Micro Self-reconfigurable Robotic System using Shape Memory Alloy

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Abstract. This paper presents micro self-reconfigurable modular robotic systems using shape memory alloy (SMA). The system is designed so that various shapes can be autonomously formed by a group of identical mechanical units. The unit realizes rotational motion by using an actuator mechanism composed of two SMA torsion coil springs. We have realized micro-size prototype units and examined their fundamental functions by experiments. An extended 3D system and its self-reconfiguration algorithm are also discussed.

Key words: Modular Robotic System, Self-reconfiguration, Shape Memory Alloy Actuator, Micro-robot

1 Introduction

Recently, reconfigurable systems composed of robotic units have been investigated intensively for their versatility, flexibility, and fault-tolerance. This paper focuses on a micro-scale self-reconfigurable model aiming such applications as inspection robots in hazardous environments or micro-scale dextrous manipulators (Fig. 1).

Various self-reconfigurable robotic systems have so far been proposed that generate 3D shapes and motions [1]–[8] as well as 2D models [9]–[11]. Conventional electric motors used in these studies impose a limitation on miniaturization of the size of the system, due to their poor power/weight ratio in micro-scale. This has been major barriers to develop a micro modular robotic systems that can *actively* reconfigure themselves. Some micro-scale self-assembly systems have been reported [12,13]. These are developed by using microfabrication technology, but the driving force of the units is passive force such as surface tension that is not controllable.

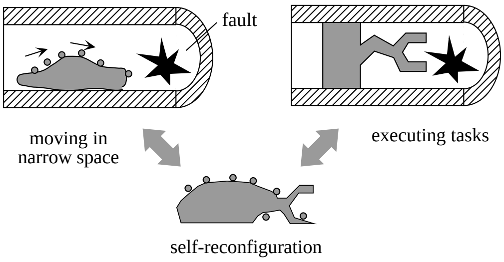


Fig. 1. Applications of a micro reconfigurable robotic system.

In this paper, we adopt an actuating mechanism driven by shape memory alloy (SMA) that has a high power/weight ratio even in micro-scale. Simple discrete end-to-end motion of SMA can overcome its major drawback, difficulty of precise control.

Although several micro SMA actuators have already been developed [14]–[16], it is still difficult to meet the requirements for self-reconfigurable systems. We have devised a rotational actuator mechanism using SMA torsion coil springs which satisfies both requirements of torque and motion area. So far we have confirmed the feasibility of the proposed actuator [17]. In this paper, we present 2D prototype units (5[cm] span and 80[g] weight) equipped with a microprocessor and inter-unit communication device. Their self-reconfiguration function will be verified through experiments. We will also report the development of the second prototype whose span and weight are reduced to 3[cm] and 15[g]. Finally, we will show that the unit system can be extended to three dimensions, and that the formerly developed distributed algorithm [18] can be applied to its self-reconfiguration.

2 Mechanism of Unit

This section outlines a 2D self-reconfigurable robotic system composed of identical units. We have designed the units' mechanism to be simple enough for miniaturization. The unit has a square shape, where two actuators at orthogonal vertices rotate male connecting parts that can be connected to female parts in another unit. Figure 2(a)∼(c) shows the basic motion between two units. Unit U1 changes its relative position clockwise (CW) around U2 through appropriate operations of rotating actuators and connection mechanisms. By repeating the basic motion, a group of units can form various 2D shapes.

3 Actuator Mechanism using SMA

This section briefly presents an actuator mechanism dedicated to micro mechanical units. This actuator should have a rotation range of ±90° with

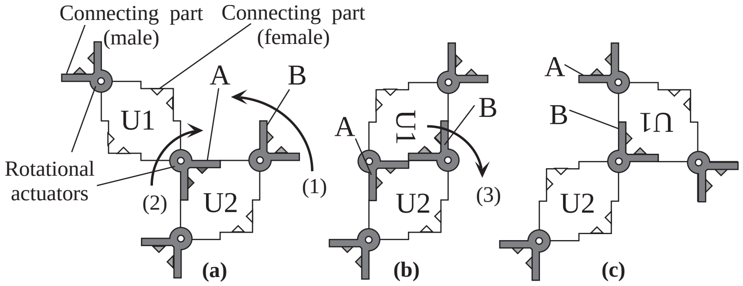


Fig. 2. Basic motion of two units.

enough torque to carry another unit. The reconfiguration operations require only three positions (−90°, 0°, 90°) realized by a simple end-to-end motion.

We have devised an actuator mechanism by using two SMA counter-torsion coil springs as shown in Fig. 3. The SMA torsion coil springs (memorizing the 0° rotation shape) are pre-loaded by twisting reversely 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 (Fig. 4(a)).

The rotation takes place when one of the springs is heated, usually by electric current. Since Young's modulus of SMA increases drastically when the temperature exceeds its phase transformation temperature $\mathrm{A_f}$, the heated spring generates a large torque in the direction to restore the memorized 0° rotation state.

Let us evaluate the performance of the actuator. The spring constant of a torsion coil spring k_τ [kgf·mm/deg] is in proportion to Young's modulus E [17]:

$$k_\tau = \frac{\pi d^4 E}{11520 n D} = cE. \tag{1}$$

where d and D are the wire and spring diameters respectively, and n is the number of turns. The relationship between its rotational angle $x°$ and the generated output torque T[kgf] is given as follows:

$$cE_2(B - x) = cE_1(B + x) + T \quad . \tag{2}$$

where E_1, E_2 ($E_2 > E_1$) are Young's moduli below and above temperature $\mathrm{A_f}$, and $B°$ is the angle by which both springs are twisted for pre-loading. By using Ti-Ni-Cu SMA that has a large difference between E_1 and E_2, we can diminish the reverse torque from the non-heated spring.

This actuator mechanism is appropriate to micro-size robotic systems since SMA keeps a relatively high power/weight ratio even in small scale compared to conventional electric motors [14]. The slow response in control (especially cooling) becomes less significant as the ratio of surface area to volume becomes large in small scale.

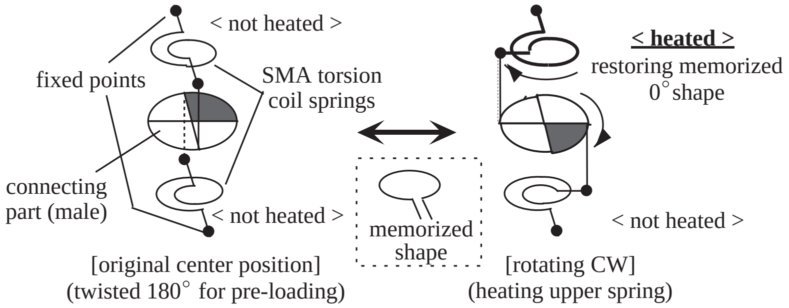


Fig. 3. Rotating actuator mechanism using SMA torsion coil springs.

4 Hardware Implementation and Experiments

We have developed prototype units and conducted experiments to verify their basic functions. Figure 4 shows the schematic view of the unit, which has a span of 5[cm] and weighs 80[g]. The unit is equipped with two SMA actuators at the orthogonal vertices which rotate the drums (male connecting parts). The original 0° position of a rotating drum is maintained rigidly by the stopper. The rotation becomes possible when the stopper is pulled back by heating the SMA spring. The stopper also limits the drum rotation within the range from $-90°$ to $90°$ as illustrated in Fig. 4(a). The female connecting part has an auto-locking mechanism, also driven by SMA, which can hold and release the drum of male connecting part (Fig. 4(b)).

We adopt Ti-Ni-Cu SMA with $\mathrm{A_f} = 70°\mathrm{C}$ and $(E_1, E_2) = (500, 7000)$ [kgf/mm^2] for the prototype. The specifications of the actuator are $d = 0.6$[mm], $D = 8$[mm], $n = 2$ and $B = 270°$. For rotational angle $x = 0°$ and $90°$, T is calculated as 12.2[kgf·mm] and 7.68[kgf·mm] from (2), which is enough to move another unit.

Figure 5 shows a picture of units. The SMAs are driven by PWM (50[Hz], duty ratio 25%) through low-resistance MOS-FET (4[mΩ]). The current was approximately 1[A] for input voltage 5[V] per SMA. The response of the actuator mechanism was prompt enough to complete 90° rotation within five seconds. Each unit is equipped with a controller using PIC microprocessor module BasicStamp II (Parallax Inc.) as shown in Fig. 6. It allows a unit to serially communicate with the wired host PC as well as other connecting units through connecting pins and electrodes in rotating drums as shown in Fig. 7.

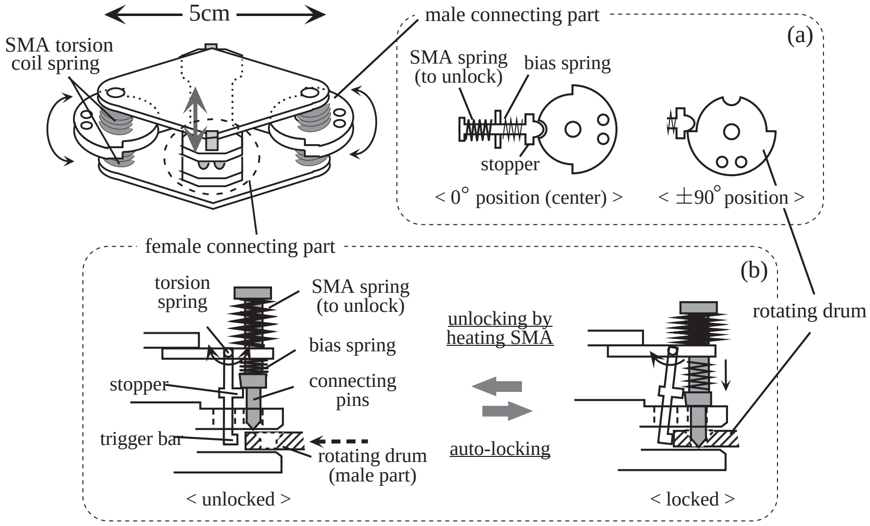


Fig. 4. Structure of the prototype unit.

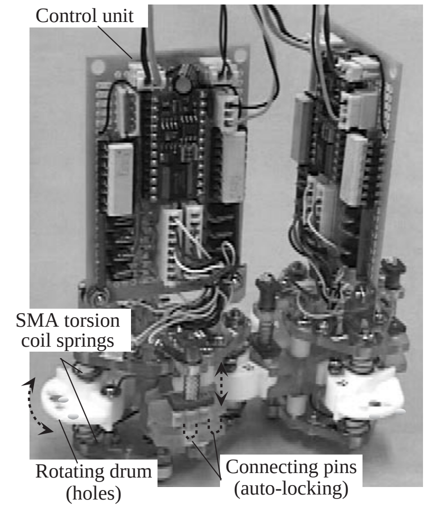


Fig. 5. Prototype unit (1st model).

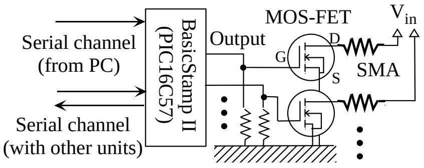


Fig. 6. Unit controller.

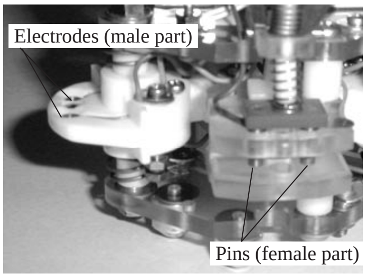


Fig. 7. Inter-unit connection.

In the current implementation, the motion sequence for the unit generated by a self-reconfiguration algorithm described later, is given from the host PC. A step motion of a unit requires locally coordinated motion of neighboring units as shown in Fig. 8. When a unit receives the command to make a step motion (clockwise or counterclockwise rotation), the unit asks neighboring units that the motion be supported by rotating and releasing of appropriate male and female connecting parts.

We have performed a self-reconfiguration experiment using six units illustrated in Fig. 9(a), where a group of units changes its shape from the initial to the final state on a horizontal plane. In this experiment, the units moves according to the commands from the host PC and the inter-unit communication device is used only as a sensor to detect the connection. As can be seen in Fig. 9(b)∼(d), the desired inter-unit motion has been realized by repeating basic step motions.

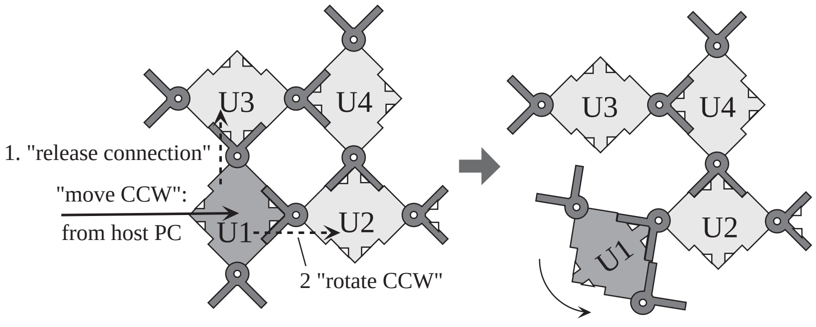
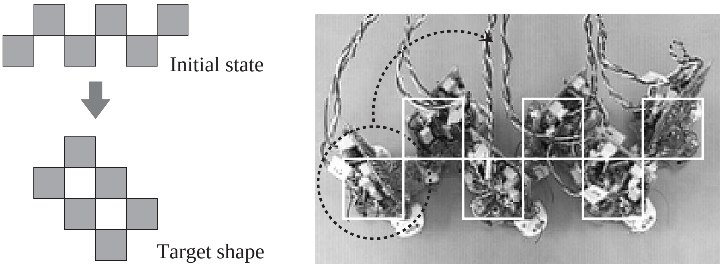
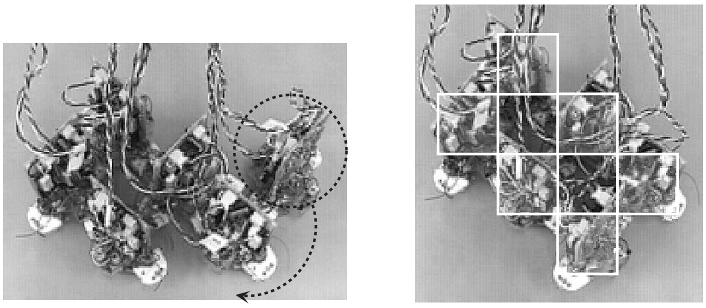


Fig. 8. Local motion coordination through inter-unit communication.



(a) Unit Motion (b) Initial state



(c) Transient state (d) Self-reconfiguration completed

Fig. 9. Reconfiguration experiment using six units.

5 Development of Micro-size Units

As mentioned in section 3, SMA actuator is advantageous both in power/weight ratio and response in micro-scale. In pursuit of wider applications requiring motion or tasks in narrow spaces, we are attempting further miniaturization.

Figure 10 describes a micro-size unit. Its structure is basically the same as the first model, but there are some differences in stopper mechanisms to lock and unlock rotating drums and connecting pins.

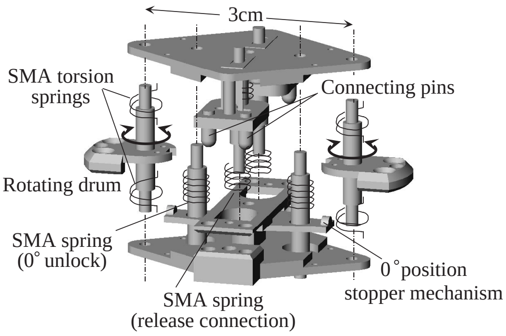


Fig. 10. Structure of micro-unit (2nd model).

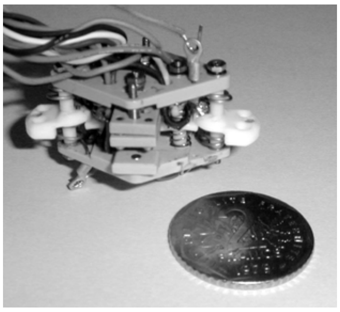


Fig. 11. Prototype of micro-unit.

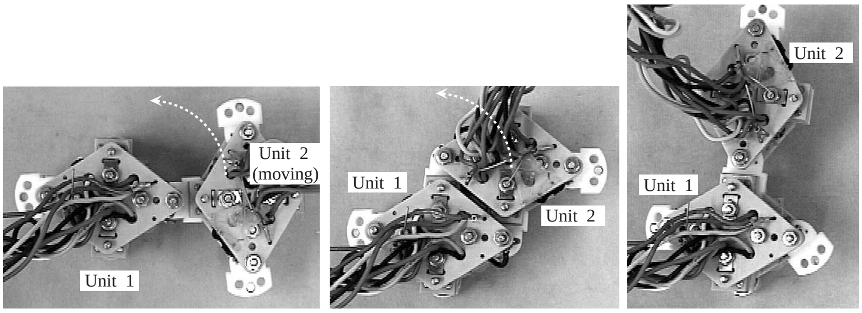


Fig. 12. Experiments of basic motion by two micro-units.

Figure 11 shows the prototype of the second model. It measures approximately 3[cm] span with 2[cm] height and weighs 15[g]. The dimensions of the torsion coil springs are $d = 0.6$[mm], $D = 3$[mm], $n = 2$ and $B = 270°$. The unit currently does not include the onboard microprocessor and is driven by an outside controller. The response was improved here as 90° rotation is made in approximately two seconds. Figure 12 demonstrates the units effectively realized the basic motion in Fig. 2. We are currently collecting experimental data to evaluate the performance of the actuator.

6 Extension to 3D Reconfigurable System

A 3D unit is designed by combining three 2D square units into a regular octahedron which can be connected at its vertices as shown in Fig. 13. This extension needs the current 2D connecting mechanism to be modified so that two male parts, meeting at the vertex with right angles, can interconnect each other. The SMA actuator should also be redesigned to generate sufficient torque.

The 3D units rotate in vertical and horizontal direction around the connecting vertex as shown in Fig. 14. A group of units can move on orthogonal-cubic lattice and form various 3D shapes as shown in Fig. 15. As this motion is compatible to that of the 3D self-reconfigurable structure [1,2], its distributed self-reconfiguration methods [18] can be applied to the octahedral 3D units.

We apply a self-assembly and self-repair method for large-scale systems (Fig. 16). It is based on a recursive description of the target shape by using a layered graph. Primitive description types are introduced that determine the geometrical relationship between “nodes”, denoting a group of units here. By assigning another sub-structure to each nodes, various complex shapes can be described in a recursive manner [18]. A unit can belong to multiple levels in the course of self-assembly.

Given the description of a target shape, self-reconfiguration proceeds by assembling first top-level structure, then down to sub-structure and so forth, using inter-unit communication. Figure 17 shows an example of self-assembly

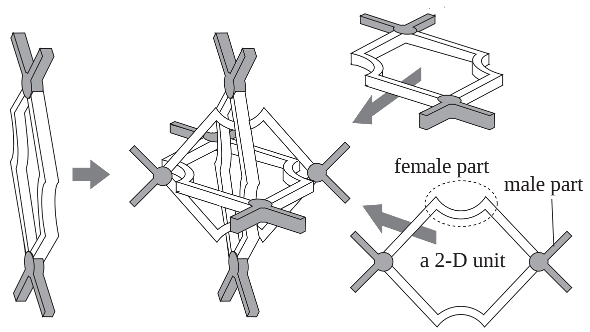


Fig. 13. A 3D unit composed of three 2D SMA units.

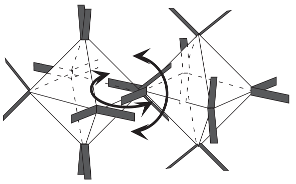


Fig. 14. Connected units.

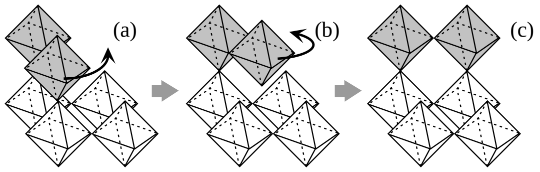


Fig. 15. Motion of 3D SMA units.

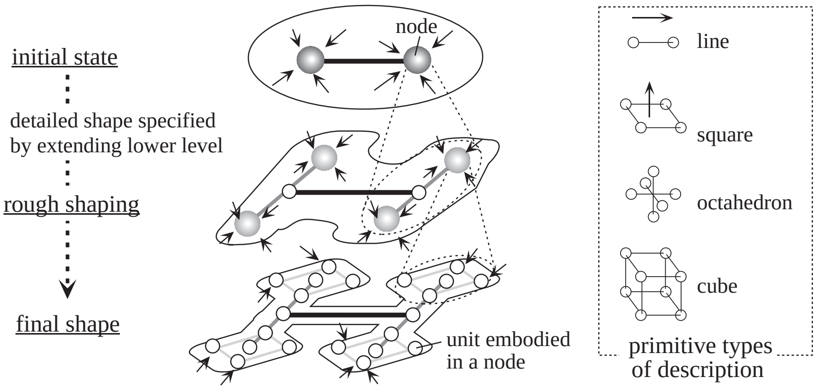
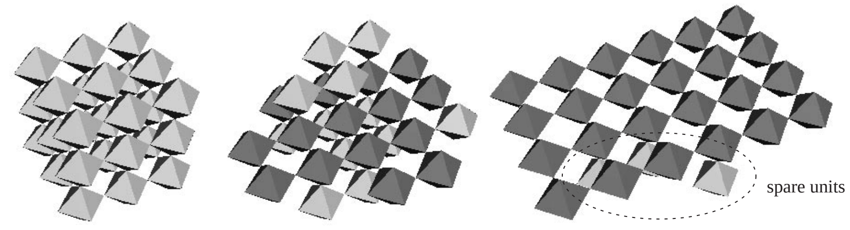


Fig. 16. Hierarchical graph structure for self-assembly.

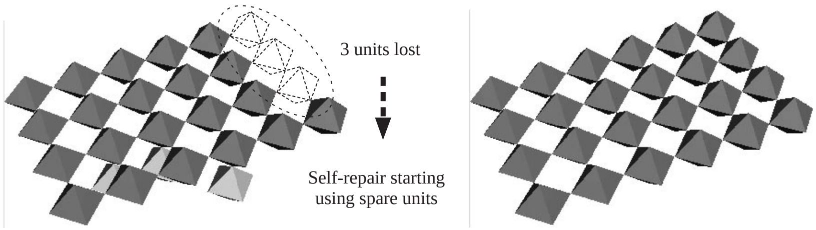
process of the 24-unit planar shape from 27-unit cube, where shaded units have already reached a position in the target shape.

Self-repair is also possible when some of the units are lost or damaged. Upon the detection of fault, surrounding units send messages to spare units in order that they move and repair the faulty part. If the damaged part includes multiple units in different levels of the target description, first the status of the units involved in the self-repair is reset back to the relatively highest level in the target description. Then self-repair is performed from the higher level



initial state (cube) 10 steps after 35 steps after (completed)

Fig. 17. Self-assembly of many-unit structure.



Starting self-repair 20 steps after (completed)

Fig. 18. Self-repair of many-unit structure.

down to lower levels. Figure 18 shows a simulation result of self-repair after three units have been removed.

The algorithm can be applied to small-size space structure such as solar panels or antennas. Launched in a compact folded form, they can expand the structure for the mission, and repair themselves if some part is damaged.

7 Conclusions

This paper presented micro self-reconfigurable robotic systems using an SMA actuator mechanism. We realized simple 2D mechanical units by using an actuator mechanism composed of SMA torsion coil springs, which can provide sufficient torque and motion range. The fundamental self-reconfiguration function was verified through self-assembly experiments using the first prototype units. Further miniaturization was also investigated by developing the second prototype that demonstrated the basic motion successfully. We have also discussed a 3D reconfigurable system. It was shown that the formerly developed distributed self- reconfiguration algorithm can be applied to the 3D SMA units. Future work includes equipment of controller to the second micro-size unit model and hardware implementation of 3D SMA units.

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