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Fabrication of 3D soft morphing structure using shape memory alloy (SMA) wire/polymer skeleton composite †

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Abstract

The most common method of fabricating a smart structure using a shape memory alloy (SMA) is to create an SMA-embedded structure. However, if the structure is too thick, actuation is decreased significantly. Hence, SMA-embedded structures and robots are usually thin, leaving no space for additional parts. In this research, an SMA-embedded soft morphing structure with large thickness and deformation was developed. A skeletal structure and hinges, which could amplify actuating displacement, were used to increase the overall actuation by maximizing the actuation in a specific area. Also payload of prototype is enough to lift additional weight. A prototype of the design was fabricated via rapid prototyping (RP) and casting. The performance of the prototype was evaluated, and large deformation and actuation force were demonstrated. A cell phone robot was suggested as an application, and the resulting fabricated prototype exhibited crawling actuation.

Keywords: Polymer skeleton composite; Robot; SMA; Soft morphing structure

1. Introduction

Shape memory alloys (SMAs) are materials that have the shape memory effect (SME), caused by martensitic transformation. Because of this effect, a deformed SMA can recover its original shape when heat is applied [1].

Nitinol, developed by the U.S. Navy in the 1960s, is one of the most popular SMAs because of its stability, repeatability, pseudo-elasticity, and SME. The SME and pseudo-elasticity allow an SMA to be used as an actuator. In particular, since actuators made from SMAs can be any desired shape, they can be used to fabricate actuators with a simple structure and much smaller volume and mass than classical actuators. Compared to other smart materials used as actuators, such as IPMC or PZT, SMAs are the nearest to practical usage, thanks to their high energy density and good repeatability. Moreover, other functions, such as precision control and vibration suppression, are also possible, thereby facilitating research in various fields.

Yang measured mechanical property of SMA by changing temperature made actuator by fix SMA with composite. Performance test is executed and actuation is measured [2]. To fix SMA with composite, they use mechanical fastening.

An SMA embedded composite was invented by Rogers to suppress vibration. Rogers attempted to apply additional stress to structure by embedding wire in a composite and actuating the wire [3]. SMA embedded composites have attracted the interest of many researchers because of their large damping capacity and large deformation recovery.

Baz made an SMA embedded structure, executed actuation test of structure and measured actuation [4]. Tobushi made actuator by embedded SMA with shape memory polymer (SMP) and executed performance test [5]. Jung made smart structure by embedding SMA wires with glass fiber. They made U-shape actuator and used mechanical fastening way to increase actuation. With this actuator they made prototype of air-intake [6].

SMAs are also used in small-scale robots with a simple structure. SMA wire requires very little space and no additional parts (such as gears), since linear actuation is induced by direct application of heat or electrical power.

Koh made Omegabot inspired by inchworm with SMA spring and composite. Composite made by using smart composite microstructures (SCM), composite can have complex pattern at surface of composite, so Omegabot can make various motions with simple structure [7]. Kim made inchworm robot with U-shape SMA embedded composite and simple lower structure. With hinge, connecting point with ground of each side is changed automatically. They made friction coefficient of each point different [8]. Fabrication method to manu-

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facture the flexible body of the robot and their performances are reviewed [9-12]. Numerical simulations of smart soft composite and experimental results were investigated [13].

However, to produce large deformation, SMA-embedded smart structures and small-scale robots must be thin, since the force generated by an SMA wire is small compared to that of classical actuators. Thus, space for additional parts (such as batteries or control circuits) is generally lacking, and these parts must either be attached externally or omitted altogether. Moreover, the assembly process for SMA-based small-scale robots is difficult, and their performance is fraught with uncertainty.

In this study, an SMA-embedded smart structure with a polymer skeletal structure was proposed. The skeletal structure ensured the availability of space for additional parts. To minimize the mass, volume, and thickness of the skeletal structure, fused deposition method (FDM) rapid prototyping (RP) was employed for its fabrication. To increase the overall actuation, the deformation was focused in specific areas by hinges, which were designed with a low degree of stiffness. Bending actuation was induced, and the amount of actuation increased, by applying eccentricity.

A manufacturing process consisting of RP and casting was proposed. The skeletal structure was created via RP. The casting process allowed the empty space to be filled with a soft material that bonded with the SMA wires and skeletal structure.

2. Design and manufacturing

The smart structure consisted of two parts: the SMA wire actuator and the actual structure. Thus, there were two main factors that determined the amount of deformation: the design of the structure and the positioning of the SMA wires.

2.1 Design of smart structure and hinges

The smart structure was composed of two kinds of material, one stiff and the other soft. There was no empty space and the volume of the SMA wires could be neglected. Hence, the stiffness of the overall structure was determined by the shape of the skeletal structure.

To increase the actuation, eccentricity was applied. This was accomplished by fabricating the upper and lower sides with differing degrees of stiffness, thereby inducing bending actuation. In this way, a small contraction of the SMA could cause a large bending actuation of the structure. Factors determining the amount of deformation were the stiffness of each side and the gaps between the upper side, lower side and SMA wires.

When designing the structure, space for an embedded part had to be considered. We assumed that a battery would be installed inside the structure. To decrease the mass and stiffness of the overall structure and skeletal structure, a thin filament had to be used.

However, even though the stiffness of the skeleton was small, if the embedded part had been too stiff, deformation of the stiff area would have been difficult to achieve. Moreover, if the depth of the embedded part and the gap between the SMA and the upper side had been too thick, the bending deformation would have been small. Hinges were used to maximize the deformation.

The skeletal structure was designed to be thin com-pared to the embedded part. Thus, hinges were in-stalled in the skeletal structure. Each filament was located in the lowest area, and the SMA wires were placed just below the filaments. Fig. 2 shows the design of the skeletal structure and hinges.

2.2 Detail design of prototype

Fig. 3 shows the detailed design of the prototype and Table

Table 1. Specifications of the prototype.

Size	120 mm * 65 mm * 3.6 mm (L * W * D)
Gap between hinge	37 mm
Length of hinge	4.5 mm
Number of SMA wires	10 ea

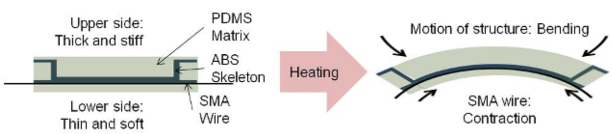


Fig. 1. Eccentricity of structure.

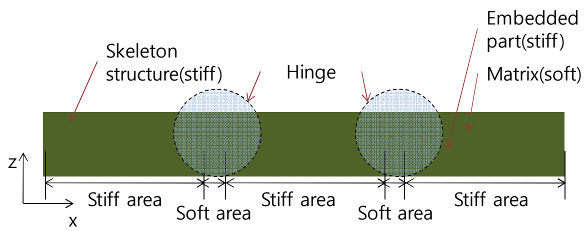


Fig. 2. Design of skeletal structure and hinges.

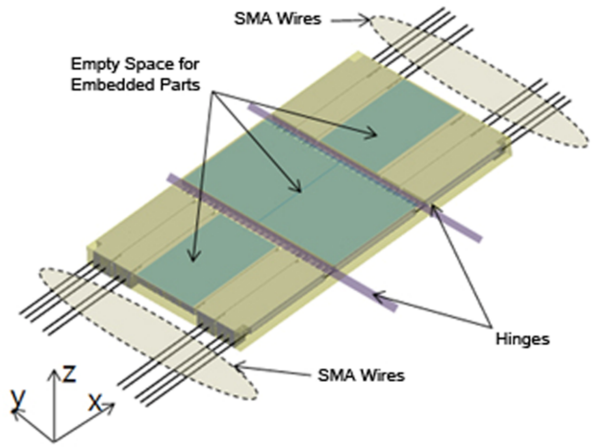


Fig. 3. Detail design of prototype.

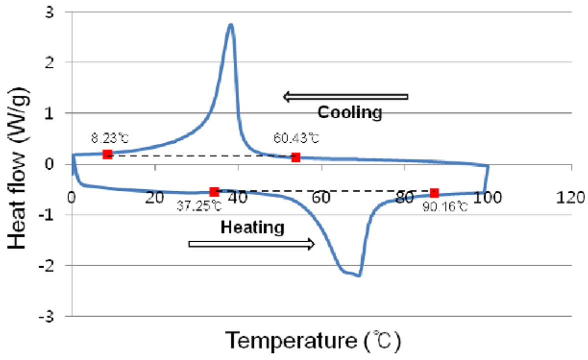


Fig. 4. Transformation temperature of FLEXINOL.

1 lists the design specifications. The size of the prototype was chosen to match the size of a cell phone.

The depth of the prototype and the gap between the hinges were based on the size of a Li-polymer battery. A Li-polymer battery was selected because an SMA requires a considerable amount of current. The size of the battery was 31 mm x 29 mm x 2.9 mm (L x W x D), and the capacity and voltage were 160 mAh and 3.7 V, respectively.

2.3 Materials

To fabricate smart structure, SMA wire and 2 kinds of materials are used.

2.4 Shape memory alloy

The SMA used in this research is FLEXINOL (Ni: 55 wt%, Ti: 45 wt%, Dynalloy, US). The transformation temperature was measured using a differential scanning calorimeter (DSC). The measured transformation temperature is plotted in Fig. 4. The specifications of the SMA wire are listed in Table 2.

2.5 Materials of structure

The material used for the skeleton was ABS, which is a stiff, thermoplastic polymer that is often used in structures. The ABS used in this research was P400 (Stratasys, US), a model material for the FDM rapid prototyping machine (SST768, Stratasys, US).

The material used for the matrix was PDMS, which is flexible and has good thermal resistance. The PDMS used in this research was Sylgard 184 elastomer (Dow Corning, Korea).

The mechanical properties of these materials are listed in Table 3.

2.6 Manufacturing process

First, the rapid prototyping machine (SST 768, Stratasys, US) was used to fabricate the skeletal structure. The skeletal structure was placed in a pre-fabricated mold, and the SMA wires were inserted in the planned positions. The wires were then tightened and fixed in the mold. Resin (PDMS) was then poured into the mold and allowed to harden. The curing conditions were 100℃ for 3 h. Once the PDMS had cured, the fabricated smart structure was removed from the mold.

Table 2. Specifications of SMA wire.

Diameter	300 μm
Pre-strain	4%
Recommended current	1.5 A
Density	6.45 g/cm^3
Resistance	12.2 Ω/m

Table 3. Mechanical property of materials.

Properties	ABS	PDMS
Density	1.05 g/cm^3	1.05 g/cm^3
Tensile modulus	1627 MPa	1.8 MPa
Yield strength	22.0 MPa	6.2 MPa

3. Actuation prediction of smart structure

3.1 Basic concept and assumptions

Normally predict the actuation of SMA embedded composite, stress analysis is essential. However, calculating stress of embedded composite is very complicated. And actuation force of an SMA changing when current applied. Otherwise, in case of hinge smart structure composite, stiffness of each part are very different, especially stiffness of hinges are very lower than skeleton, therefore one of an assumptions is an SMA embedded at hinges can fully contract to its original length. Moreover, with principle of eccentricity and geometry model, it is possible to predict actuation without stress analysis.

Following statements are assumed.

1. Only length of SMA wires is changed.
2. Final shape is an arc.
3. Distances between inner arc and outer arc are constant.
4. Only hinges are deformed.
5. SMA wires contract to original length.

3.2 Shape change of hinge part

Before actuation, length of upper part and lower part are the same to original hinge length (L). Distance between ABS hinges and SMA wires are equal to half of sum of thickness of ABS hinges and SMA wires.

After SMA wires actuate, length of the lower part changes to contracted SMA wires ($(1-p)\cdot L$, p = pre-strained proportion of SMA wire). Each variable are shown in Figs. 5 and 6. Length of lower part can be also expressed as

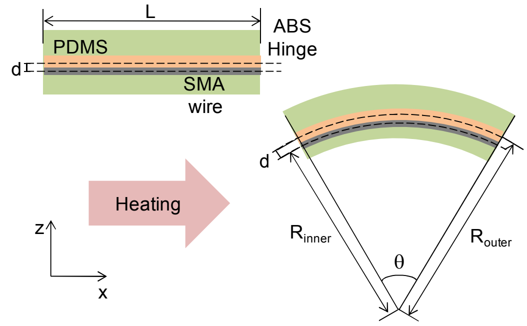


Fig. 5. Prediction of hinges' shape.

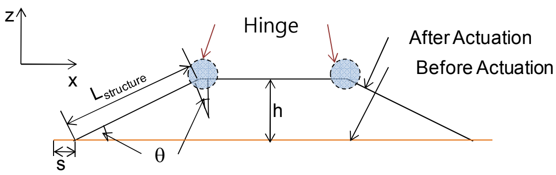


Fig. 6. Prediction of whole structure's shape.

$$(1-p)L = R_{inner}\theta = (R_{outer} - d)\theta\ . \tag{1}$$

However, length of upper part is still original length of hinges (L), and it can be also expressed as

$$L = R_{outer}\theta\ . \tag{2}$$

With Eqs. (1) and (2), following equation can be induced.

$$(1-p)L = R_{inner}\theta = (R_{outer} - d)\theta\ . \tag{3}$$

However, length of the upper part is still original length of hinge (L), and it can be also expressed as

$$L = R_{outer}\theta\ . \tag{4}$$

With Eqs. (3) and (4), following equation can be induced.

$$L(1-p) = R_{outer}(1-p)\theta = (R_{outer} - d)\theta \tag{5}$$

$$R_{outer} = \frac{d}{p} \tag{6}$$

$$R_{inner} = R_{outer} - d = \frac{d(1-p)}{p} \tag{7}$$

$$\theta = \frac{(L \cdot P)}{2}\ . \tag{8}$$

Followings are values of design parameters
L = 4.5 mm, p = 4% = 0.04, t = 0.5 mm.

The predictions of actuating are obtained.
R_{outer} = 12.5 mm, R_{inner} = 12 mm, θ = 20.6°.

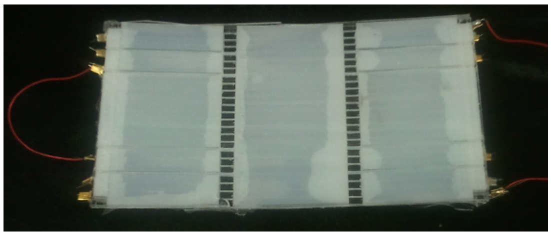


Fig. 7. Fabricated prototype.

3.3 Shape change of smart structure

With prediction of shape change of hinges, it is able to predict the shape of whole part. According to assumption, only hinges are changed. Therefore, the other parts keep remain their original shape. Moreover, amount of lift (h) and stroke(s) can be expressed as

$$h = L_{structure}\sin(\theta), \quad s = L_{structure}(1-\cos(\theta))\ .$$

And, calculated values are
h = 14.09 mm, s = 2.55 mm.

4. Performance evaluation

The fabricated prototype is shown in Fig. 7. To evaluate the performance of the prototype, 3 types of actuation test are executed.

4.1 Deformation

In the experiment to measure the deformation of the smart structure, a laser displacement sensor and digital camera were used. A current of 1.2 A was applied for 8 sec without additional mass and with additional mass (100 g). The experimental setup and results are shown in Fig. 8.

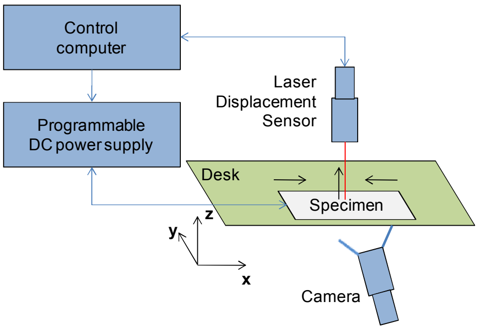
When current is applied, visible actuation is measured. And with additional mass (100 g), amount of actuation is 11.70 mm, almost same to 12.72 mm, actuation without additional mass.

4.2 Actuating force

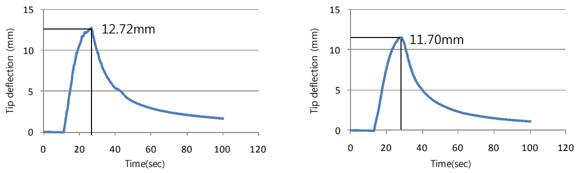
To measure the actuating force of the smart structure, a force sensor (dynamometer) was used. The experiment was performed with the tip of the specimen in the initial position, deflected by 2 mm, and deflected by 5 mm. A current of 1.2 A was applied for 8 sec. A support block was used to control the distance through which the specimen could actuate freely. The experimental setup for measuring the actuating force is shown in Fig. 8.

4.3 Repeatability of actuation

To measure repeatability of actuator, repeat actuation test is

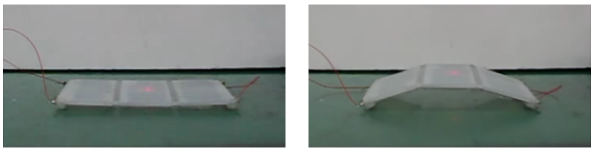


(a) Experimental setup

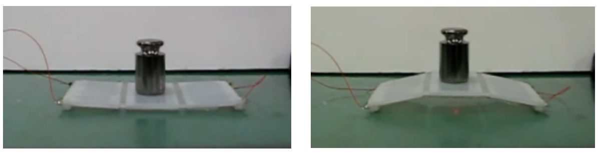


Without additional mass　　With additional mass (100 g)

(b) Measured deformation



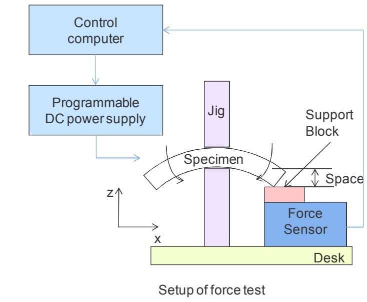
Actuation without additional mass



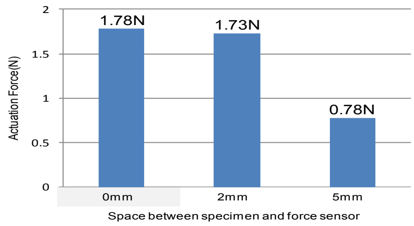
Actuation with additional mass (100 g)

(c) Deformation of prototype

Fig. 8. Result of experiment to measure deformation.

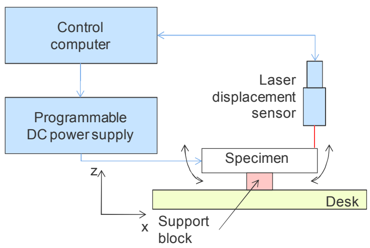


(a) Experimental setup

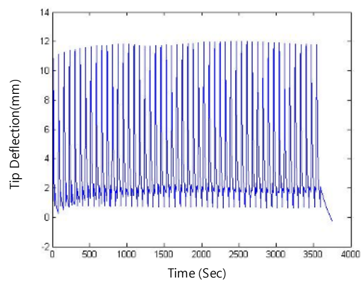


(b) Actuating force of prototype

Fig. 9. Experiment to measure actuating force.



(a) Experimental setup to measure tip deflection



(b) Tip deflection of prototype at repeatability test

Fig. 10. Experiment to validate repeatability.

executed. A current of 1.2 A was applied for 8 sec and cooling time is 60 sec. Test repeated 50 times. Laser displacement sensor is used to measure tip deflection and programmable DC power supply is used to apply current. Experimental setup and result of repeatability test is shown in Fig. 10.

5. Application: cell phone case type robot

5.1 Concept and basic design of application

A practical application of the smart structure developed in this research involved a cell phone case type robot.

Cell phones are extremely popular electrical devices with the highest communication/process performance. If a cell phone with mobility were developed, the ripple effect would be large, because such a cell phone could be a small, high-performance robot.

When the SMA wires were contracted and released, the co-efficients of friction of the front and bottom parts of the robot converted the bending motion of the structure into a crawling motion of the robot. The lower structure was designed to change the co-efficient of friction of each side.

The size was set at 120 mm x 65 mm x 6.6 mm (L x W x D). The depth of the lower structure was 3 mm, and 18 SMA wires were used.

5.2 Design of lower structure

To control friction coefficient, two kinds of materials are

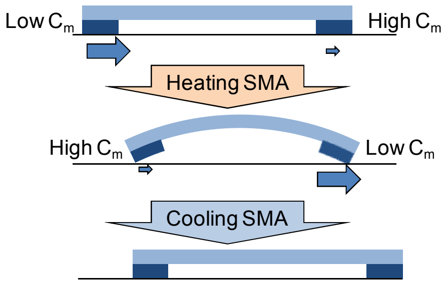


Fig. 11. Motion mechanism of cell phone case type robot.

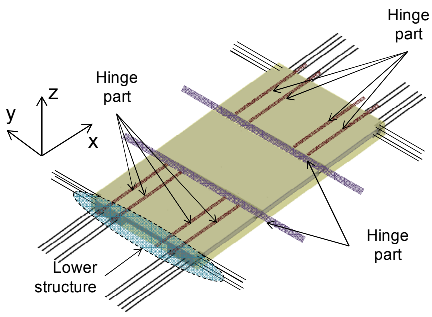
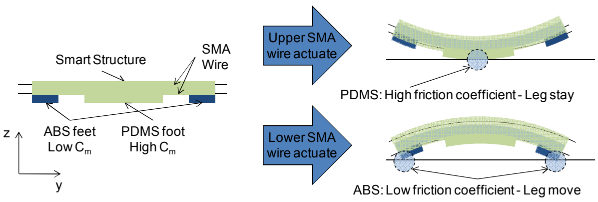
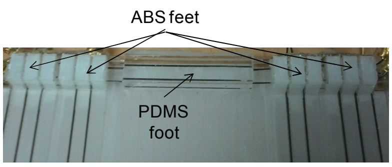


Fig. 12. Design of prototype.



(a) Design of lower structure



(b) Lower structure of fabricated prototype

Fig. 13. Lower structure.

used. Side foot is made of ABS with low friction coefficient and another foot is made of PDMS with high friction coefficient. Upper and lower SMA wires are installed though SMA wires and hinges also installed middle of the structure. When upper SMA wires actuate, lower structure bend to ∪-shape and only PDMS foot is connect to ground and when lower SMA wires actuates, lower structure bend to ∩-shape and only ABS foot is connect to ground. Therefore, friction coefficient of each side can be controlled with this mechanism.

5.3 Actuation of prototype

The fabricated prototype exhibited a crawling action. The distance covered in one stroke was 5 mm, and about 18 sec

(a) Motion of the cell phone case type robot

(b) Cell phone case type robot

Fig. 14. Application of skeleton structure.

were required for one stroke. The linear velocity of the prototype was 0.3 mm/sec. The motion of the prototype is shown in Fig. 14.

6. Conclusion

To induce large deformation in a thick smart structure, a structure consisting of a skeleton and hinges was proposed and tested. The resulting smart structure design was fabricated via a rapid prototyping and casting process. The performance of the prototype was evaluated, and visible actuation and a large actuation force were measured. The cell phone robot was suggested as an application, and the fabricated prototype of the device exhibited a perceptible crawling motion.

Acknowledgment

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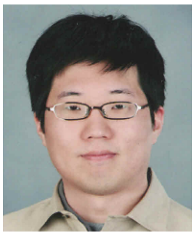

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