for generating robot behaviors, with which the phase of oscillator is kicked forward or backward according to the situation encountered [9].

In this study, we define the discrepancy function I_i as:

$$I_i = \frac{\sigma_i}{2}\tau_i^2, \tag{4}$$

$$\tau_i = -k_i(\phi_i - \phi_{n,i}), \tag{5}$$

where σ_i is a coefficient specifying the sensitivity for discrepancy detected at each joint. k_i is a constant defining the corresponding joint elasticity. The function is defined so as to increase its value when the discrepancy τ_i increases. Note that τ_i provides rich information about the discrepancy between its control system, mechanical system and environment. It should be also noted that the discrepancy function I_i can be calculated only with locally available variables.

Next, let us now move on to how to design local sensory feedback $g(\phi_i, \phi_{n,i}, \theta_i)$. We assume that animal-like supple locomotion emerges as a result of reducing the discrepancy

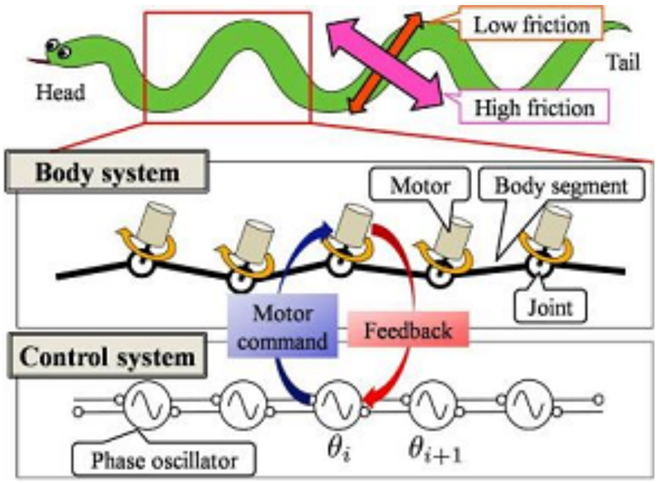

Fig. 1. Schematic of body and control system of two-dimensional serpentine robot.

Fig. 2. Real physical serpentine robot.

[9]. Based on this hypothesis, we design the local sensory feedback term as:

$$g(\phi_i, \phi_{n,i}, \theta_i) = -\frac{\partial I_i}{\partial \theta_i} = \sigma_i k_i^2 \phi_0 (\phi_i - \phi_{n,i}) \cos\theta_i. \tag{6}$$

III. THE ROBOT

A. Development

Fig. 2 shows the entire structure of the two-dimensional real physical serpentine robot developed for the verification under real world constraints. The robot consists of 28 body segments and 27 joints. Each body segment is 0.11 (m) long and has a mass of 0.60 (kg). As shown in Fig. 3, each body segment is equipped with a control circuit board with a microcomputer, a wireless communication circuit board for acquiring internal data, a rotary encoder for detecting the angle of the joints, a power source battery, and a servo motor for driving the corresponding joint. Moreover, an LED is mounted on the top of each body segment. As illustrated in Fig. 4 (a), when a joint shifts out of the neutral (central) position and moves to the right, the LED lights up and when it shifts to the left, the LED is turned off. This alternate illumination and extinguishing of LEDs act as an aid in observing the behavior of the robot. Figure 4 (b) explains a wired-communication cable between the microcomputers of neighboring body segments, by which the phase difference set term (3) is implemented. In order to generate propulsion force leading to the lateral undulation effectively, each body segment has two undirectional passive wheels as illustrated in Fig. 4 (c).

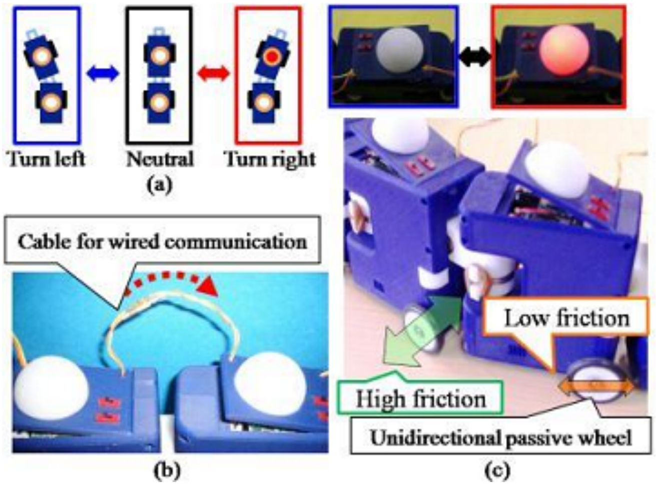

Fig. 4. (a) Operation of LED according to bending movement of robot, (b) Cable for wired communication in order to realize interaction between neighboring oscillators, (c) Unidirectional passive wheels implemented.

B. Key Mechanism Exploiting Elastic Material

Here, we explain a key mechanism that allows us to implement the local sensory feedback as expressed in (6) into the mechanical system. As illustrated in Fig. 5, each joint of the robot is equipped with an elastic material. More specifically, the motor mounted at each joint is not "directly" connected to its neighboring body segment to be moved, but is rather "indirectly" connected to the corresponding body segment via "elastic material". In other word, soft materials are used as an integral part of the motor control system. This allows each joint to generate a certain amount of displacement between the actual joint angle ϕ_i, which represents the current state of mechanical system, and the desired joint angle $\phi_{n,i}$, which is given by the control system as a motor output. Note that since the elastic materials imple-

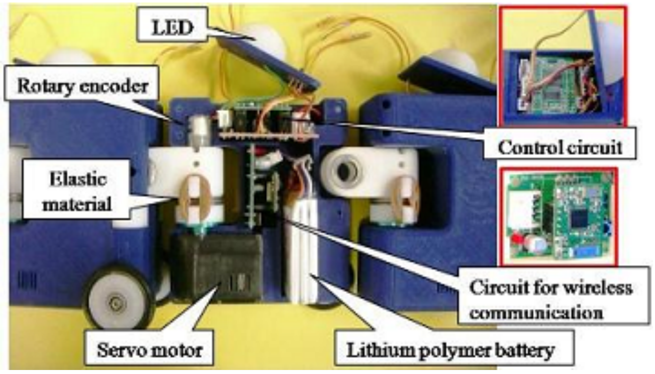

Fig. 3. Internal structure of body segment.

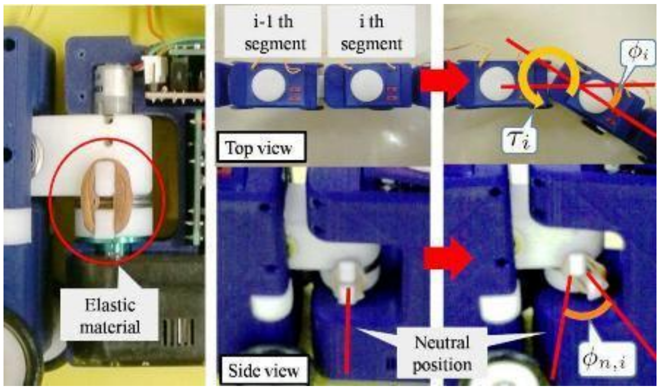

Fig. 5. Elastic material implemented on each joint of robot.

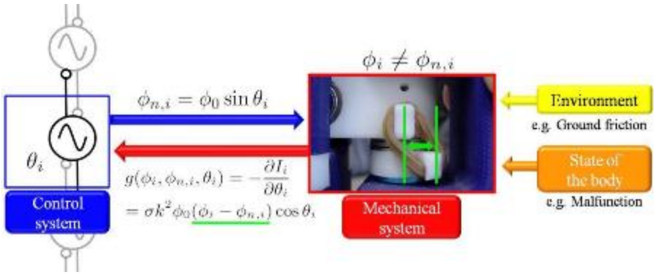

Fig. 6. The brain-body interaction via elastic materials.

mented deform in ways reasonably to the motion underway, the displacement generated provides rich information about how the robot is interacting with the environment, *i.e.*, how the control system, mechanical system and the environment are interacting each other (see Fig. 6). In sum, the key mechanism of this robot is the extensive use of soft materials, leading to the physically reasonable deformation reflecting the way of interacting with the environment, which are then exploited for modifying the phase of oscillation, which in turn will lead to generating adaptive behavior.

IV. EXPERIMENTAL RESULTS

In this section, we show some of the highlight data of experimental verification using the real physical serpentine robot. Here, we illustrate experimental data particularly from the view points of adaptability and fault tolerance. In the experiments discussed below, the experimental conditions employed are as follows: the parameters for all oscillators were the same; the initial phase of all oscillators were $\theta_i = 0.0$; the oscillator angular frequency was $\omega = 1.0$ (rad/s); the desired joint angle amplitude was $\phi_0 = 0.60$ (rad); the mutual entrainment strength was $\varepsilon = 0.18$; phase difference between neighboring oscillators was $\psi = 0.36$ (rad); the joint stiffness was $k_i = 10.8$ (N/mm); and local sensory feedback strength was $\sigma_i = 1.0 \times 10^{-3}$.

A. Verification of Adaptability against Environmental Changes

Here, we show the experimental results showing how the proposed decentralized control scheme exhibits adaptability against environmental changes. The experimental setup employed is schematically illustrated in Fig. 7. As the figure explains, the task of the robot in this experiment is to traverse the ground with different friction. The representative data obtained is shown in Fig. 8. As in the figure, the robot is able to self-regulate a phase distribution in response to the frictional change, thereby effectively increasing the number of undulations and decreasing the amplitude of its undulation, allowing the robot to continue its locomotion. Fig. 9 displays the time evolution of total amount of discrepancies I_i (top) and the spatio-temporal pattern of phases of the oscillators (bottom). The periodic fluctuations observed in the total amount of discrepancies are due to the rhythmic alternation of the desired joint angles. Interestingly, when the robot enters the ground with high friction, the total amount of discrepancies increases. Immediately after this, the robot modifies the phase differences between the oscillators so as to decrease the discrepancies, leading to successful negotiation with the environmental changes.

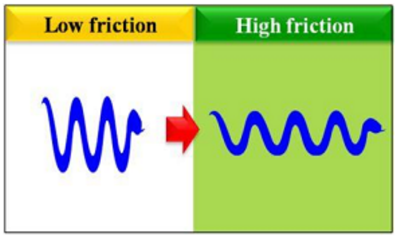

Fig. 7. Experimental setup in order to validate adaptability against environmental changes.

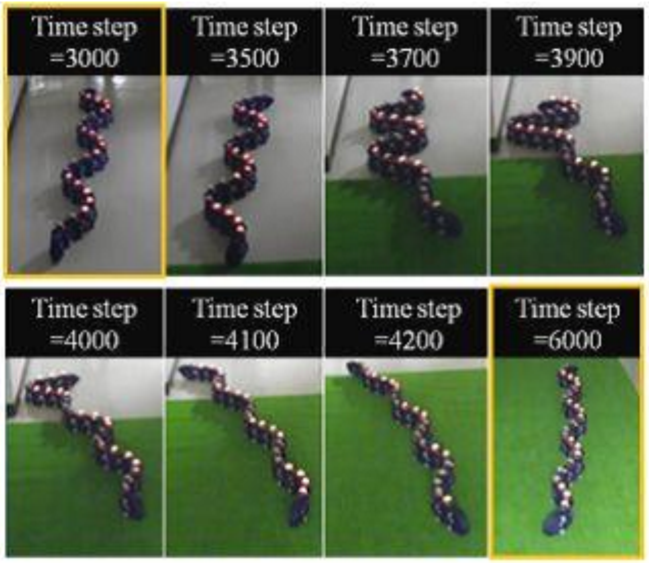

Fig. 8. Representative data of the robot's locomotion when the robot traverses the ground with different friction.

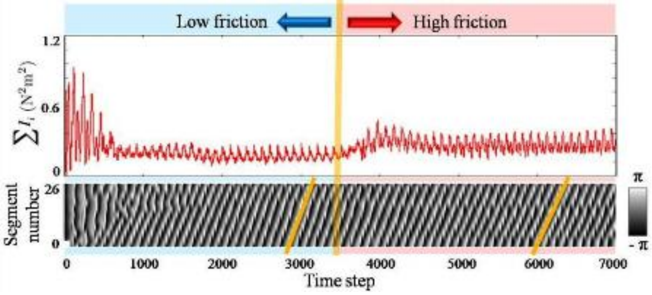

Fig. 9. The time evolution of total amount of I_i (top) and the spatio-temporal pattern of phases of the oscillators (bottom) when the robot traverses the ground with different friction. The friction change leads to increase of total amount of I_i, which then enlarges its phase gradient from its head to tail by the local sensory feedback.

In order to confirm the validity of the local sensory feedback proposed, we conducted the same experiment under the condition where the local sensory feedback is removed. The obtained results are shown in Fig. 10 and Fig. 11. Obviously from these figures, the robot cannot negotiate the environmental changes. This means that the proposed decentralized control scheme yields significant adaptability without the use of any centralized control mechanism.

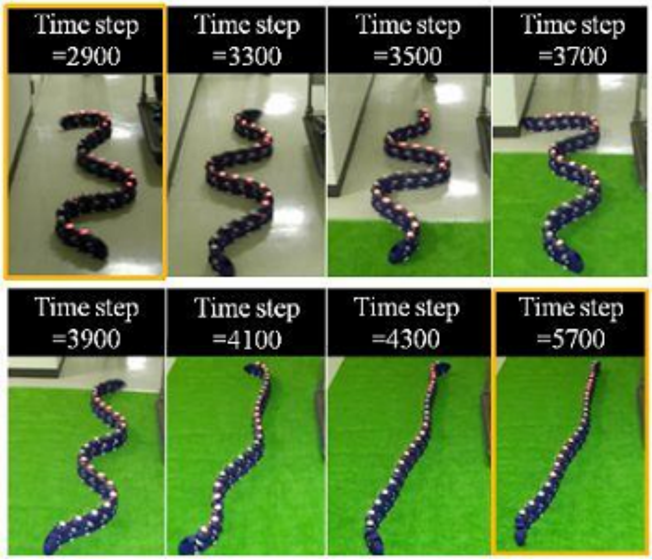

Fig. 10. Representative data of the experiment of the robot without the local sensory feedback.

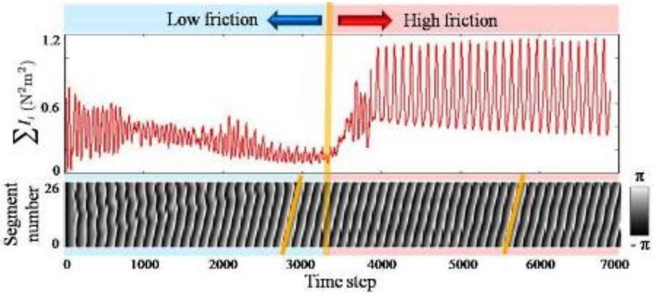

Fig. 11. The time evolution of total amount of I_i (top) and the spatio-temporal pattern of phases of the oscillators (bottom) when the robot traverses the ground with different friction. The total amount of I_i does not decrease and phase modification does not occur without the local sensory feedback.

B. Verification of Fault Tolerance against Local Malfunctions

In what follows, we show some of the experimental data in terms of fault tolerance. For simplicity, we consider the fault tolerance by disconnecting some of the inter-connections between the oscillators. More specifically, we examined the fault tolerance under the existence of six "neuronal" disconnections as illustrated in Fig. 12. The experimental results observed are shown in Fig. 13 and Fig. 14. Very interestingly, this robot can exhibit highly fault tolerance against these malfunctions. This is because the local sensory feedback loops sense the physical interactions between body segments, thereby compensate the disconnections of neuronal interactions.

In order to observe how the local sensory feedback contributes to the fault tolerance, the experiments without the local sensory feedback were conducted. The results are displayed in Fig. 15 and Fig. 16. As these figures explain, the robot no longer exhibits significant fault tolerance. In sum, the proposed brain-body interaction scheme allows the robot to generate different compensatory behaviors according to the situation encountered, which leads to highly adaptive and resilient abilities.

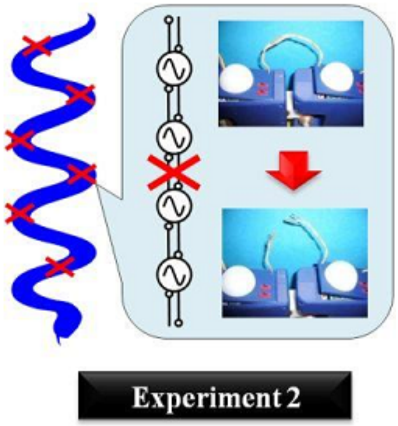

Fig. 12. Experimental setup in order to validate fault tolerance against local malfunctions. The robot has six malfunctions in its body.

V. CONCLUSIONS AND FUTURE WORKS

In order to discuss a common principle that underlies various types of locomotion, in this paper, we implemented the decentralized control scheme we had extracted from true slime mold in our earlier works to the control of a real physical two-dimensional serpentine robot. The experimental results strongly support that the control scheme implemented displays highly adaptive and resilient capabilities to environmental changes and malfunctions, without relying on centralized control. This suggests that the design scheme extracted from true slime mold could be widely used to the control of various types of locomotion, and is expected to shed a new light on design principle for taming many degrees of freedom.

Future works will focus on developing a highly soft-bodied serpentine robot with significantly many degrees of freedom, and investigating the brain-body interaction by taking not only phasic control but also tonic control into account.

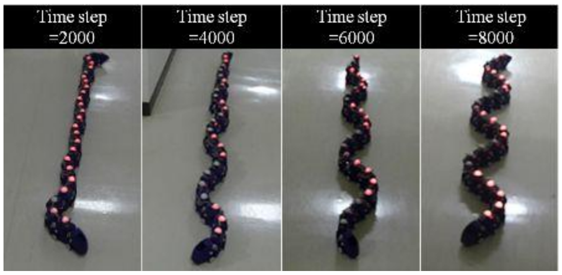

Fig. 13. Representative data of the locomotion of the robot under the malfunction condition.

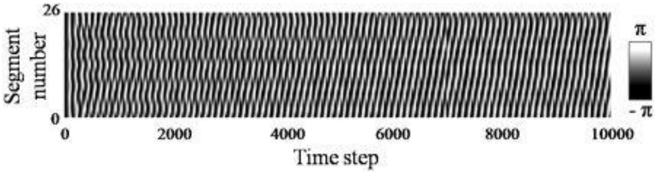

Fig. 14. The evolution in time of the spatio-temporal pattern of phases of the oscillators when the robot has local malfunctions. As time passes, the phase gradient from its head to tail is gradually generated by the local sensory feedback.

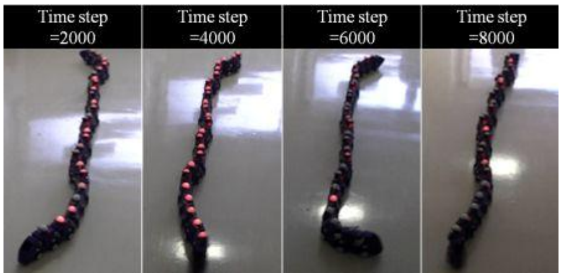

Fig. 15. Representative data of the locomotion of the robot under the malfunction condition. In this experiment, the robot is not able to sustain the locomotion without local sensory feedback.

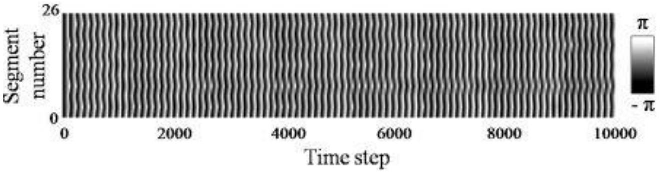

Fig. 16. The evolution in time of the spatio-temporal pattern of phases of the oscillators when the robot has local malfunctions. The robot cannot generate phase gradient for locomotion without the local sensory feedback.

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