The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

An Amoeboid Modular Robot That Exhibits Real-time Adaptive Reconfiguration

Masahiro Shimizu and Akio Ishiguro

Abstract— **This paper discusses experimental verifications of a two-dimensional modular robot called "Slimebot", consisting of many identical modules, each of which has simple motile functions. We have so far investigated a fully decentralized algorithm able to control the morphology of the modular robot in real-time according to the environment encountered. One of the most significant features of our approach is that we explicitly exploit "emergent phenomena" stemming from the interplay between control and mechanical systems. In order to verify our proposed control scheme, we have constructed real physical Slimebot. Experiments with 10 modules suggest that this robot exhibits significant abilities, i.e., adaptivity, scalability, and fault tolerance.**

I. INTRODUCTION

Understanding of the design principles for implementing adaptive functions with respect to engineering currently remains stalled in conceptual level. However, living organisms develop great adaptive function by skillfully relating shape and function in a spatiotemporal manner[1]. In the natural world, there exist organisms that have a variety of functions, and that produce intrinsic adaptive locomotion such as walking, flying, swimming and so on by dynamically changing the relative positional relationship between the positions of body parts.

In this study, we focus on amoeboid organisms (physarum polycephalum, etc.)[2][3] because these organisms have a variable morphology that relates shape and function in the most simple and primitive manner. Amoeboid organisms in the natural world (slime molds, etc.) locomote through changing shape by inducing the internal flow of their protoplasm (protoplasmic streaming). It should be noted that the control of locomotion in slime molds is realized in an autonomous decentralized manner without being mediated by a central nervous system. Therefore, in this study, the locomotion of amoeboid organisms is employed as a practical example that enables adaptive locomotion with reconfiguration in autonomous decentralized manner. That adaptive function (i.e., amoeboid locomotion) could be modeled by exploiting a modular robot[4]-[19] that is capable of changing shape and locomotion by altering the relative positional relationship between mechanical modules according to environmental changes.

Based on the above consideration, we have so far developed a two-dimensional modular robot, called *Slimebot*[20]. In this study, in order to realize an emergent adaptive control, the coupling between the control and mechanical systems of Slimebot has been carefully designed as follows: we have particularly focused on a *functional material*, *i.e.*, a genderless *Velcro strap*, and *mutual entrainment* among nonlinear oscillators, *i.e.*, *van der Pol*(*VDP*) oscillators, the former of which is used as a spontaneous connectivity control mechanism between the modules, and the latter of which acts as the core control mechanism for the generation of locomotion and ensures the scalability. The behaviors of the Slimebot are based on the same principle as well as the amoeboid locomotion generated by slime molds[2][3]. Simulation results indicate that the proposed method can induce amoebic locomotion, which allows us to successfully control the morphology of the modular robot in real time according to the situation without losing the coherence of the entire system. To verify the feasibility of our proposed method, experiments with a real physical Slimebot are also significantly important in order to verify the validity of the proposed method with a high degree of reliability.

The main contribution of this paper is development of the real physical Slimebot that enables not only the adaptive amoeboid locomotion but also the adaptive reconfiguration with 10 modules. More specifically, we here report on the deeply interesting experimental results as follows: (1) high adaptivity; (2) high scalability; (3) high fault tolerance.

This paper is organized as follows: The related works are introduced in the section II; In the section III, the design strategies of the Slimebot are explained; The experimental results are presented in the section IV; And, the paper is finalized with conclusions and the future works.

II. RELATED WORKS

So far various modular robots[4]-[19] have been successfully proposed, that are expected to show significant abilities, *e.g.*, adaptivity, fault tolerance, scalability, compared with a robot on a fixed-morphology basis. Most of these studies, however, have the following problems: (1) morphological alteration is discussed in some studies, but is usually resolved by turning into a module rearrangement problem in a centralized-planning manner; and/or, (2) modules are normally connected mechanically and/or electromagnetically by highly rigid mechanisms. Under these frameworks, however, the control algorithm required usually ends up to be extremely complicated and intractable since it has to always specify which modules should be connected physically as well as how each module should be moved. In addition, module connections done by such a highly rigid

M. Shimizu is with the Department of Electrical and Communication Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan shimizu@cmplx.ecei.tohoku.ac.jp

A. Ishiguro is with the Department of Electrical and Communication Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan ishiguro@ecei.tohoku.ac.jp

mechanism may impair some of the advantages expected, particularly the flexibility against environmental changes. In order to fully exploit the advantages mentioned above, (1)each module should be controlled in a fully decentralized manner, and (2)the resultant morphology of the entire system should *emerge* through the module-to-module and module-to-environment interactions. To do so, Slimebot incorporated two major contrivances into its control and mechanical systems: (1) the utilization of mechanical characteristics of functional materials; and (2) the utilization of the mutual entrainment between nonlinear oscillators.

III. DESIGN STRATEGIES

So far, we have confirmed real-time adaptive reconfiguration under the simulations (see Fig. 1). In what follows, the design strategies introduced in this study are explained.

A. The Mechanical Structure

A two-dimensional Slimebot has been developed, consisting of many identical modules, each of which has a mechanical structure like the one shown in Fig. 2 and 3. Fig. 4 shows schematic representation of the control system for the real physical Slimebot. Each module is equipped with telescopic arms, a ground friction control mechanism, and an omnidirectional light-detecting sensor. Note that the module is covered with a functional material. More specifically, we used a genderless Velcro strap as a practical example, since this intrinsically has interesting properties: when two halves of Velcro contact each other, they are connected easily; and when a force greater than the yield strength is applied, the halves will come apart automatically. Exploiting the property of this material itself as a spontaneous connectivity control mechanism, we can expect not only to reduce the computational cost required for the connection control dramatically, but also to induce emergent properties in morphology control. The property of the connectivity control mechanism is mainly specified by the yield stress of Velcro employed: connection between the modules is established spontaneously where the arms of each module make contact; disconnection occurs if the disconnection stress exceeds the Velcro's yield stress. We also assume that local communication between the connected modules is possible(see Fig. 5), which will be used to create phase gradient inside the modular robot (discussed below). In this study, each module is moved by the telescopic actions of the arms and by ground friction. Note that each module itself does not have any mobility but can move only by the collaboration with other modules.

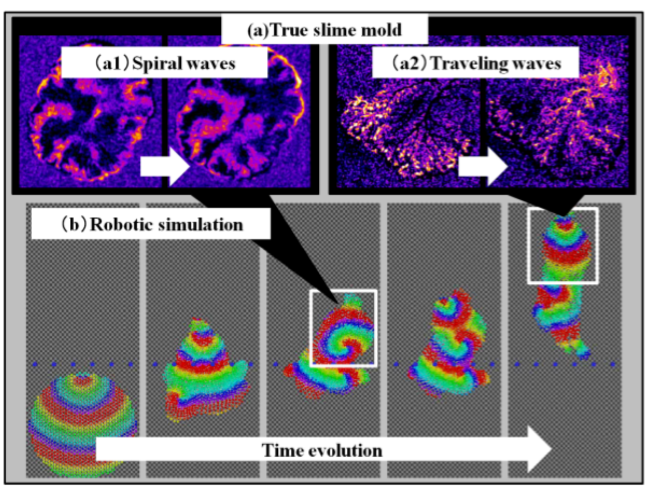

Fig. 1. Representative data of qualitative agreements between the Slimebot and rhythmic protoplasmic movement in the true slime mold. Note that no active control mechanism that precisely specifies connection/disconnection among the modules is implemented. Instead, a spontaneous connectivity control mechanism exploiting a functional material, *i.e.*, genderless Velcro strap, is employed. Experimental results(*i.e.*, a1 and a2) of true slime mold were provided by Prof. Takamatsu, Waseda University.

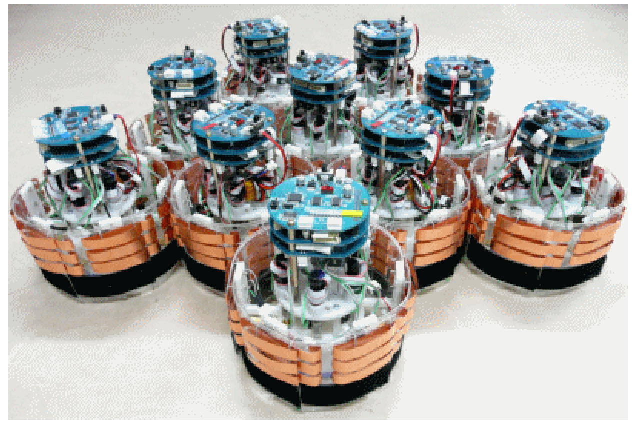

Fig. 2. A real physical Slimebot consisting of 10 modules.

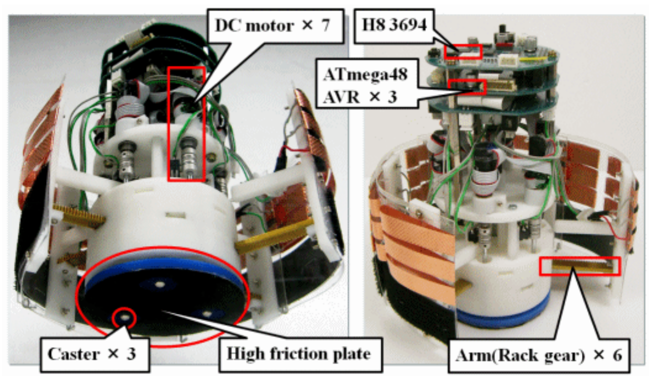

Fig. 3. Photo of the real physical module. The module has 7 DC motors. 6 motors of which are for extension/contraction of the arms, and the rest is for the ground friction control mechanism.

B. 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 onto each module, allowing us to generate rhythmic and coherent locomotion through the *mutual entrainment* among the oscillators. In the following, we will give a detailed explanation of this algorithm.

Active Mode and Passive Mode: Each module in the Slimebot can take one of two exclusive modes at any time:

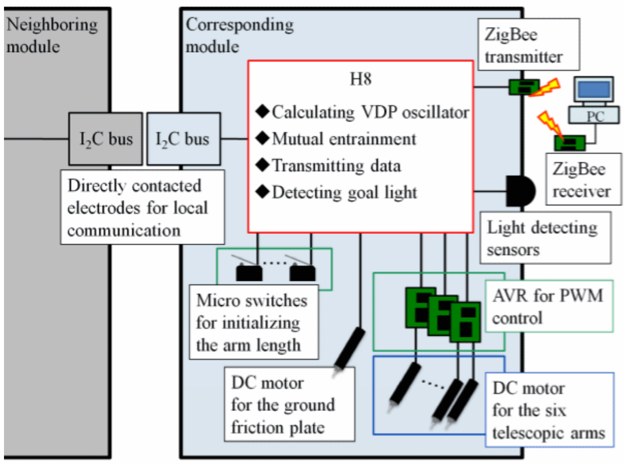

Fig. 4. Schematic representation of the control system for the real physical Slimebot.

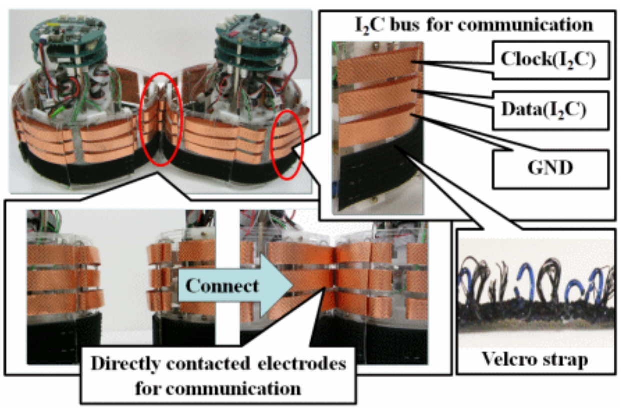

Fig. 5. The physical connection control mechanism by exploiting genderless velcro straps.

active mode and *passive mode*. A module in the active mode actively contracts/extends the connected arms, and simultaneously reduces the ground friction. In contrast, a module in the passive mode increases the ground friction, and returns its arms to their original length. Note that a module in the passive mode does not move itself but serves as a *supporting point* for efficient movement of the module group in the active mode.

Creating the Phase Gradient through Mutual Entrainment: In order to generate rhythmic and coherent locomotion, the mode alternation in each module should be controlled appropriately. Of course, this control should be done in a *decentralized* manner, and its algorithm should not depend on the number of the modules and the morphology of the Slimebot. To do so, we have focused on the *phase gradient* created through the mutual entrainment among locally-interacting nonlinear oscillators in the Slimebot, exploiting this as a key information for the mode alternation. Therefore, the configuration of the resulting phase gradient is extremely important. In the following, we will explain this in more detail.

As a model of a nonlinear oscillator, the *van der Pol oscillator* (hereinafter VDP oscillator) was employed, since this oscillator model has been well-analyzed and widely used for its significant entrainment property. The equation of VDP oscillator implemented on module i is given by

$$\alpha_i \ddot{x}_i - \beta_i (1 - x_i^2)\dot{x}_i + x_i = 0, \tag{1}$$

where the parameter α_i specifies the frequency of the oscillation. β_i corresponds to the convergence rate to the limit cycle.

The local communication among the physically connected modules is done by the local interaction among the VDP oscillators of these modules, which is expressed as:

$$x_i = x_i^{\mathrm{tmp}} + \varepsilon \left\{ \frac{1}{N_i(t)} \sum_{j=1}^{N_i(t)} x_j^{\mathrm{tmp}} - x_i^{\mathrm{tmp}} \right\}, \tag{2}$$

where x_i^{tmp} and $N_i(t)$ represent the state before the local interaction, and the number of modules neighboring module i at time t, respectively. The parameter ε specifies the strength of the interaction. Note that this local interaction acts like a *diffusion*.

When VDP oscillators interact according to Equation (2), significant phase distribution can be created effectively by varying the value of α_i in Equation (1) for some of the oscillators. In order to create an equiphase surface effective for generating locomotion, we set the value of α_i as:

$$\alpha_i = \begin{cases} 0.7 & \text{if the goal light(attractant) is detected} \\ 1.3 & \text{if the module is outer surface} \\ 1.0 & \text{otherwise} \end{cases} \tag{3}$$

Note that except the modules detecting the attractant, the modules on the boundary, *i.e.*, the outer surface, have the value of $\alpha_i = 1.3$. This allows us to introduce a kind of effect of *surface tension*, which is indispensable to maintain the coherence of the entire system.

Generating Locomotion: Here, we consider a control algorithm exploiting the phase distribution created from the aforementioned mutual entrainment among the VDP oscillators. To do so, the two possible modes, *i.e.*, the active and passive modes, of each module should be appropriately altered according to the phase distribution that emerges. The timings of the mode alternation are propagated from the front to the rear inside the modular robot as traveling waves. In this study, the extension/contraction of each arm of module i in the active mode is determined according to the phase difference with its corresponding neighboring module. Due to this, the degree of arm extension/contraction of each module will become most significant along the phase gradient, enabling the entire system to move toward the attractant while maintaining its coherency.

IV. EXPERIMENTAL VERIFICATIONS

Mutual Entrainment between Real Physical Modules: Here, we have carried out the verification of mutual entrainment between 3 modules arranged so as to form a string-like shape. Fig. 6 shows the experimental result. As the figures explain, in the gray region, each module is set to $\alpha = 1.0$, thus all the oscillators will be synchronized. On the other

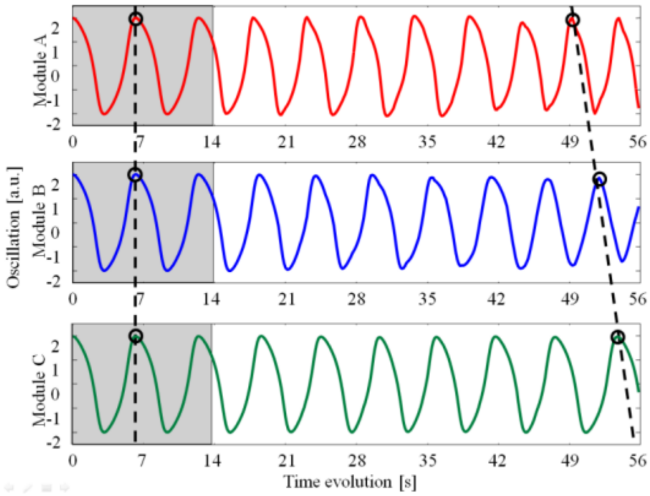

Fig. 6. A verification of mutual entrainment among the VDP oscillators embedded into the modules.

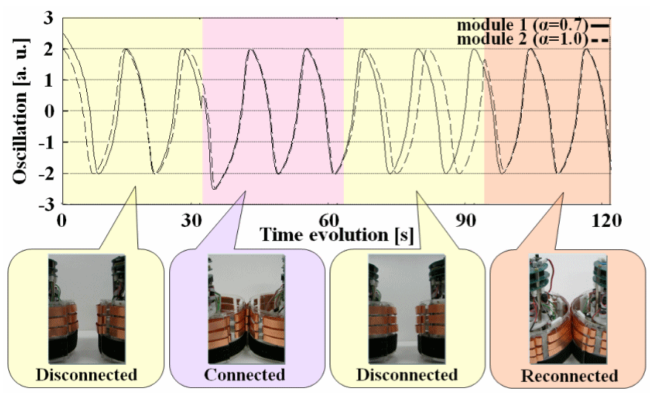

Fig. 7. A verification of connection mechanism.

hand, in the white region, only module A is allowed to detect attractant($\alpha = 0.7$), thus the phase gradient will be occurred.

Connection and Disconnection between Real Physical Modules: We have verified the mechanism for mutual entrainment with two modules. As Fig. 7 shows, the oscilloators of these modules can successfully exhibit mutual entrainment.

Experimental Verification of The Adaptivity: Based on the above preliminary experiments, we verified the adaptivity. Fig. 8 shows the experimental result obtained. Time evolution developed in alphabetical order of snapshots. This figure explains the significant interesting result as follows: (a) first, the slimebot consisting of 10 modules started to locomote at an arrow-like configuration in the environment containing two cylindrical obstacles (*i.e.*, blue objects); (b) here, the Slimebot got stack around the obstacles at the moment; (c) then, the Slimebot got over the obstacle by disconnection between some modules; however, a module in frontal part ejected from the swarm after passing through the narrow aisle at this moment; (d) in this figure, interestingly, the ejected

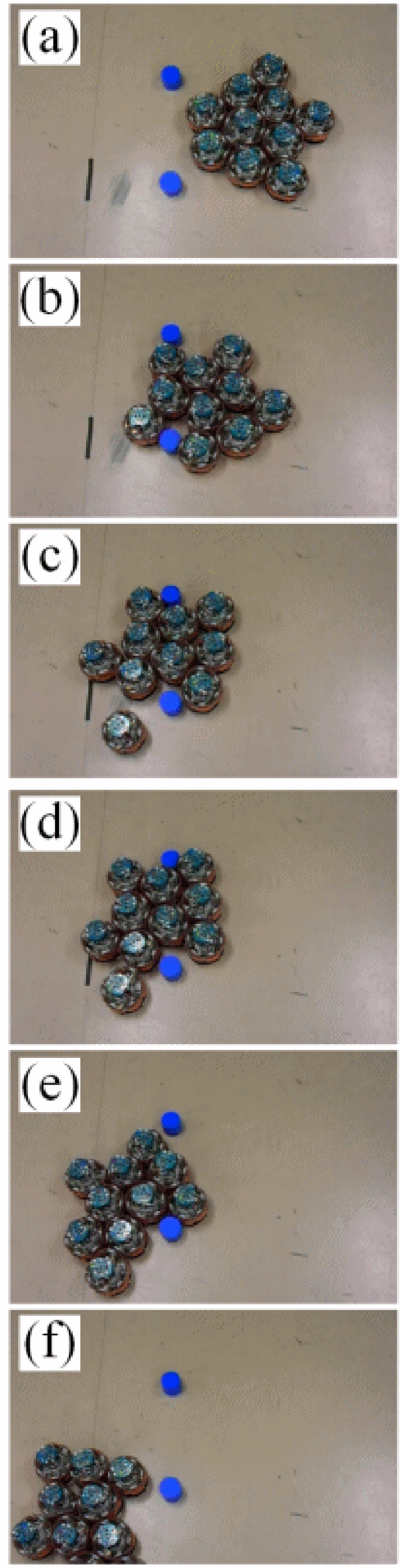

Fig. 8. Experimental verification of the adaptivity with 10 modules in the environment containing two cylindrical obstacles. See from (a) to (f).

module at snapshot (c) gathered with the swarm; note that this is not only the effect of the functional material (*i.e.*, velcro strap) but also mutual entrainment stemming from the coupled oscillators; (e) after that, the Slimebot passed through the obstacles by narrowing the width of the entire system; (f) finally, the Slimebot successfully negotiated its environment by the real-time adaptive reconfiguration. Note again that these behavior are not pre-programmed, but are totally emergent through the interplay between the control system (*i.e.*, coupled oscillators), the mechanical system (*i.e.*, velcro strap) and the environment (*i.e.*, two cylindrical obstacles).

Experimental Verification of The Scalability: Here, experimental verification of the scalability is shown. Fig. 9 indicates the result obtained. See from (a) to (d) in this figure. In contrast to the Fig. 8, (a) Slimebot here initially divided into 3 and 7 modules; (b) these modules are connected physically. (c)(d) the coherent swarm consisting of 10 modules locomote. Note that both 10 (*i.e.*, Fig. 8) and 2 (*i.e.*, Fig. 9) modules successfully perform amoeboid locomotion without any change of the control algorithm and parameters.

Experimental Verification of The Fault Tolerance: Finally, We show the experimental verification of the fault tolerance. Fig. 10 indicates the result obtained. See from (a) to (c). Here, the Slimebot with 10 modules included 3 mal-functional modules (*i.e.*, blue modules depicted in (b) and (c)). Actually, the modules depicted with blue color were shut down the control system. Hence, these 3 mal-functional modules cannot communicate between neighboring ones. However, this figure explains that the Slimebot including 3 mal-functional modules can locomote.

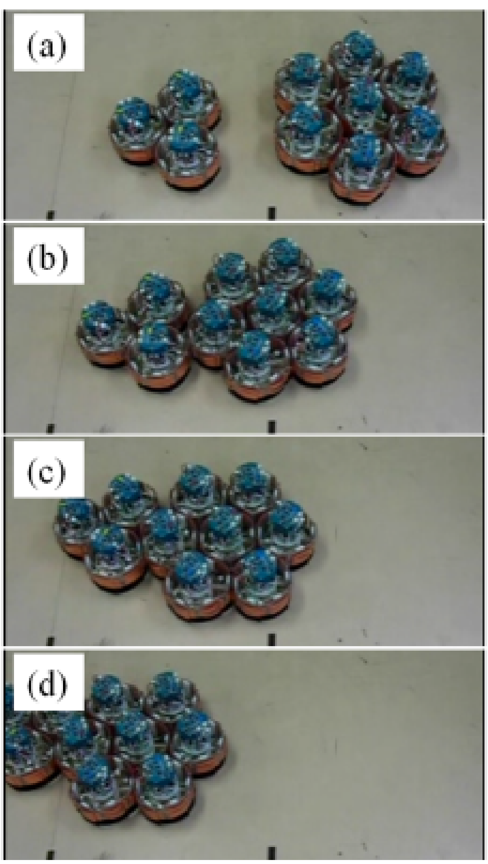

Fig. 9. Experimental verification of the scalability. See from (a) to (d).

V. CONCLUSION AND FUTURE WORKS

In this study, we have developed a real physical modular robot that enables to control its morphology in real time by explicitly exploiting emergent phenomena stemming from the interplay between the control and mechanical systems. To this end, we have implemented a functional material (*i.e.*, genderless Velcro strap) and a locally-interacting nonlinear oscillator (*i.e.*, VDP oscillators) into each module, the former of which was utilized as a spontaneous connectivity control mechanism and the latter of which as a core mechanism for generating locomotion.

The main contribution of this paper is development of the real physical Slimebot that enables not only the adaptive amoeboid locomotion but also the adaptive reconfiguration with 10 modules. More specifically, we here report on the

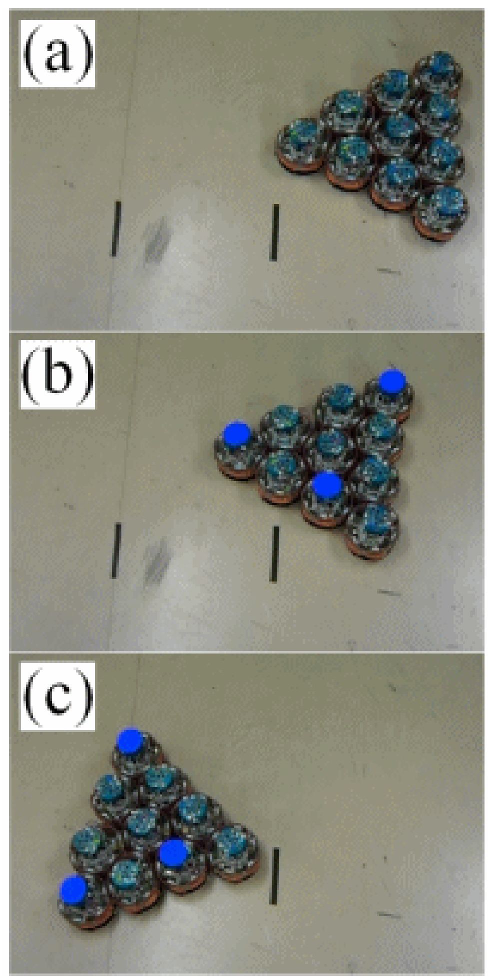

Fig. 10. Experimental verification of the fault tolerance. Here, the Slimebot with 10 modules included 3 mal-functional modules (*i.e.*, blue modules depicted in (b) and (c)). See from (a) to (c).

deeply interesting experimental results as follows: (1) high adaptivity; (2) high scalability; (3) high fault tolerance. The Slimebot successfully negotiated its environment (*i.e.*, obstacles) by the real-time adaptive reconfiguration. Note again that these behavior are not pre-programmed, but are totally emergent through the interplay between the control system (*i.e.*, coupled oscillators), the mechanical system (*i.e.*, velcro strap) and the environment (*i.e.*, two cylindrical obstacles). The experiments conducted suggest that our modular robot Slimebot is highly promising, which can be summarized as: (1) while each module is simply controlled with the VDP oscillator, adaptive reconfiguration can be self-organized according to the situation encountered; and (2) the spontaneous connectivity control mechanism provided by the functional material was fully exploited.

On the other hand, we have so far found an interesting phenomenon through the simulations: the Slimebot exhibits significant cohesive force inside effective to maintain the coherence of the entire system as the number of the modules exceeds a certain *critical number*; and this critical number exists around 10 modules in the simulation. Considering this fact, as a next step, the verification of the cohesive force with the real physical Slimebot is important. This is currently under investigation.

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" from the Japanese Ministry of Education, Culture, Sports, Science and Technology. The authors would like to thank Prof. Atsuko Takamatsu, Waseda University, for frequent, stimulating, and helpful suggestions. Many helpful suggestions for the hardware of Slimebot from Ryo Matsuzawa and Takuma Kato at our laboratory are greatly appreciated.

REFERENCES

[1] H. Asama, et al., "System Principle on Emergence of Mobiligence and Its Engineering Realization", *in Proc. of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2003, pp.1715–1720.

[2] Haruki Miura and Masafumi Yano, "A Model of Organization of Size Invariant Positional Information in Taxis of Physarum Plasmodium - A Reaction-Diffusion System Regulated by Phase of Chemical Oscillation -", *Progress of Theoretical Physics*, Vol. 100, 1998, pp.235–251.

[3] Atsuko Takamatsu, et al, "Spatiotemporal Symmetry in Rings of Coupled Biological Oscillators of Physarum Plasmodial Slime Mold", *Phys. Rev. Lett.*, Vol. 87, No. 7, 2001, pp.0781021–4.

[4] T. Fukuda and Y. Kawauchi, "Cellular Robotic System (CEBOT) as One of the Realization of Self-Organizing Intelligent Universal Manipulators", *in Proc. of IEEE ICRA*, 1990, pp.662–667.

[5] S. Murata, H. Kurokawa, and S. Kokaji, "Self-Assembling Machine", *in Proc. of IEEE ICRA*, 1994, pp.441–448.

[6] E. Yoshida, S. Murata, H. Kurokawa, K. Tomita and S. Kokaji, "A Distributed Reconfiguration Method for 3-D Homogeneous Structure", *in Proc. of 1998 IEEE/RSJ IROS*, 1998, pp.852–859.

[7] A. Kamimura, S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji, "Self-Reconfigurable Modular Robot – Experiments on Reconfiguration and Locomotion –", *in Proc. of 2001 IEEE/RSJ IROS*, 2001, pp.590–597.

[8] M. Dorigo, et al., "Evolving Self-Organizing Behaviors for a Swarm-bot", *Autonomous Robots*, 2004, pp.223–245.

[9] M. W. Jorgensen, E. H. Ostergaard and H. H. Lund, "Modular ATRON: Modules for a Self-Reconfigurable Robot", *in Proc. of 2004 IEEE/RSJ IROS*, 2004, pp.2068–2073.

[10] K. Kotay and D. Russ, "Generic Distributed Assembly and Repair Algorithms for Self-Reconfiguring Robots", *in Proc. of 2004 IEEE/RSJ IROS*, 2004, pp.2362–2369.

[11] M. Yim, C. Eldershaw, Y. Zhang, and D. Duff, "Self-reconfigurable Robot Systems: PolyBot", *Journal of the Robotics Society of Japan*, Vol.21, No.8, 2003, pp.851–854.

[12] A. Castano, W.-M. Shen, and P. Will, "CONRO: Towards Miniature Self-Sufficient Metamorphic Robots", *Autonomous Robots*, 2000, pp.309–324.

[13] C-J. Chiang and G. Chirikjian, "Modular Robot Motion Planning Using Similarity Metrics", *Autonomous Robots*, Vol.10, No.1, 2001, pp.91-106.

[14] K. Kotay and D. Rus, "Locomotion Versatility through Self-Reconfiguration", *Robotics and Autonomous Systems*, Vol.26, 1999, pp.217-232.

[15] J. Bishop et al., "Programmable Parts: A Demonstration of the Grammatical Approach to Self-Organization", *in Proc. of 2005 IEEE/RSJ IROS*, 2005, pp.2644-2651.

[16] A. Lyder, R. F. Mendoza Garcia and K. Stoy, "Mechanical Design of Odin, an Extendable Heterogeneous Deformable Modular Robot", *in Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.883–888.

[17] M. Asadpour, et al., "Graph Signature for Self-Reconfiguration Planning", *in Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.863–869.

[18] S. Miyashita, et al., "Peltier-Based Freeze-Thaw Connector for Waterborne Self-Assembly Systems", *in Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.1325–1330.

[19] D. J. Dewey, et al., "Generalizing Metamodules to Simplify Planning in Modular Robotic Systems", *in Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.1338–1345.

[20] A. Ishiguro, M. Shimizu, and T. Kawakatsu, "Don't Try to Control Everything!: An Emergent Morphology Control of a Modular Robot", *in Proc. of 2004 IEEE/RSJ IROS*, 2004, pp.981-985.