A Fully Decentralized Morphology Control of an Amoeboid Robot by Exploiting the Law of Conservation of Protoplasmic Mass

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***Abstract*— Self-reconfigurable robots are expected to exhibit various interesting abilities, such as adaptivity and fault tolerance. These remarkable abilities originate from the fact that their mechanical systems intrinsically possess very large degrees of freedom. This, however, causes a serious problem, *i.e.*, controllability. To overcome this, autonomous decentralized control is expected to play a crucial role, as widely observed in living organisms. However, much is still not understood about how such decentralized control can be achieved. This is mainly because the logic connecting local behaviors to global behaviors is still not understood. In this study, we particularly focus on a very primitive living organism, slime mold (*physarum polycepharum*), since it is believed to employ a fully decentralized control based on coupled biochemical oscillators. We modeled a decentralized control algorithm based on coupled nonlinear oscillators and then implement this into a two-dimensional modular robot consisting of incompressive fluid (*i.e.*, protoplasm) covered with an outer skin composed of a network of passive and real-time tunable springs. Preliminary simulation results showed that this modular robot exhibits significantly supple locomotion similar to amoeboid locomotion and that the exploitation of the "long-distant interaction" stemming from "the law of conservation of protoplasmic mass" performs some of the "computation" that the controller would otherwise have to carry out. As a consequence, adaptive amoeboid locomotion emerges without the need for any centralized control system. The results obtained are also expected to shed new light on how control and mechanical systems with large degrees of freedom should be coupled.**

I. INTRODUCTION

Self-reconfigurable robots have been increasingly attracting considerable attention since they intrinsically have significant abilities such as adaptivity and fault tolerance. These remarkable abilities are due to very large degrees of freedom of their mechanical systems. This, however, causes a serious problem, *i.e.*, controllability, in that the number of possible movements of components becomes astronomical, which means that centralized control methods may encounter serious scalability problems.

To overcome this, autonomous decentralized control is expected to play a crucial role. In fact, living organisms exhibit surprisingly adaptive behavior by orchestrating and maneuvering large degrees of freedom in their own bodies. Despite its appealing concept, much is still not understood about how such decentralized control can be achieved so that useful functionalities can emerge. In other words, currently there are virtually no principles for designing a decentralized control algorithm. This is mainly because there is still an undeniable lack in the logic connecting the local behaviors to the global behaviors.

Taking these facts into account, in this study, we employed a so-called "minimalistic approach". To this end, we particularly focused on a very primitive living organism, slime mold (*physarum polycepharum*), since it is believed to employ purely decentralized control based on coupled biochemical oscillators [1]. We modeled a decentralized control algorithm based on coupled nonlinear oscillators with a local sensory feedback mechanism, and then implemented this into a two-dimensional modular robot consisting of incompressive fluid (*i.e.*, protoplasm) covered with a soft, flexible outer skin. This outer skin is composed of a network of springs, some of which are so-called "real-time tunable springs" able to actively change their original length. Note that the protoplasm made of incompressive fluid —as observed in water beds— efficiently induces *long-distant physical interaction* between the modules [2], *i.e.*, real-time tunable springs.

Preliminary simulation results showed that the modular robot exhibits significantly supple locomotion by flexibly changing its morphology, similar to amoeboid locomotion, and that the exploitation of the "long-distant interaction" stemming from "the law of conservation of protoplasmic mass" performs some of the "computation" that the controller would otherwise have to carry out [3][4][5]. As a consequence, adaptive amoeboid locomotion emerges without the need for any centralized control system. Despite its simplicity, the results obtained are also expected to shed new light on how control and mechanical systems with large degrees of freedom should be coupled.

The remainder of this paper is structured as follows. Section II explains the proposed method that enables the amoeboid robot to exhibit adaptive locomotion in real time. Section III then presents some of the important data obtained by simulations, followed by the conclusion and recommendations for further work.

II. THE METHOD

A. The Mechanical System

A two dimensional amoeboid robot considered in this study consists of soft outer skin and protoplasm. A schematic of the entire system is illustrated in Fig. 1. The outer skin

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consists of modules, each of which possesses a sensor to detect light, *i.e.*, attractant, and a ground friction control mechanism (explained later). Each module is connected with its nearest neighboring modules via a passive spring in such a way that they form a membrane. Each module is also connected with its “second” nearest neighboring modules via a real-time tunable spring that is able to change the original length actively. This allows the original curvature of its partial outer skin to alter dynamically, which causes contraction of the part, and then exerts pressure on the protoplasm. Inside the outer skin, there is protoplasm which satisfies the law of conservation of mass. Hence, the pressure transfers through the protoplasm to the other part of the outer skin. In the following, we show how we calculated force on each module from the protoplasm.

The protoplasm satisfies the law of conservation of mass inside the outer skin. In this paper, in order to endow this as long-distant interaction, we implemented the constraint condition; the area surrounded by the outer skin is conserved for simplicity. The constraint condition φ is described as follows:

$$\varphi = 0, \tag{1}$$

where

$$\varphi = \frac{1}{2}\sum_{i=0}^{N-1}(x_i - x_{i+1})(y_i + y_{i+1}) - S_0. \tag{2}$$

In (2), $\boldsymbol{r}_i(= (x_i, y_i))$ is position of module i, the first term on the right is the area surrounded by the outer skin, and the second term is a constant representing the nominal area which is defined by the initial condition of the outer skin. Hence, (1) describes that the area surrounded by the outer skin is conserved. [1]

With the above-mentioned constraint condition, the motion of module i can be described as:

$$m_i \frac{d^2\boldsymbol{r}_i}{dt^2} = \boldsymbol{F}_i + \boldsymbol{R}_i, \tag{3}$$

where $\boldsymbol{F}_i$ is force acting on module i (*i.e.*, the force from the springs and external force from its environment) and $\boldsymbol{R}_i$ is the force of the constraint on module i. $\boldsymbol{R}_i$ is described by using Lagrange multiplier λ for constraint condition φ as:

$$\boldsymbol{R}_i = -\lambda \frac{\partial \varphi}{\partial \boldsymbol{r}_i}. \tag{4}$$

Therefore, by solving (1) and (3) as simultaneous equations, λ is obtained, then $\boldsymbol{r}_i$ can be calculated.

Depending on the constraint force from the protoplasm, the ground friction on each module and the force from each spring, the morphology of the amoeboid robot changes dynamically. Hence, locomotion of the amoeboid robot is generated as a consequence of the interactions of all acting forces on the amoeboid robot. Note that each module itself does not have any mobility but can move only by the corporation with other modules. For this reason, in order to generate efficient locomotion, it is necessary to design control system that induces corporation between the modules with soft property of the outer skin and long-distant interaction stemming from the protoplasm. In the following section, we will give a detailed explanation of this control system.

[1]In case of $i+1 = N$ in the summation, the values of 0 are assigned.

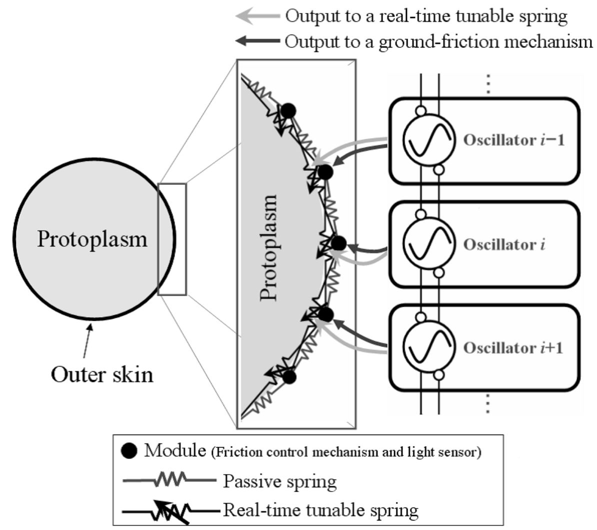

Fig. 1. A schematic of an amoeboid robot developed.

B. The Control System

Under the above mechanical structure, now we consider how we can generate stable and continuous supple locomotion. In order to generate amoeboid locomotion, the original length of each real-time tunable spring and the ground friction on each module should be controlled appropriately and rhythmically. Since this mechanical system has large degrees of freedom, the control algorithm to be implemented should be designed in a fully “decentralized” manner.

To do so, we have focused on so-called a mutual entrainment phenomenon stemming from locally interacting nonlinear oscillators [6][7]. Exploiting this together with a local sensory feedback mechanism, we intended to induce periodic “protoplasmic streaming” inside the modular robot by generating a “pumping motion” between the anterior and posterior of the entire system. In what follows we will give a detailed explanation on how we have achieved this.

1) Nonlinear Oscillator Model: Here, we introduce the dynamics of nonlinear oscillator model to be implemented into each module. We assume that each module has it own nonlinear oscillator, the equation of which is expressed as [8]:

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

where θ_i represents the phase of oscillator i in module i. ω specifies the intrinsic angular velocity of oscillator i. l_i and l_i^{RTS} are the actual length and the original length of real-time tunable spring i, respectively. Note that each oscillator has the identical intrinsic angular velocity. Before moving on to a detailed explanation about how we designed

$f(\theta_{i+1}, \theta_i, \theta_{i-1})$ and $g(l_i, l_i^{RTS})$, we will explain the control of the original length of each real-time tunable spring and the ground friction on each module.

2) Control of Real-time Tunable Spring: In order to change the morphology of the amoeboid robot rhythmically and effectively, we assume that the original length l_i^{RTS} of real-time tunable spring i is varied according to the phase of oscillator i, which is given by

$$l_i^{RTS} = \bar{l}^{RTS} + a \sin\theta_i, \tag{6}$$

where a is constant in space and time and $\bar{l}^{RTS}$ represents the mean length.

3) Ground Friction Control: Each module can take one of two exclusive modes at any time, either *anchor mode* or *anchor-free mode*, according to the phase of its own oscillator θ_i. A module in the anchor mode sticks to the ground by increasing the ground friction, whereas a module in the anchor-free mode moves passively by reducing the ground friction. For simplicity, we use the following algorithm for the mode alternation:

$$\begin{cases} \text{anchor mode} & \text{if } \sin\theta_i \geq h \\ \text{anchor-free mode} & \text{otherwise,} \end{cases} \tag{7}$$

where h is a parameter specifying the time duration engaged in the anchor mode.

4) Generating Amoeboid Locomotion: Based on the above arrangements, now we explain how we realize amoeboid locomotion. As mentioned above, for generating continuous and stable amoeboid locomotion, a pumping motion between the anterior and posterior of the entire system leading to periodic protoplasmic streaming is indispensable. To this end, we carefully designed the functions $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ and $g(l_i, l_i^{RTS})$ in (5), and introduced an additional control mechanism, *i.e.*, a symmetry breaking mechanism.

The function $f(\theta_{i+1}, \theta_i, \theta_{i-1})$ represents *informational* interaction between the modules, and plays an important role for inducing a mutual entrainment phenomenon between their nonlinear oscillators. Therefore, we designed this function so as to express a simple diffusive interaction, which is given by

$$f(\theta_{i+1}, \theta_i, \theta_{i-1}) = \varepsilon_c \sum_{j=i-1,i+1} \sin(\theta_j - \theta_i), \tag{8}$$

where ε_c specifies the strength of the local interaction, *i.e.*, phase diffusion.

On the other hand, the function $g(l_i, l_i^{RTS})$ represents local sensory feedback, by which each module reduces the "discrepancy" between the local behavior underway and the global behavior desired by modifying the phase of its oscillation. We employed the following index of performance as a practical example for detecting the discrepancy:

$$I_i = \frac{\sigma}{2} p_i^2, \tag{9}$$

$$p_i = k_i^{RTS}(l_i - l_i^{RTS}), \tag{10}$$

where σ represents a coefficient and k_i^{RTS} is spring constant of real-time tunable spring i. Note that p_i substantially indicates the pressure received by real-time tunable spring i from the nearby protoplasm. Hence, the phase modification to be done at module i is described as:

$$\begin{aligned} g(l_i, l_i^{RTS}) &= -\frac{\partial I_i}{\partial \theta_i}, \\ &= \varepsilon_m (l_i - l_i^{RTS}) \frac{\partial l_i^{RTS}}{\partial \theta_i}, \end{aligned} \tag{11}$$

where $\varepsilon_m = \sigma \frac{(k_i^{RTS})^2}{a}$. The important thing to be noted here is that although this phase modification is calculated only by locally available variables, this sensory feedback bridges the local behavior and the global behavior. This is because each module can interact with distant modules through the protoplasm. Note that this long-distant physical interaction cannot be effectively exploited without the softness of body.

Next, we introduce an additional mechanism, *i.e.*, a symmetry breaking mechanism, which acts an essential role for inducing a pumping motion between the anterior and the posterior of the modular robot. To this end, we employed the following simple stiffness control mechanism by varying the value of k_i^{RTS} spatially according to the situation:

$$k_i^{RTS} = \begin{cases} 100 \text{ [N/m]} & \text{if the goal light is detected} \\ 200 \text{ [N/m]} & \text{otherwise.} \end{cases} \tag{12}$$

Note that the value of k_i^{RTS} is decreased when module i detects the light (see Fig.2). The advantages of this stiffness control can be summarized as: (i) pumping motion between the anterior and the posterior parts of the entire system can be easily induced without increasing the complexity of the control system; and (ii) softer outer skin in the anterior enables relatively large deformation, which allows the robot to negotiate unstructured environment easily. In the next section, we introduce some of the highlight data of simulations conducted.

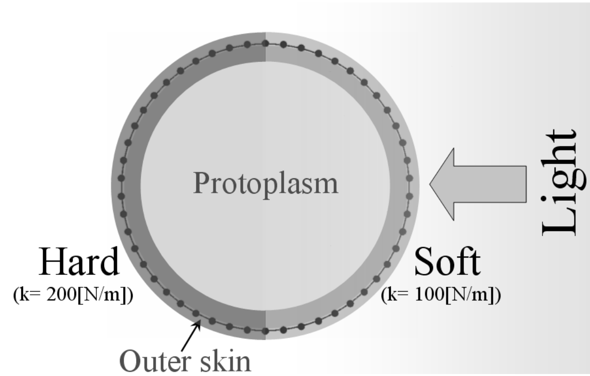

Fig. 2. Simulation setup.

III. SIMULATION RESULTS

A. Problem Setting

In this study, phototaxis behavior is adopted as a practical example: the task of the amoeboid robot is to move toward the goal light (see Fig 2). The simulation conditions employed are as follows:

Initial arrangement: 50 modules are put in a circular form, connected with the passive springs and the real tunable springs (as shown in Fig. 2). Area surrounded by the outer skin S_0 is defined by this initial condition.

Mechanical parameters: a is 50% of $\bar{l}_i^{RTS}$.

Controller parameters: $\varepsilon_c = 0.1; \varepsilon_m = 0.1; h = 0.8; \omega = 0.1$.

In this paper, we will discuss the validity of our model, in particular, whether informationally separated oscillators can interact each other through the law of the conservation of protoplasmic mass. To this end, we conducted three simulation experiments: (I) the verification of the generation of locomotion with the protoplasm and $g(l_i, l_i^{RTS})$; (II) simulation without the protoplasm; (III) simulation without $g(l_i, l_i^{RTS})$. For the purpose of visualizing the interaction, module i and module j are connected with a line when $\cos(\theta_j - \theta_i) \leq -0.99$, *i.e.*, in antiphase.

B. Verification of the Generation of Locomotion with the Protoplasm and $g(l_i, l_i^{RTS})$

In order to confirm the validity of the proposed method, simulations have been performed under the above problem settings. Figure 3 shows representative results obtained under the condition. These snapshots are in the order of the time transition (see from top to bottom in each figure). As you can see from the figure, the amoeboid robot exhibits phototaxis locomotion even with this simple control system. The figure shows the lines are connecting the anterior modules and the posterior modules. This describes that the oscillation in the anterior and the posterior are antiphasic due to interactions between the anterior modules and the posterior modules through the law of the law of conservation of protoplasmic mass. In addition to this, the interactions enable informationally separated modules to interact each other through the protoplasm.

C. Simulation without the Protoplasm

The previous simulation showed the phototaxis locomotion, however what will happen without the protoplasm? In order to verify the necessity of the protoplasm, we conducted experimental simulation without the protoplasm. Figure 4 shows representative results obtained without the protoplasm. These snapshots are in the order of the time transition (see from top to bottom in each figure). The simulation shows that the robot shrinks without the protoplasm and then failed to generate locomotion.

D. Simulation without $g(l_i, l_i^{RTS})$

Likewise, what will happen without $g(l_i, l_i^{RTS})$? In order to verify the necessity of $g(l_i, l_i^{RTS})$, we conducted experimental simulation without $g(l_i, l_i^{RTS})$. Figure. 5 shows representative results obtained under the condition. These snapshots are in the order of the time transition (see from top to bottom in each figure). The simulation shows that the robot failed to generate the pumping motion and any locomotion.

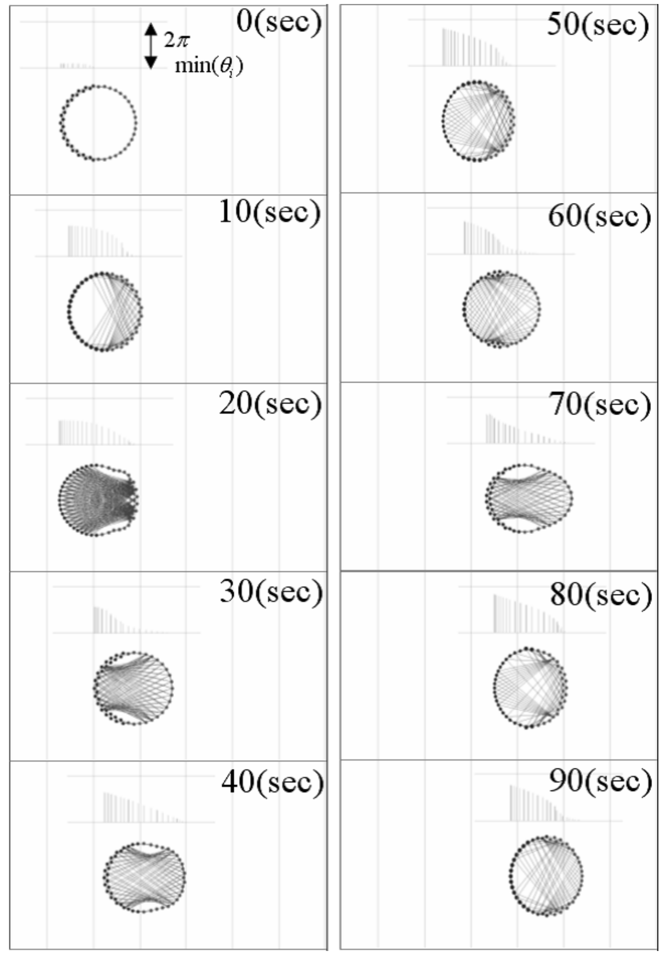

Fig. 3. Representative data of the locomotion of the amoeboid robot without $g(l_i, l_i^{RTS})$ (see from top to bottom in each figure).

IV. CONCLUSION AND FURTHER WORK

This paper has investigated a fully autonomous decentralized control of a modular robot that exhibits supple amoeboid locomotion. The main contributions of this paper to the field of modular robotics are twofold. The first one concerns the emphasis on taking into account of long-distant physical interaction between the modules. We clearly showed that the long-distant physical interaction stemming from the softness of body can significantly reduce the amount of computation that would otherwise be the task of the control system. The second one is related to the importance of the law of conservation if one wants to control a system with very large degrees of freedom in a decentralized manner. In fact, we best illustrated that the law of conservation of protoplasmic mass plays crucial roles for orchestrating and maneuvering large degrees of freedom. We expect that this is also a key for understanding the behavior of primitive animals. Despite its simplicity, the results obtained are expected to shed new light on self-reconfigurable robots with regard to how control and mechanical systems with large degrees of freedom should be coupled.

Further work will focus on the following:

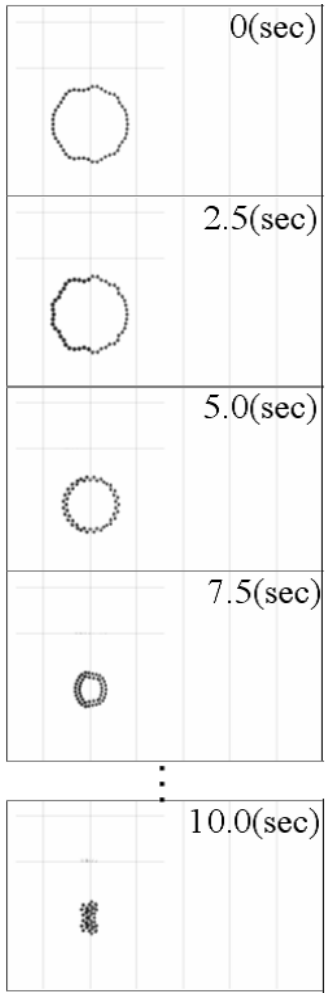

Fig. 4. Representative data of the simulation of the amoeboid robot without the protoplasm (see from top to bottom in each figure).

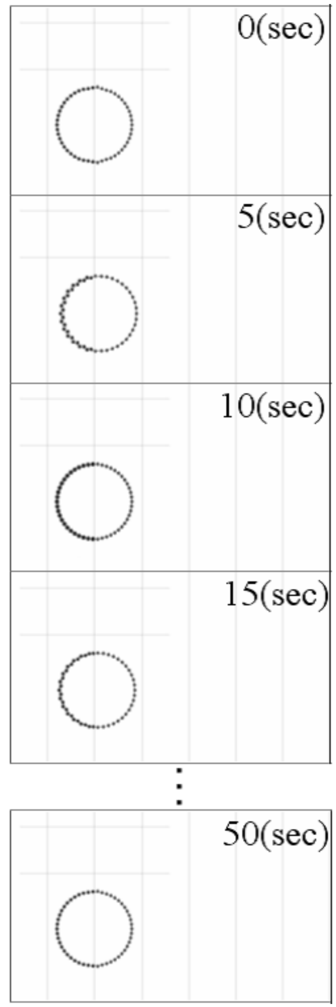

Fig. 5. Representative data of the simulation of the amoeboid robot without $g(l_i, l_i^{RTS})$ (see from top to bottom in each figure).

- Investigation of capability to switch interacting modules when the robot encounters environmental alteration *e.g.*, going through a narrow aisle.
- Building prototype of the amoeboid robot: To do this, validity of this method can be verified in the real world.

V. ACKNOWLEDGMENTS

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