Miniaturized Self-reconfigurable System using Shape Memory Alloy

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Abstract

This paper presents a miniaturized self-reconfigurable modular robotic system using shape memory alloy (SMA). The system is designed so that various shapes can be actively 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 which generate sufficient motion range and torque for reconfiguration. The fundamental functions of the system are tested by experiments. Applicability of the developed unit model to a 3-D self-reconfigurable system is also discussed.

1 Introduction

Self-reconfigurable robotic systems composed of mechanical units have been attracting more and more researchers' interest for their versatility, flexibility, and fault-tolerance. Especially, their miniaturized or micro-scale model may open up many emerging application fields like inspection robots in hazardous environments or micro-scale dextrous manipulators. For instance, a robot is very useful which moves around inside pipes by changing its shape and reorganizes itself as a manipulator to execute repairing tasks when it detects a faulty part as shown in Fig. 1.

We have been studying self-reconfigurable mechanical systems composed of identical units [1, 2, 3, 4, 5]. Many other studies have been made on reconfigurable robots [6, 7, 8, 9, 10]. In [9, 10], small units called "self-reconfigurable robotic molecules" have been developed which construct 3-D structures. Conventional electromagnetic motors used in above studies, however, have limitations in miniaturization since they become ineffective as its power/weight ratio decreases significantly in micro-scale.

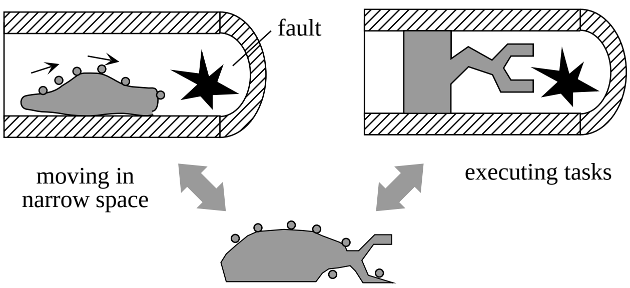


Fig. 1: Applications of a miniaturized reconfigurable robotic system.

Miniaturized model of such robots requires actuators which yield both enough torque and wide motion area to transport units themselves in self-reconfiguration. These strict requirements have been major barriers to development of miniaturized self-reconfigurable robotic system which can *actively* form a variety of shapes. Although some micro-scale self-assembly systems have been reported [11, 12], they are passively assembled to predetermined shape by surface tension and cannot consist arbitrary shapes.

To develop a miniaturized modular robot which can actively reconfigure themselves, we adopt an actuating mechanism driven by shape memory alloy (SMA). The SMA keeps a relatively high power/weight ratio even in micro-scale, which is more advantageous than conventional electromagnetic motors. Furthermore, desired self-reconfiguration can be realized by connection/disconnection mechanism and simple discrete motion control, which does not need either precise control of SMA and simplifies the control system as a result.

Although several types of micro/miniature SMA actuators have been developed [13, 14, 15], it is still difficult to provide sufficient torque and wide motion range required for micro/miniature reconfigurable units' movement. We have therefore devised a rotational actuator mechanism using SMA torsion coil springs which satisfies both requirements of torque and motion area. This actuator makes it possible to design our first 2-D prototype units whose size and weight is around 5[cm] cube and 80[g] respectively. Their basic functions have been verified through experiments. Unlike conventional robotic systems using electric motors, the size of developed units can potentially be much reduced. We will also mention that the unit system can be extended to 3-D space and that the formerly developed distributed algorithm [5] can be applied to its self-reconfiguration.

2 Mechanism of Unit

We have designed a self-reconfigurable robotic system composed of identical units which have a mechanism simple enough for the sake of miniaturization. The units are designed to satisfy the homogeneity so that any unit can play any part in the system. In this section, we will introduce a 2-D model in which identical units construct various shapes. The mechanism can be extended to 3-D as described later in section 5.

A unit has a square shape, where two actuators at orthogonal vertices rotate male connecting parts which can be linked to female connecting parts in another unit. Figure 2(a)∼(c) shows a basic motion of a pair of units U1 and U2. Unit U1 rotates by 90[deg] clockwise (CW) around U2 by the following operations of their male connecting parts A and B:

(1) U2 rotates B by 90[deg] counterclockwise (CCW)
(2) U1 rotates itself CW by rotating A by 90[deg]
(3) U2 connects B to U1
(4) U1 releases A from U2
(5) U2 rotates B by 90[deg] CW

As shown in Fig. 3, various 2-D shapes can be formed by repeating the basic motion.

3 Rotation Mechanism using SMA

This section presents first an actuator mechanism dedicated to miniaturized model of mechanical units and shows that it provides sufficient performance through calculation of its torque and motion range.

3.1 Actuator Mechanism using SMA Torsion Coil Springs

To realize basic unit motion shown in Fig. 2, the rotating part should have rotation range of ±90[deg] from the original center position (in the connection state of Fig. 2(a) and (c)) and also an enough torque to rotate another unit.

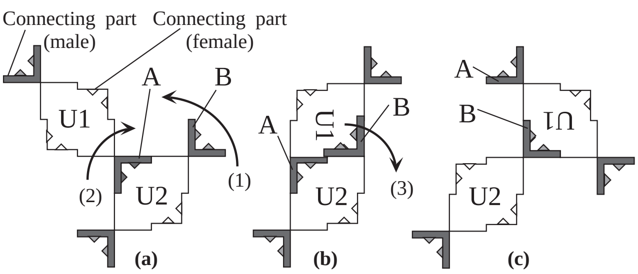


Fig. 2: Basic motion of two units.

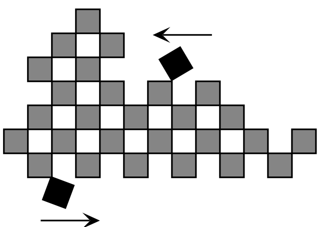


Fig. 3: Various shape and movements generated by the units.

On the other hand, we need only three positions in reconfiguration operations, i.e. the original center position, two positions ±90[deg] from there. This means that precise position control is not required, but simple discrete switching is enough.

For these reasons, we have devised an actuator mechanism by using two SMA torsion coil springs producing torques in the opposite directions as shown in Fig. 4.

The principle of actuator is as follows. Suppose the two SMA springs memorize the 0[deg]-rotation shape shown at the top-left in Fig. 4. In the actuator mechanism, they are pre-loaded by twisting each of them reversely (by 180[deg] in Fig. 4). The static torques balance and both spring stay at the original center position without heating.

The rotation takes place when one of the springs is heated (usually by electric current). Since the Young's modulus of SMA increases drastically through phase transformation caused by a rise in temperature as described later, the heated spring generates a large torque in the direction to restore the memorized 0[deg]-rotation state, and then makes resulting rotational motion by breaking the balance. The desired rotational angle ±90[deg] is obtained by using stoppers.

This mechanism suit the above requirements as we will show in the evaluations in 3.2. It is appropriate to miniaturized or micro-scale robots since SMA keeps a relatively high power/weight ratio even in small scale compared to conventional electromagnetic motors [13]. A major draw-

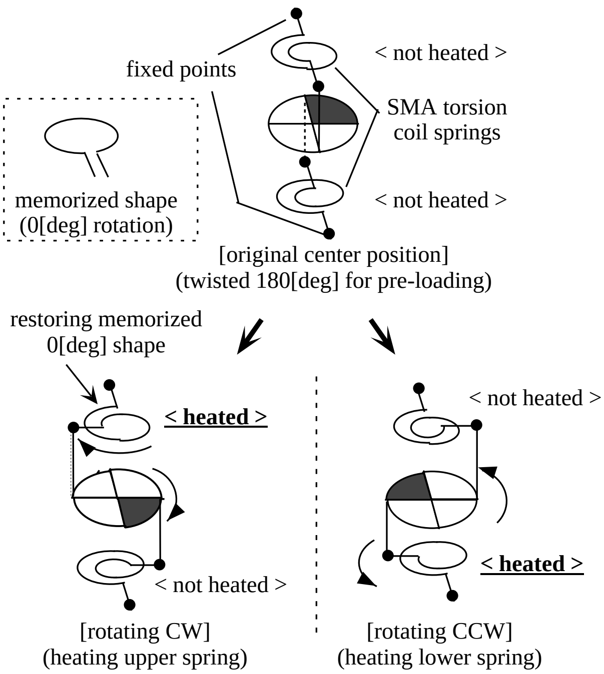


Fig. 4: Rotating actuator mechanism using SMA torsion coil springs.

back of SMA is the slow response in control, especially when it should be cooled. However, this problem becomes less significant in small or micro-scale applications where the ratio of surface area to volume becomes large.

3.2 Mechanical Analysis

The performance of the actuator mechanism is analyzed to show it has sufficient torque and motion area for units' motion shown in Fig. 2. The spring constant of torsion coil spring k_τ [kgf·mm/deg] can be calculated as follows (see Appendix for its derivation):

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

where E [kgf/mm^2] : Young's modulus,
d [mm] : Diameter of SMA wire,
D [mm] : Diameter of spring,
n : Turns of spring.

The Young's modulus E of SMA increases from E_1 to E_2 when the temperature exceeds the phase transformation temperature A_f while it is actuated by heating. As shown in (1), k_τ is in proportion to E, so it can be written as:

$$k_\tau = cE, \quad \text{where } c = \frac{\pi d^4}{11520 n D} \quad . \tag{2}$$

Next, we evaluate the performance of the actuator mechanism. Let x [deg] and T [kgf] be its rotational angle and the generated output torque respectively. When one of the SMA spring is heated for actuation as shown in Fig. 4, the equation of torque balance is given as:

$$cE_2(B - x) = cE_1(B + x) + T \quad . \tag{3}$$

where B[deg] is the angle by which both springs are twisted for pre-loading. By solving this in terms of x, the following is derived.

$$x = \frac{Bc(E_2 - E_1) - T}{c(E_2 + E_1)} \quad . \tag{4}$$

This describes the relationship between the generated output torque and the angle of rotational motion.

The actuator mechanism has a disadvantage that the output torque decreases as it rotates because of increasing torque in the reverse direction caused by the spring which is not heated. One solution to this problem is using recently developed Ti-Ni-Cu SMA. While its rigidity is almost zero at low temperature, namely it has very small E_1 value, E_2 is nearly equal to that of typical Ti-Ni SMA over the A_f temperature. This property is preferable for our actuator mechanism because the output torque is much less dependent on rotational angle.

For Ti-Ni-Cu SMA, the Young's moduli are measured approximately as E_1 = 500[kgf/mm^2] and E_2 = 7000[kgf/mm^2] which means the rigidity increases by more than ten times. For instance, consider an actuator whose parameters are d=0.8[mm], D=8[mm] ($c = 4.65 \times 10^{-6}$), n=3, pre-loaded by twisting angle $B = 270$[deg]. For rotational angle $x = 0$[deg] and 90[deg], T is calculated as 8.16[kgf·mm] and 5.12[kgf·mm] respectively from (4). Although the actual output torque is smaller than this value due to friction, this is enough for the miniaturized unit model. For example, if the distance between the actuator and the center of unit's mass is 25[mm] (which corresponds to the size of the prototype unit described in section 4), the actuator with the above specification has enough torque to lift another unit against gravity if the unit weighs less than 200[gf].

4 Hardware Implementation and Experiments

We have developed prototype units and conducted experiments to verify their fundamental functions.

The schematic view of a developed unit is shown in Fig. 5. The unit is equipped with two SMA actuators at orthogonal vertices which rotate the drums, the male connecting parts. The female connecting part has an auto-locking mechanism illustrated in Fig. 6, also driven by SMA which can hold and release the drum of male connecting part. When the drum of other unit pushes the trigger bar, the stopper is shifted so that the bias spring knocks two pins into holes of drums. By heating the SMA coil spring, the pins are pulled upward to unlock. Units' connection is maintained only by locking mechanism and the electric heating of SMA is used just when the unit motion is made.

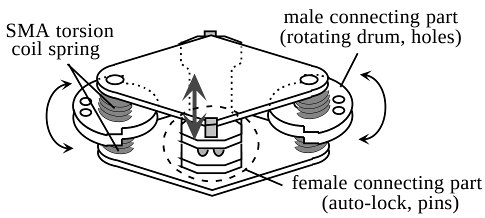


Fig. 5: Schematic view of a prototype unit.

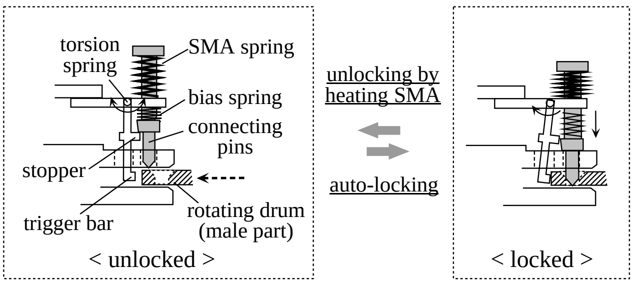


Fig. 6: Auto-lock mechanism of female connecting part.

Although the unit is operated without a battery for the moment, we believe it can be equipped in the future model as the usage of energy-consuming SMA heating is minimized.

Figures 7 and 8 shows the actual design and a picture of the designed unit. Its span and height is about 50[mm] and 40[mm] respectively, and its weight is approximately 80[g]. The original 0[deg] position of a rotating drum is maintained rigidly as a stopper slides into the center notch by spring pressure. The rotation becomes possible when the stopper is pulled back by heating SMA spring. The stopper also limits the drum rotation within the range from -90[deg] to 90[deg]. We adopt Ti-Ni-Cu SMA with A_f temperature approximately 70[deg.C] for the prototype, and the specifications of torsion coil springs in the actuator mechanism are $d = 0.6$[mm], $D = 8$[mm] and $n = 3$.

Figure 9 shows snapshots taken from a fundamental experiment of two unit where one of them lift the other against gravity. As can be seen, the prototype units effectively realized the basic motion shown in Fig. 2. The experiments have also revealed that the response of the actuator mechanism is prompt as each ±90[deg] rotation was

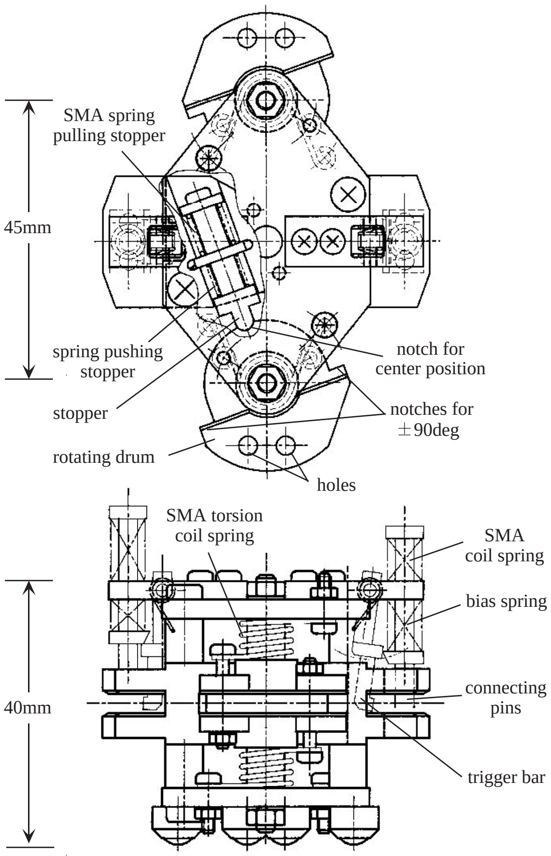


Fig. 7: Prototype design of SMA unit model.

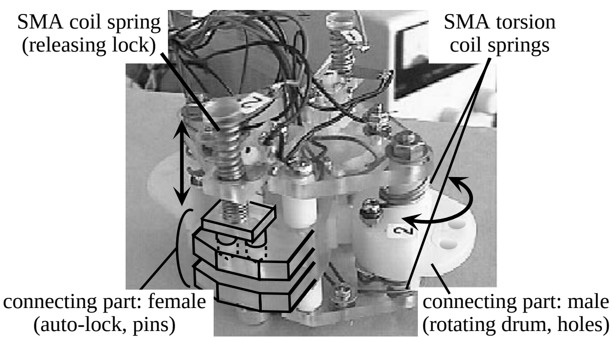


Fig. 8: A picture of a prototype unit.

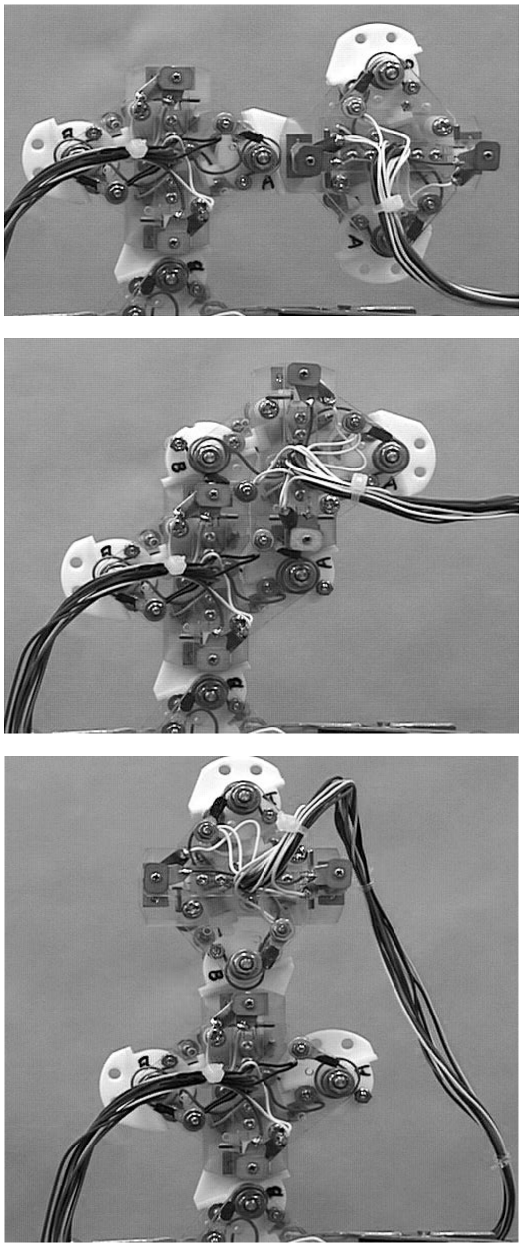


Fig. 9: Fundamental experiment of unit motion. a unit (fixed, left) lift the other unit (wright) by 90[deg] from horizontal connection state.

completed within five seconds.

We have also carried out a self-reconfiguration experiment using six units illustrated in Fig. 10, where the "moving unit" changes its position from the initial to the final state on a horizontal plane. As can be seen in Fig. 11(a)∼(c), the desired many-unit motion has been realized by repeating basic step motions. These experimental results have demonstrated the basic function of the miniaturized self-reconfigurable system.

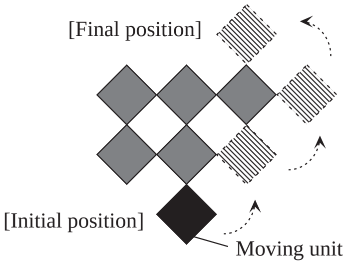
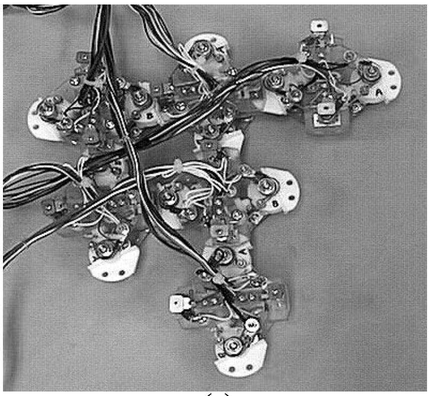
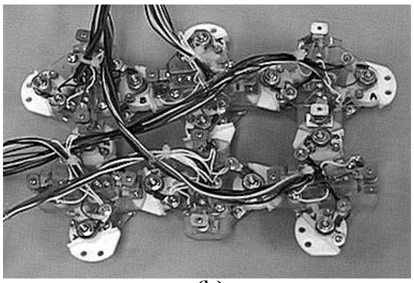


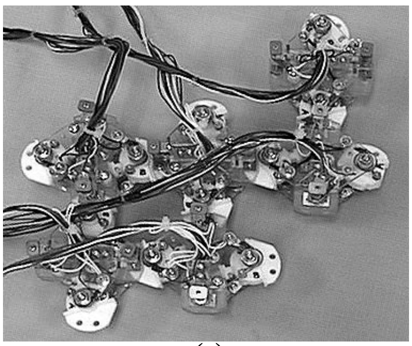
Fig. 10: Reconfiguration motion by many SMA units.



(a)



(b)



(c)

Fig. 11: Reconfiguration experiment using 6 units.

In the experiments, SMA is currently powered by a power supply unit and requires approximately 5[W] in rotation. We are now attempting to mount a compact controller using PIC microprocessor (weighs about 20[g]) and to save the power by using pulse control (Fig. 12). We are also redesigning the connecting part so that it can allow communication and power supply can be done through embedded electrodes.

5 Extension to 3-D Reconfigurable System

Through further investigations on the proposed unit system, we have revealed that it can be extended to a 3-D self-reconfigurable modular robot. We have also made an interesting finding that the distributed self-reconfiguration algorithms [5] formerly developed for our 3-D modular structure can be applied to the 3-D SMA unit. This section discusses these possible extensions of the developed miniaturized unit.

5.1 Constructing 3-D Units

A 3-D unit can be constructed by combining three 2-D square units into a regular octahedron which can be connected at its vertices as shown in Fig. 13. This extension

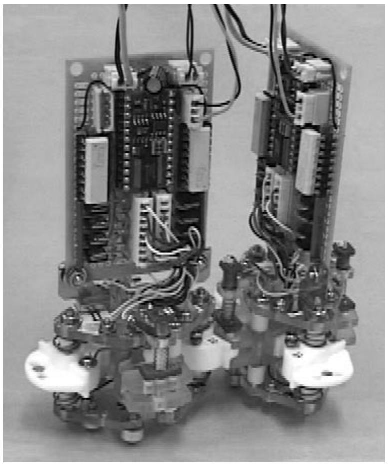


Fig. 12: Units equipped with controller using PIC microprocessor.

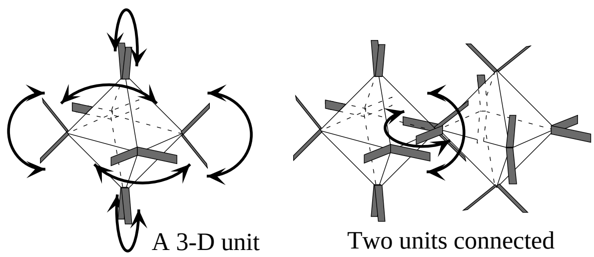


Fig. 13: A 3-D unit composed of three 2-D SMA units.

needs the current 2-D 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.

This unit can move on orthogonal-cubic lattice and form various 3-D shapes as shown in Fig. 14(a)∼(c).

This motion style of 3-D SMA units includes that of the 3-D self-reconfigurable structure [3, 4]. While the latter model requires at least one other unit when a unit moves, a 3-D SMA unit can change its position by itself and thus has fewer constraints on self-reconfiguration.

5.2 Self-reconfiguration Method

We have developed distributed methods of self-reconfiguring small and large structure [5] by formerly developed 3-D units [3, 4]. These methods can be applied to the 3-D SMA units as the two unit models have motion compatibility.

We apply self-reconfiguration method to a system composed of small number of units as an example. Here, we mention the method briefly as the details of method is given in another paper of ours [5]. The connection of units in one-neighborhood of 3-D lattice space is classified into nine types as shown in Fig. 15 where a unit is described by an octahedron with connection arms. As a target shape of self-reconfiguration, consider a 12-unit box, shown in Fig. 16, composed of C31 and C41 types. In this target, a C31 type unit is connected to two C31 and C41 types, which can be written as a“type-list” C41[C31, C31, C41, C41]. The target shape is therefore described by two type-lists as:

$$\begin{array}{l} C31\ [C41,\ C31,\ C31]\ , \\ C41\ [C41,\ C41,\ C31,\ C31]\ . \end{array} \tag{5}$$

Figure 17 shows a sequence of self-reconfiguration simulation. Each unit makes movements in such a way that

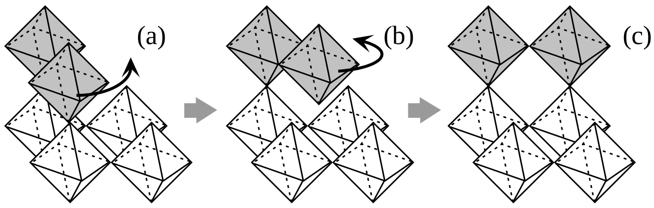


Fig. 14: Motion of 3-D SMA units.

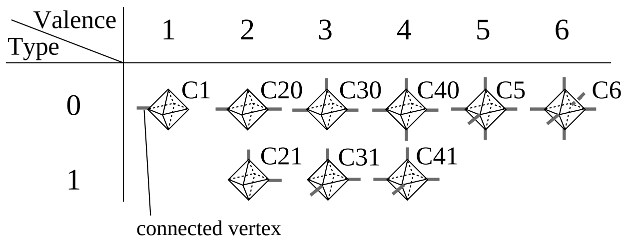


Fig. 15: Connection types of 3-D units.

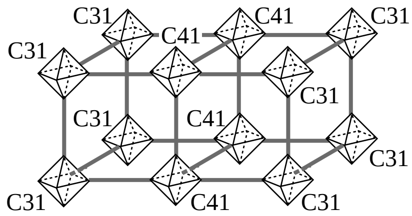


Fig. 16: 12-unit target structure.

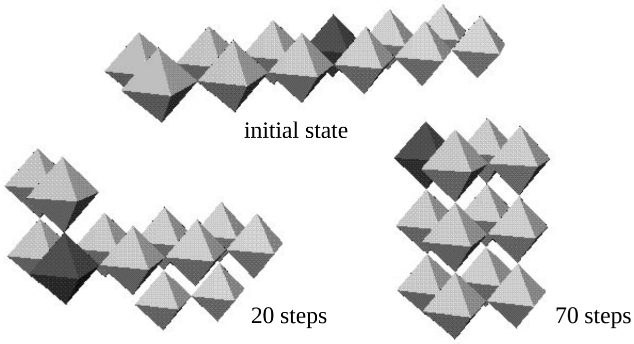


Fig. 17: Self-assembly simulation of 3-D SMA units.

it approaches either of type-lists in given target shape description in (5) based on a distributed method called Markov Random Field (MRF). From initial ladder shape, the target shape is completed in a distributed manner. We can also implement the self-reconfiguration method of many-unit structure [5] for the 3-D SMA units in the same way. These methods can be straightforwardly applied to the developed prototypes by restricting their motion to 2-D plane.

6 Conclusions

This paper presented a miniaturized model of a self-reconfigurable modular robotic system by using an SMA actuator mechanism. We have first designed a simple system composed of identical units which can form various 2-D shapes. Next, we realized an actuator mechanism which provide sufficient torque and wide motion range using SMA torsion coil springs. Its performance was demonstrated by fundamental experiments using 2-D prototype units. We have also discussed using the units to build a 3-D reconfigurable system. It was shown that the formerly developed distributed self-reconfiguration algorithm can be applied to the 3-D SMA units.

As we have verified the basic function of reconfigurability of the developed prototype units, we are planning to reduce its size in pursuit of wider applications. The mechanism is simple enough for further miniaturization using such techniques as rapid prototyping. Implementation of autonomous units with microprocessor and realization of 3-D SMA units are other important issues.

Acknowledgment

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Appendix: Spring Constant k_τ

The spring constant of torsion coil spring is obtained through calculation of its deflection by regarding it as "wound" beam. If the torque τ[kgf·mm] is applied to a beam, it is known that deflection angle θ[rad] is given as

$$\theta = \frac{\tau L}{EI} \ , \tag{A1}$$

where L[mm] and I[mm^4] is the beam's length and moment of inertia of area [16]. As $L = \pi D n$, where D[mm] and n are the diameter and the number of turns of the torsion coil spring in (1), and $I = \frac{\pi d^4}{64}$ for the cylinder beam whose diameter is d, the relationship between τ and θ is written from (A1) as:

$$\tau = \frac{d^4 E}{64 n D}\, \theta \ . \tag{A2}$$

By using the unit of angle [deg], the spring constant k_τ in (1) is derived.