

Taming Large Degrees of Freedom –A Case Study with an Amoeboid Robot–

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Abstract—Animals exhibit astoundingly adaptive and supple locomotion under real world constraints. In order to endow robots with similar capabilities, we must implement large degrees of freedom, equivalent to animals, into the robots' bodies. For taming large degrees of freedom, the concept of autonomous decentralized control plays a pivotal role. However, a systematic way of designing such autonomous decentralized control system is still missing. Aiming at understanding the principles that underlie animals' locomotion, in our early studies, we focused on true slime mold, a primitive living organism, and extracted a decentralized control scheme. In order to validate this control scheme, this paper presents a soft-bodied amoeboid robot inspired by true slime mold. Significant features of this robot are twofold: (1) the robot has truly soft and deformable body stemming from real-time tunable springs and a balloon, the former is used for an outer skin of the body and the latter serves as protoplasm; and (2) a fully decentralized control using coupled oscillators with completely local sensory feedback mechanism is realized by exploiting the long-distance physical interaction between the body parts stemming from both the softness of the body and the law of conservation of protoplasmic mass. Experimental results show that this robot exhibits truly supple locomotion without relying on any hierarchical structure. The results obtained are expected to shed new light on design scheme for autonomous decentralized control system.

I. INTRODUCTION

Animals exhibit astoundingly adaptive, supple, and versatile locomotion under real world constraints. In order to endow robots with similar capabilities, we must implement significantly large degrees of freedom into the robots' bodies. However, this causes a serious problem, *i.e.*, controllability and scalability; as the number of possible movements of body parts increases, the centralized control approach, which still seems dominant, may encounter difficulties in controlling the body movements.

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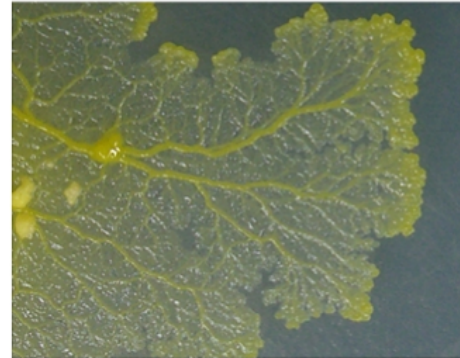


Fig. 1. True slime mold (*Physarum polycephalum*). True slime mold exhibits amoeboid locomotion, which is controlled in a fully decentralized manner.

To overcome these problems, *autonomous decentralized control* is an important concept and the key to understanding how animals successfully tame their surprisingly large degrees of freedom according to the situation encountered. In fact, animals nicely orchestrate and maneuver their large 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][3][4][5].

Albeit 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.*, adaptivity 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: (i) intra-dynamics of an individual component to be implemented; (ii) inter-dynamics between the components to be implemented; and (iii) local sensory feedback provided to an individual component. As the pioneering works done by Taga *et al.* [2][3] indicate, issues (i) and (ii) are often modeled as coupled (nonlinear) oscillator systems. In contrast to this, with regard to issue (iii), local sensory feedback mechanism has been designed completely on an ad-hoc and tailor-made basis for specific applications. In sum, presently an undeniable lack of a consistent scheme for designing local sensory feedback mechanisms still exists.

In light of these facts, we have employed a so-called

“back-to-basics” approach. More specifically, we have focused on *true slime mold* (see Fig. 1). True slime mold is of interest to biologists as well as roboticists for several reasons: first, it is one of the most primitive living organisms and exhibits remarkably adaptive behaviors, such as avoiding hazardous conditions and approaching nutrients and humidity; second, it employs purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPG [6]; third, it exhibits one of the most primitive forms of locomotion, *i.e.*, amoeboid locomotion; fourth, the body of true slime mold is truly soft and deformable; fifth and finally, there is an explicit conserved quantity, *i.e.*, mass of protoplasm. Note that owing to the last two points, the long-distance physical interaction 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, true slime mold is a good biological organism that allows us to extract the design scheme of the local sensory feedback mechanism in a systematic way.

Based on the above observations, in our earlier works we introduced a systematic design scheme for the local sensory feedback mechanism based on “discrepancy function”, and we successfully simulated amoeboid locomotion [7][8]. In this paper, aiming at validating the design scheme proposed, we present a real physical amoeboid robot called *Slimy*. In contrast to most robots built from very stiff components, *Slimy* is equipped with a number of truly soft and deformable components. Experimental results strongly suggest that our proposed decentralized control scheme based on the discrepancy function enables *Slimy* to exhibit significantly supple locomotion similar to true slime mold, in which the long-distance physical interaction between the body parts stemming from the law of conservation of protoplasmic mass (*i.e.*, protoplasmic mass is conserved) is exploited to realize fully decentralized control. Despite the simplicity, the results obtained are expected to shed new light on how autonomous decentralized control should be designed.

The remainder of this paper is structured as follows. The following section briefly outlines previous and related studies. Section III introduces the real physical robot and explains its control system that enables the robot to exhibit locomotion in a decentralized manner. Section IV then presents some of the important data obtained by the experiments, followed by the conclusions and recommendations for future works.

II. PREVIOUS AND RELATED STUDIES

This section briefly introduces several previous and related studies on designing robots inspired by amoeboid locomotion. Shimizu *et al.* presented a modular robot called “Slimebot” that enables an amoeboid locomotion [9]. Hong *et al.* presented a mobile robot inspired by how single celled organisms use cytoplasmic streaming to generate pseudopods for locomotion. In this paper, particularly aiming at achieving design scheme for local sensory feedback, we focused on

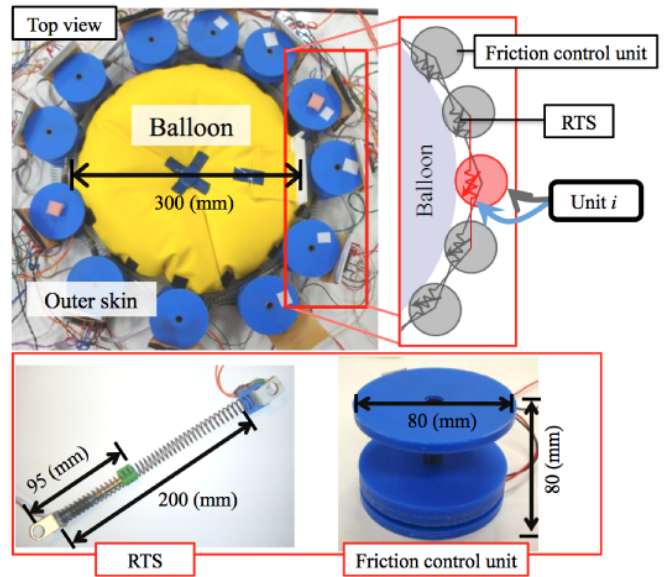


Fig. 2. The real physical robot, *Slimy*. The robot consists of the friction control units, the RTSes, and the balloon.

the long-distance physical interaction stemming from the protoplasm and deformable outer skin.

III. THE ROBOT

A. Mechanical System

Slimy (Fig. 2) consists of protoplasm and a supple outer skin. A balloon is embedded inside the outer skin to serve as protoplasm and is bonded with the outer skin in order to induce long-distance physical interaction. Since the robot is designed to move in two-dimensional space, in order to prevent expansion of the balloon in the height direction, magnets are attached on both top and bottom of the balloon (x mark on the balloon in this figure). Hence, the area surrounded by the outer skin are mostly conserved. Note that this interaction allows distant units to interact physically, and therefore influences the behavior of the complete mechanical system. The outer skin consists of several autonomous mechanical units. Each unit is composed of a friction control unit and a Real-time Tunable Spring (RTS) that is able to actively alter its resting length (*i.e.*, un-stretched length of the spring). As shown in Fig. 2, each friction control unit is connected with its second nearest neighboring units via an RTS. Therefore, by altering the resting length of the RTS, the original curvature of its portion of the robot’s outer skin can be changed dynamically, leading to pushing and pulling the protoplasm. Here, as shown in Fig. 2, we define friction control unit i and RTS i as unit i which is controlled according to the phase, θ_i , of oscillator i . The detail of the mechanical system is described below.

1) *Ground Friction Mechanism*: Each friction control unit has a ground friction mechanism that has two exclusive modes: *anchor mode* and *anchor-free mode*, according to θ_i . To implement these modes, an electromagnet is embedded in the bottom of each friction control unit (Fig. 3), and the

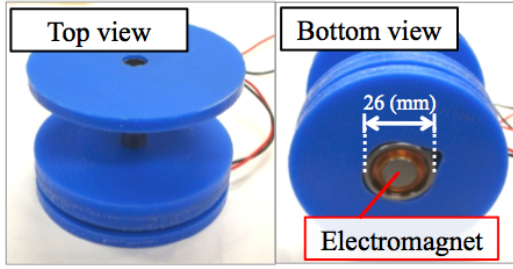


Fig. 3. The friction control unit. The electromagnet is embedded in the bottom of the friction control unit in order to switch between the anchor mode and anchor-free mode.

robot is put on an iron plate. A unit in the anchor mode sticks to the ground by switching on its electromagnet, whereas a unit in the anchor-free mode moves passively by switching off its electromagnet. For simplicity, we use the following algorithm for the mode alternation,

$$\begin{cases} \text{anchor mode} & \text{if } \Theta \leq \theta_i \leq \Theta + d\Theta \\ \text{anchor-free mode} & \text{otherwise,} \end{cases} \quad (1)$$

where Θ is a starting phase of the anchor mode and $d\Theta$ are parameters specifying the amount of time in the anchor mode.

2) *RTS*: The RTS is composed of a DC motor, winding/unwinding mechanism, coil spring, and force sensor (Fig. 4). The coil spring can be wound and unwound by rotating the winding/unwinding mechanism forcibly, which allows the RTS to alter its resting length. The spring constant, $k_i^{RTS}(\theta_i)$, of RTS i is described as

$$k_i^{RTS}(\theta_i) = \frac{\alpha}{l_i^{RTS}(\theta_i)}, \quad (2)$$

where $l_i^{RTS}(\theta_i)$ is the resting length of RTS i , and α is a constant given by the material and geometric properties of the coil spring. The tension on RTS i , T_i , can be measured by the force sensor, and then the actual length, l_i , can be calculated from the following equation:

$$T_i = k_i^{RTS}(\theta_i)(l_i - l_i^{RTS}(\theta_i)). \quad (3)$$

The resting length of RTS i , $l_i^{RTS}(\theta_i)$, alters according to θ_i to push and pull the protoplasm rhythmically, and is given by

$$l_i^{RTS}(\theta_i) = \bar{l}_i(1 - a \cos \theta_i), \quad (4)$$

where a is a constant in space and time and \bar{l}_i represents the mean length that can be changed according to the situation (explained in III-B.3). Attention should be paid to the fact that RTS behaves as not only an actuator but also a spring. Due to this active-passive mechanical feature, by sensing tension on RTS i , force from the other units, the protoplasm, and its environment can be measured as “discrepancy” between the controlled value, $l_i^{RTS}(\theta_i)$, and the actual value, l_i . In this study, this discrepancy plays a key role in designing local sensory feedback, which will be explained in the next subsection.

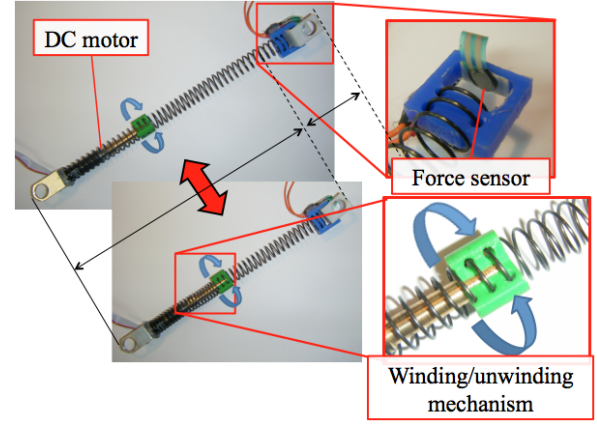


Fig. 4. The RTS is able to alter its resting length at any time by winding or unwinding the coil spring.

TABLE I
COMMON ABBREVIATIONS, NOMENCLATURE, AND CONVENTIONS USED TO DISCUSS THE OSCILLATOR IN THIS ARTICLE

RTS	Real-time Tunable Spring
θ_i	Phase of oscillator of unit i
ω	Intrinsic frequency of oscillators
$f(\theta_{i+1}, \theta_i, \theta_{i-1})$	Diffusion term
$g(l_i, l_i^{RTS}(\theta_i))$	Local sensory feedback term
$k_i^{RTS}(\theta_i)$	Spring constant of RTS i
$l_i^{RTS}(\theta_i)$	Resting (un-stretched) length of RTS i
l_i	Actual length of RTS i
\bar{l}_i	Mean length of Resting length of RTS i
T_i	Tension exerted on RTS i
l_i	Discrepancy function of RTS i

B. Control System

In this subsection, we will introduce a way of designing autonomous decentralized control under conditions of the above-mentioned mechanical structure. For generating amoeboid locomotion, the resting length of each RTS and the ground friction on each friction control unit should be controlled appropriately and rhythmically. To this end, we have focused on oscillators [6][11][12]. In Table 1, the common abbreviations, nomenclature, and conventions used to discuss oscillators in this article are given.

Here, we introduce the dynamics of the oscillator model to be implemented in each unit. The equation of the oscillator is expressed as [7] [8]

$$\frac{d\theta_i}{dt} = \omega + f(\theta_{i+1}, \theta_i, \theta_{i-1}) + g(l_i, l_i^{RTS}(\theta_i)), \quad (5)$$

Note that the intrinsic frequency ω of each oscillator is identical, which means that phase modification should be done by $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ and $g(l_i, l_i^{RTS}(\theta_i))$ for generating locomotion. Furthermore, it should be noted that in-phase oscillation between all oscillators is difficult due to the physical constraints stemming from the law of conservation

of protoplasmic mass. This is because the RTSes distributed throughout the outer skin exert pressure on each other via the internal pressure of the protoplasm. Competitive pushing underlies the interactions between the distant units; they compete in terms of the pressure they exert on one another. Therefore, in order to generate locomotion, anti-phase oscillation toward attractant between distant units can be desired global behavior.

In short, the following features of the oscillators have to be designed.

- Firstly, each oscillator should interact with its neighboring oscillators in the induction of coherent motion, *i.e.*, in-phase oscillation, between its neighboring units (explained in III-B.1).
- Secondly, each oscillator should interact with distant oscillators through the long-distance physical interaction stemming from the protoplasm in order to bridge local and global behaviors (explained in III-B.2).
- Thirdly, the anti-phase oscillation should be induced between the anterior and posterior toward attractant by these interactions (explained in III-B.3).

1) *Diffusion term* $f(\theta_{i+1}, \theta_i, \theta_{i-1})$: This term plays an important role in inducing coherent motion of a portion of the robot's outer skin. The function is designed to express a simple diffusive interaction, given by

$$f(\theta_{i+1}, \theta_i, \theta_{i-1}) = \varepsilon_c \sum_{j=i-1, i+1} \sin(\theta_j - \theta_i) \quad (6)$$

where ε_c specifies the strength of the local interaction, *i.e.*, phase diffusion. This function allows the actuation of the RTSes and the friction mode alternation of the friction control units to achieve coherent motion between neighbors.

2) *Local Sensory Feedback* $g(l_i, l_i^{RTS}(\theta_i))$: Now, let us consider how to design local sensory feedback, $g(l_i, l_i^{RTS}(\theta_i))$, which allows each oscillator to modify its behavior so as to emerge useful functionalities from the entire system. In what follows, a design scheme of how this was achieved is presented.

First, we introduce *discrepancy function* and how to design this. The discrepancy function plays an important role for generating robot behaviors, with which the phase of oscillator is kicked forward and backward to be relaxed when the pressure of protoplasm is higher in a cycle of oscillation. The main role of the function is that, in a nutshell, the oscillator is not likely to push the protoplasm back strongly against its higher pressure of protoplasm. The function introduces nonlocal interaction among the local oscillators through the physical law (*i.e.*, the law of conservation of protoplasmic mass) in a very natural way.

For the purpose of defining the discrepancy function, let us discuss possible cytological process that plays the role of discrepancy function. It is well-known that a type of Ca^{2+} channel is regulated by mechanical deformation of cell shape, so-called "stretch-activated Ca^{2+} channel". This means that the channel can detect local curvature of cell and it opens or closes then. This type of channel can work to relax the rhythmic contraction since high concentration of

Ca^{2+} leads to relaxation of actomyosin contraction in true slime mold [16]. When a local oscillator is pushed strongly by protoplasm with high pressure, it is to be stretched even if trying to contract. The stretching is related to increase of Ca^{2+} , which leads to relax of the oscillator. This is a possible cytological scenario of the role of discrepancy function.

Based on this biological finding, we define the discrepancy function for this robot as:

$$I_i = \frac{\sigma}{2} T_i^2 = \frac{\sigma}{2} k_i^{RTS}(\theta_i)^2 (l_i - l_i^{RTS}(\theta_i))^2 / 2, \quad (7)$$

where σ represents a coefficient. The function is designed so as to increase its value when T_i increases. Note that I_i can be calculated only with locally available variables, which include the discrepancy between the controlled value, $l_i^{RTS}(\theta_i)$, and its actual value, l_i . In other words, the discrepancy function includes discrepancy between its mechanical system, control system, and environment, due to the active-passive mechanical property of the RTS (mentioned in III-A.2) and the law of conservation of protoplasmic mass.

Next, let us now move on to how to design local sensory feedback, $g(l_i, l_i^{RTS}(\theta_i))$. Similar to the above-mentioned possible cytological process, we assume that animal-like supple locomotion emerges as a result of reducing the discrepancy. Based on the hypothesis, we design the local sensory feedback so as to reduce the discrepancy between the local behavior underway and the global behavior, which involves the law of conservation of protoplasmic mass, as follows:

$$g(l_i, l_i^{RTS}(\theta_i)) = -\frac{\partial I_i}{\partial \theta_i} = \sigma \alpha^2 \left(\frac{l_i}{l_i^{RTS}(\theta_i)} - 1 \right) l_i \bar{l}_i a \sin \theta_i \quad (8)$$

Note that this phase modification is calculated only with locally available variables.

3) *Symmetry-breaking Mechanism*: Here, in order to induce anti-phase oscillation effectively between the robot's anterior and posterior toward attractant, a simple control mechanism is employed by varying the stiffness of the outer skin. More specifically, we vary the value of \bar{l}_i spatially according to the situation (see Fig. 5),

$$\bar{l}_i = \begin{cases} \bar{l}_a & \text{if unit } i \text{ detects an attractant} \\ \bar{l}_p & \text{otherwise,} \end{cases} \quad (9)$$

where $l_a > l_p$. Note that the value of \bar{l}_i is increased when unit i detects the attractant. This means that a portion of the outer skin become softer when detecting the attractant (see Eq. 4), leading to an imbalance of the competitive pushing on the protoplasm between anterior and posterior parts toward the attractant, which in turn generates anti-phase oscillation between the anterior and posterior parts. Furthermore, due to the local sensory feedback, the anti-phase oscillation will be kept continuously.

The advantages of this control can be summarized as follows: (i) anti-phase oscillation between the anterior and posterior parts of the entire system can be easily induced

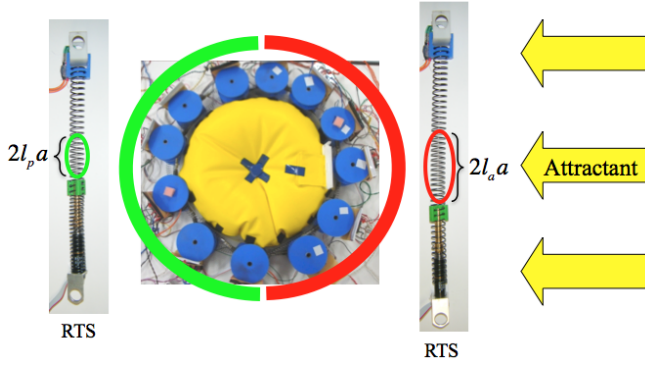


Fig. 5. Implementation of the symmetry-breaking mechanism.

without increasing the complexity of the control system; and (ii) the softer outer skin in the anterior enables relatively large deformation, which allows the robot to negotiate an unstructured environment easily. In the next section, highlights of the data obtained by experiments using the robot are presented.

IV. EXPERIMENTAL RESULTS

A. Problem Setting

In order to demonstrate the validity of our model, in particular, whether distant units can interact with each other through the protoplasm and the local sensory feedback, two experiments were conducted: (I) the verification of the generation of locomotion; and (II) violation of the law of conservation of protoplasmic mass. In this study, taxis behavior was adopted as a practical example (see Fig 5). Attractant comes from the right side constantly. The experimental conditions employed are as follows:

Initial arrangement: Twelve units were arranged in a circular form (as shown in Fig. 5) with $\theta_i = 0.0$.

Parameters: $\bar{l}_a = 100$ (mm); $\bar{l}_p = 70$ (mm); $a = 0.24$; $\Theta = 0.0$; $d\Theta = \pi/2$; $\omega = 0.03$ (rad/timestep)¹.

B. The verification of the generation of locomotion

The result of the experiment with the protoplasm is presented in Fig. 6. The snapshots show Slimy generates locomotion toward the attractant stably. The phases of the units at the anterior extreme and posterior extreme positions are shown in Fig. 7. This indicates that the oscillations in the anterior and posterior become anti-phasic over time due to interactions between them through the law of conservation of protoplasmic mass. As can be seen in the plot, due to the protoplasm and the local sensory feedback, phase modification occurs in the beginning (top), which then generates phase gradient from the head to tail, which finally leads to stable anti-phase oscillation (bottom).

¹ Θ and $d\Theta$ were chosen according to our previous simulation study [8]. \bar{l}_a and \bar{l}_p were determined by the balloon size. ω was determined so as to be relatively slow compared to the DC motor speed.

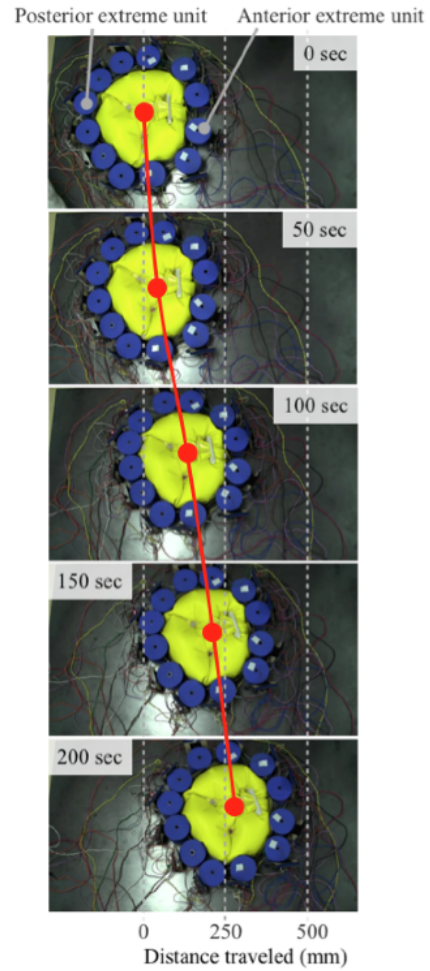


Fig. 6. Representative data of the locomotion of Slimy (see from top to bottom in each figure). The red dot-line describes the trajectory of the center over time.

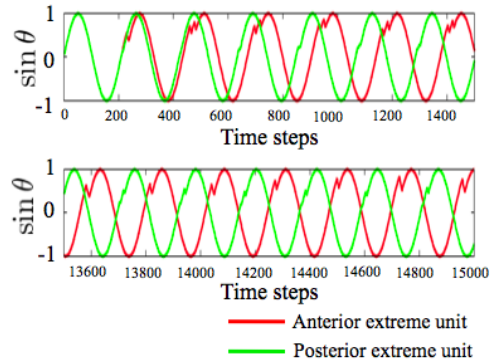


Fig. 7. Phase analysis of the units at the anterior extreme and posterior extreme positions. Phase modification (top) and stable anti-phase oscillation (bottom) stemming from the protoplasm and the local sensory feedback are confirmed.

C. Violation of the law of conservation of protoplasmic mass

In order to observe the effect of the law of conservation of protoplasmic mass, the experiment in violation of the law of conservation of protoplasmic mass was conducted. As can be seen in Fig. 8, we knifed the balloon during locomotion in order to evacuate the air inside the balloon. The snapshots

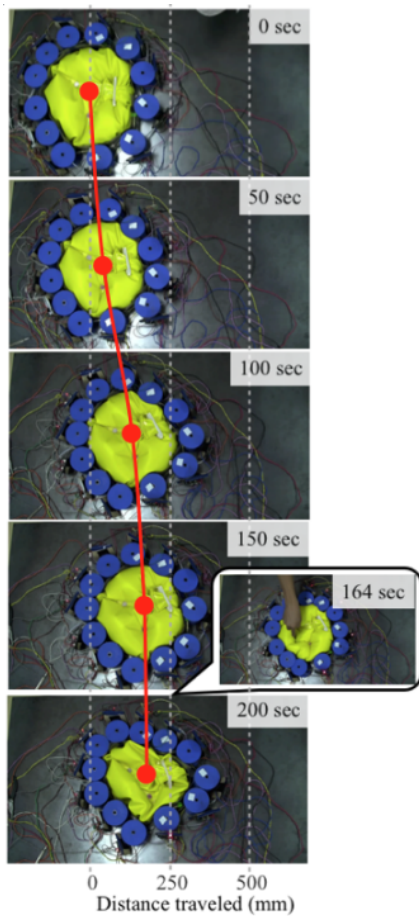


Fig. 8. Representative data of the experiment of Slimy when the effects of the protoplasm is eliminated during locomotion (see from top to bottom in each figure). In order to eliminate the effect of the protoplasm, we evacuated the air inside the balloon during the locomotion. The red dot-line describes the trajectory of the center over time.

show that locomotion speed of the robot drastically decreases without the protoplasmic effect.

V. CONCLUSIONS AND FUTURE WORKS

A fully autonomous decentralized control scheme was investigated with a soft-bodied robot that exhibits amoeboid locomotion inspired by true slime mold. The main contributions of our findings to the field of robotics are twofold. The first concerns the emphasis on taking into account the long-distance physical interaction between the body parts. We clearly showed that this global interaction stemming from both the softness of body and the law of conservation of protoplasmic mass can significantly reduce the amount of computation that would otherwise be performed by the control system, leading to the realization of fully decentralized control. The second is related to the systematic way of designing local sensory feedback mechanism based on the discrepancy function. The results demonstrate that the local sensory feedback mechanism successfully orchestrates and maneuvers large degrees of freedom without the need for any hierarchical structure. In addition to this study, validation of the design scheme has been numerically and experimentally

confirmed on a serpentine robot [14] [15], and therefore the design scheme can be expected to be applicable to designing decentralized control with different morphology, e.g., quadruped robots and multiped robots.

Future works will focus on (a) data analysis of phase of all units, especially when attractant direction is changed during locomotion, (b) increasing the number of mechanical units of the robot, and (c) implementing chaotic oscillators instead of the phase oscillators, which allows not only motion stabilization but motion exploration as well to be an integral part of the motor control system.

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