2008 IEEE International Conference on
Robotics and Automation
Pasadena, CA, USA, May 19-23, 2008

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

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Abstract— **The control and mechanical systems of an embodied agent should be tightly coupled so as to emerge useful functionalities such as adaptivity. This indicates that the mechanical system as well as the control system should be responsible for a certain amount of computation for generating the behavior. However, there still leaves much to be understood about how such "computational offloading" from the control system to the mechanical system can be achieved. In order to intensively investigate this, here we particularly focus on the "softness" of the body, and show how the computational offloading derived from this property is exploited to simplify the control system and to increase the degree of adaptivity. To this end, we employ a two-dimensional amoeboid robot as a practical example, consisting of incompressive fluid (*i.e.* protoplasm) covered with an outer skin composed of a network of real-time tunable springs. Preliminary simulation results show that the exploitation of the "long-distant interaction" stemming from "the law of conservation of protoplasmic mass" allows us to simplify the control mechanism; and that adaptive amoeboid locomotion can be realized without the need of a central controller. The results obtained are expected to shed light on how control and mechanical systems should be coupled, and what the "brain-body-interaction" carefully designed brings to the resulting behavior.**

I. INTRODUCTION

The behavior of an embodied agent is generated through the tight interaction between its control system (*i.e.* brain), mechanical system (*i.e.* body), and the environment [1][2]. Considering the fact that the control and mechanical systems, which are normally the targets to be designed for robotic agents, are positioned at the source of this interaction, these two systems should be treated with an equal emphasis. This strongly suggests that a certain amount of computation for generating the behavior should be *offloaded* from the control system to its mechanical system. In order to explicitly indicate this kind of "embodied" computation to be embedded in the mechanical system, Pfeifer *et al.* have recently coined the term called *morphological computation* [3] which is expected to be an indispensable concept for building adaptive agents. Despite its appealing concept, there still leaves much to be understood about how such "computational offloading" can be achieved so as to emerge useful functionalities such as adaptivity.

In light of these facts, this study is intended to deal with the following questions:

- To what extent computational offloading from the control system to the mechanical system should be done?
- What sort of the body's properties should be focused on so as to effectively exploit the morphological computation?

Since this research field is still in its infancy, it is of great worth to accumulate various case studies at present. In order to intensively investigate the questions above, here we have particularly focused on the "softness" of the body [4], and show how the computational offloading derived from this property is exploited to simplify the control system required as well as to increase the degree of adaptivity.

To this end, we have employed a two-dimensional amoeboid robot as a practical example, in the hope that this primitiveness allows us to consider the questions above effectively. The amoeboid robot employed in this study is consisted of incompressive fluid (*i.e.* protoplasm) covered with an outer skin (*i.e.* epitheca). This outer skin is composed of a network of springs, some of which are so-called "real-time tunable springs" able to change the original length actively. Note that the protoplasm made of incompressive fluid —as observed in water beds— efficiently induces the *long-distant physical interaction* between the components, *i.e.*, the real-time tunable springs. Preliminary simulation results obtained indicate that the exploitation of this long-distant interaction derived from "the law of conservation of protoplasmic mass" allows us to simplify the control mechanism. Adaptive amoeboid locomotion can be realized without need of a central controller. Despite its simplicity, the results obtained are expected to shed a new light on how the control and mechanical systems should be coupled, and what the "brain-body-interaction" carefully designed brings to the resulting behavior, *e.g.* increasing the degree of adaptivity and simplifying the control algorithms.

The rest of this paper is structured as follows. The following section explains the proposed method that enables the amoeboid robot to exhibit adaptive locomotion in real-time. Section III then illustrates some of the highlight data taken from the simulations conducted, followed by the conclusion and the further work.

II. THE PROPOSED METHOD

A. The Mechanical System

As an initial step of the investigation, a two-dimensional amoeboid robot has been considered, consisting of soft outer skin and protoplasm. A schematic of the entire system is illustrated in the Fig. 1. The outer skin consists of spring-mass system (*i.e.* passive springs and point masses) in the

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form of closed link, plus real-time tunable springs which link a point mass and the next but one. The passive spring keeps the parameters, spring constant $k^{Passive}$ and original length $l^{Passive}$, constant. The real-time tunable spring is capable to change its original length and has fixed spring constant k^{RTS}. By changing original length of the real-time tunable spring, original curvature of the partial outer skin can be changed. In addition to this, controlling ground friction on each point mass (explained later) enables the robot to locomote. Furthermore each point mass is equipped with a sensor to detect light for phototaxis locomotion. Inside the outer skin, there is protoplasm which satisfies the law of conservation of mass: this constraint from the protoplasm will be described in the following subsections.

B. Law of Conservation of Protoplasmic Mass

The amoeboid robot has the protoplasm, which satisfies the law of conservation of mass, inside the outer skin. In this paper, it means that area surrounded by the outer skin is kept constant. Hence, position of each point mass must satisfy the following constraint condition:

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

where

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

In (2), $\boldsymbol{r}_i(= (x_i, y_i))$ is position of point mass i, the first term is area surrounded by the outer skin, and the second term is constant value of the area which is defined by initial condition of the outer skin. Hence, (1) describes that the area surrounded by the outer skin is kept constant. In case of $i+1 = N$ in the summation, the values of 0 are assigned.

In this paper, motion of the outer skin 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 except one from constraint condition φ and $\boldsymbol{R}_i$ is force of the constraint on point mass i. $\boldsymbol{F}_i$ includes force from the springs and force from obstacles (the ground friction is not included, which will be explained later). $\boldsymbol{R}_i$ is described by using Lagrange multiplier λ for constraint condition φ as:

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

Hence, by solving (1) and (3) as simultaneous equations, λ is obtained, then $\boldsymbol{r}_i$ can be calculated. In this paper, the law of conservation of protoplasmic mass is described by the aforementioned constraint, instead of fluid dynamics, in order to embed incompressive fluid as long-distant interaction for simplicity.

Depending on the constraint force from the protoplasm, ground friction on each point mass, and force from each spring, morphology of the amoeboid robot changes dynamically. In addition to this, when there is external force, such as force from obstacles, morphology of the robot is generated through interaction between the above forces plus force from the environment. Hence, locomotion of the amoeboid robot is generated as a consequence of interactions of all acting forces on the amoeboid robot. Specially, the law of conservation of protoplasmic mass play an interesting role for the whole mechanical system to generate stable and continuous locomotion, because the constraint is used to deal with "long-distant interaction".

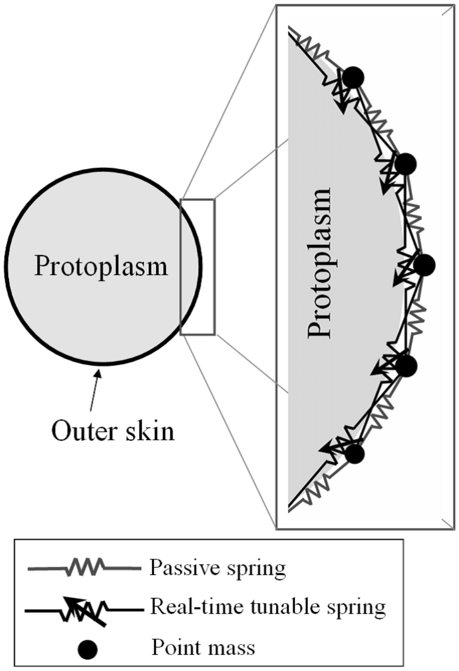

Fig. 1. A schematic of an amoeboid robot developed.

C. The Control Algorithm

Under the above mechanical structure, now we consider how we can generate stable and continuous locomotion. To this end, a nonlinear oscillator is implemented to control the original length of each real-time tunable spring and the ground friction on each point mass, allowing us to generate rhythmic and coherent locomotion through mutual entrainment among the oscillators. In the following, we will give a detailed explanation of this algorithm.

In order to generate locomotion of the amoeboid robot, the original length of each real-time tunable spring and the ground friction on each point mass should be controlled appropriately and rhythmically. Since this mechanical system has large degrees of freedom, it is preferable that this control should be done in a "decentralized" manner in order to exploit the interactions on the mechanical system. To do so, we have focused on the "phase gradient" created through the mutual entrainment among locally interacting nonlinear oscillators [5][6] in the amoeboid robot (see Fig. 2), exploiting this as a key information for controlling the original length and the ground friction. Therefore, the configuration of the resulting phase gradient is extremely important. In the following, we will explain this in more detail.

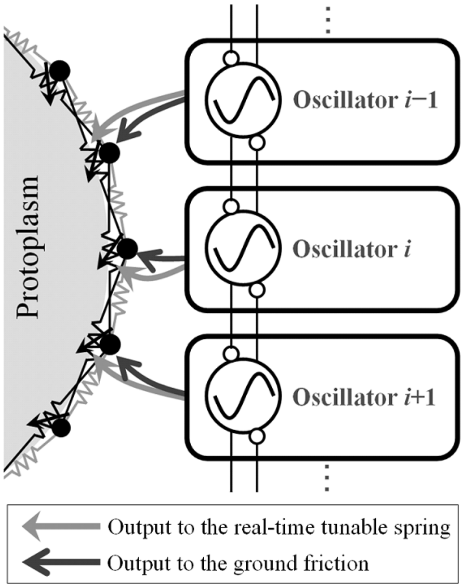

Fig. 2. CPG output corresponds to the original length of the real-time tunable springs and the ground friction on the masses.

As a model of a nonlinear oscillator, the phase equations by Kuramoto [8] are employed, since this oscillator model has been well-analyzed and widely used for its significant entrainment property. The equation implemented on oscillator i is given by:

$$\frac{d\theta_i}{dt} = \omega_i + \varepsilon \sin(\theta_{i+1} - \theta_i) + \varepsilon \sin(\theta_{i-1} - \theta_i), \tag{5}$$

where parameter ω_i specifies natural frequency of oscillator i and parameter ε specifies strength of the interaction. In case of $i - 1 = -1$, the values of $N - 1$ are assigned. In case of $i + 1 = N$, the values of 0 are assigned. As described in (5), the local communication is done between neighboring oscillators. When the oscillators interact according to (5), significant phase distribution can be created effectively by varying value of ω_i for some of the oscillators. In order to generate phototaxis locomotion, we set the value of ω_i :

$$\omega_i = \begin{cases} 0.78 & \text{if the goal light is detected} \\ 0.74 & \text{otherwise.} \end{cases} \tag{6}$$

Note that the value of ω_i is increased when point mass i detects goal light. This allows us to create the phase gradient toward the moving direction (see Fig.3), which can be effectively exploited to endow the entire system with the locomotion force. In the next subsection, we will describe how to generate the locomotion force with this control system.

D. Generating Locomotion

Here, we consider how to control the original length of each real-time tunable spring and the ground friction on each point mass, exploiting phase distribution created from the aforementioned mutual entrainment between the oscillators. In the following, we will explain these in more detail respectively.

1) Original length of each real-time tunable spring: In order to change morphology of the amoeboid robot, the original length of each real-time tunable spring should be changed dynamically. Original length l_i^{RTS} of real-time tunable spring i is defined as:

$$l_i^{RTS} = \bar{l}^{RTS} + a \sin(n\theta_i). \tag{7}$$

2) Ground friction on each point mass: Point mass i in the amoeboid robot can take one of two exclusive modes in accordance with θ_i: *fixed mode* and *moving mode*. A point mass in *fixed mode* increases the ground friction. In contrast, a point mass in *moving mode* reduces the ground friction. In this simulation model, position of point mass in *fixed mode* is fixed regardless of acting force on the point mass, and position of point mass in *moving mode* moves according to acting force on the point mass. The ground friction mode is altered in accordance with the following condition;

$$\text{Ground friction} = \begin{cases} \text{fixed mode} & \text{if } \sin(n(\theta_i + \phi)) \geq h \\ \text{moving mode} & \text{otherwise,} \end{cases} \tag{8}$$

where h specifies time length of fixed mode in periodic time and ϕ specifies phase difference between the ground friction control and the original length control.

The phase gradient of the nonlinear oscillators propagates expansion and contraction of the outer skin front to back according to (7), satisfying the constraint from the protoplasm. As a result of the interactions, morphology of the robot changes. In addition to this, by optimizing the ground friction parameters, h and ϕ in (8), locomotion of the amoeboid robot can be generated.

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. To this end, the parameters of the ground friction control and original length control, h, φ, and n, were optimized from 0 to 2π by $\pi/6$, from -0.9 to 0.9 by 0.1, and from 1 to 5 by 1 respectively. In the simulation discussed below, the light from the goal is given from the right side (see Fig 4). The simulation conditions employed are as follows:

Initial arrangement: 50 point masses are put in a circular form, connected with the passive springs and the real tunable springs (as shown in Fig. 4). Area surrounded by the outer skin S_0 is defined by this initial condition.
Mechanical parameters: See Table I.
Controller parameters: $n = 3; \phi = -\frac{\pi}{3}; \varepsilon = 0.1; \omega_i$ is varied according to (6).

B. Verification of the Generation of Locomotion

In order to confirm the validity of the proposed method, simulations have been performed under the above problem settings. Fig. 5 shows representative results obtained under the condition. These snapshots are in the order of the time

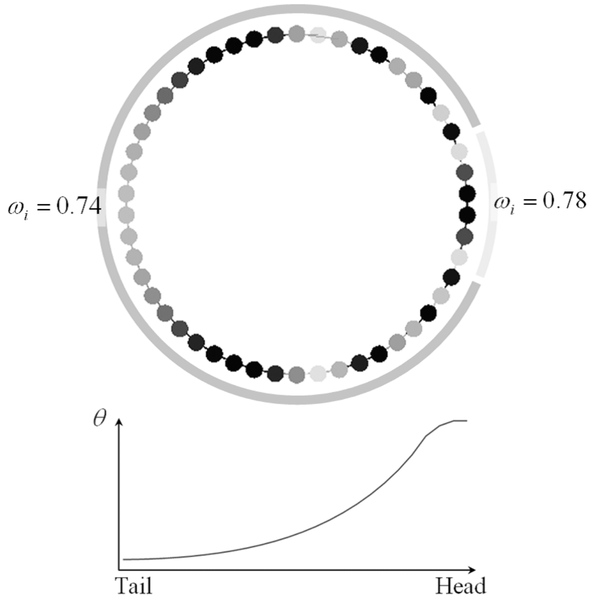

Fig. 3. Phase distribution created through the mutual entrainment between the oscillators in a circular arrangement. The gray scale in the upper figure denotes the value of the phase at the corresponding point, and the lower plot shows the phase gradient from the head to the tail.

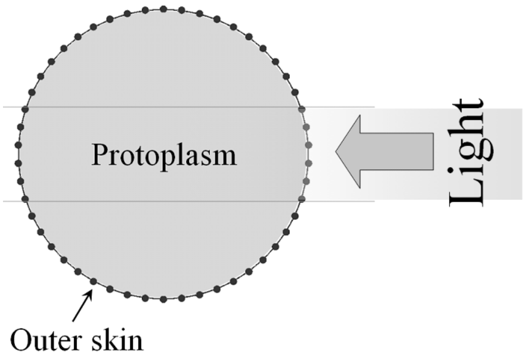

Fig. 4. Simulation Setup.

TABLE I
MECHANICAL PARAMETERS

Parameters	Values
m	500 (g)
$k^{Passive}$	200 (N/m)
$l^{Passive}$	10 (cm)
$dl^{Passive}$ (Pretension)	0 (%) of the length
k^{RTS}	200 (N/m)
$\bar{l}^{RTS}$	Calculate by the initial condition
a	50 (%) of $\bar{l}^{RTS}$
dl^{RTS} (Pretension)	30 (%) of the initial length

transition (see from top to bottom in each figure). Fig. 6 shows distance traveled of the amoeboid robot. As you can see from Fig. 5 and Fig. 6, the amoeboid robot exhibits a phototaxis locomotion even with this simple control system stemming from the phase distribution created through the mutual entrainment. Again, notice that the original length of each real-time tunable spring and the ground friction on each point mass are only the controlled values. The locomotion of the amoeboid robot is generated, through interaction between the ground friction, the force from the springs, and the constraint force from the protoplasm.

C. Verification of the Generation of Locomotion through a Narrow Aisle

In order to confirm the validity of the proposed method when the robot is moving through a narrow aisle, simulations have been performed under the same parameters as the previous setting. Fig. 7 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 thick circles in the figures denote obstacles. These obstacles are described by soft-core potential. As shown in the figure, the amoeboid robot can successfully negotiate the environment, dynamically changing its morphology. As we clearly see from Fig. 7, the robot moves through the narrow aisle in such a way that the morphology is well-suited along with the ongoing motion and the obstacles, even though the parameters of the robot have not changed at all. As shown from 39 (sec) to 79 (sec) in Fig. 7, rear area of the protoplasm is shrinking, meanwhile front area of the protoplasm is expanding. It means that the protoplasm is helping the whole system move forward through the narrow aisle coherently. By exploiting deformation of the flexible outer skin and the law of conservation of protoplasmic mass, the morphology of the robot is generated through interaction between the forces from the mechanical system plus force from the environment. Notice that these behaviors are not preprogrammed (*i.e.*, the position of each point mass is not controlled explicitly), but are totally emergent.

IV. CONCLUSION AND FURTHER WORK

This paper has investigated "brain-body-interaction" with the perspective of "soft" mechanical system to simplify the control system required as well as to increase the degree of adaptivity. In this paper, aiming at designing brain-body-interaction carefully in order to realize the adaptive locomotion, we focused on the law of conservation of protoplasmic mass and the soft outer skin consisting of the spring-mass system in the form of closed link and the real-time tunable springs. By exploiting the interaction between the forces on the amoeboid robot, especially the law of conservation of protoplasmic mass as the long-distant interaction, although the control system is stupidly simple to control only the original length of each real-time tunable spring and the ground friction, the amoeboid robot can exhibit real-time adaptive locomotion.

The results obtained in this paper strongly supports the validity of our suggestions, stating that "soft" mechanical

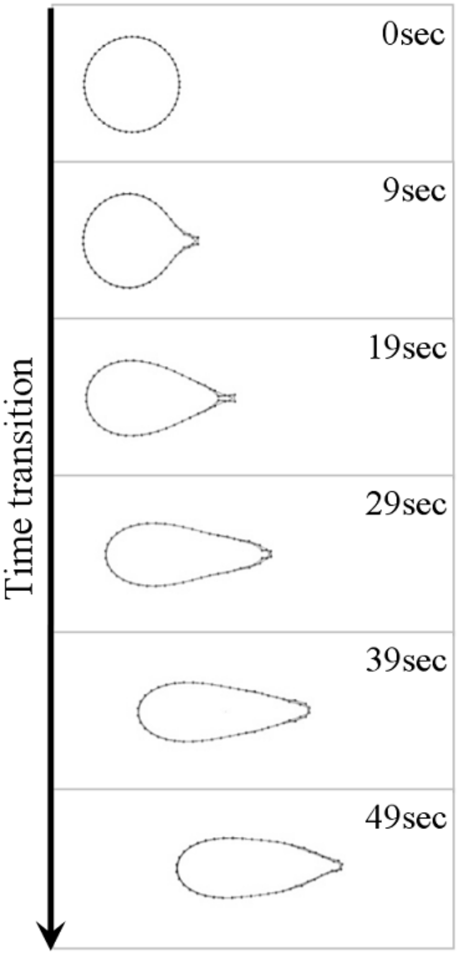

Fig. 5. Representative data of the locomotion of the amoeboid robot (see from top to right in each figure).

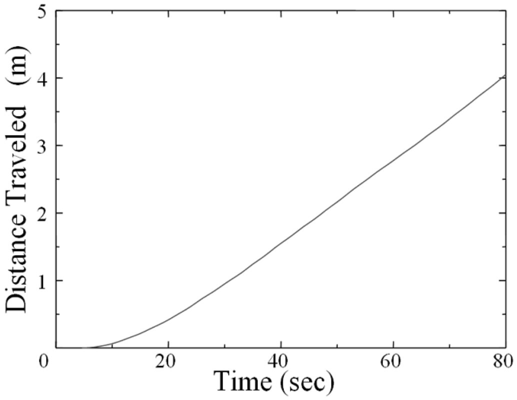

Fig. 6. Representative data of distance traveled of the amoeboid robot.

system so as to design brain-body-interaction appropriately plays an essential role to elicit interesting emergent phenomena, which can be exploited to increase the degree of adaptivity and to simplify the control algorithms. However, there still remains much to be understood about how "brain-body interaction" can be designed. This research is one

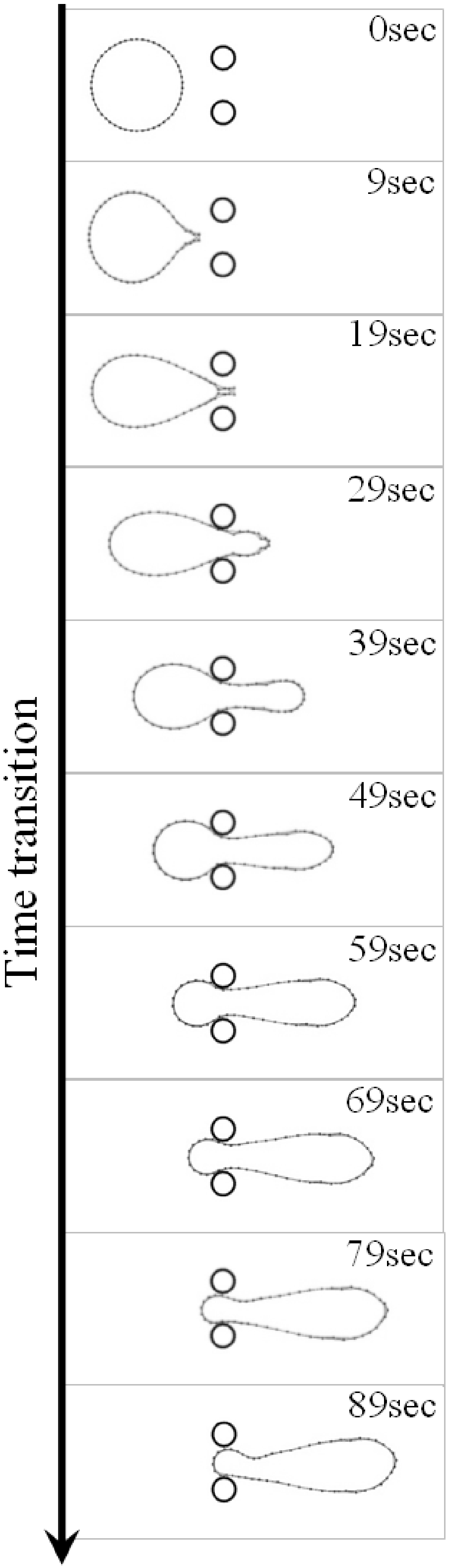

Fig. 7. Representative data of the locomotion of the amoeboid robot through the narrow aisle (see from top to bottom in each figure). The thick circles in the figures are the obstacles.

step to shed light on this point in terms of computational offloading derived from softness of the body and long-distant interaction stemming from the law of conservation of protoplasmic mass.

Further work will focus on the following:

- Embedding some feedback in the real-time tunable spring: For example, by embedding sensor system to detect pressure from the protoplasm and exploiting the sensor values to control the original length of each real-time tunable spring, sensor system exploiting the mechanical system can be realize. Concerned that this mechanical system is fully grounded in its environment, more adaptive behavior can be emerged, we consider.
- Investigation of effects of the law of conservation of protoplasmic mass: In order to analyze effect of the protoplasm more precisely, in particular, we will conduct simulation when the law is broken, such as by replacing this incompressive protoplasm with compressive one. By varying the degree of the compressibility, results can be obtained to shed a new light on how control and mechanical systems should be coupled in a synthetic way.
- Building a real amoeboid robot: To do this, validity of this method can be verified.

V. ACKNOWLEDGMENTS

This work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas “Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment” and “Tohoku Neuroscience Global COE Basic & Translational Research Center for Global Brain Science” from the Japanese Ministry of Education, Culture, Sports, Science and Technology. The authors also would like to thank Prof. Toshihiro Kawakatsu, Tohoku University, for frequent, stimulating, and helpful suggestions.

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