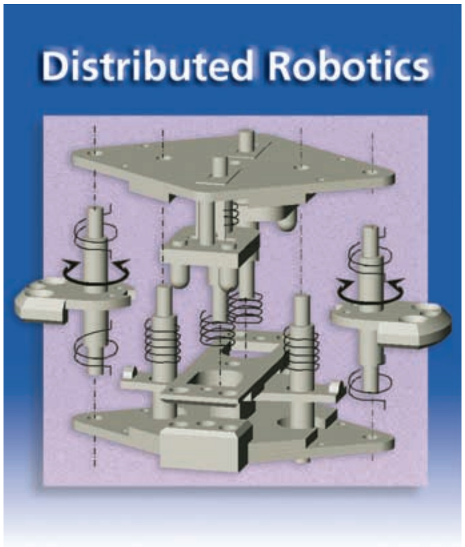

Get Back in Shape!

A Hardware Prototype Self-Reconfigurable Modular Microrobot that Uses Shape Memory Alloy

By EIICHI YOSHIDA, SATOSHI MURATA, SHIGERU KOKAJI, AKIYA KAMIMURA, KOHJI TOMITA, and HARUHISA KUROKAWA

Self-reconfigurable robotic systems composed of multiple modules have been investigated intensively with respect to their versatility, flexibility, and fault-tolerance. In particular, recent studies examined their feasibility through hardware and software experiments [1]-[6]. Homogeneity enables the system to adapt itself to the external environment by changing its configuration. It can also repair itself if some part becomes faulty or damaged, as any module can function as any part in the system. This article focuses on a microsized model of a self-reconfigurable homogeneous modular robot that opens up many applications, such as inspection robots in hazardous environments or microscale simple manipulators. One example of an application is a microrobot that moves around inside pipes in nuclear or chemical plants by changing its shape and reorganizing itself as a manipulator to execute repairing tasks when it detects a fault (Fig. 1). Other applications include a robot that searches for survivors through narrow spaces in buildings destroyed by natural disasters and space applications like microsize planetary exploring robots, solar panels, or satellite antennas.

Recently developed lightweight self-reconfigurable modular robots [2], [4], [6] use conventional electromagnetic motors that have limitations in microsizing; they become ineffective because the power-weight ratio decreases significantly on microscales. Moreover, self-reconfigurable microrobots require actuators that yield enough torque and motion range to transport other modules. These severe requirements have been major barriers to developing self-reconfigurable microrobots. Although some microscale self-assembly systems have been reported [7], they are passively assembled to predetermined shape by surface tension in an irreversible manner and cannot form arbitrary shapes.

To develop a modular microrobot that can *actively* reconfigure itself, we adopt an actuating mechanism driven by a shape memory alloy (SMA). One of the advantages of an SMA actuator is that it keeps a higher power-weight ratio on microscales than electromagnetic motors [8]. It is especially difficult to find micromotors that have comparable size and torque to our second micromodule model, which is described later in this article. The simplicity of the overall actuator mechanism is another advantage, whereas microsize electromagnetic mechanisms require microsize gear reductions that are difficult to fabricate. In addition, the slow response (especially in cooling) becomes less significant as the ratio of surface area to volume becomes large on microscales.

Although several types of SMA microactuators have been developed [8], [9], it is still difficult to provide the sufficient torque and wide motion range required for self-reconfigurable microrobots. Therefore, we devised a rotational actuator mechanism using SMA torsion coil springs that satisfies both requirements of torque and motion area. Using this SMA actuator, we designed two-dimensional (2-D) modules that measure $4 \times 4 \times 8$ cm and weigh 80 g, respectively. Each module is equipped with a microprocessor and an intermodule communications device. The self-reconfiguration capacity of the modules will be verified by a multimodule experiment. To confirm the ease of microsizing SMA actuators, we developed a half-size model of the first model. The half-size module measures 2 cm^3 and weighs 15 g without the control unit. Its self-reconfiguration function

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will be verified through an experiment. Extension to three dimensions will also be discussed.

Module Mechanism

We have designed the modules' mechanism to be both self-reconfigurable and simple enough for microsizing. It is also designed to be homogeneous so that any module can function as any part in the overall robotic system.

The module is square, and two actuators at orthogonal vertices rotate male connecting parts that can be connected to female parts in another module. Fig. 2 shows a "step motion"; this is the most basic motion by which one module (M1) connected to another module (M2) changes its connection point from one vertex to another of M2. This example shows a clockwise step motion that is made by the following operations of male connecting parts A and B.

- M2 rotates B 90° counterclockwise (CCW)
- M1 rotates itself clockwise (CW) by rotating A by 90°, and M2 connects B to M1
- M2 rotates B 90° CW after M1 releases A from M2.

By repeating these steps, a collection of modules can generate various 2-D shapes and motions. As shown in Fig. 3(a), a modular structure can move on a rough terrain by adapting its shape through motions of modules at the perimeter. Fig. 3(b) illustrates an example of simple object handling and transportation, assuming coordinated fine control and sufficient torque of actuators.

Actuator Mechanism Using SMA

This actuator should have a broad rotation range of ±90° with enough torque to carry another module even on microscales. Therefore, we devised an actuator mechanism by using two antagonistic SMA torsion coil springs (Fig. 4). The SMA torsion coil springs memorize the 0° rotation shape in this case and are preloaded by twisting by 180°. Without heating, the static torques balance and generate no torque. In this state, the connecting part is fixed at the original 0° position by a mechanical stopper.

The rotation takes place when one of the springs is heated, usually by electric current. It is known that the spring constant of a torsion coil spring k_τ kgf-mm/degree is proportional to Young's modulus E, as

$$k_\tau \text{ kgf-mm/degree} = \pi d^4/(11{,}520nD)E,$$

where d and D are the wire and spring diameters, and n is the number of turns. Since Young's modulus of SMA increases by a large amount when the temperature exceeds its phase transformation temperature, the heated spring generates torque in

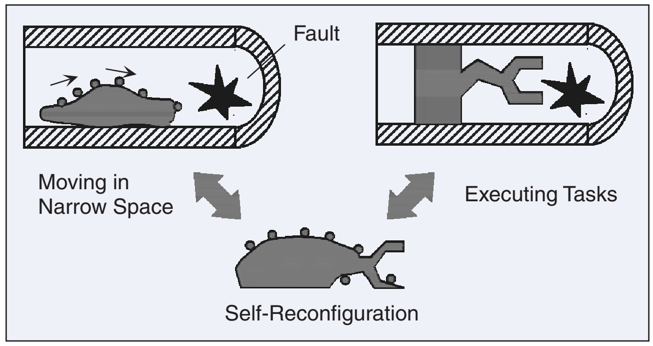

Figure 1. Applications of a micro self-reconfigurable robotic system.

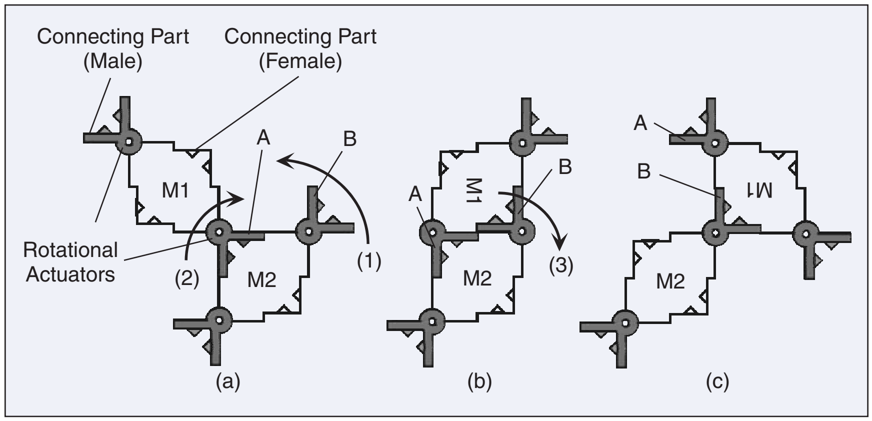

Figure 2. "Step motion" of two modules.

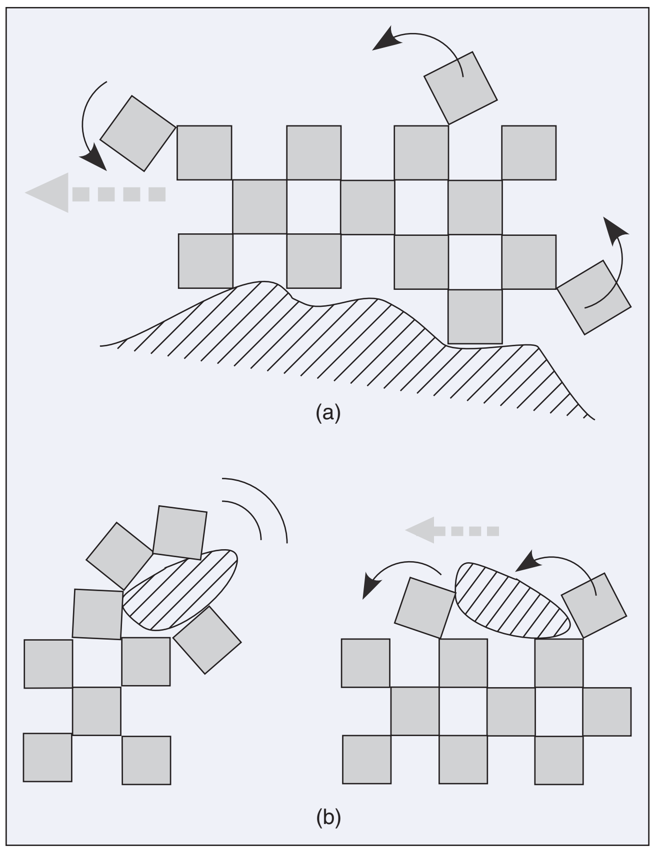

Figure 3. Various shapes and movements generated by self-reconfigurable modules. (a) Moving. (b) Handing and transporting an object (with fine control of SMA).

the direction to restore the memorized 0° shape. The rotation of 90° can be guaranteed by using a stopper mechanism. We can estimate that the actuator can generate enough torque to carry another module for self-reconfiguration, as described later in this article.

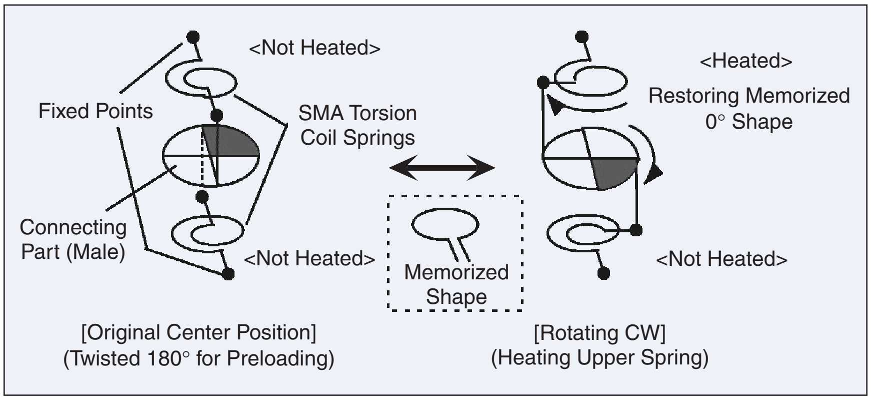

Figure 4. *Rotating actuator mechanism using SMA torsion coil springs.*

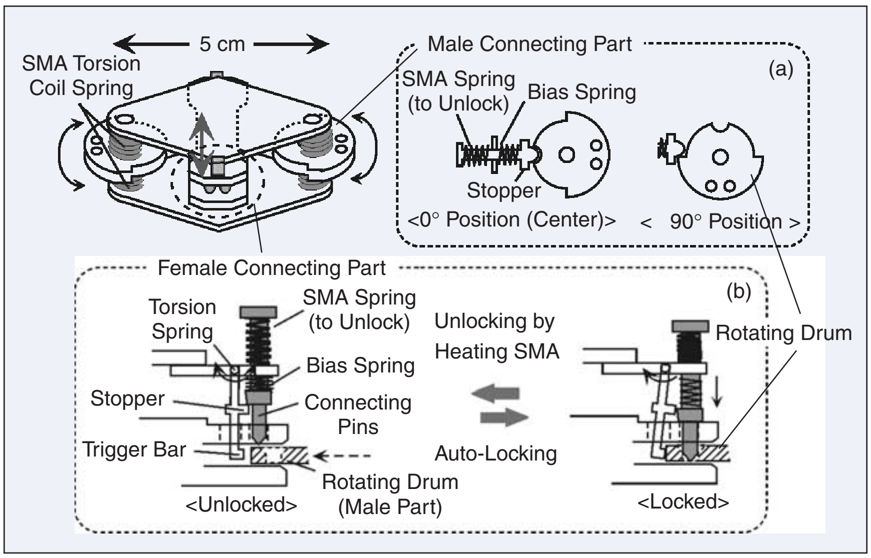

Figure 5. *Structure of the prototype module.*

Hardware Implementation and Experiments

We developed prototype modules and conducted multimodule experiments to verify their self-reconfiguration functions. Fig. 5 shows a schematic view of one such module. The module is equipped with two SMA actuators at the orthogonal vertices that rotate the drums (male connecting parts). The original 0° position of a rotating drum is rigidly maintained by a stopper. Rotation becomes possible when the stopper is pulled back by heating the connection-releasing SMA spring [Fig. 5(a)]. The stopper also limits the drum rotation within the range from −90 to +90°. The female connecting part has an auto-locking mechanism, also driven by an SMA, that can hold and release the drum of a male connecting part [Fig. 5(b)]. Since the modules can mechanically maintain the configuration using the locking connection mechanism, energy-consuming SMA heating is required only for moving modules during the reconfiguration process. This minimizes the energy consumption of the overall microrobotic system.

A module consists of a motion generation part and a control unit (Fig. 6). The SMAs are driven by pulsewidth modulation (PWM) (50 Hz, duty ratio 40%) through low-resistance metal- oxide-semiconductor field-effect transistors (MOSFETs) (4 mΩ). The mean current measured in the power supply was approximately 2 A for an input voltage 3 V per SMA. The response of the actuator mechanism was prompt enough to complete 90° rotation within 6 s. Each module is equipped with a controller using a microprocessor BasicStamp II (Parallax Inc.) using a PIC16C57 processor (Microchip Technology, Inc.) (Fig. 7). It allows a module to serially communicate with a wired host PC, as well as with other connecting modules through connecting pins and electrodes embedded in rotating drums (Fig. 8). In the current implementation, each module is connected to the host PC that gives motion commands and an outside power supply through tethers.

We can apply the distributed self-reconfiguration and self-repair algorithms we have developed so far [1], [3]. Due to

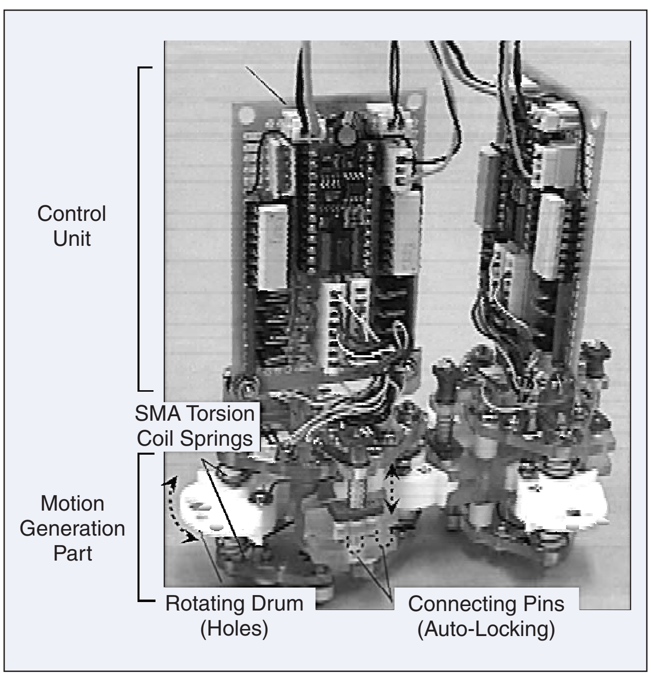

Figure 6. *Overview of prototype module (First model).*

shortage of space, we do not go into details here, but their effectiveness has been experimentally shown. These algorithms basically take the following three steps; each module:

1) collects local information by communicating with neighboring modules and using sensors if available
2) decides its behavior, to move or not, and in which direction, if it moves, based on local information in a distributed manner through local negotiation if necessary
3) makes the planned motion through local coordination (Fig. 9).

Although the algorithms can be implemented in each module by using more powerful processors in future development, only the low-level control of Step 3 is implemented in the current prototype. Here, a host PC plans the self-reconfiguration motions and sends commands to each module as a sequence of locally coordinated operations. When a module receives the command to make a step motion (CW or CCW rotation), the module sends signals to neighboring modules so that the motion may be supported by rotating and releasing the appropriate male and female connecting parts. In the example in Fig. 9, module M1 intends to move CCW, so it sends signals asking "releasing" to M3 and "rotate CCW" to M2.

We performed several multimodule experiments to verify the fundamental self-reconfiguration capacity of the developed modules. As shown in Fig. 10, we have confirmed that the desired target state was realized by repeating step motions in an experiment where a collection of modules changes its configuration from the initial to the target state on a horizontal plane.

Further Microsizing—Half-Size Module

As mentioned earlier, the SMA actuator has advantages of both power-weight ratio and response, especially on smaller scales. In pursuit of wider applications requiring motion or tasks in narrow spaces, we are attempting further microsizing of the modules.

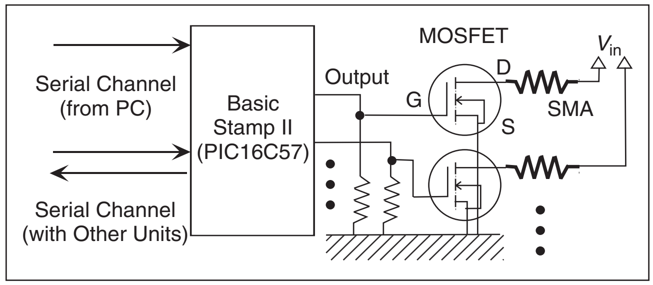

Figure 7. Control unit architecture.

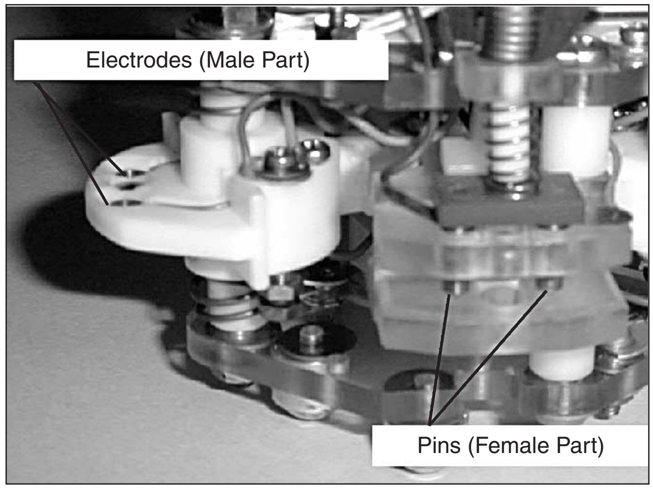

Figure 8. Intermodule connection for communication.

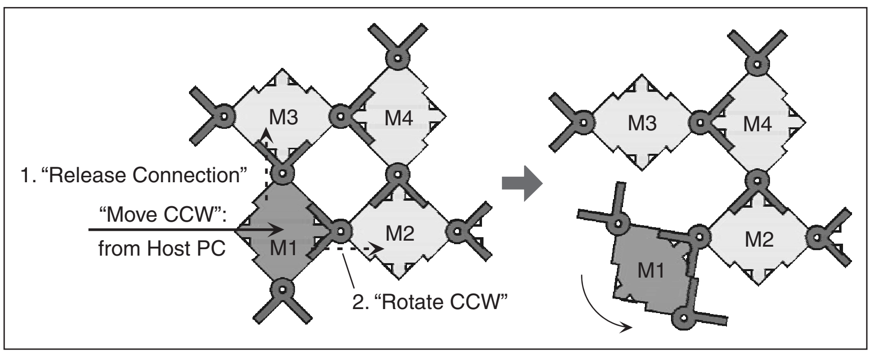

Figure 9. Local motion coordination through intermodule communication.

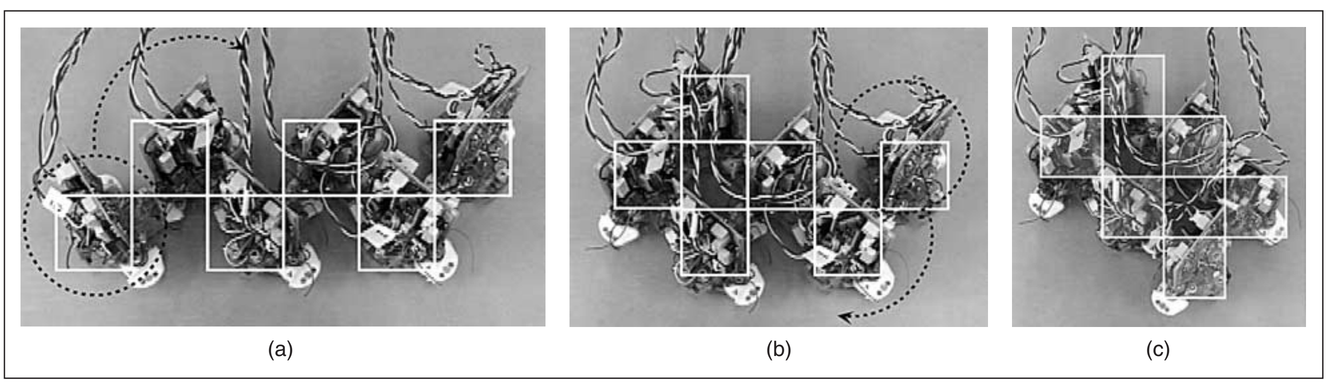

Figure 10. Self-reconfiguration experiment using six modules. (a) Initial state. (b) Transient state. (c) Self-reconfiguration completed.

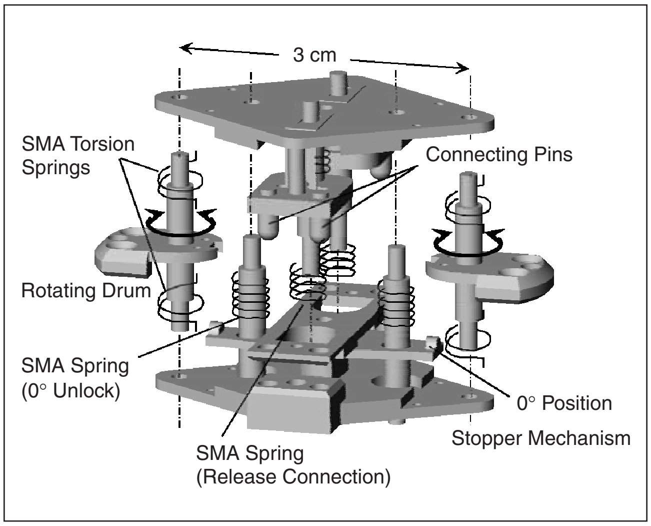

Figure 11. *Structure of micromodule (second model).*

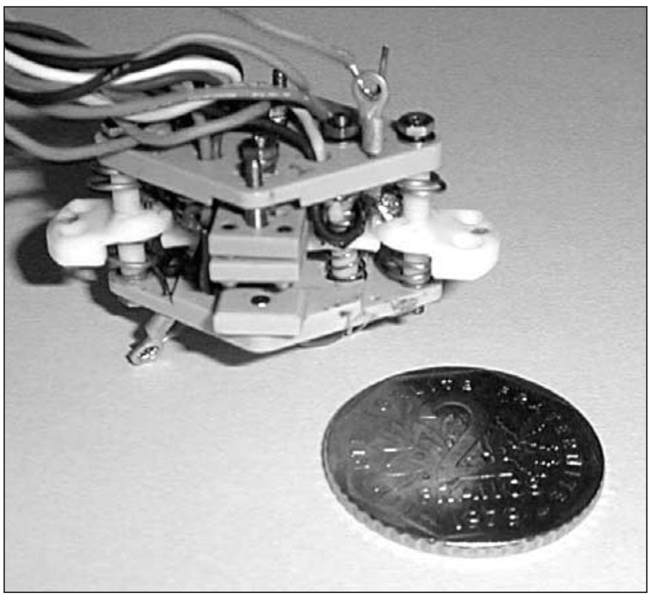

Figure 12. *Prototype of micromodule.*

Fig. 11 illustrates the second model of a self-reconfigurable microrobot. While the basic mechanisms are the same as in the first model, there are some differences in stopper mechanisms to lock and unlock rotating drums and connecting pins. These parts were redesigned to be simple enough for further microsizing. As in the first model, the original 0° position and connection are maintained rigidly by locking mechanisms. Therefore, the SMAs need only be heated when moving modules during self-reconfiguration.

Fig. 12 shows a prototype of the second model of a microrobotic module. It measures 2 cm^3 and weighs 15 g. The module currently does not include an onboard microprocessor but is driven by a separate control unit that is the same as that of the first model. The feasibility of the step motion of self-reconfiguration was confirmed by two modules (Fig. 13).

Through the experiments, we confirmed that the measured torque using a torque gauge resulted within the estimated ranges to transport another module against gravity. For example, the second model of the micro module uses SMA three-turn springs of wire. The spring diameters are 0.45 and 4.5 mm with 270° preloading angle. The average measured torque at 0° rotation was 1.1 kgf-mm, where the estimated torque range, calculated using Young's modulus of Ti-Ni-Cu SMA varying between certain values (0 ~ 1,800 and 7,000 ~ 10,000 kgf/mm^2 for heated and nonheated states), is 0.9 ~ 1.9 kgf-mm. This is enough to lift another module, whose weight and span is 15 g and 30 mm, against gravity.

As to the response time and power consumption, the time required for 90° rotation is reduced from 6 to 3 s, and the current per SMA actuator is reduced from 2 to 1 A. This validates that microsizing the module improved the response and power consumption.

Extension to Three Dimensions

We can design a module that can configure 3-D structures by combining three of the proposed 2-D square modules into a regular octahedron that can be connected at its vertices, as shown in Fig. 14. This extension needs the current 2-D con-

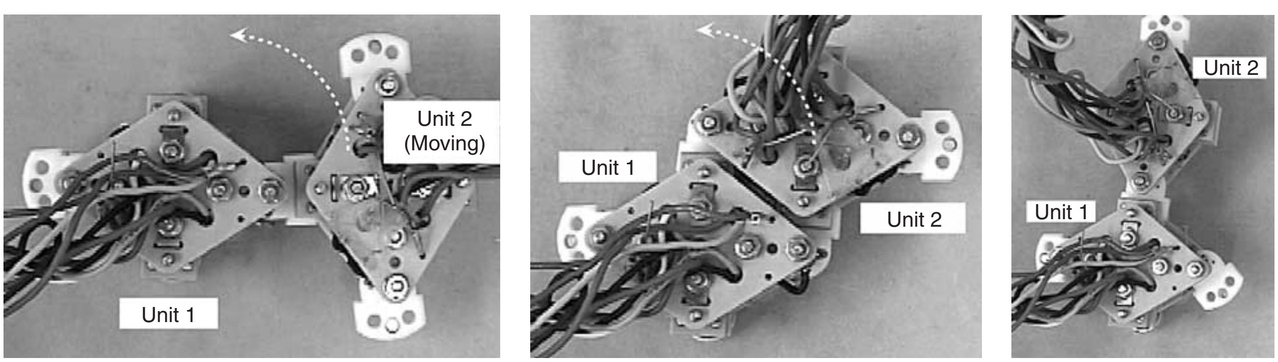

Figure 13. *Experiment of basic motion by two microsize modules.*

necting mechanism to be redesigned so that two male parts meeting at the vertex with right angles can interconnect with each other. The SMA actuator should also be properly designed to generate sufficient torque.

The 3-D modules rotate in vertical and horizontal directions around the connecting vertex, as shown in Fig. 15, in the same way as the 2-D step motion. A group of modules can move on an orthogonal cubic lattice and form various 3-D shapes (Fig. 16).

This motion in 3-D lattice space turned out to be compatible with that of the formerly developed 3-D self-reconfigurable modular structure [3]. While the previously developed 3-D module needs at least one other module to make a motion, the octahedral 3-D module can change its position by itself and has fewer constraints on self-reconfiguration. Therefore, the distributed self-reconfiguration methods [1], [3] developed for the previous 3-D modular structure can be applied to the octahedral 3-D modules. The computer simulations showed the validity of the self-reconfiguration and self-repair by many modules based on these distributed methods. We leave their details to the referenced papers.

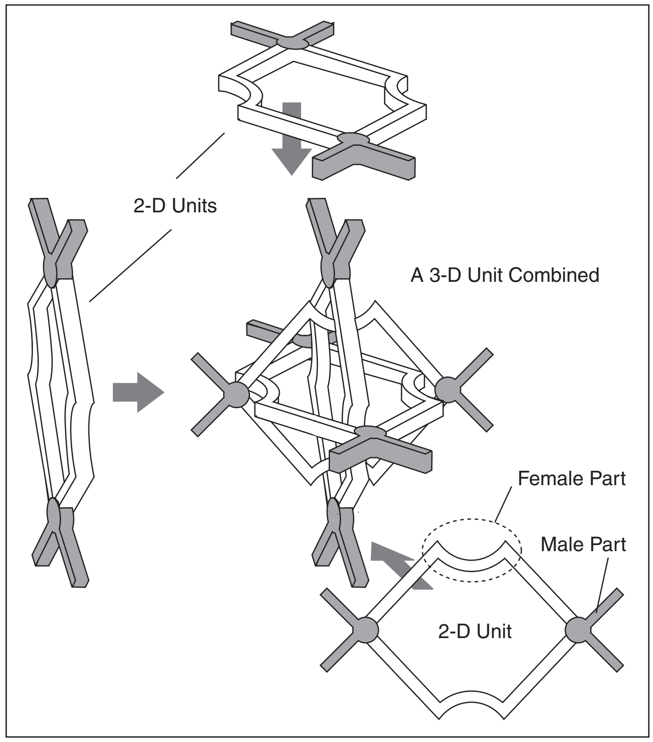

Figure 14. *A 3-D module composed of three 2-D SMA modules.*

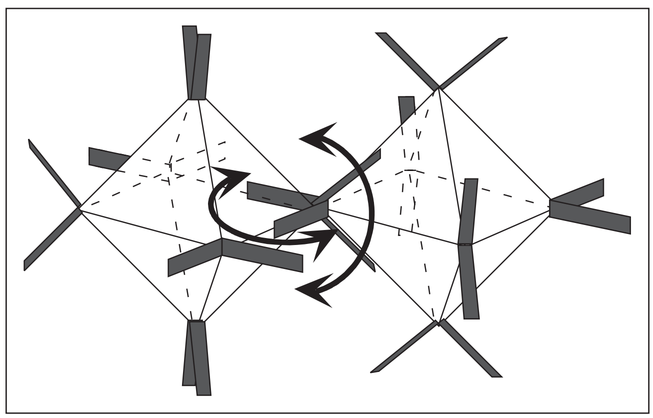
Figure 15. *Connected modules.*

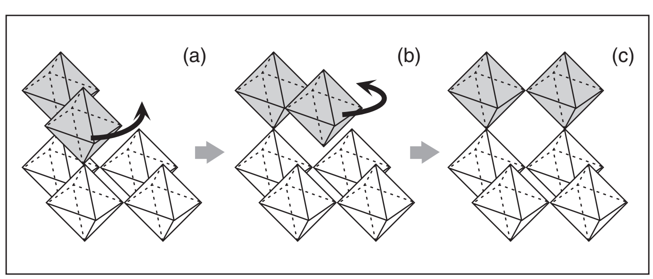

Figure 16. *Motion of 3-D SMA modules.*

Conclusion

This article presented a self-reconfigurable, modular microrobot based on SMA actuators. A new type of actuator mechanism was developed using SMA torsion coil springs that can provide sufficient torque and motion range required for self-reconfiguration. We implemented a hardware prototype of a 2-D modular microrobot, and each module is equipped with a control unit that drives actuators and facilitates intermodule communication. The fundamental functionality of a modular microrobot was verified through multimodule experiments of self-reconfiguration by using the first model. Further microsizing was also investigated by developing a 2-cm^3 second prototype that successfully demonstrated the step motion of self-reconfiguration. We also addressed an extended 3-D self-reconfigurable microrobot.

Future work includes issues concerning autonomy from aspects of power supply and computing. As to power supply, we are first going to reduce tethers by redesigning the electrode so that power can be distributed through them, and also by improving efficiency of SMA heating using microheaters, for instance. Looking at recent technical trends, we can expect that advances in such technologies as micro fuel cell or wireless energy supply will solve the energy problem to remove tethers in future. Microsizing the control unit with more computing power should also be addressed to implement autonomous distributed computing.

Another future development is the equipment of modules with sensors. There are possibilities of adding some simple tactile or proximity sensors to each module and mounting more complex sensors like cameras to a few specific modules. Precise control of SMA actuators using encoder sensors is also important to realize more dextrous manipulation.

To develop a modular microrobot that can actively reconfigure itself, we adopt an actuating mechanism driven by an SMA.

Keywords

Self-reconfigurable robot, microrobot, modular robot, SMA actuator.

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Eiichi Yoshida received B.E., M.E., and Dr. Eng. degrees in precision machinery engineering from the University of Tokyo in 1990, 1993, and 1996, respectively. From 1990-1991, he was with the Department of Microtechnique at Swiss Federal Institute of Technology at Lausanne (EPFL). He joined the Mechanical Engineering Laboratory, AIST, MITI in 1996, and since 2001, he has been conducting research at the National Institute of Advanced Industrial Science and Technology (AIST). He received the Best Paper Award at the 1998 International Symposium on Distributed Autonomous Robotic Systems (DARS '98) and Inoue Research Award for Young Scientists from the Inoue Foundation for Science, Japan, in 1999. His research interests include decentralized autonomous systems and modular robotics.

Satoshi Murata received B.E., M.E., and Dr. Eng. degrees in aeronautical engineering from Nagoya University, Nagoya, Japan, in 1984, 1986, and 1997, respectively. In 1986, he joined the Mechanical Engineering Laboratory, AIST, MITI. Since 2001, he has been an associate professor at the Tokyo Institute of Technology. His interests include distributed mechanical systems, modular robotics, and graph automata. He received the IEEE-IE Outstanding Paper Award and SICE Outstanding Paper Award in 1991 and 1996, respectively.

Shigeru Kokaji received B.E., M.E., and Dr. Eng degrees in precision machinery engineering from the University of Tokyo in 1970, 1972, and 1986, respectively. He is currently the deputy director of the Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology (AIST). His research interests include distributed control of mechanical/robotic systems.

Akiya Kamimura received M.E. and Dr. Eng. degrees from the Graduate School of Engineering at the University of Tokyo in 1997 and 2000, respectively. He joined the Mechanical Engineering Laboratory, AIST, MITI, in 2000 and has been conducting research at the National Institute of Advanced Industrial Science and Technology (AIST) since 2001. His research interests include modular robotics and rapid prototyping systems. He received the Best Paper Award in 2002 at the International Symposium on Distributed Autonomous Robotic Systems (DARS '02).

Kohji Tomita received the B.E., M.E., and Ph.D. from the University of Tsukuba in 1988, 1990, and 1997, respectively. He joined the Mechanical Engineering Laboratory, AIST, MITI, in 1990 and has been conducting research at the National Institute of Advanced Industrial Science and Technology (AIST) as a senior research scientist since 2001. He was a visiting researcher at Dartmouth College from 2000-2001. His research interests include modular robots, distributed software systems, and graph automata.

Haruhisa Kurokawa received a B.E and an M.E in precision machinery engineering, and a Dr. Eng. in aero- and astronautical engineering from the University of Tokyo in 1978, 1981, and 1997, respectively. He is currently the head of the Distributed System Design Research Group, Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology (AIST) 2001. His main research subjects are kinematics of mechanisms, distributed autonomous systems, and nonlinear control.

Address for correspondence: Eiichi Yoshida, Distributed System Design Research Group, Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology (AIST), 1-2 Namiki, Tsukuba-shi, Ibaraki 305-8564 Japan. E-mail: e.yoshida @aist.go.jp.