Get Back In Shape! – A Hardware Prototype Self-Reconfigurable Modular Microrobot that Uses Shape Memory Alloy –

Eiichi Yoshida* Satoshi Murata** Shigeru Kokaji*
Akiya Kamimura* Kohji Tomita* Haruhisa Kurokawa*

* 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
** Department of Computational Intelligence and Systems Science,
Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology
4259 Nagatsuda Midori-ku, Yokohama, 226-8502 Japan
e-mail: murata@dis.titech.ac.jp

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 paper focuses on a micro-sized model of a self-reconfigurable homogeneous modular robot, which opens up many applications, such as inspection robots in hazardous environments or micro-scale simple manipulators. One example of an application is a micro-robot that moves around inside pipes in nuclear or chemical plants by changing its shape, and reorganizes itself as a manipulator to execute repairing tasks when it detects some fault as illustrated in Fig. 1. Other applications include a robot that searches for survivors through narrow spaces in buildings destroyed by natural disasters, and also space applications like micro-size 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 micro-sizing: They become ineffective because the power-weight ratio decreases significantly on micro-scales. Moreover, self-reconfigurable micro-robots require actuators that yield enough torque and motion range to transport other modules. These severe requirements have been major barriers to developing self-reconfigurable micro-robots. Although some micro-scale 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 micro-robot 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 micro-scales than electromagnetic motors [8]. It is especially difficult to find micro-motors that has comparable size and torque to our second micro-module model. The simplicity of the overall actuator mechanism is another advantage whereas micro-size electromagnetic mechanisms require micro-size 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 micro-scales.

Although several types of SMA micro-actuators have been developed [8, 9], it is still difficult to provide the sufficient torque and the wide motion range required for self-reconfigurable micro-robots. We therefore 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 modules that measure 4×4×8cm and weigh 80g respectively. Each module is equipped with a microprocessor and inter-module communications device. The self-reconfiguration capacity of the modules will be verified by a multi-module experiment. To confirm the ease of micro-sizing SMA actuators, we developed a half-size model of the first model. The half-size module measures 2cm cube and weighs 15g without the control unit. Its self-reconfiguration function will also be verified

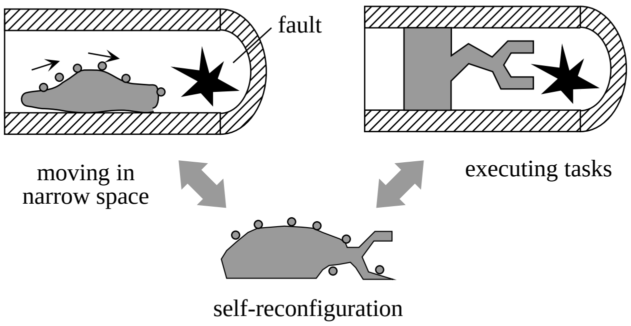


Fig. 1: Applications of a micro self-reconfigurable robotic system.

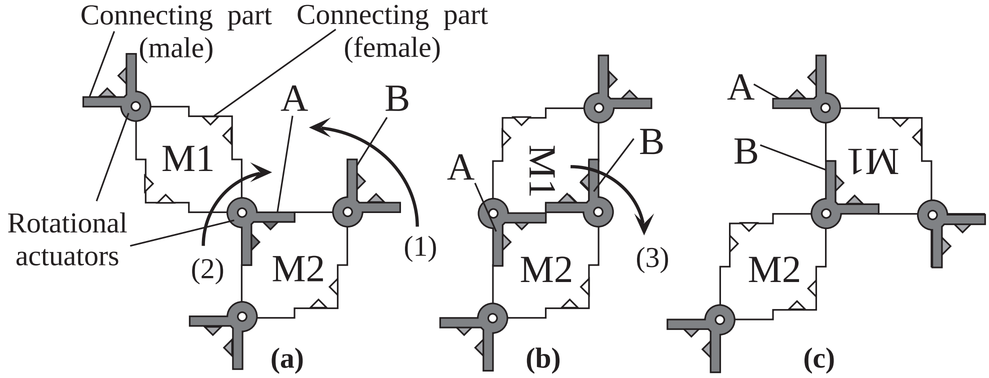


Fig. 2: “Step motion” of two modules.

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 micro-sizing. 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. Figure 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, which is made by the following operations of male connecting parts A and B.

(1) M2 rotates B 90° counterclockwise (CCW),

(2) M1 rotates itself CW by rotating A by 90° and M2 connects B to M1,

(3) M2 rotates B 90° CW after M1 releases A from M2.

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

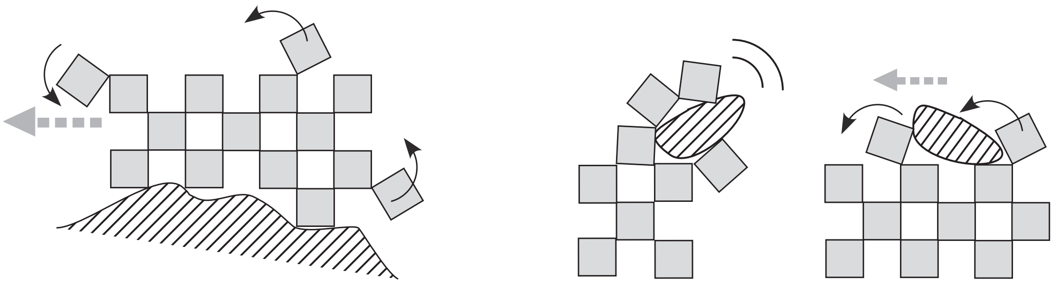
Actuator Mechanism using SMA

This actuator should have a broad rotation range of ±90° with enough torque to carry another module even on micro-scales. Therefore, we devised an actuator mechanism by using two antagonistic SMA torsion coil springs as shown in Fig. 4. The SMA torsion coil springs memorize the 0° rotation shape in this case and are pre-loaded 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/deg is proportional to Young's modulus E, as k_τ kgf·mm/deg = $\frac{\pi d^4}{11520nD}E$, 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 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 shown later.

Hardware Implementation and Experiments

We developed prototype modules and conducted multi-module experiments to verify their self-reconfiguration functions. Figure 5 shows a schematic view of one such module. The module is equipped with two SMA actuators at the orthogonal vertices which rotate the drums (male connecting parts).



(a) Moving

(b) Handing and transporting an object
(with fine control of SMA)

Fig. 3: Various shapes and movements generated by self-reconfigurable modules.

The original 0° position of a rotating drum is maintained rigidly by a stopper. Rotation becomes possible when the stopper is pulled back by heating the connection-releasing SMA spring as illustrated in Fig. 5a. 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 SMA, that can hold and release the drum of a male connecting part (Fig. 5b). Since the modules can mechanically maintain the configuration using the locking connection mechanism, the energy-consuming SMA heating is required only for moving modules during the reconfiguration process. This minimizes the energy consumption of the overall micro-robotic system.

A module consists of a motion generation part and a control unit as shown in Fig. 6. The SMAs are driven by PWM (50Hz, duty ratio 40%) through low-resistance MOS-FETs (4mΩ). The mean current measured in the power supply was approximately 2A for an input voltage 3V per SMA. The response of the actuator mechanism was prompt enough to complete 90° rotation within six seconds. Each module is equipped with a controller using PIC microprocessor BasicStamp II as shown in 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 as shown in 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 shortage of space, we do not go into details, but their effectiveness have 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

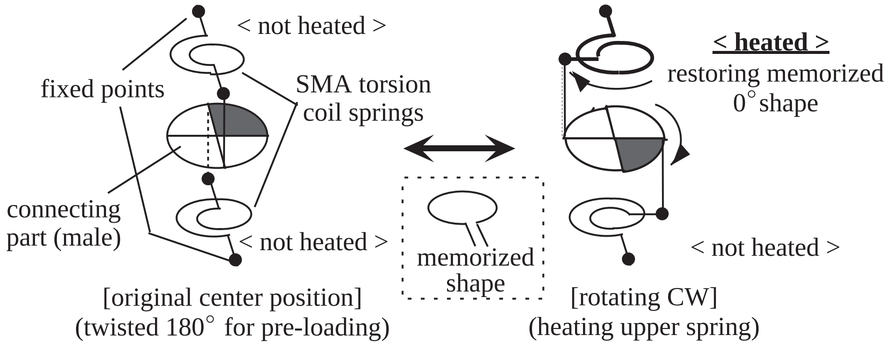


Fig. 4: Rotating actuator mechanism using SMA torsion coil springs.

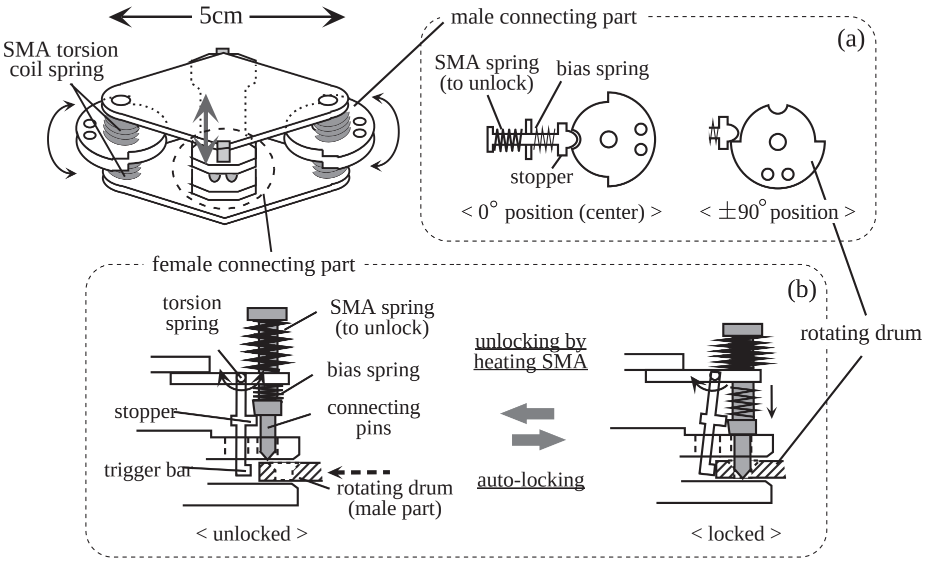


Fig. 5: Structure of the prototype module.

available,

(2) decides its behavior, to move or not, 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 processor in future development, only the low-level control of step 3 is implemented in the current prototype. Here,

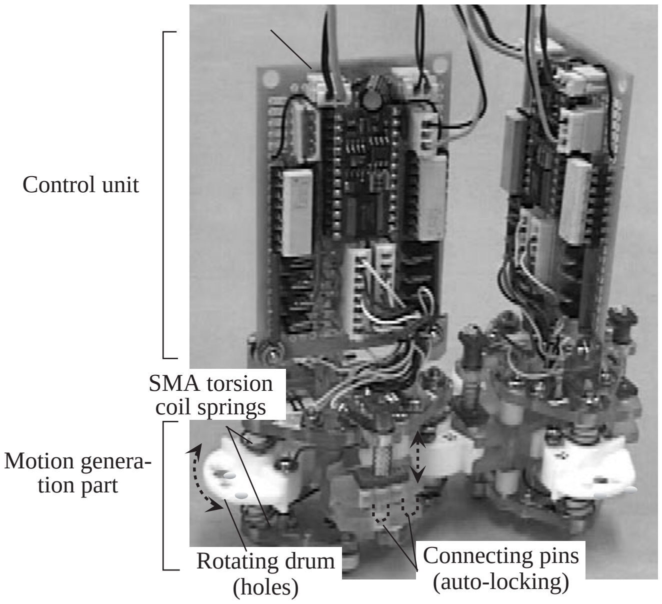


Fig. 6: Overview of prototype module (1st model).

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 (clockwise or counterclockwise rotation) the module sends signals to neighboring modules so that the motion may be supported by rotating and releasing of appropriate male and female connecting parts. In the example in Fig. 9, module M1 intends to move counterclockwise, so it sends signals asking “releasing” to M3 and “rotate counterclockwise” to M2.

We performed several multi-module 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 Micro-sizing: 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 micro-sizing of the modules.

Figure 11 illustrates the second model of a self-reconfigurable micro-robot. 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 micro-sizing. As in the first model, the original 0° position and connection are maintained

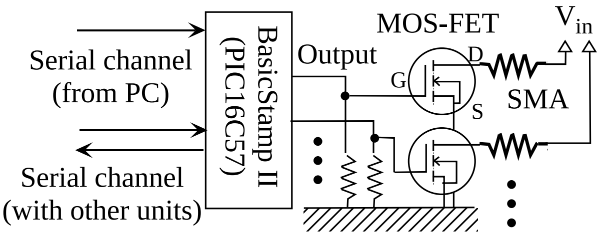


Fig. 7: Control unit architecture.

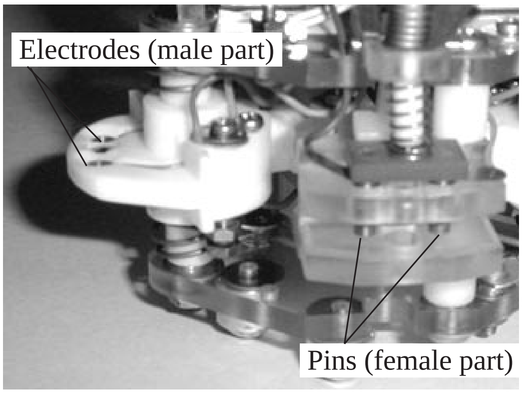


Fig. 8: Inter-module connection for communication.

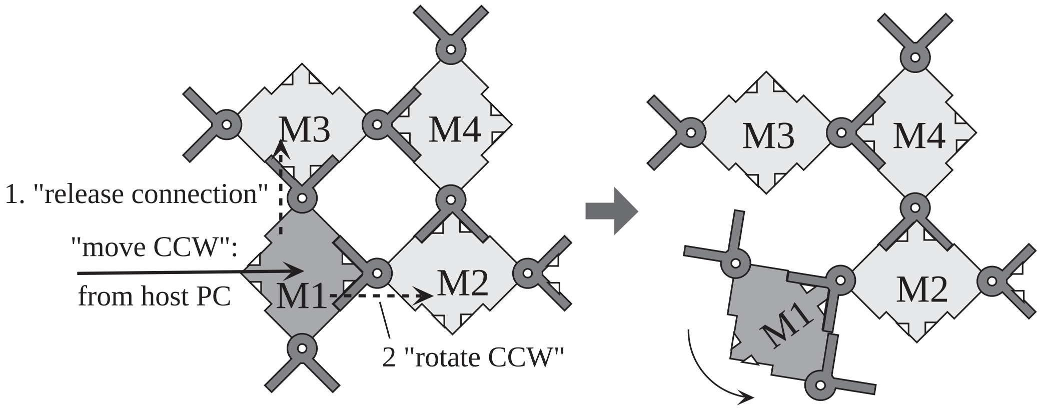
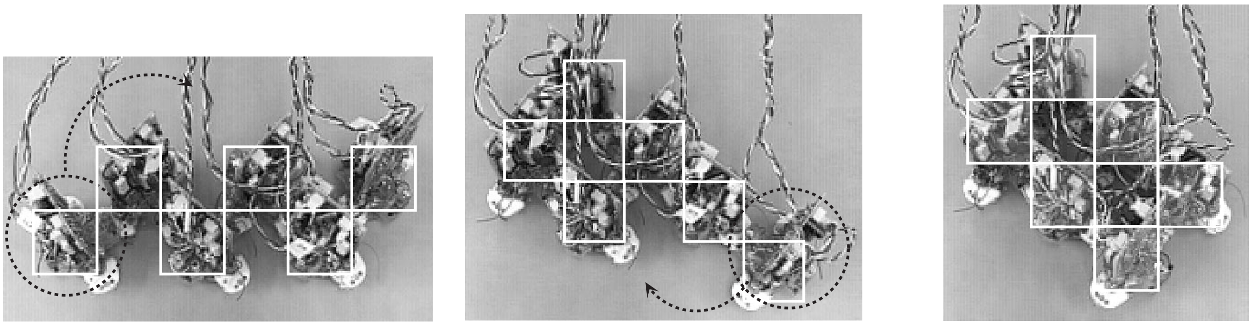


Fig. 9: Local motion coordination through inter-module communication.

rigidly by locking mechanisms. The SMAs therefore need only be heated when moving modules during self-reconfiguration.

Figure 12 shows a prototype of the second model of micro-robotic module. It measures 2cm cube


(a) Initial state

(b) Transient state

(c) Self-reconfiguration completed

Fig. 10: Self-reconfiguration experiment using six modules.

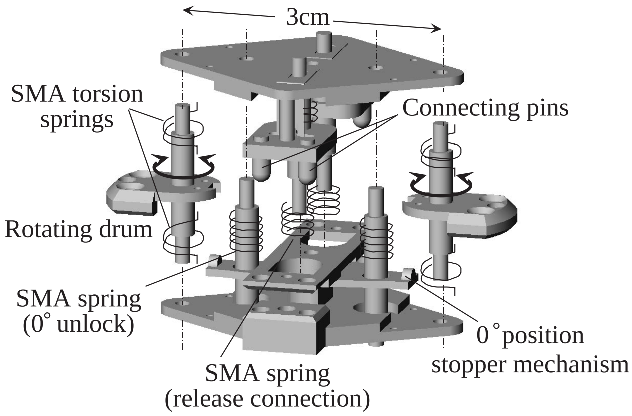


Fig. 11: Structure of micro-module (2nd model).

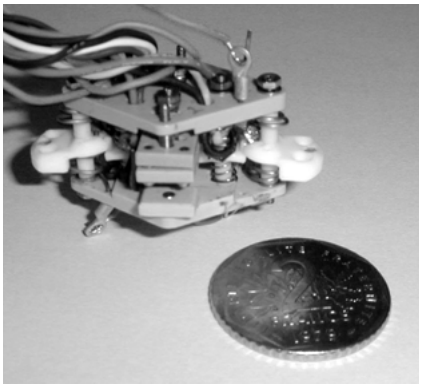


Fig. 12: Prototype of micro-module.

and weighs 15g. 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 as shown in Fig. 13.

Through the experiments, we confirmed that the measured torque using torque gauge resulted within the estimated ranges to transport another module against gravity. For example, the second model of micro module uses SMA three-turn springs of wire spring diameters are 0.45mm and 4.5mm with 270° pre-loading 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 ($0 \sim 1800$ and $7000 \sim 10000$ kgf/mm^2 for heated and non-heated state), is $0.9 \sim 1.9$ kgf·mm. This is enough to lift another module, whose weight and span is 15g and 30mm, against gravity.

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

Extension to Three Dimensions

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

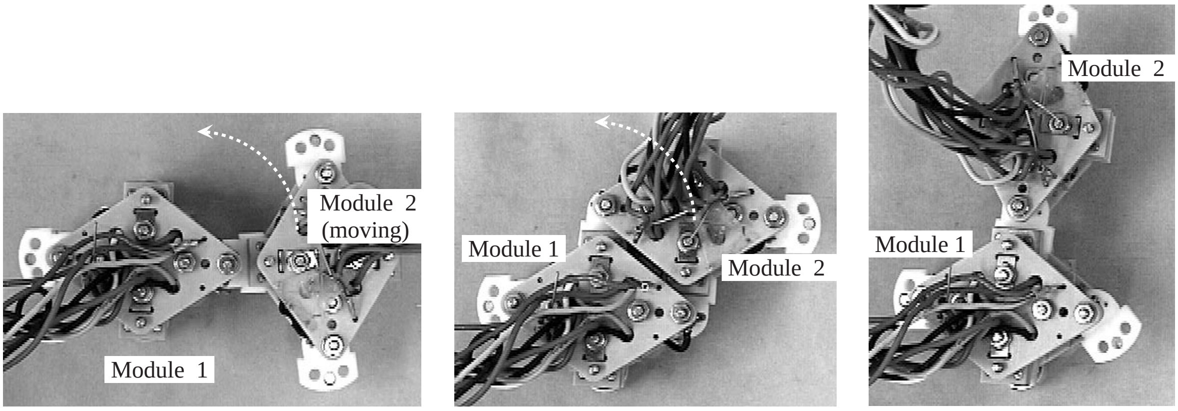


Fig. 13: Experiment of basic motion by two micro-size modules.

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

This motion in 3D lattice space turned out to be compatible with that of the formerly developed 3D self-reconfigurable modular structure [3]. While the previously developed 3D module needs at least one other module to make a motion, the octahedral 3D 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 3D modular structure can be applied to the octahedral 3D 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 referred papers.

Conclusions and Future Work

This paper presented a self-reconfigurable, modular micro-robot 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 pro-

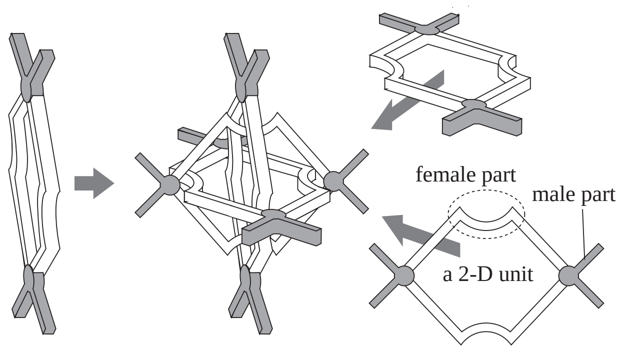


Fig. 14: A 3D module composed of three 2D SMA modules.

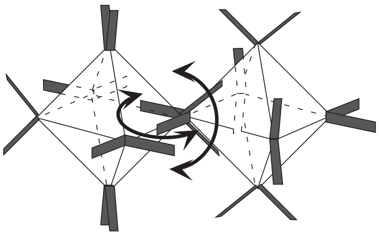


Fig. 15: Connected modules.

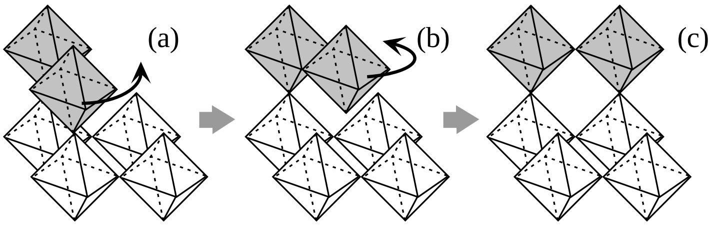


Fig. 16: Motion of 3D SMA modules.

totype of a 2D modular micro-robot, and each module is equipped with a control unit that drives actuators and facilitates inter-module communication. The fundamental functionality of a modular micro-robot was verified through multi-module experiments of self-reconfiguration by using the first model. Further micro-sizing was also investigated by developing a 2cm cube second prototype that successfully demonstrated the step motion of self-reconfiguration. We also addressed an extended 3D self-reconfigurable micro-robot.

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 micro-heaters for instance. Looking around the recent technical trend, we can expect the advances in such technologies as micro fuel cell or wireless energy supply will solve the energy problem to remove tethers in future. Micro-sizing the control unit with more computing power should also be addressed to implement autonomous distributed computing.

Another future development is equipping 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.

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