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# A Fully 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 based on 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 by taking a two-dimensional serpentine robot exhibiting undulatory slithering locomotion as a practical example. Preliminary simulation results derived strongly indicate that our design methodology allows us to endow the robot with highly adaptability and fault tolerance. These results obtained are expected to shed a new light on design methodology for autonomous decentralized control system. Furthermore, together with a validity verification of the simulation results, this paper introduces a real two-dimensional serpentine robot that is currently under development.**

## 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, the bodies of robots 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]. Due to 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 logic connecting the behavior of an individual component to the behavior of the entire system 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.
(2) Interaction between the components to be implemented.
(3) Local sensory feedback provided to an individual component.

As the pioneering works done by Taga *et al.* [4]-[6] indicate, the issues (1) and (2) are often modeled as coupled (nonlinear) oscillator systems. In contrast to this, with regard to the issue (3), local sensory feedback mechanism 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 local sensory feedback mechanism 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* which employs purely decentralized control mechanisms based on coupled 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 two points, 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 the local sensory feedback mechanism in a systematic way. By studying the primitive mold, in our earlier works we have introduced a systematic design methodology for the local sensory feedback mechanism based on "discrepancy function" that extracts the discrepancies between body (*i.e.*, mechanical system), brain (*i.e.*, control system) and environments [8][9]. However, in order to clarify the control mechanisms that are universal to the diverse locomotion forms exhibited by living organisms, it is important to apply this design scheme to the more complicated bodies of multi-cellular organisms and to verify its usefulness.

Consequently, the primary objective of this paper is to verify the validity of the design methodology for the local sensory feedback control obtained from the mold case example. As a practical example, we demonstrate an autonomous decentralized control of a two-dimensional serpentine robot, which exhibits undulatory slithering locomotion that is phy-

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logenetically secondary to amoeboid locomotion, based on the discrepancy function. The preliminary simulation results derived indicate that the adaptability to environmental changes and fault tolerance for local faults in interactions between the components have been remarkably improved by implementing our design methodology proposed. Furthermore, together with a validity study of the simulation results, this paper introduces a real two-dimensional serpentine robot that is currently under development.

In what follows, section II illustrates our proposed method by taking a two-dimensional serpentine robot controlled in a fully decentralized manner. Then section III presents some simulation results in terms of exhibition of adaptability and fault tolerance obtained by employing the local sensory feedback control based on the discrepancy function. Section IV subsequently introduces a real two-dimensional serpentine robot under development, 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 the head to the 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 will introduce a way of designing autonomous decentralized control under conditions of the

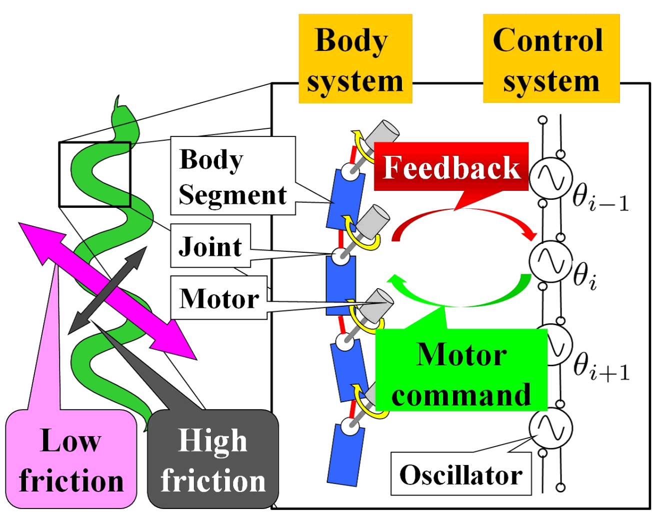



Fig. 1. A schematic of the body and control system of a two-dimensional serpentine robot employed.

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 formula:

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

Here, $\theta_i$ is the phase of the $i$'th oscillator, $\omega$ is the angular frequency, $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ is the phase difference 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, $\phi_i$, $\phi_{n,i}$ represent the $i$'th joint angle and target joint angle, respectively. This robot is controlled by setting each of the joint target values responding to each oscillator's output to drive the motor so as to reach the target value. The formula for the target joint angle $\phi_{n,i}$ is as follows:

$$\phi_{n,i} = \phi_0 \sin\theta_i, \quad (2)$$

Here, $\phi_0$ is the constant defining the target joint angle amplitude, and from (1) and (2), the target joint angle $\phi_{n,i}$ changes periodically. In addition to generating undulatory slithering locomotion, it is important to create a travelling wave by rotating each joint with appropriate timing (phase). In order to achieve this, the manner in which the adjustment of the movement phase of each joint is performed is essential. In this model, the adjustment of each joint movement phase is performed in conformity with the phase difference set term of (1) *i.e.*, $f(\theta_{i+1}, \theta_i, \theta_{i-1})$, $g(\phi_i, \phi_{n,i}, \theta_i)$. The details are as follows.

*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 the head to tail and create a travelling wave, it is necessary to set a certain fixed phase difference between adjacent joints. Because this model is simple, in order to set the phase difference between the adjacent oscillators to $\psi$, the mutual entrainments between the oscillators are designed using the following equation:

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

Here, $\varepsilon$ is a constant defining the mutual entrainment strength.

*2) Local Sensory Feedback Term $g(\phi_i, \phi_{n,i}, \theta_i)$ Based on the Discrepancy Function::* The local sensory feedback control, which is based on the discrepancy function obtained from the case studies related to amoeboid locomotion, can detect the discrepancy occurring in autonomous components in the form of a function, and can send feedback to the concerned component in order to reduce that discrepancy [9]. In this model, the discrepancy function $I_i$ is defined using (4):

$$I_i = \frac{\sigma_i}{2}\tau_i^2, \quad (4)$$

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

Here, $\sigma_i$ is a constant defining sensitivity for discrepancy of each autonomous component, and $\tau_i$ and $k_i$ are constants representing the torque generated in the joints and the joint elasticity, respectively. Joint torque is used as the discrepancy function so that we can define the differences (discrepancies) between the oscillator (brain) output $\phi_{n,i}$, and the body. This difference decides the interaction with the environment, as has been clarified from the defining formula for this model. In addition, joint torque is squared to erase the positive and negative mark that accompanies the rotation direction. The local feedback $g(\phi_i, \phi_{n,i}, \theta_i)$ of each specific oscillator phase $\theta_i$ can be designed as shown in (6), based on the principle of changing the phase in the direction that reduces the discrepancies:

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

*3) Specific Mechanical Characteristics for Taking Advantage of the Control Method::* In the proposed method the existence of mutual dependencies between adaptation and discrepancies is essential. This means that there must be discrepancies in order to adapt. Therefore, it is necessary to produce discrepancies intentionally. Based on this relationship, we conclude that it is of prime importance to produce discrepancies intentionally to facilitate adaption of robots; therefore, we installed an elastic element at each joint of the robot as a prototype for a mechanical system that utilizes this control method. From this, a "physically reasonable change" responding to the changing environment can be produced, and it thus possible to effectively generate discrepancy information. In addition, by installing the elastic element, the $k_i$ of (5) is determined depending on the elasticity of the elastic element. By adjusting this elasticity, it is possible to change the degree of discrepancies extracted.

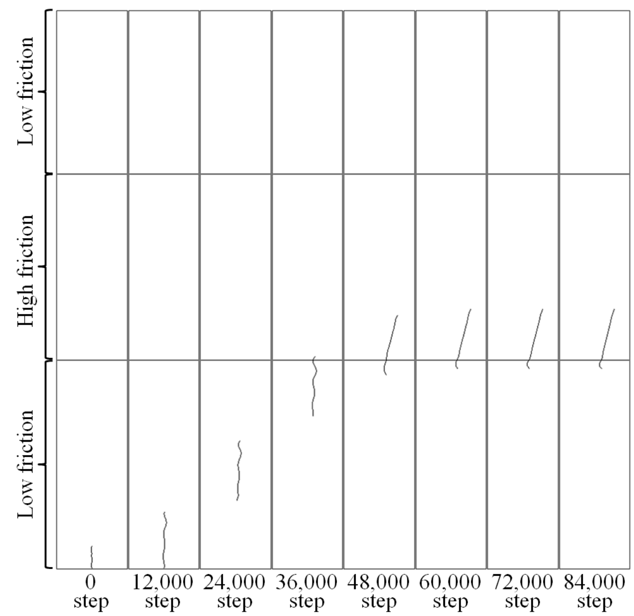
## III. SIMULATION RESULTS

In this research, we constructed a kinetic simulator and conducted experiments based on simulation to verify the validity of the design scheme of the local sensory feedback control based on the discrepancy function that extracts discrepancies between the body, brain and environment. It specifically investigates the effect of introducing the local sensory feedback control from the following two perspectives: firstly, adaptability in response to environmental changes when the robot moves from an environment with low coefficient of ground friction to an environment with high coefficient of ground friction; secondly, the fault tolerance in response to local faults in the interaction between the oscillators ($f(\theta_{i+1}, \theta_i, \theta_{i-1})$ term in (1)).

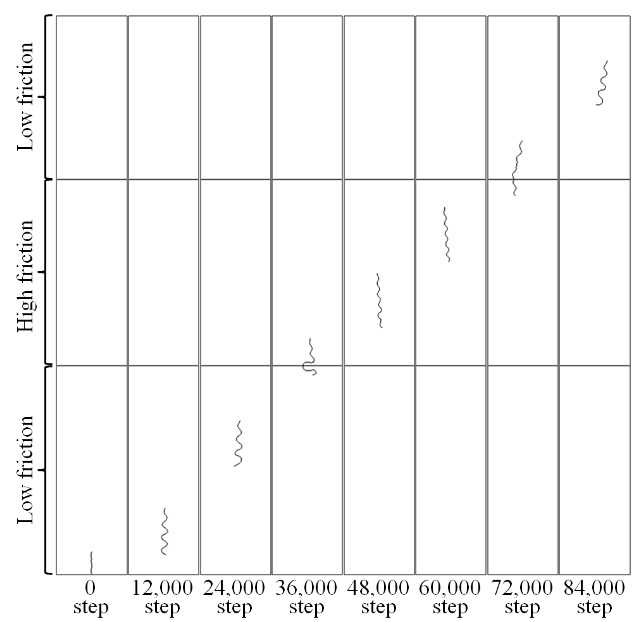
In this simulation, the number of segments $n$ was 30, the length of each segment was 0.09 (m), the mass of each segment and joint was 0.01 (kg), the angular frequency of the oscillators $\omega$ was $0.15\pi$ (rad/s), and the amplitude of the target joint angle $\phi_0$ was 30 (deg). In addition, $k_i$ and $\sigma_i$ were set as an equal value at $k_i = 0.013$ (Nm/rad) and $\sigma_i = 10.0/k_i^2$ for all $i$, respectively.

### *A. Adaptability in Response to Environment (Friction) Changes*

Robot movement from an environment with low frictional coefficient, through an environment with high frictional coefficient, to the one with low friction was compared using local sensory feedback control and also without the control. Fig. 2 (a) and (b) show the simulation result without local feedback control and with local feedback control, respectively. In




(a) Without the local sensory feedback control.




(b) With the local sensory feedback control.

Fig. 2. Representative data of the locomotion of the serpentine robot in response to environment (friction) changes.

this experiment the phase difference between the adjacent oscillators $\psi$ was $0.14\pi$ (rad) and the strength of the mutual entrainment between the oscillators $\varepsilon$ was $1.0$. As observed from both figures, when the local sensory feedback control was installed, the robot was able to respond to changes in the friction by changing the magnitude and wave number of slithering movement. When the local sensory feedback control was not installed, it was unable to respond to changes in friction.

To analyze this result, in the case where the local sensory feedback control was installed, the time evolution of the total amount of discrepancy, of the average of phase difference between the consecutive oscillators, and of the phase of each oscillator were measured. The measurements are shown in Fig. 3. The band shown in Fig. 3 represents the period of environment transit between when the robot started to enter the high friction environment until it started to enter the low friction environment. The time evolution of the total amount of discrepancy during the environment transit period, sharply increased right after the whole body entered the new environment (high friction), and reduced once it passed a certain peak. Upon the completion of environment transit, it again settled into a steady state. In addition, from the average of phase difference between the adjacent oscillators and the phase of each oscillator, it is seen that right after

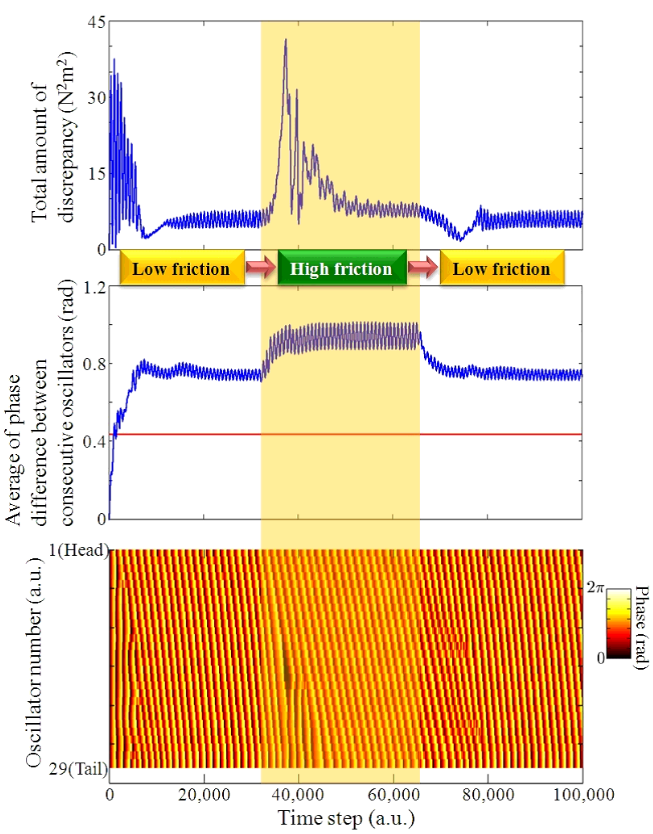



Fig. 3. Time evolution of (upper) the total amount of discrepancy, (middle) the average of phase difference between consecutive oscillators, and (lower) the phase of each oscillator.

entering into a new environment each oscillator changed its phase and converged into a steady state after completing the transition. In this manner, by embedding a mechanism that effectively produces discrepancy within the mechanical system, and by reducing the produced discrepancy with local sensory feedback control, adjustment to the phase relation in response to the environment change for each oscillator is autonomously performed and the improvement in the adaptability can be observed.

### *B. Fault Tolerance for Local Faults of Interaction between Oscillators*

This experiment investigates what kinds of action will be exhibited by the existence of the local sensory feedback when the movement phase difference between consecutive joints required to generate locomotion can no longer be generated locally because of a fault in oscillator function. Specifically, a faulty oscillator is said to have completely lost the application of the phase difference set term $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ in (3) between adjacent oscillators (in this state, the connection between a faulty oscillator and the oscillator immediately next to it is cut). However, at this moment, the dynamics of the faulty oscillator itself is not lost, and the output is still the control command to the motor. Corresponding to the degree of the fault, while increasing the number of faulty oscillators in this manner from the body center to the front and aft symmetrically, the distance traveled of the robot is measured for the period the local feedback exists. The relationship between the position of the faulty oscillator and the degree of damage is defined as follows (Fig. 4):

Degree of damage $0$: no damage.
Degree of damage $1$: interaction between one oscillator in front of body center and one oscillator aft of body center ($\theta_{center}$) is damaged ($2/28$ path).
Degree of damage $2$: interaction between the oscillators at two positions in front and two positions aft from the body center is damaged ($4/28$ path).

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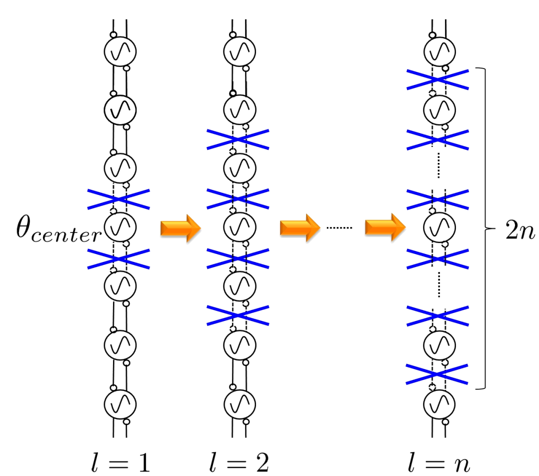


Fig. 4. The lesion study employed.

Degree of damage $n$: interaction between oscillators at $n$ positions in front and $n$ positions aft of the body center is damaged ($2n/28$ path).

Furthermore, in this experiment the phase difference between the adjacent oscillators $\psi$ was $0.20\pi$ (rad), the strength of the mutual entrainment between the oscillators $\varepsilon$ was 3.0, and the environment (friction) was constant.

Fig. 5 shows a graph illustrating the relationship between the degree of damage and the distance traveled. The data is the average result obtained from the 30 varied initial phase relationships, and the error bar represents the standard deviation. The vertical axis shows the normalized value of the distance traveled within a certain constant period when the degree of damage is 0. Also, it is clear that with the local feedback installed, the average and the standard deviation up to the 10th degree of damage (about 70% of the overall path damaged) exhibit the same performance as when there is no damage. In addition, it is confirmed that even when the degree of damage is 14 (all paths damaged), an appropriate phase difference is generated between the oscillators and locomotion can be produced. On the other hand, when the local feedback is not installed, data dispersion is high and the performance deteriorates abruptly as the degree of damage increases. From these results, we conclude that each autonomous component performs its respective feedback control to reduce the discrepancy, regardless of the damage to the interaction between the oscillators, and a consistent behavior of the whole body is realized.

## IV. REAL PHYSICAL ROBOT DEVELOPMENT

To verify the validity of the above mentioned simulation result in the real world, the development of an actual two-dimensional serpentine robot is underway. Fig. 6 shows an overall image of the actual device being developed. The device consists of 30 segments and 29 joints; when straight, its length is 2.4 (m), weight is 3 (kg), and servo motors are used to move the joints.

As mentioned in section II-B.3, in order to intentionally produce the discrepancy required for adaptability, elastic elements are installed at each joint in the mechanical model. Fig. 7 shows the joint construction of the robot. Also, consecutive body segments are connected via the elastic element (rubber) installed in the joint construction, and are in a decoupled state. In this research, the bent angle produced by this elastic element is detected by the rotary encoder installed at the joint axis, using which the discrepancy is calculated.

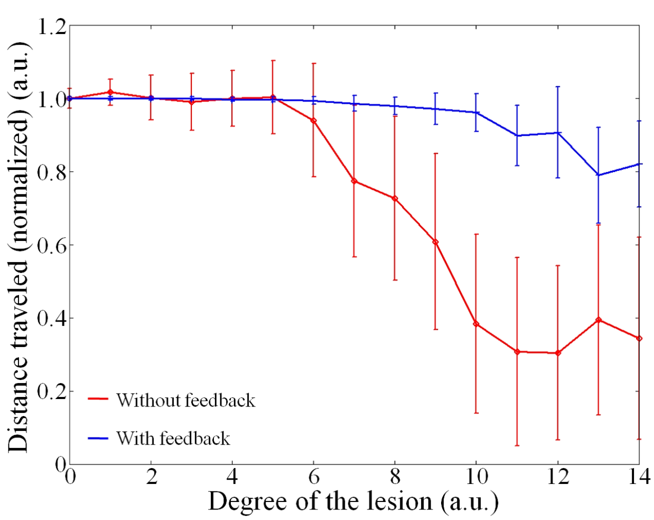


Fig. 5. Fault tolerance of generating locomotion for each degree of the lesion.

Fig. 6. A whole image of the 2D serpentine robot developed.

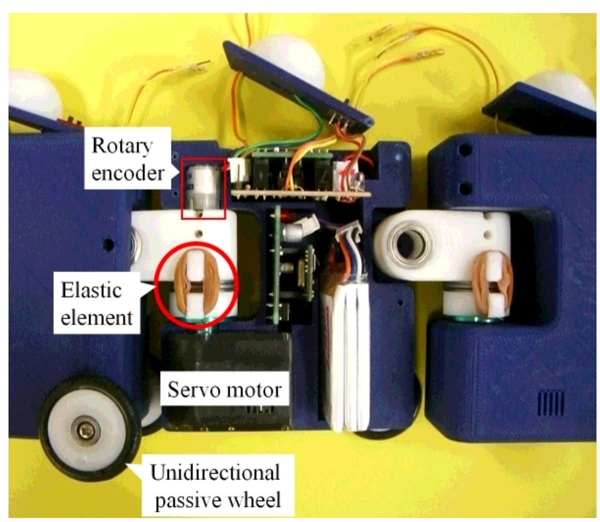


Fig. 7. Joint mechanism of the robot in which an elastic element enabling to generate the discrepancy is implemented.

Motor movement, discrepancy detection, and the local sensory feedback control are performed using the micro-computer shown in Fig. 8. In addition, interactions between oscillators are realized using the wireless communication circuit board also shown in Fig. 8. Furthermore, to reproduce the multi-directionality of the ground friction for undulatory slithering locomotion, a unidirectional passive wheel is used in this research as a specific method (Fig. 7). With this wheel mounted beneath each body segment, the ground friction becomes relatively low along the longitudinal direction compared to the latitudinal direction.

## V. CONCLUSIONS AND FUTURE WORKS

In this paper, aiming at validating the design methodology for the local sensory feedback control extracted from the mold case example, we demonstrated an autonomous decentralized control of a two-dimensional serpentine robot based on the discrepancy function as a practical example; in which this robot exhibits undulatory slithering locomotion that phylogenetically follows to amoeboid locomotion. The preliminary simulation results derived presented that the adaptability in response to environment changes and fault tolerance corresponding to the local faults of interaction between oscillators were remarkably improved. These results obtained are expected to shed a new light on design methodology for autonomous decentralized control system. Furthermore, a real two-dimensional serpentine robot that is presently under development to verify the validity of the results obtained in the simulation experiments in the real world was described and the details of the actual device were shown.

As our future works, we hope to develop a real serpentine robot equipped with this mathematical model and to verify the validity of the design methodology for the local sensory feedback control based on the discrepancy function obtained in the simulation experiment in the real world. In addition, although joint torque was used in the discrepancy function in this study, it is believed that there are many other discrepancy detection methods. In terms of effective discrepancy detection methods, we are expanding the debate involving the future robot physical characteristics. Furthermore, it can be considered that a conserved quantity that ensures a long-distant physical interaction between the body parts such as protoplasm does not exist in snakes. Therefore, by substituting a part of that role with the body's physical characteristics or neural system, an interesting study related to the necessity of neural system belonging to the multi-cellular organisms can be expected.

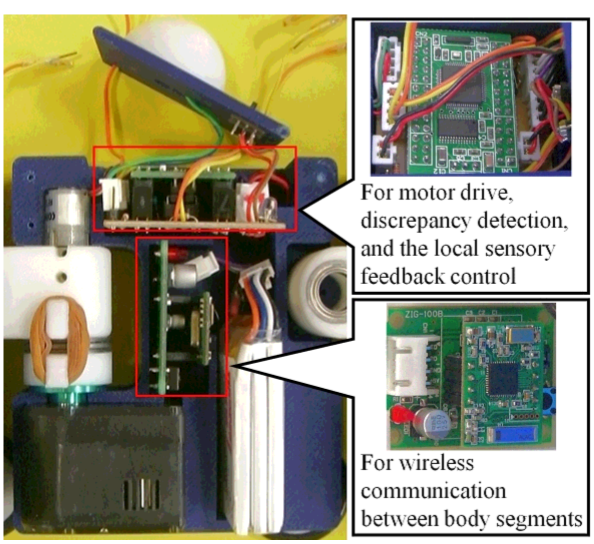


Fig. 8. Electronic circuits for motion control and wireless communication between the body segments.

## VI. ACKNOWLEDGMENTS

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