International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 3 (2011) pp.185-192

Robotics Modules with Realtime Adaptive Topology

Pitoyo Hartono[1] and Aito Nakane[2]

[1] Department of Mechanics and Information Technology,
School of Information Science and Technology, Chukyo University,
Kaizucho Tokodachi 101, Toyota, Japan
hartono@sist.chukyo-u.ac.jp

[2] Department of Complex Intelligent Systems,
School of Systems Information Science,
Future University Hakodate,
Kamedanakanocho 116-2, Hakodate, Japan

Abstract: ***In this study, we physically built hardware modules that allow us to flexibly construct robots with various morphologies. As opposed to the existing studies of modular robotics, where the connection topology among the modules has to be hand-designed, our modules are able to adaptively modify their connection topology. The gradual self-adaptation of the inter-module connection generates a topology that allows the modules to collectively produce a coordinated behavior as one robot. The adaptive mechanism is based on a human specified target behavior, thus allowing us to assemble robots with various morphologies and tasks without having to run cost-intensive designing process. We ran several physical experiments, where robots with various morphologies are assembled from the proposed modules. We also tested the flexibility and resiliency of the proposed modules with some promising initial results.***

Keywords: *modular robots, adaptive topology, realtime adaptation, robotics morphology, simulated annealing, central pattern generator*

I. Introduction

In recent years, we have been seeing the proliferation of robots outside their traditional industrial usages. It is easy to predict that in the near future, robots will play important roles in our society. Consequently, demands for robots with various morphologies and abilities to flexibly run various tasks can be expected to increase significantly. The resiliencies of these robots in the face of environmental changes and partial failures are also crucial in keeping the operational and maintenance costs manageable. At present, fully functional robots are often produced at the cost of their flexibilities, resiliencies and cost-efficiencies. The traditional manufacturing process of robots includes rigorous morphological and software designs, selecting mechanical and electrical elements for building the morphology, assembling the hardware, designing the hardware-software interface and testing the robots. The success of industrial robots is a proof that robots built in this manner are reliable to run specialized tasks in highly controlled environments, such as factories. However, for robots operating in our unpredictable and dynamic daily environment, the flexibility and resiliency will be more important than the industrial-level precision. In this study, flexibility points to a property that allows human, to change the morphologies and behavior of the robots without having to redesign them, while resiliency refers to the ability of the robots to self-discover alternative strategies or morphologies, so that in facing environmental changes or partial failures, the given tasks can still be executed, albeit with reduced efficiency.

In this study, we constructed hardware modules that can be assembled to form robots with various morphologies. As opposed to the traditional robotics modules where the connections between them must be carefully engineered, our modules have a realtime adaptive mechanism to automatically discover a connection topology that allows them to generate a target overall behavior as one robot. Though still in the preliminary states, the adaptive characteristics of our proposed modules can potentially simplify the cost-intensive conventional robots' production process.

The ideas for self-assembling machines have been considered for very long. It is known that John von Neumann developed ideas for self-replicating artifacts [1]. In recent years, ideas for adopting nature's characteristics in creating not only intelligence but also morphologies for artifacts have been proliferating [2,3,4]. The ideas also include a promising field of modular robotics that is beginning to be extensively studied [5,6]. We are also aware of some novel ideas in building mechanical and electrical mechanisms that support the realization of viable modular robots [7,8]. The main objective behind modular robotics is to build robotics components or modules which can be freely assembled to form complicated robots without having to run complicated designing process. This objective will naturally lead to the realization of robots that are able to reconfigure their modules to change their morphologies or behavior when encountering different environments or tasks. This reconfigurable characteristic, which are crucial to their applicability in unstructured environments, will increase not only the flexibility but also the resiliency of the robots [9,10,11,12]. There are many interesting modular robots that have been physically built in the past few years. However, for most of these modular robots, the connection topology between the modules still needs to be carefully engineered. While designing the connection topology for simple robots is easy, the task will not be manageable for complex robots containing significant number of modules. In our study, while there are still parameters to be hand-set, the modules are able to adaptively discover a connection topology that is needed for generating cumulative behavior given as a target by human designer. One of the strengths of our study is that this topology discovery is executed in realtime without requiring simulations. We are also aware of some studies that nicely utilized evolutionary computational methods for evolving not only controllers but also morphologies for robots or formation for a group of robots, for example [3,13,14,25]. In these studies, the formation of the robots' morphologies is based on computer simulations. While these methods proved to be effective, they are computationally prohibitive to be embedded in hardware modules with very limited power and computational resources. In this study, the mechanism for adaptive topological connection is embedded in the modules, thus, no additional computational resources are required.

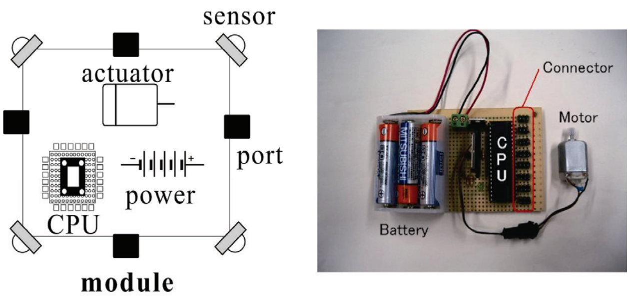
Similar to the previous studies [16,17], in our study, each module acts as an oscillator, and the cumulative behavior of them produces a Central Pattern Generation (CPG) that governs the overall behavior of the robot. Traditionally, in CPG, the connections between the oscillators have to be designed and fixed. However, a fixed topology prevents the CPG to adapt to the changing morphology, environment or task, thus limiting its flexibility as well as its resiliency. In the previous studies of robots with CPG as controller, we failed to find a case where these robots are tested against partial failure in one of the modules which is possible to occur in the real world environment. In the case of modular robots with predefined connections, failure in one of the modules is likely to significantly degrade the overall performance of the controller. In our study, because of the realtime adaptive nature of the modules, a failure in one of the modules will trigger the rest of the modules to discover an alternative topology that still allows them to generate the target behavior, albeit with a reduced efficiency. The adaptive characteristics to enable the modular robots to perform "graceful degradation" when encountering partial failures, are important in improving their resiliency

This paper, which is an extension of our previous brief papers [18,19], is structured as follows. The hardware modules and their connections properties are explained in Section II. Section III is for explaining the mechanism for the adaptation of the modules' connection topology. Several hardware experiments are explained in Section IV, while conclusions and discussions for future studies are given in the final section.

II. Hardware Module

The objective of this study is to build robotics hardware modules that when arbitrarily connected, gradually establish a connection topology that allows them to generate a human-specified cumulative behavior as a robot. Traditionally, the process for constructing robots involves complicated and costly procedures of thoroughly designing and assembling the relevant modules. The characteristics of hardware modules in this study can potentially simplify the construction process by adaptively establishing the connection topology, thus relaxing the cost for designing.

As illustrated in Fig.1(a), each module is equipped with limited power supply, small computation resource, simple sensors, actuators and connections ports for inter-module signal exchanges. Utilizing its limited calculation resource, each module has the ability to control its actuator, thus generating simple movements. It also has the ability to adjust its movement, based on the signal exchange with other modules. The actual hardware module built in this study is shown in Fig.1(b). Each module is equipped with a microcontroller (PIC16F877-20/P), a battery, several serial ports, and an actuator. Independently, each module behaves as an oscillator with a signal exchanging behavior described in Eq.1. Hence, the collection of several connected modules can be considered as coupled-oscillators which are expected to act as a Central Pattern Generator (CPG) that generates a coordinated behavior as modular robots, as in Fig. 2. The significant difference between this study and the existing CPG's implementation for robots' behavior is that in the existing works, the connections between the oscillators have to be designed and fixed, while in this study the connections between the modules are adaptively obtained to enable the connected modules to generate a target coordinated behavior.



(a) (b)

Fig.1 Hardware Module

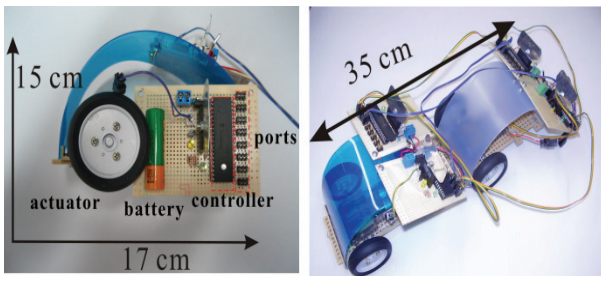


Fig.2 Modular Robots: Combination of Modules

$$\frac{d\theta_i(t)}{dt} = \omega_i - \sum_j \varepsilon_{ij} \sin\left(\theta_i(t) - \psi_{ij} + \eta(t)\right)\delta(T_j - t)$$

$$\forall i,j \;\; \varepsilon_{ij} \in \{1,0\}, \quad \epsilon_{ii} = 0 \qquad (1)$$

$$\delta(t) = \begin{cases} 1 & t = 0 \\ 0 & t \neq 0 \end{cases}$$

Here, $\theta_i(t)$ is the phase of the module i at time t, ω is the intrinsic angular velocity which is common for all the modules, and ε_{ij} denotes the asymmetric physical connection between module i and module j. In this equation, ψ_{ij} denotes the ideal phase difference between modules i and j, while $\eta(t)$ is the random perturbation introduced at time t, and T_j denotes the time when the phase of module j is 2π. Equation (1) shows that module j only sends signal to other connected modules when its phase is 2π. When a module receives a signal from another module, it modifies its angular velocity so that the phase difference between the two modules moves closer to the given ideal phase difference, ψ. Small random perturbation η is introduced to avoid the condition in which no regulatory signal is transmitted in the case of $\theta - \psi = \pi$. The phase of a module is then translated into a motory action, as illustrated in Fig.3. In this phase-action transformation, the motor attached to the module moves clockwise when the phase is in the first quadrant, and moves counter clockwise when the phase is in the third quadrant or otherwise it stays stationary.

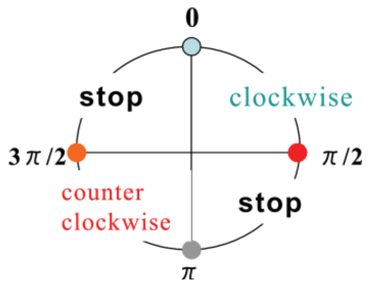


Fig.3 Phase-Action Transformation

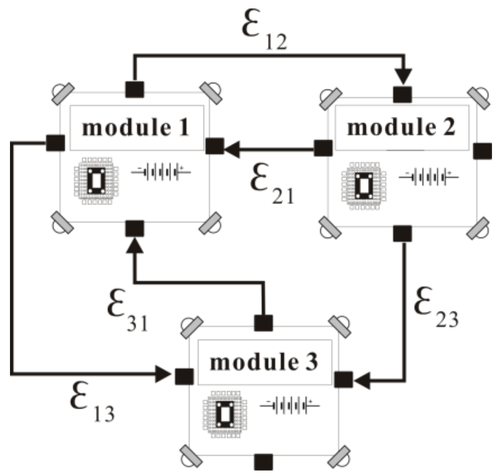


Fig. 4 Physical Connection Topology (3 modules)

Each hardware module executes signal exchanges with other modules that are physically located in its neighborhood and connected through the connection ports. Here, in executing the adaptive connection mechanism, the task of human is to set the ideal phase differences between the modules which allow this collection of modules to generate a coordinated behavior as one robot and to randomly connect the modules. It should be noted that setting the ideal phase differences between modules does not guaranty the generation of the target behavior, because the collective behavior of this collection of modules is directly dependent on the connection topology. For a given target movement of a robot, while it is relatively easy to decide the phase differences between the modules, the connection topology that supports the generation of that movement is usually hard to design.

Figure 4 illustrates an example of physical connections between three modules. The topology of the physical connections can be expressed as matrix T in Eq. 2, where * indicates the absence of the one-way physical connection between the two modules associated with the position of the * in the matrix. Here, a non * element can take the value of 1 when the connection is utilized for signal transfer or 0, when it is not.

$$T = \begin{pmatrix} * & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & * & \epsilon_{23} \\ \epsilon_{31} & * & * \end{pmatrix} \qquad (2)$$

Figure 5 is an example of a signal-exchange network that can be generated from the physical topology shown in Fig. 4, where a dotted line indicates the signal transfer between the two physically connected modules. We called the structure of the signal exchange network, *logical topology*, to distinguish it with the physical one. Once the logical topology is decided, the value of the topology matrix T in Eq. 2 can be fixed as in Eq. 3.

$$T = \begin{pmatrix} * & 1 & 0 \\ 0 & * & 1 \\ 1 & * & * \end{pmatrix} \qquad (3)$$

In this study, the adaptation mechanism is applied to the logical topology. Hence, while the physical topology must be hand-set by human, the modules are able to self-discover a logical topology that allows them to produce a coordinated behavior given as a target.

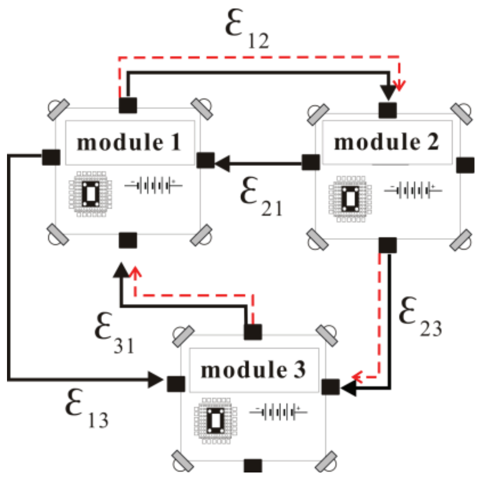


Fig. 5 Logical Topology

III. Topology Adaptation

One of the main difficulties in designing robots is the process of connecting the robots' components. If through signal exchanging process the connected components are able to adaptively regulate their independent behavior to produce a coordinated overall behavior as a robot, the design-complexity can be relaxed. In this study, we assembled various robots from several modules. The physical and logical connections are set randomly, without any consideration for inter-module network design. The modules generate independent actions according to their initial states and logical connections, and cumulatively generate an overall action as one robot. The action of the robot will be evaluated with respect to the predefined target. Based on this evaluation, each module adaptively regulates its behavior until eventually the intended overall behavior is produced. The simplicity of the modules' hardware and the limitation of their calculation resources prevent us to implement complex adaptation mechanism. Here, we implemented Simulated Annealing (SA) [20] for adaptively modifying the logical topology by flipping the value of a randomly chosen logical connection according to Eq.4, which is equivalent with severing or establishing a new logical connection, until the target behavior is reached.

$$\varepsilon'(t+1) = 1 - \varepsilon'(t) \qquad (4)$$

Here, $\varepsilon'(t)$ is a randomly chosen non-$*$ element of the topology matrix, T, at time t as a candidate for connection adaptation.

During SA process, the overall behavior of the robot is observed for a given time, τ, and evaluated with an evaluation function, $E(t)$, which compares the current behavior of the robot with the target behavior. After which, the matrix $T(t)$ is mutated by randomly choosing one element, generating a new topology $T(t+1)$. When the mutation brought an improvement in the evaluation, $E(t+1)$, the searching process of SA is restarted from the improved topology, $T(t+1)$. However, when deterioration is observed, the search process will be restarted from the inferior topology, $T(t+1)$ with a probability, p, in Eq. 5, or restarted from the original topology $T(t)$ with the probability of $1-p$

$$p = e^{-\frac{D(T(t),T(t+1))}{\alpha(t)}} \qquad (5)$$

Here, $D(T(t), T(t+1))$ measures the absolute deterioration of the robot's behavior, while $\alpha(t)$ is a monotonically decreasing function. This process will be reiterated until a stopping criterion is met.

The topology adaptation is illustrated in Fig. 6(a), while the flowchart for the topological formation in this study is shown in Fig. 6(b), where the designing procedure by human designer and the adaptive mechanisms can be distinguished.

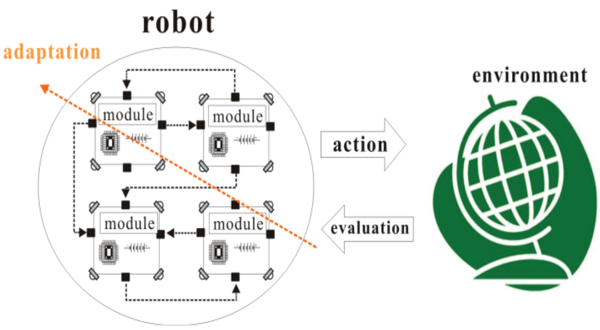


Fig. 6(a) Outline of Topology Adaptation

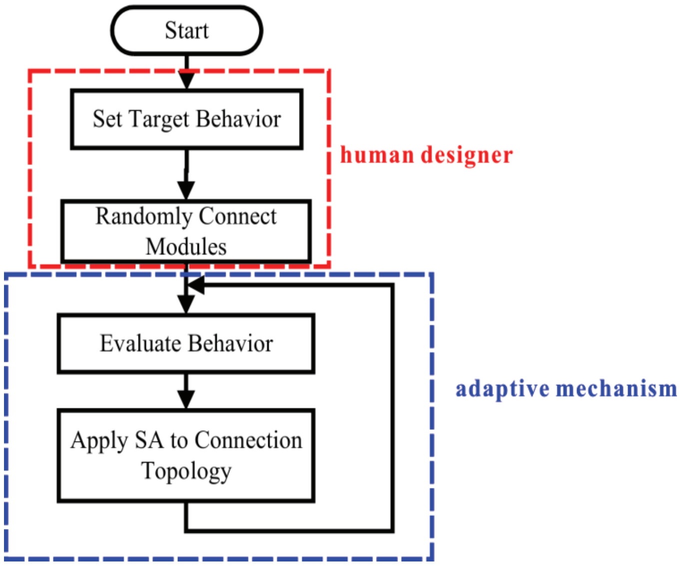


Fig. 6(b) Flowchart of Topology Adaptation

IV. Experiments

For experiments we built several module robots with different morphologies as shown in Fig. 7. Robot in Fig. 7(a) is constructed from two modules, each with a DC motor as actuator, while robot in Fig. 7(b) is the combination of six identical modules. The leg-typed robot in Fig. 7(c) is a combination of 4 modules, each with a servo motor as actuator. The robot in Fig. 7(d) is a complex combination of four servo motor-modules and two wheel-typed modules used for robot in Fig. 7(a).

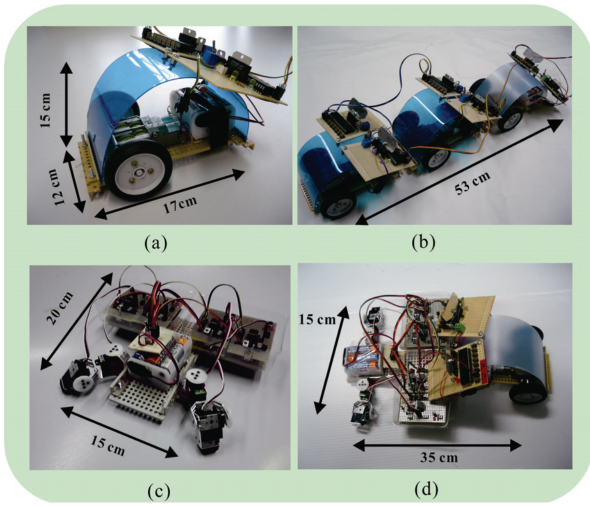


Fig. 7 Modular robots for experiments

In the experiments, the robots are tested against different evaluation functions to adaptively discover feasible connection topologies which optimized those functions. We also ran initial experiments to test the scalability and resiliency of our proposed adaptive modules.

A. Internal State-based Adaptation

For the initial experiments, we directly used the information about the phases of all the modules for the topology adaptation. Here, piston movement is given as the target behavior of the robots. Therefore, the modules have to self-discover a connection topology that allows them to synchronize their phases. The evaluation function given for the adaptation mechanism is as follows.

$$E(t) = -\sum_{i=1}^{4} p_i(t) \log p_i(t) \quad (6)$$

Here, $p_i(t)$) is the ratio of modules whose phases are in the i-th quadrant at time t, hence the evaluation $E(t)$ is the entropy of the states of the modules. Because in these experiments the objective is to generate an overall behavior where all the modules act in unison, the objective of the adaptation mechanism is to discover a feasible topology for minimizing the entropy in Eq. 6.

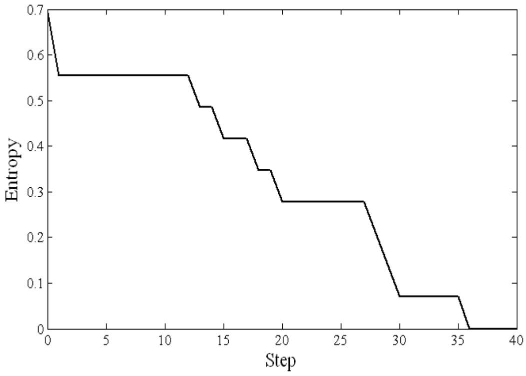


Fig. 8 Two Modules Experiment

Figure 8 shows the time development of the evaluation of the robot composed from two modules shown in Fig. 7(a) over several learning steps, where the topology is randomly initialized. It is obvious that the modules gradually discover a feasible connection topology that allows them to reach the target.

Figure 9 shows the development of the evaluation of the robot composed from six modules shown in Fig. 7(b). We can observe that while the minimization process of the evaluation function is slower than in the previous experiment, the modules are able to reach the target. Gradual topology adaptation for this experiment is shown in Fig. 10. It is clear that while the initial topology is not feasible for producing the target behavior, the final topology is.

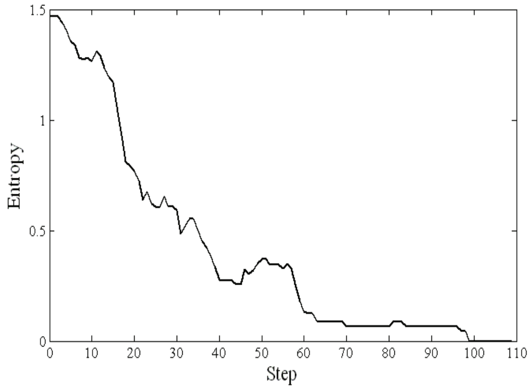


Fig. 9 Six Modules Experiment

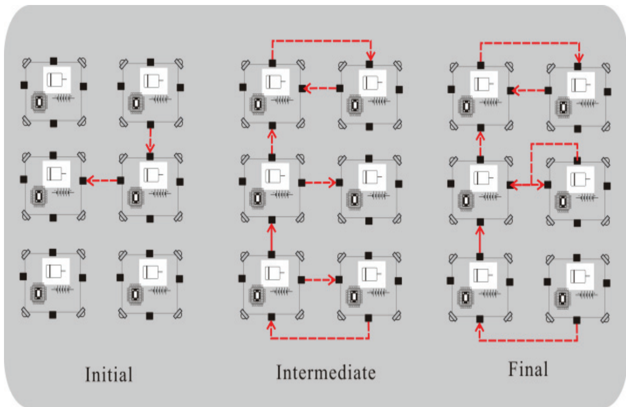


Fig. 10 Topology Adaptation (Six Modules)

We are aware that while this internal state-based adaptation is feasible for modular robots with only a few modules, the cost for monitoring all the states will not be manageable for robots with numerous modules. This problem should be solved by monitoring not the internal states of the modules but the overall behavior of the robots as the cumulative outcome of those internal states. In the next subsection we described the experiments where the evaluation function is based on the sensors attached to the robot for monitoring the overall behavior.

B. Sensor-based Adaptation

In the next experiments, we attached two acceleration sensors to observe not the individual behavior of the modules but the overall behavior of the robot, and based the evaluation feedback on this sensor's values.

We utilized leg-typed robot shown in Fig. 7(c). The task of the modules is to discover a topology that allows them to generate a crawling movement in frontal direction. Because the robot has to maximize its movement in one direction while suppressing the movement to other direction, it should maximize the evaluation function, E_1 in Eq. 7.

$$E_1(t) = \sum_{\tau=1}^{S} \left| A_x(t+\tau) - A_y(t+\tau) \right| \quad (7)$$

Here, A_x and A_y are the values of the acceleration sensors attached to the robot's frontal and side direction, respectively.

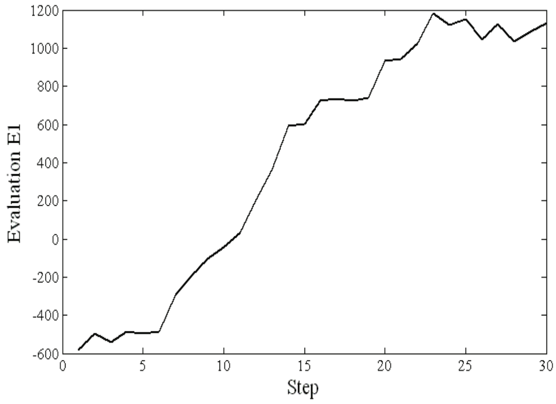


Fig. 11 Evaluation Leg Robot (Four Modules)

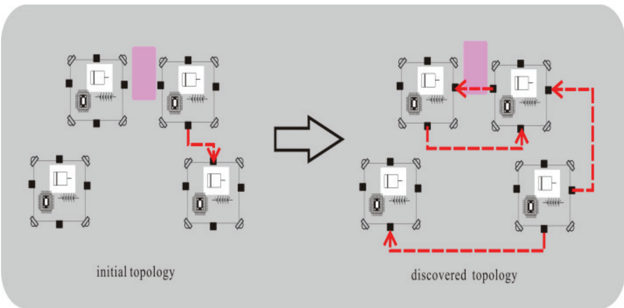


Fig. 12 Topology for Leg Robot

Figure 11 shows that the modules rapidly discovered a connection topology that enable them to maximize the given evaluation function, while Fig. 12 shows the actual topology discovery.

In the next experiment, we utilize a mix between leg and wheel modules shown in Fig. 7(d). Here, the task is to create large movements in any direction, hence the modules should maximize the evaluation function, E_2, defined as follows.

$$E_2(t) = \sum_{\tau=1}^{S} |A_x(t+\tau)| + |A_y(t+\tau)| \quad (8)$$

From Fig. 13 we can learn that the six modules were able to discover a feasible topology for generating the given target movement, while the actual topology is shown in Fig. 14.

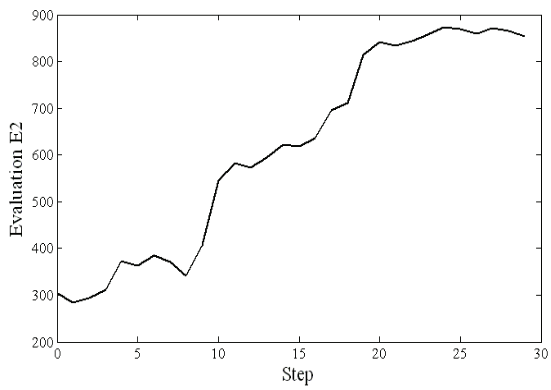


Fig. 13 Evaluation of Mix Robot (Six Modules)

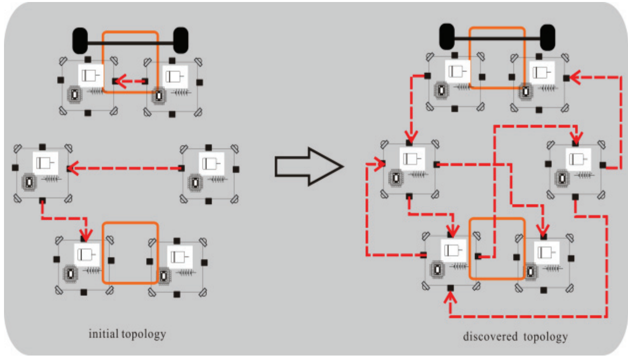


Fig. 14 Topology for Mix Robot

In the next experiment, we tested the flexibility of the proposed adaptive module. In this case, we used the leg-typed robot in Fig. 7(c), where initially only three modules are activated, while one of the modules stays dormant. After the three modules discovered a feasible topology to maximize the evaluation function in Eq. 8, we activated the dormant module. From Fig. 15, we can see that a new topology, which includes the initially dormant module, emerges. It is obvious from Fig. 16 that the newly discovered topology brings significant improvements for the robot's evaluation.

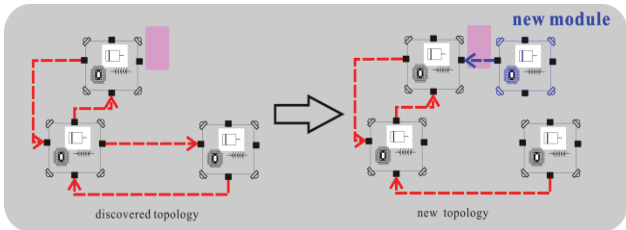


Fig. 15 New Topology

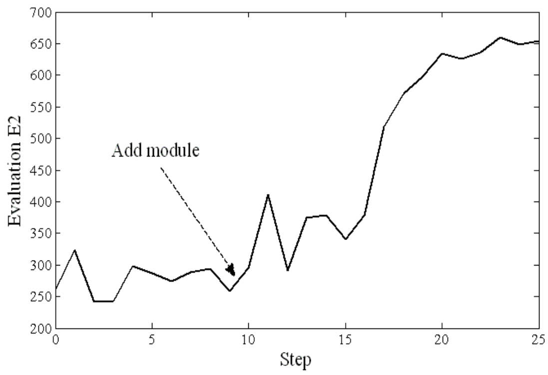


Fig. 16 Module Addition

While we only ran limited tests on the flexibility of our proposed adaptive modules, the results give a good indication for the feasibility of the proposed modules to be used as building-blocks for complex robots without having to run the costly designing process.

In the next experiment, we tested the resiliency of our adaptive modules. In this case, we also used the leg-typed robot in Fig. 7(c), where all of the four modules are activated to discover a topology that maximizes Eq. 8. After these four modules discover a feasible topology, we deliberately stop one of the modules, as explained in Fig. 17, which naturally cause a sudden drop in evaluation as shown in Fig. 18.

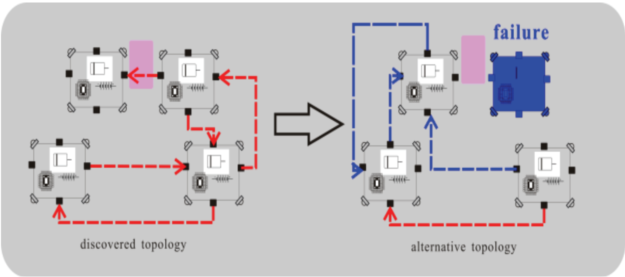


Fig. 17 Alternative Topology

However, from Fig. 17 and Fig. 18, we can observe that the three remaining modules rapidly discovered an alternative topology, which allows them to keep performing the task, albeit with a reduced efficiency. This experiment, although simple, indicates that the proposed adaptive mechanism is able to adaptively discover an alternative strategy for the robot to sustain its target movement in the face of partial failure, thus realizing graceful degradation, a property that is crucial for autonomous robots running in unstructured environments.

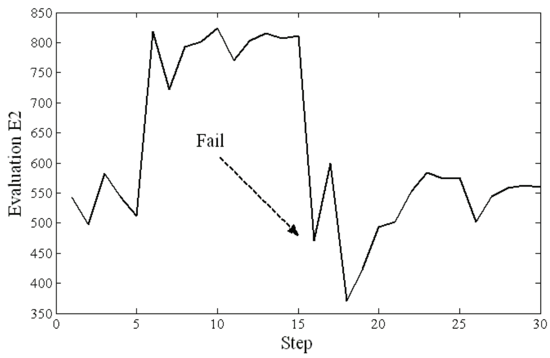


Fig. 18 Module Failure

The movies for some of the experiments are available in: **www.st.chukyo-u.ac.jp/z110118/module.html**

V. Conclusion and Future Works

In thus study, we physically built several robotics modules that can be flexibly assembled to form robots with various morphologies. These modules have a mechanism to self-discover a connection topology which enables them to generate a behavior given as the target by human designer. This adaptive topology mechanism partly relaxes the requirement to rigorously designing the connections between robotics' components. Although there are still some aspects that have to be hand-designed, our study shows the potential of the modular robotics in simplifying the conventionally complex production process of robots. We supported our arguments about the adaptive properties of our proposed hardware modules with some experiments, where we can observe that modules were able to efficiently discover feasible topologies that allow them to generate the targeted coordinated behavior. The flexibility and resiliency of the proposed mechanism are also tested through physical experiments. Our immediate future works include building not only motory modules but also sensors modules and considering a mechanism for emerging a hierarchical topology that allows the modular robots to perform more complex tasks.

References

[1]. J.v. Neumann, *Theory of Self-Reproduction Automata*, Univ. Illinois Press, Urbana (1966).

[2]. D. Floreano, C. Mattiussi, *Bio-Inspired Artificial Intelligence*, The MIT Press, Cambridge (2008).

[3]. H. Lipson, and J. Pollack, "Automatic Design and Manufacture of Robotic Lifeforms", *Nature*, Vol. 406, pp. 974-978 (2000).

[4]. V. Zykov, E. Mytilinaios, B. Adams, and H. Lipson, "Self-reproducing Machines", *Nature*, Vol. 435, pp. 163-164 (2005).

[5]. M. Yim, Y. Zhang, and D. Duff, "Modular Robots", *IEEE Spectrum*, Vol. 39, No. 2, pp. 30-34 (2002).

[6]. K. Gilpin, and D. Rus, "Modular Robot Systems", *IEEE Robotics & Automation Magazine*, Vol.17, No.3, pp. 38-55 (2010).

[7]. M. Shimizu, K. Suzuki, "A self-repairing structure for modules and its control by vibrating actuation mechanisms", *Proc. of the 2009 IEEE Intl. Conf. on Robotics and Automation (ICRA)* , pp. 4077-4082 (2009).

[8]. A. Castano, A. Behar, and P. Will, "The Conro Modules for Reconfigurable Robots", *IEEE/ASME Trans. on Mechatronics*, Vol. 7, No. 4, pp. 403-409 (2002).

[9]. M. Yim, et al., "Modular Self-reconfigurable Robot System", *IEEE Robotics and Automation Magazine*, Vol. 14, No. 1, pp. 43-52 (2007).

[10]. J. Bongard, V. Zykov and H. Lipson, "Resilient Machines Through Continuous Self-Modeling", *Science*, Vol. 314, pp. 1118- 1121 (2006).

[11]. S. Murata, et al., "Automatic Locomotion Design and Experiments for a Modular Robotic System", *IEEE/ASME Trans. Mechatronics*, Vol. 10, No. 3, pp. 431-441 (2002).

[12]. A. Kamimura, et al., "Automatic Locomotion Design and Experiments for a Modular Robotic System", *IEEE/ASME Trans. on Mechatronics*, Vol. 10, No. 3, pp. 314-325 (2005).

[13]. H. Lipson, J. Pollack, "Evolving Physical Creature" 6th International Conference on Artificial Intelligence in Design, pp. 269-285 (2000).

[14]. Y. Meng, Y. Zhang, Y. Jin, "Autonomous Self-Reconfiguration of Modular Robots by Evolving a Hierarchical Mechanochemical Model", *IEEE Computational Intelligence Magazine* , Vol. 6, No.1, pp. 43-54 (2011).

[15]. H. Guo, Y. Meng, Y. Jin, "Analysis of Local Communication Load in Shape Formation of a Distributed Morphogenetic Swarm Robotic System", *Proc. Of IEEE Congress on Evolutionary Computations*, pp. 1- 8 (2011).

[16]. A. Ijspeert, A. Crespi, D. Ryczko, and J-M. Cabelguen, "From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model", *Science*, Vol. 315, pp. 1416-1419 (2007).

[17]. A. Crespi, and A. Ijspeert, "Online Optimization of Swimming and Crawling in an Amphibious Snake Robot", *IEEE Trans. on Robotics*, Vol. 24, No. 1, pp. 75-87 (2008).

[18]. P. Hartono, and A. Nakane, "Modular Robots with Adaptive Connection Topology", *Proc. Int. Conf. on Hybrid Intelligent Systems*, pp. 191-196 (2010).

[19]. P. Hartono, and A. Nakane, "Adaptive Coupled Oscillators for Modular Robots", *IEEJ Trans. on Electronics, Information and Systems* (in press) (2011)

[20]. S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, "Optimization by Simulated Annealing", *Science*, Vol. 220, No. 4598, pp. 671-680 (1983).

Acknowledgment

The authors would like to thank Support Center for Advanced Telecommunication Research (SCAT) for supporting this study.

Author Biographies

Pitoyo Hartono received B.Eng., M. Eng. and Dr. Eng. degrees in Pure and Applied Physics from Waseda University, Tokyo, Japan in 1993, 1995 and 2002, respectively. He worked for Software Development Center, Hitachi, Ltd, during 1995-1998. From 2001-20023 he was a Research Associate in Advanced Research Institute for Science and Engineering, Waseda University and from 2003-2005 was a Visiting Lecturer in Comprehensive Research Association, Waseda University. He was an Associate Professor in Future University Hakodate, Hakodate, Japan from 2005-2010, and currently is a Professor in School of Information Science and Technology, Chukyo University, Toyota, Japan. His research interests include, machine learning, adaptive and evolutionary robotics, and intelligent interfaces.

Aito Nakane received his Bachelor and Master degrees from School of Systems Information Science Future University Hakodate, Hakodate Japan, in 2008 and 2010, respectively. From 2010 he joined Hitachi ULSI Co., Ltd as an engineer.