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Author(s)	Umedachi, Takuya; Idei, Ryo; Nakagaki, Toshiyuki; Kobayashi, Ryo; Ishiguro, Akio
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Relation	



Fluid-filled Soft-bodied Amoeboid Robot Inspired by Plasmodium of True Slime Mold

Takuya Umedachi^{1,4}, Ryo Idei², Toshiyuki Nakagaki^{3,5}, Ryo Kobayashi^{1,5}
and Akio Ishiguro^{2,5}

¹*Department of Mathematical and Life Sciences, Hiroshima University, 1-3-1 Kagamiyama, Higashi Hiroshima, 7398526, Japan, takuya.umedachi@gmail.com*

²*Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 9808577, Japan*

³*Department of Complex and Intelligent Systems, Faculty of Systems Information Science, Future University Hakodate, Kameda Nakano 116-2, Hakodate, 0418655, Japan*

⁴*Research Fellow of the Japan Society for the Promotion of Science*

⁵*Japan Science and Technology Agency, CREST, Tokyo, Japan*

Abstract

This paper presents a fluid-filled soft-bodied amoeboid robot inspired by plasmodium of true slime mold. The significant features of this robot are twofold: (1) the robot has fluid circuit (*i.e.*, cylinders and nylon tubes filled with fluid) and truly soft and deformable body stemming from Real-time Tunable Springs (RTSs), the former seals protoplasm to induce global physical interaction between the body parts and the latter is used for elastic actuators; and (2) a fully decentralized control using coupled oscillators with completely local sensory feedback mechanism is realized by exploiting the global physical interaction between the body parts stemming from the fluid circuit. The experimental results show that this robot exhibits adaptive locomotion without relying on any hierarchical structure. The results obtained are expected to shed new light on design scheme for autonomous decentralized control systems.

keywords: Biologically-inspired robot, fluid circuit, decentralized control, sensory-motor coordination, modular robot

1 INTRODUCTION

Animals, by exploiting soft and continuum mechanical properties of their bodies, exhibit astoundingly adaptive, supple, and versatile locomotion under real world constraints. In order to endow robots with the comparable capabilities, we must incorporate soft and continuum materials (*i.e.*, enormous degrees of freedom) into the mechanical design. However, this requires significantly high computational resources if it is based on the traditional centralized control approach, *e.g.*, controllability and scalability problems.

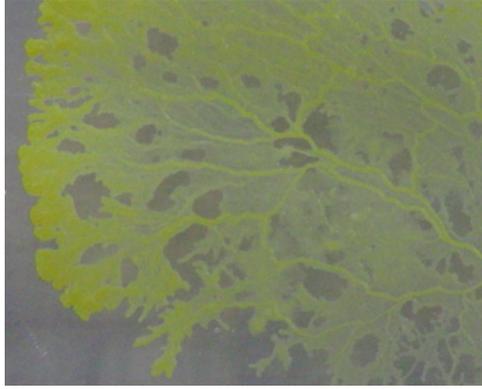


Figure 1: Plasmodium of true slime mold (*Physarum polycephalum*). The plasmodium exhibits amoeboid locomotion by taming and maneuvering its soft and continuum body, which is controlled in a fully decentralized manner.

To overcome these problems, *autonomous decentralized control* is an alternative concept and the key to understanding how animals successfully tame their complex dynamics according to the situation encountered. In fact, animals 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 biological findings, thus far various studies have been investigated for implementing decentralized control into robots to generate adaptive locomotion, mainly focusing on legged locomotion [2][3][4][5].

Despite its appealing concept, a systematic scheme 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 achieved. In order to alleviate this, we have to intensively consider the following issues which can be summarized as:

- (i) intra-dynamics of an individual component to be implemented,
- (ii) inter-dynamics between the components to be implemented,
- (iii) sensory-motor coordination [6], *i.e.*, brain-body interaction.

As the pioneering work done by Taga *et al.* [2][3] indicates, issues (i) and (ii) are often modeled as coupled (nonlinear) oscillator systems. Whereas, with regard to issue (iii), sensory-motor coordination has been designed completely on an ad-hoc and tailor-made basis for specific applications. In other words, presently an undeniable lack of a consistent design scheme for sensory-motor coordination still exists.

In order to alleviate this problem, we have proposed the design scheme for autonomous decentralized control system, employing a so-called “back-to-basics” approach. More specifically, for the purpose of achieving the design scheme, we have focused on one of the most primitive living organisms, *plasmodium of true slime mold* (see Fig. 1). The plasmodium is of interest to biologists as well as roboticists for the following reasons: first, its body consists of soft and continuum tissues (*i.e.*, enormous degrees of freedom); second, the plasmodium

exhibits remarkably adaptive behaviors (*e.g.*, avoiding hazardous conditions and performing chemotaxis) despite the absence of any nervous system; third, in order to achieve this amoeboid locomotion, the plasmodium employs purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPG [7]; finally, these oscillators are physically interacted each other with an explicit conserved quantity, *i.e.*, mass of protoplasm. Note that owing to the first and last points, the global physical interaction is induced inside the plasmodium, which is akin to what is observed in waterbeds and guarantees the connection of the local with the global behavior [8]. Due to these intrinsic properties, the plasmodium is a good biological organism that allows us to extract the design scheme of sensory-motor coordination in a systematic way. Based on the above observations, in our earlier work we introduced Real-time Tunable Spring (RTS) as an elastic actuator and a systematic design scheme for the local sensory feedback mechanism based on “discrepancy function” on the RTS, and we have represented the validity of our design scheme for autonomous decentralized control system numerically [9][10] and experimentally [11].

In this paper, aiming at confirming the validity of the proposed design scheme against environmental changes, we develop a real physical robot called *Slimy II*. In contrast to most robots built from very stiff components, *Slimy II* is a fluid-filled soft-bodied amoeboid robot, which equipped with fluid circuit to seal the protoplasm (*i.e.*, fluid) closely and a number of truly soft and deformable components. One of the significant features of this robot is the fluid circuit for implementing continuum materials (*e.g.*, fluid and viscoelastic liquid) into robots bodies and inducing global physical interaction between the body parts. The experimental results clearly shows that the global physical interaction stemming from the fluid circuit enables *Slimy II* to exhibit adaptive locomotion against environmental changes in fully decentralized manner. 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 work.

2 PREVIOUS and RELATED STUDIES

One interesting study focusing on designing robots inspired by amoeboid locomotion was done by Hong *et al.*. They presented a mobile robot inspired by how single celled organisms use cytoplasmic streaming to generate pseudopods for locomotion [13]. In particular, the authors proposed a mechanical design of an elongated toroid of the outer skin which turns itself inside out in a single continuous motion, aiming at realizing three dimensional caterpillar-like locomotion of amoeba. This work does not focus on the decentralized control mechanism on amoeba. Furthermore, they only shows the concept and have not brought about the realization of the real physical robot.

A pioneering work realizing decentralized control mechanism on amoeboid locomotion was done by Shimizu *et al.* [12]. This study presented a modular robot, consisting of many identical modules, called “Slimebot” that enables amoeboid locomotion in a decentralized manner. Although, global physical interaction between the modules stemming from soft and continuum materials is not taken into account.

This study, in contrast to the above-mentioned studies, aims at achieving design scheme for autonomous decentralized controllers and adaptive behaviors in fully decentralized manner. To this end, we confirmed the validity of our design scheme for sensory-motor coordination against environmental changes. One goal of the research described here is to understand how continuum materials contributes to robots' adaptive behavior as an integral part of the motor control system. In particular, we build the robot that embedded with fluid circuit for the purpose of inducing the global physical interaction between the body parts and conduct locomotion experiment against environmental changes.

3 THE ROBOT

3.1 Mechanical system

The fluid-filled soft-bodied amoeboid robot inspired by plasmodium of true slime mold, Slimy II, is presented in Fig. 2. One of the most significant features, in contrast to our previous work [11], is the fluid circuit to seal the protoplasm closely and transfer the protoplasm between the body parts for the purpose of inducing the global physical interaction between the body parts. In particular, this robot consists of the fluid circuit, RTSs and ground friction mechanisms. As shown in Fig. 2, we define RTS i and friction control unit i as unit i which is controlled according to the phase, θ_i , of oscillator i . For calculating θ_i and controlling the RTS and friction control unit, each unit has a microcomputer (Renesas Electronics Corporation H8/3694). The weight of one unit is 200 (g). The total weight of the robot is 2900 (g), including the fluid circuit. The diameter of the robot in Fig. 2 is approximately 75 (cm). The detail of the mechanical system is described below.

3.1.1 Fluidic circuit

The fluid circuit is for keeping the volume of the body constant while performing a deformable task. To this end, we design the fluid circuit with cylinders (KURODA Pneumatics Ltd. Z3G2-10-30-N)* for sealing the protoplasm closely and guaranteeing the law of conservation of protoplasmic mass (*i.e.*, protoplasmic mass is conserved) inside the circuit †. In particular, as shown in Fig. 3, the fluid circuit is made of the cylinders, which are arranged radially, and nylon tubes filled with fluid (*i.e.* protoplasm).

On the edge of each cylinder rod, RTS and friction control mechanism are connected to push and pull the protoplasm with the cylinder rod. This elastic device, RTS, is able to alter its resting length of the spring (*i.e.*, un-stretched length of the spring). Hence, by altering the resting length of each RTS distributed throughout the periphery of the fluid circuit, the protoplasm is pushed and pulled, leading to the competitive pushing and pulling through the protoplasm. Due to the fluid circuit, the mass of protoplasm are conserved, which induces the global physical interaction between the body parts.

*The stroke of the cylinder is 30 (mm), which limits one unit deformation.

†On the previous two dimensional robot, Slimy, a balloon was equipped, instead of the fluid circuit. The problem of the previous robot is that the balloon is not able to guarantee the law of conservation of protoplasmic mass precisely. By using the cylinders, we improved the problem.

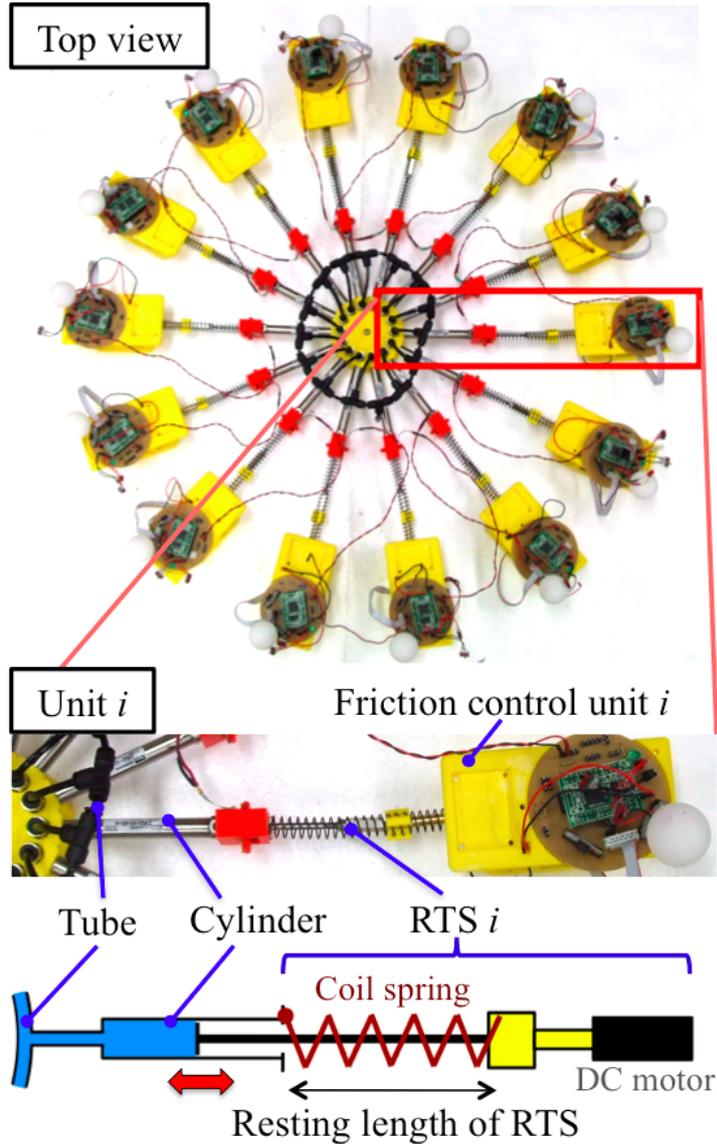


Figure 2: The real physical robot called *Slimy II*. The robot consists of the fluid circuit, RTSs, and friction control units. The fluid circuit is made of the cylinders and nylon tubes filled with the fluid. By changing the resting length of the RTS, the fluid is pushed and pulled with the cylinder rod, which is describes as the red arrow.

3.1.2 RTS

This elastic actuator is a key device to our design scheme for the following reasons; (i) the device is an actuator that is allowed to have discrepancy between the controlled value and actual value due to the softness of the device; (ii) the device is able to change the softness, (*i.e.*, spring constant) depending on its resting length. As can be seen in Fig. 4, the RTS is composed of a DC motor (maxon DC motor RE10 with gear head GP10A and encoder MR), winding/unwinding mechanism, coil spring, and force sensor (Interlink electronics, Standard 400 FSR). 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 resting length of RTS i , $l_i(\theta_i)$, alters according to θ_i to push and pull the protoplasm

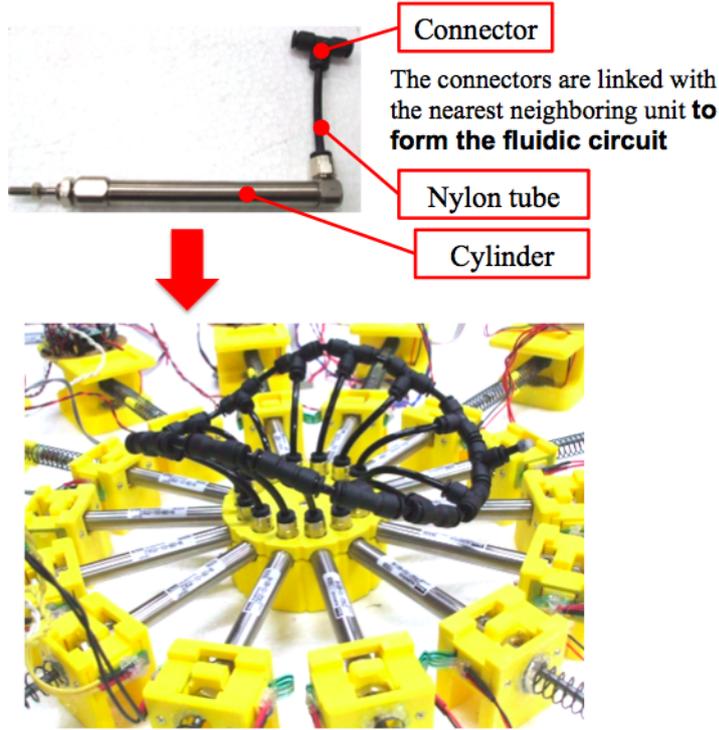


Figure 3: The fluid circuit implemented with Slimy II. The connectors are linked to form the fluid circuit for sealing the fluid closely and transferring the fluid between distant units

rhythmically, and is given by

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

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 3.2.2). Note that spring constant $k_i(\theta_i)$ of RTS i varies dynamically depending on its resting length, as follows:

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

where α is a constant given by the material and geometric properties of the coil spring.

The tension of 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:

$$T_i = k_i(\theta_i)(l_i - l_i(\theta_i)). \quad (3)$$

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, $l_i(\theta_i)$, and the actual value, l_i .

3.1.3 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 (gigateco TMN-2613S) is

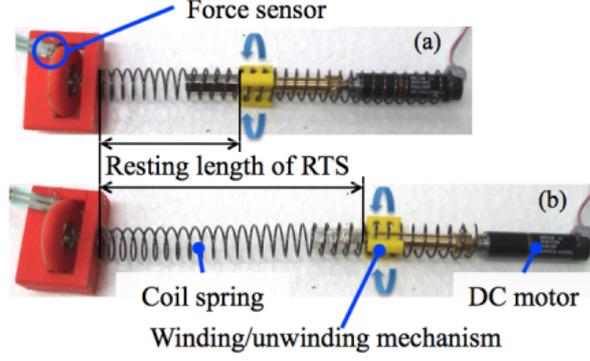


Figure 4: By rotating the winding/unwinding mechanism (the blue arrows), the RTS is able to alter its resting length at any time.

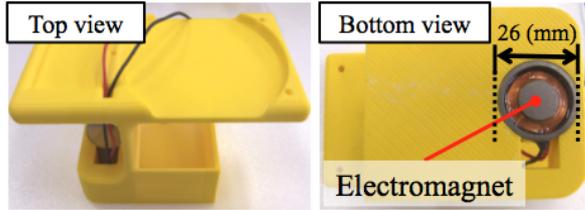


Figure 5: The friction control unit. The electromagnet is embedded in the bottom of the friction control unit in order to switch between the anchor mode and anchor-free mode.

embedded in the bottom of each friction control unit (Fig. 5), and the 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,

$$\begin{cases} \text{anchor mode} & \text{if } \theta_l + 2\pi n \leq \theta_i \leq \theta_h + 2\pi n \\ \text{anchor-free mode} & \text{otherwise,} \end{cases} \quad (4)$$

where n is any integer, θ_l is a start phase of the anchor mode, and θ_h is an end phase of the anchor mode.

3.2 Control system

In this subsection, we will briefly summarize the way of designing autonomous decentralized control, which have been proposed in our earlier work [10][11], under conditions of the above-mentioned mechanical structure.

3.2.1 Coupled oscillator system with local sensory feedback based on discrepancy function

For generating adaptive amoeboid locomotion, we have employed coupled oscillator system with the local sensory feedback in order to control the resting length of each RTS and the ground friction on each friction control unit.

The coupled phase oscillator system is expressed as:

$$\frac{d\theta_i}{dt} = \omega + \varepsilon_c \sum_{j=i-1, i+1} \sin(\theta_j - \theta_i) + g(l_i, l_i(\theta_i)), \quad (5)$$

The first term is intrinsic frequency of each oscillator, the second term is diffusion term (see Fig. 6) to achieve coherent motion between neighbors[‡], and the third term is the local sensory feedback based on the discrepancy function.

The discrepancy function is a function which measures the discrepancy between the controller, body, and environment. When using this design scheme, there are two mechanical properties to be prepared:

- Elastic actuator, like RTS,
- Long-distance physical interaction between the body parts, in this case, physical interaction stemming from the fluid circuit.

Due to these two mechanical properties, the mechanical system is allowed to have a discrepancy between the controlled value (in this case, the resting length of the RTS) and actual mechanical value (in this case, the actual length of the RTS). Based on this discrepancy between the control and mechanical systems, we can design discrepancy function as follows:

$$I_i = \frac{\sigma}{2} T_i^2 \quad (6)$$

where σ represents a coefficient that defines the strength of the local sensory feedback. The function is designed so as to increase its value when absolute value of T_i increases.

Based on this discrepancy function, we can design local sensory feedback in ways that each oscillator modify its phase so as to reduce the discrepancy function, as follows:

$$\begin{aligned} g(l_i, l_i(\theta_i)) &= -\frac{\partial I_i}{\partial \theta_i}, \\ &= \sigma \alpha^2 \left(\frac{l_i}{l_i(\theta_i)} - 1 \right) \frac{l_i \bar{l}_i a \sin \theta_i}{l_i(\theta_i)^2}. \end{aligned} \quad (7)$$

This local sensory feedback can be calculated with the locally available variables, however, the local feedback guarantees to connect the local with global behavior, due to the global physical interaction with the fluid circuit and the softness of the elastic actuators.

3.2.2 Symmetry-breaking mechanism

Here, in order to achieve taxis behavior, 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. 7),

$$\bar{l}_i = \begin{cases} \bar{l}_a & \text{if unit } i \text{ detects an attractant,} \\ \bar{l}_p & \text{otherwise,} \end{cases} \quad (8)$$

where $\bar{l}_a > \bar{l}_p$. 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 becomes softer when detecting the attractant (see Eq. 1), leading to an imbalance of the competitive

[‡] ε_c specifies the strength of the local interaction, *i.e.*, phase diffusion.

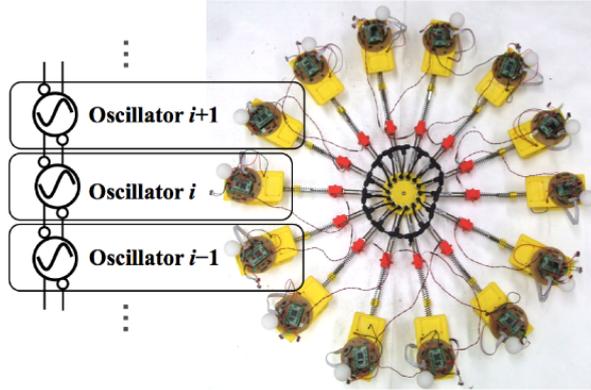


Figure 6: Implementation of the diffusive interaction between the oscillators.

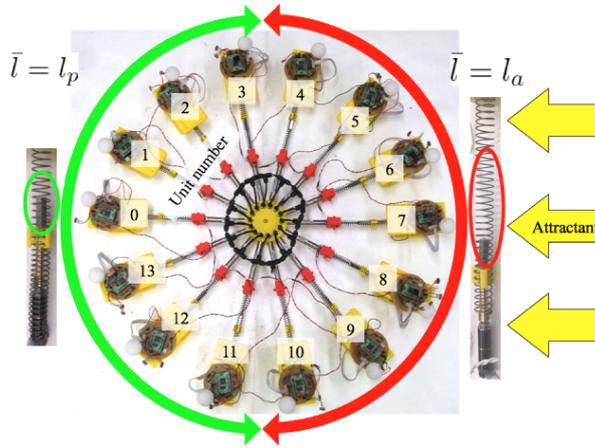


Figure 7: Implementation of the symmetry-breaking mechanism.

pushing on the protoplasm between the anterior and posterior parts toward the attractant, which in turn generates phase gradient from the anterior and posterior parts. This resultant phase gradient generates taxis locomotion toward the attractant. In the next section, highlights of the data obtained by experiments using the robot are presented.

4 EXPERIMENTAL RESULTS

4.1 Problem Setting

In order to demonstrate the validity of the proposed design scheme on the real physical robot, in particular, whether the robot is able to generate locomotion according to the situation encountered, the following experiment were conducted: (i) the verification of the generation of locomotion and its phase analysis; and (ii) locomotion experiment when the robot goes through narrow aisle (*i.e.*, environmental changes) and its phase analysis. DC electricity was supplied by a direct current stabilized power supply with power cables. In this study, taxis behavior

was adopted as a practical example. In this paper, assuming that external attractant (*e.g.*, phototaxis or chemotaxis stimuli) comes from the right side constantly, we set the softness distribution as can be seen in Fig 7. The movie is available at <http://www.youtube.com/user/TakuyaUMEDACHI>.

The experimental conditions employed are as follows:

Initial arrangement: Fourteen units were connected with the fluid circuit[§] (as shown in Fig. 7) with $\theta_i = \pi$.

Parameters: $\bar{l}_a = 90$ (mm); $\bar{l}_p = 55$ (mm); $a = 0.5$; $\theta_l = -\pi/2$ (rad); $\theta_h = 0$ (rad); $\omega = 0.45$ (rad/sec)[¶]

4.2 The verification of the generation of locomotion

The results of the experiment are presented in Fig. 8 (a) and Fig. 9. As can be seen in Fig. 8 (a), Slimy II generates locomotion toward the attractant stably. Fig. 9 represents the time evolution of total amount of I_i and phase analysis of the all units. The phase of the oscillators and total amount of I_i were attained from the microcomputers on the units via the usb cables. This figure shows that, due to the global physical interaction stemming from the fluid circuit, phase modification occurs in the beginning so as to reduce the discrepancy, which then generates phase gradient against the attractant, which finally leads to stable taxis locomotion.

4.3 Locomotion experiment when the robot goes through narrow aisle

In order to confirm the validity of the proposed design scheme against environmental changes, we conducted the locomotion experiment in a narrow aisle. The experimental setup is shown in Fig 10^{||}. Note that the parameters of the robot are the same to the previous experiment. The results are presented in Fig. 8 (b) and Fig. 11. As can be seen in Fig. 8 (b), Slimy II is able to overcome the narrow aisle. Fig. 11 represents the time evolution of total amount of I_i and phase analysis of the all units. It is clear that expansion of RTSs that touch the obstacles be considerably restricted in comparison with the previous experiment due to the obstacles, which causes more discrepancy between the controlled value and actual value of the RTSs. Fig. 11 shows that, while the robot is overcoming the narrow aisle, the total amount of I_i increases, which then induces phase re-modification under the situation of the robot, which in turn allows the robot to overcome the narrow aisle. After overcoming the narrow aisle, the RTSs become free from the restriction from the obstacles, and then the total amount of I_i recovers autonomously.

5 CONCLUSION and FUTURE WORK

The fluid-filled soft-bodied robot that exhibits adaptive amoeboid locomotion against environmental changes is represented. The main contribution of our findings to the field of robotics is the emphasis on taking into account the global physical interaction stemming from the protoplasm inside the fluid circuit between the body parts. We

[§]The number of the units is due to its experimental space limitation (size of the iron plate) and mechanical design.

[¶] \bar{l}_a and \bar{l}_p were determined by the stroke length of the cylinder. ω was determined so as to be relatively slow compared to the DC motor speed.

^{||}Considering the fact that the stroke is 30 (mm), the obstacle arrangement is reasonable.

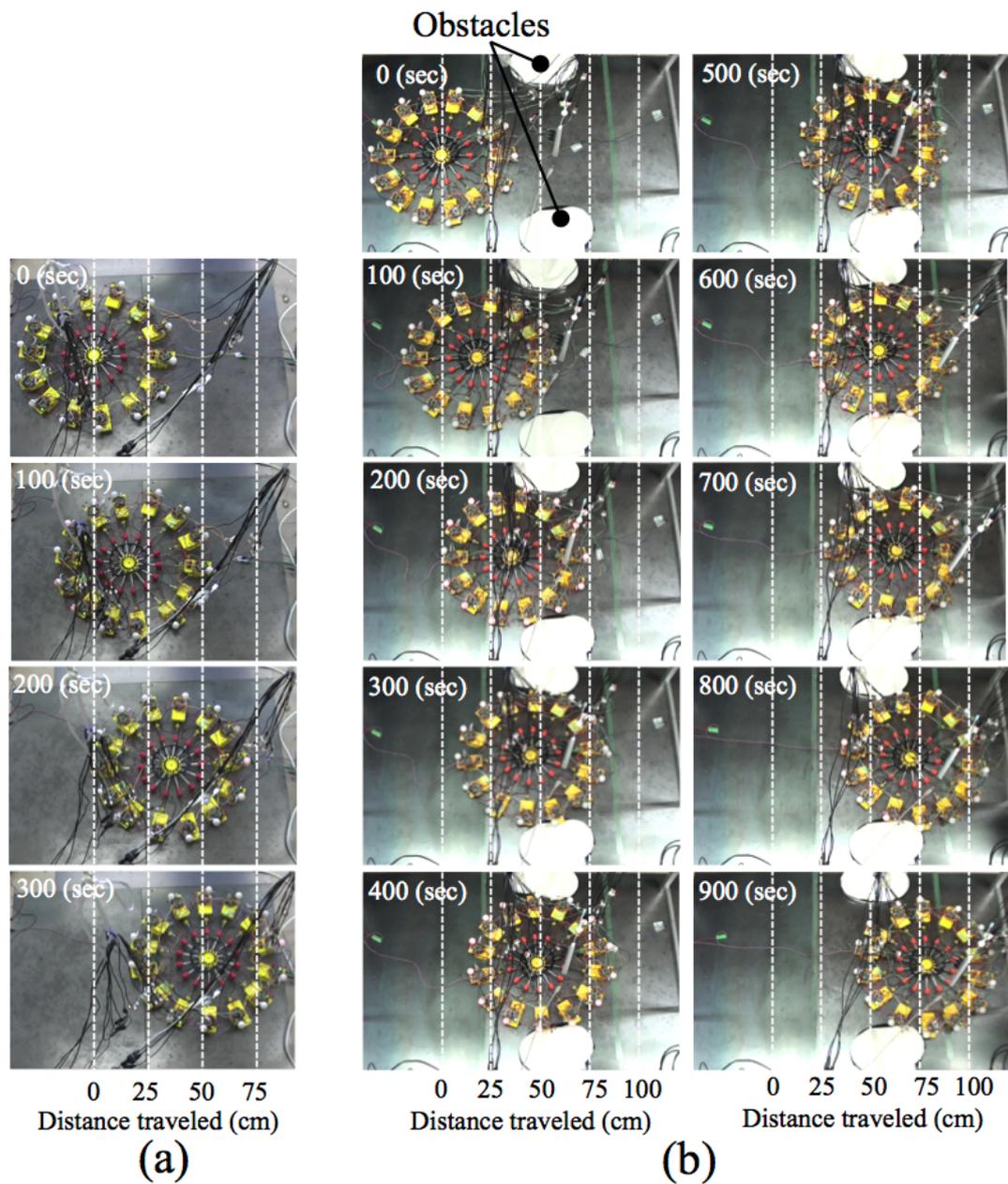


Figure 8: Representative data of the locomotion of Slimy II. (a) shows that Slimy II generates stable locomotion toward attractant without any hierarchical structure. (b) shows that Slimy II overcomes the narrow aisle with its deformability and sensory feedback.

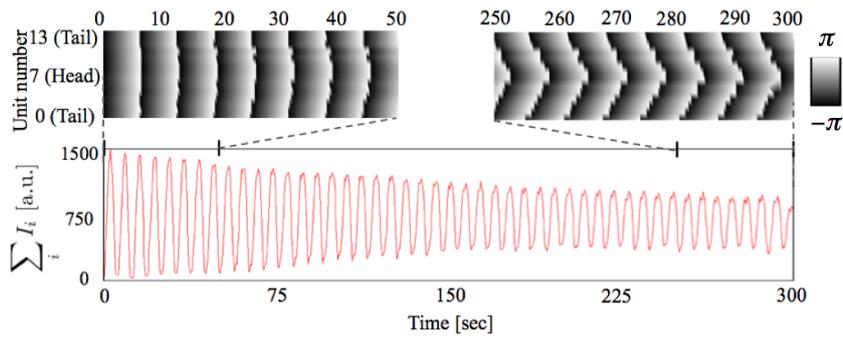


Figure 9: The time evolution of total amount of I_i and spatio-temporal pattern of phase of the oscillators (from 0-50 (sec) and 250-300 (sec)). Due to the local sensory feedback, phase modification so as to decrease total amount of I_i is confirmed in the beginning, resulting in generating stable phase gradient in order to generate locomotion toward the attractant.

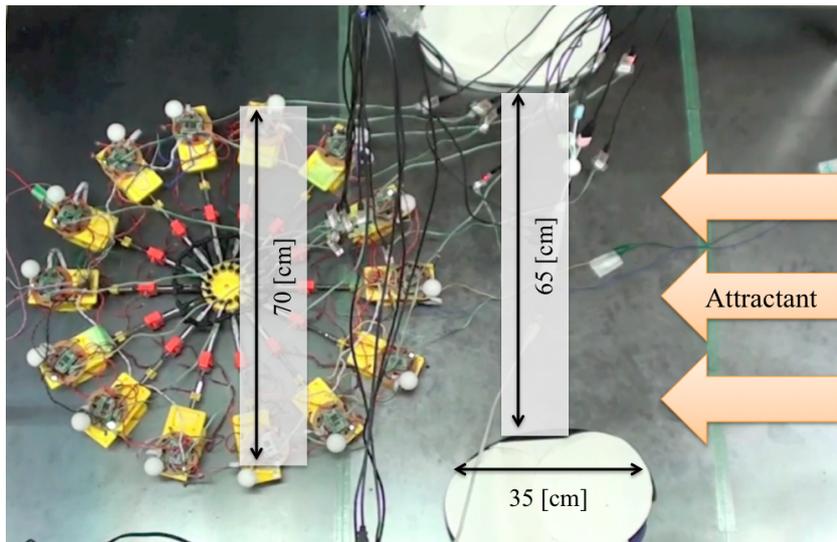


Figure 10: The experimental setup of the narrow aisle.

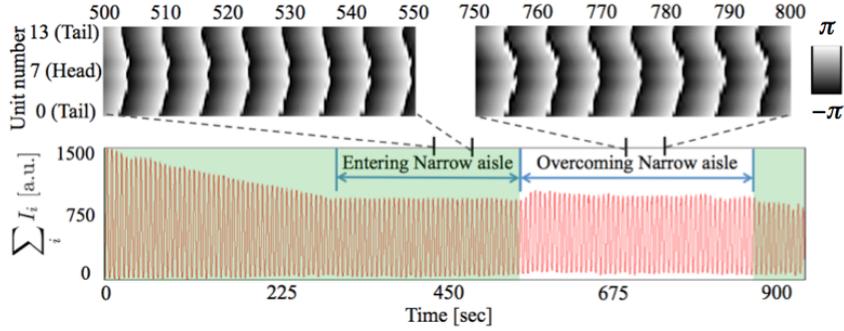


Figure 11: The time evolution of total amount of I_i when the robot goes through the narrow aisle and spatio-temporal pattern of phase of the oscillators (from 500 to 550 (sec) and from 750-800 (sec)). While the robot is overcoming the narrow aisle, the total amount of I_i increases, which then induces phase re-modification under the situation of the robot, which in turn allows the robot to overcome the narrow aisle.

clearly showed that this global physical interaction stemming from the fluid circuit endows not only significant simplification of computation, which would otherwise be performed by the centralized control system, but also adaptivity of the behavior against the environmental changes. The results demonstrate that this fluid circuit assists to modify the phase modification when the robot goes through the narrow aisle without relying on any hierarchical structure. Embedding this type of physical interaction is expected to be applicable to different morphology of robots from the perspective of morphological computation [17] and morphological communication [18]. Indeed, validation of the design scheme has been confirmed on a serpentine robot numerically [19] and experimentally [20] and a quadruped robot [21], and therefore, the results obtained are expected to shed new light on design scheme for autonomous decentralized control system.

In this work, a simple radially-connected fluid circuit was selected for the basis of a fluid-filled soft bodied robot. However, it is likely that more ideal fluid circuit structure exist for locomotion. Hence, one direction of future work will focus on increasing the number of mechanical units of the robot and building more complex construction of the fluid circuit topologies, such as tree-like, ring structures, and three dimensional structures. In that case, the weight of robot (especially weight of the cylinder and electromagnet) need to be lighter. Another direction of future work will include investigation of the change in robot performance and behavior with respect to control parameters. For example, changing softness of the body parts (*i.e.*, changing \bar{l}) dynamically might be an interesting topic, because spacial pattern of the softness can switch the robot behavior between motion stabilization and motion exploration by exploiting the robot morphology as an integral part of the motor control system.

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REFERENCES

- [1] S. Grillner, O. Ekeberg, A. Manira, A. Lansner, D. Parker, J. Tegner, and P. Wallen, Intrinsic function of a neuronal network - a vertebrate central pattern generator, *Brain Res. Reviews*, **26**, 184-197 (1998)
- [2] G. Taga, Y. Yamaguchi, and H. Shimizu, Self-organized control of bipedal locomotion by neural oscillators, *Biol. Cybern.*, **65**, 147-159 (1991)
- [3] G. Taga, A model of the neuro-musculo-skeletal system for human locomotion 11. - Real-time adaptability under various constraints, *Biol. Cybern.*, **73**, 97-111 (1995)
- [4] H. Kimura, Y. Fukuoka, and H. Nakamura, Biologically inspired adaptive dynamic walking of the quadruped on irregular terrain, in *ISRR99*, pp. 271-278 (1999)
- [5] H. Kimura, S. Akiyama, and K. Sakurama, Realization of Dynamic Walking and Running of the Quadruped Using Neural Oscillator, *Autonomous Robots*, **7-3**, 247-258 (1999)
- [6] R. Pfeifer, C. Scheier, Sensory-motor coordination: The metaphor and beyond, *Robotics and Autonomous Systems*, **20**, 157-178 (1997)
- [7] A. Takamatsu, R. Tanaka, H. Yamada, T. Nakagaki, T. Fujii, and I. Endo, Spatio-temporal symmetry in rings of coupled biological oscillators of *Physarum plasmodium*, *Phys. Rev. Lett.*, **87**, 078102 (2001)
- [8] S. A. Wainwright, *Axis and Circumference: The Cylindrical Shape of Plants and Animals*, Harvard Univ. Press (1988)
- [9] R. Kobayashi, A. Tero, and T. Nakagaki, Mathematical Model for Rhythmic Protoplasmic Movement in the True Slime Mold, *Mathematical Biology*, **53**, 273-286 (2006)
- [10] T. Umedachi, K. Takeda, T. Nakagaki, R. Kobayashi, and A. Ishiguro, Fully Decentralized Control of a Soft-bodied Robot Inspired by True Slime Mold, *Biological Cybernetics*, Doi:10.1007/s00422-010-0367-9 (2010)
- [11] T. Umedachi, K. Takeda, T. Nakagaki, R. Kobayashi, and A. Ishiguro, Taming Large Degrees of Freedom -A Case Study with an Amoeboid Robot-, in *Proc. of the 2010 International Conference on Robotics and Automation (ICRA 2010)*, Anchorage, US, pp. 3787-3792, 2010.
- [12] M. Shimizu and A. Ishiguro, An Amoeboid Modular Robot That Exhibits Real-time Adaptive Reconfiguration, in *Proc. of the 2009 International Conference on Intelligent Robots and Systems (IROS'09)*, pp.1496-1501 (2009)
- [13] D. Hong, M. Ingram, and D. Lah, Whole Skin Locomotion Inspired by Amoeboid Motility Mechanisms, *J. Mechanisms Robotics*, **1**, 011015, (2009)

- [14] A. Ishiguro and T. Kawakatsu, How Should Control and Body Systems be Coupled? — A Robotic Case Study —, *Lecture Notes in Computer Science (Eds. F. Iida, R. Pfeifer, L. Steels, and Y. Kuniyoshi)*, Springer, pp.107-118 (2004)
- [15] Y. Kuramoto, *Chemical Oscillations, Waves, and Turbulence*, Dover, Mineola, NY (2003)
- [16] S. Yoshiyama, M. Ishigami, A. Nakamura, K. Kohama, Calcium wave for cytoplasmic streaming of *Physarum polycephalum*, *Cell Biology International*, doi:10.1042/CBI20090158 (2009)
- [17] R. Pfeifer and F. Iida, Morphological Computation for Adaptive Behavior and Cognition, *International Congress Series*, doi:10.1016/j.ics.2005.12.080 (2006)
- [18] J. A. Rieffel, F. J. Valero-Cuevas, and H. Lipson, Morphological communication: exploiting coupled dynamics in a complex mechanical structure to achieve locomotion, *Journal of the Royal Society Interface*, doi: 10.1098/rsif.2009.0240 (2009)
- [19] W. Watanabe, T. Sato, and A. Ishiguro, A Fully Decentralized Control of a Serpentine Robot Based on the Discrepancy between Body, Brain and Environment, in *Proc. of The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009)*, Anchorage, pp. 2421-2426 (2009)
- [20] T. Sato, T. Kano, and A. Ishiguro, On the applicability of the decentralized control mechanism extracted from the true slime mold: a robotic case study with a serpentine robot, *Bioinsp. Biomim.*, doi:10.1088/1748-3182/6/2/026006 (2011)
- [21] T. Kano, K. Nagasawa, D. Owaki, A. Tero, A. Ishiguro, A CPG-Based Decentralized Control of a Quadruped Robot Inspired by True Slime Mold, in *Proc. of The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS2010)*, Taipei, pp. 4928-4933 (2010)