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SELF-FOLDING ORIGAMI USING TORSION SHAPE MEMORY ALLOY WIRE ACTUATORS

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ABSTRACT

Self-folding origami requires a low-profile actuator to be embedded in a sheet of paper-like planar material. Various actuation methods have been employed to actively fold such sheets. This paper presents a torsion shape-memory alloy (SMA) wire actuator embedded in patterned origami structures that actively folds the origami by twisting the SMA wire. A simple wire is aligned with the fold line, and each end is fixed to a facet. The twisting of the wire directly rotates the facets. This method has the advantage of using an easily available wire SMA and the advantage of a flat form factor similar to that of sheet SMA. Generally, SMA wire is used in a linear manner or as a spring. The torsion SMA wire presented in this paper is trained to generate torsional force when heated. The amount of rotation depends on the length of the wire; a 200-µm-diameter SMA wire 12 mm in length can induce 540° rotation. SMA wires are arranged in pairs side by side to rotate the facets in both directions. Maximum torque of 70 mNcm is generated in this antagonistic arrangement. The torsion SMA wire actuators enable a novel design for a programmable folding sheet that is easily manufactured and exhibits fast folding and unfolding.

INTRODUCTION

Self-folding origami simplifies the process of developing 3-D structures and devices at the micro-scale and the meso-scale [1]. Previously, small-scale 3-D structures have been built using various lithographic fabrication techniques such as layer-by-layer bulk micromachining and LIGA process which are used for the Micro Electro Mechanical Systems (MEMS). However, these techniques may be time-consuming. An origami-inspired design using advanced lithographic fabrication technology enables us to build 3-D structures by folding a 2-D pattern. It can reduce the layers required for developing 3-D structures because a single origami sheet forms a 3-D structure by folding. Furthermore, the design enables the 3-D structure to change its shape and volume to satisfy the requirements of specific applications, such as insertion into the human body.

Self-folding origami has been realized using various

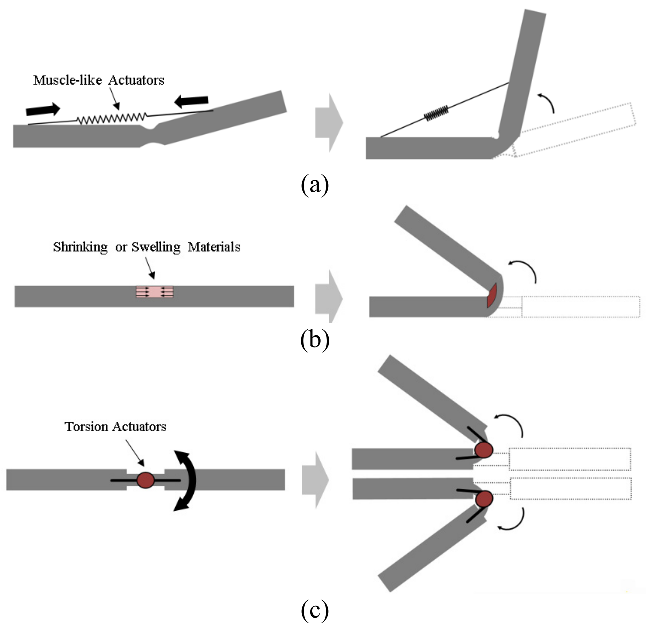


FIGURE 1. CONCEPTUAL ILLUSTRATION OF VARIOUS SELF-FOLDING MECHANISMS. (a) MUSCLE-LIKE ACTUATION, (b) SHRINKING OR SWELLING OF THE LAYER, AND (c) TORSION ACTUATORS

actuators and smart materials. We categorize the mechanisms for self-folding into three types, as shown in Fig. 1. The first type is the muscle-like actuation mechanism. The linear actuators pull the facets of the origami, as shown in Fig. 1 (a). This generates a comparatively high force, but the actuator may prevent the joint from being fully folded; the actuator on the origami is obtrusive [5, 6]. The second type is shrinking or swelling of the layer, as shown in Fig. 1 (b). Almost all self-folding mechanisms at the micro-scale use this method, because it is compatible with the laminating process. This method has been applied to build a printable robot using a shape-memory polymer layer that exhibits self-assembly at the meso-scale [2]. However, it generates low torque, and controlling the folding angle and sequence is difficult. The third type of mechanism is the torsion actuator. The torsion actuator is embedded in the fold lines and directly rotates the joint, as shown in Fig. 1 (c). Sheet shape-memory alloy (SMA) actuators have been developed as torsion actuators for self-folding in a programmable matter to change shape by programming the fold lines [3, 4, 8].

As torsion actuators for self-folding origami, torsion SMA wires (TSWs) enhance the simplicity of the joint structure. The SMA produces various shape changes that induce various forces or torque directions according to the specific shape programming. Furthermore, the high power density of the SMAs is a superior property for minimizing the form factor. SMA wires are broadly used as thermally induced linear actuators and artificial muscle actuators in biologically inspired robotics [5, 7]. SMA wire is the cheapest type of SMA and can be conveniently shape-programmed for use in various applications.

In this paper, a novel actuator for self-folding origami using a TSW actuator is presented. The TSW actuator twists a straight SMA wire to rotate the facets of origami patterns. A simple wire is aligned with the fold line, and each end of the wire is fixed to a facet. When the wire is heated, it twists and generates a torque that rotates the joint. Low-profile self-folding origami can be designed using this actuator because a simple wire is attached at the fold line for actuation. This method has the advantage of using an easily available wire SMA and the advantage of a flat form factor similar to that of sheet SMA. Generally, SMA wire is used in a linear manner or as a spring. The TSW presented in this paper is trained to generate torsional force when heated. The amount of rotation depends on the length of the wire; a 200-µm-diameter SMA wire 12 mm in length can induce 540° rotation. SMA wires are arranged in pairs side by side to rotate the facets in both directions. The pair arrangement enables not only folding but also unfolding of the origami. Maximum torque of 70 mNcm is generated in this antagonistic arrangement. We tested and built a box-pleat-patterned self-folding origami (10 cm × 10 cm). The results show that the box-pleat pattern can be folded, unfolded, and reversely folded in less than 10 s. The TSW actuators enable a novel design for a programmable folding sheet that is easily manufactured and exhibits fast folding and unfolding.

DESIGN

The torsion SMA actuator can be designed in two shapes: one is a torsion SMA coil (TSC) actuator, and the other is a TSW actuator.

TSC actuators are embedded in the folding hinges of the patterned composite sheet, as shown in Fig. 2 (a), and produce sufficient torque and strokes for the flexure hinge to be fully folded [6]. The coil is wound around the flexure hinges. The two arms are manually rotated several turns to their maximum recovery strain before being embedded and bonded at each rigid sheet. When electric current (Joule heating) or heat is applied in the SMA coil, the coil will recover its original shape, and the sheet is folded by the torque transmitted by the two arms. In Fig. 2 (b), sequential stop-motion pictures of the video show that the series links of the composite sheets are fully folded by the TSC actuators embedded at the hinges. This demonstrates the feasibility of building torsion actuators using SMA coils, which are generally used for linear actuators.

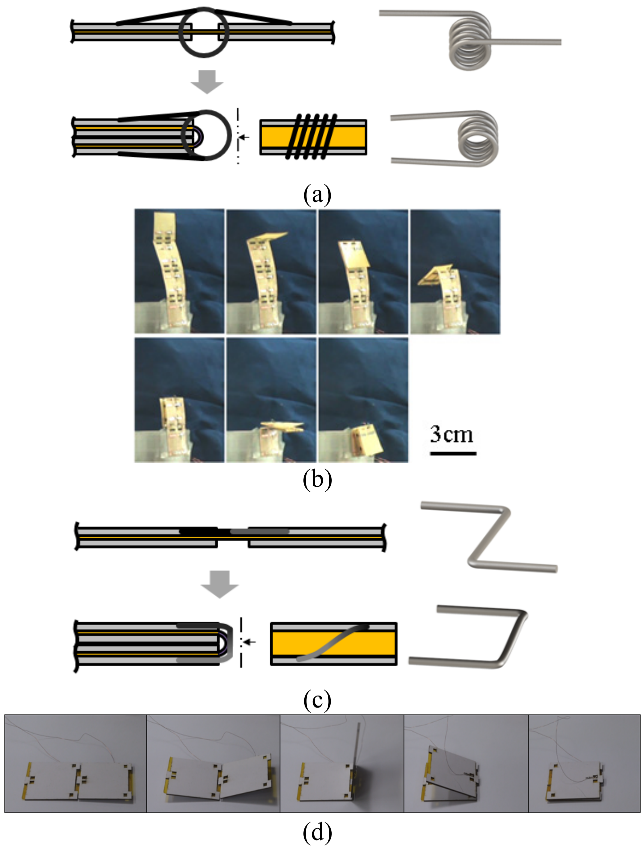


FIGURE 2. THE TWO TYPES OF TORSION ACTUATORS USING SMA WIRE. (a) TORSION SMA COIL (TSC) ACTUATOR, (b) STOP-MOTION PICTURES OF SELF-FOLDING USING TSC ACTUATOR, (c) TORSION SMA WIRE (TSW) ACTUATOR, AND (d) STOP-MOTION PICTURES OF SELF-FOLDING USING TSW ACTUATOR

The TSC actuator produces torque owing to local bending, which induces normal stress in the wire. The stress and the strain may decrease drastically with large coil numbers, increasing the permissible angle of rotation. However, the resulting torque is small. The TSC actuator is suitable for link structures that require large rotation and low payload. With regard to manufacturing, the embedding process of the SMA coil spring actuators at the folding hinges requires dexterous manual techniques for fabricating the torsion coils of the SMA wires and placing them precisely at the folding hinges without interference between them.

Figure 2 (c) shows the shape of the TSW actuator and the actuation scheme in the flexure hinges. The TSW actuator has two parts: the first is a straight wire, which is twisted and produces torsion, and the second comprises two arms, which are bent perpendicular to the wire and become bridges to deliver the torque to the link sheets. The TSW actuator also performs well in the flexure hinges. The paper linked with the TSW actuators at the flexure hinge is fully folded, as shown in Fig. 2 (d). Compared with the TSC, the design is simpler, and the payload per unit weight is higher. On the basis of these conceptual evaluations, the TSW actuator is more promising than the TSC for self-folding origami. In the following section, the self-folding origami using the TSW actuators is presented.

To apply the TSW actuator to the self-folding origami, the fundamental components of the self-folding hinge are designed as shown in Fig. 3. The SMA wire is annealed in a furnace for shape programming into a zigzag shape using the shape-memory process. To produce the torque, the wire needed to be deformed by external force manually. In our design, the TSW is twisted 360° before it is embedded in the hinge. Two arms are clamped by an off-the-shelf pin clamp and bonded onto the rigid links by soldering or gluing. When the TSW is heated by applying an electric current, it starts to twist and folds the flexure hinge of the origami. Unfolding and reverse folding are possible using a pair of antagonistic actuators.

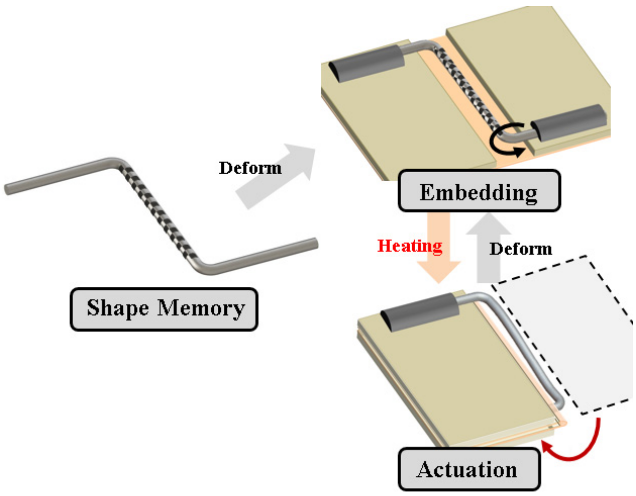


FIGURE 3. ILLUSTRATION OF THE FUNDAMENTAL SELF-FOLDING HINGE DESIGN USING THE TSW ACTUATOR

The simplicity of the shape and folding mechanism of the TSW actuator reduces manufacturing time and cost. Considering that the origami structure has a large number of folding hinges, mass production of the actuators is advantageous and avoids many problems related to the complex shape and configuration of the hinges during embedding.

With a printed circuit technique, the wiring can be hidden inside the origami sheet. By programming the routing of the circuit, the actively folding origami structure can generate various shape changes.

MODELING

Static Model of the TSW Actuator

By combining the mechanical constitutive model of the SMA and the torsional deflection model of the round wire, the equation of the TSW actuator model is derived. The mechanical constitutive model was established by Liang et al. [9] on the basis of the Tanaka model [10] as follows:

$$\sigma - \sigma_0 = E(\varepsilon - \varepsilon_0) + \theta(T - T_0) + \Omega(\xi - \xi_0),$$

where ε is the strain; T is the temperature; ξ is the phase volume fraction, which is a function of ε and T; E is Young's modulus; Θ is the thermoelastic tensor; and Ω is the transformation tensor, which can be converted to $-\varepsilon_L E(\xi,T)$, where ε_L is the maximum recovery strain, i.e., a material property of the SMA [11]. E, Θ, and Ω are functions of ε, T, and ξ. The subscript "0" denotes the initial state. To apply this model to the TSW, the stress and the strain are replaced by the shear stress, τ, and the shear strain, γ, respectively. E is replaced by the shear modulus, G. The subscript "s" of Θ and Ω denotes the shear mode. The model converted to shear mode is expressed as

$$\tau - \tau_0 = G(\gamma - \gamma_0) + \theta_s(T - T_0) + \Omega_s(\xi - \xi_0).$$

When the initial conditions are set to zero, the equation becomes

$$\tau = G\gamma + \theta T + \Omega\xi.$$

This mechanical constitutive model in shear mode can be applied in the equation for the torsion beam, $\mathrm{T} = \tau(J/r)$ ($J = \pi d^4/32$), as follows:

$$\mathrm{T} = \frac{JG}{r}\gamma + \frac{J\theta}{r}T + \frac{J\Omega}{r}\xi(\gamma, T).$$

The thermoelastic tensor, Θ, is eliminated because we need two thermal static models: one at high temperature (austenite phase) for actuation and one at low temperature (martensite phase) for releasing. The phase of the SMA depending on the temperature affects the shear modulus, G. At high temperature, the shear modulus has a high value, G_A, which is in austenite phase. At low temperature, it has a low value, G_M, which is in martensite phase. The model equation is abbreviated to

$$\mathrm{T} = \frac{JG}{r}\gamma + \frac{J\Omega}{r}\xi(\gamma).$$

The transformation tensor can be modeled as $\Omega = -\gamma_L G(T)$, where γ_L is the maximum recovery shear strain [11]. Finally, the static model of the TSW actuator is given as

$$\mathrm{T} = \frac{JG}{r}\gamma - \frac{JG}{r}\gamma_L \xi(\gamma)$$

$$\xi_\gamma = \frac{1}{2}\cos\left(\frac{\pi}{\gamma_s^{cr} - \gamma_f^{cr}}\left(\gamma - \gamma_f^{cr}\right)\right) + \frac{1}{2},$$

where γ^{cr} denotes the critical strains, i.e., the start (subscript "s") and finish (subscript "f") detwinning strains measured by experiments [11].

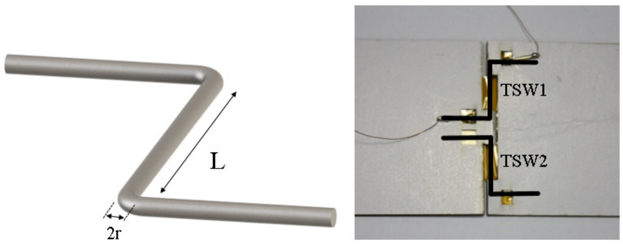
Design of the TSW Actuator

The TSW actuator has two design parameters: the radius of the wire, r, and the length of the torsional part, L, as shown in Fig. 4 (a). Figure 4 (b) shows the pair of antagonistic actuators used for folding and reverse folding. When the TSW actuators are used antagonistically as shown in Fig. 4 (b), the torque of each actuator should be designed precisely to achieve the desired folding angle. Using the static model of the TSW actuator, we can plot the relation between the torque and the rotation angle, as shown in Fig. 5 (a). The rotation angle, α, and the shear strain, γ, have the following relationship:

$$\gamma = \frac{r}{L}\alpha .$$

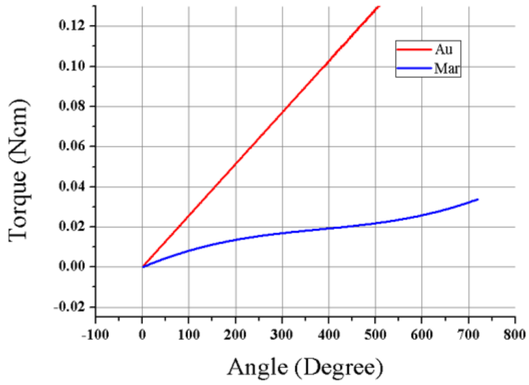
When the TSW is activated by heating, it is in the austenite phase (Au), which is characterized by high stiffness. When it cools, it is in the martensite phase (Mar), which is characterized by low stiffness, and it can be twisted easily, as shown in Fig. 5 (a). In the antagonistic actuation, the activated actuator folds the origami and should overcome the opposite actuator, which is in the martensite phase of low stiffness. To achieve full folding or the desired folding angle, two antagonistic actuators are designed to set the angle at which the torque is balanced. As described in the previous section, the actuator is embedded after being twisted 360°. Similarly, the opposite actuator is twisted 360° in the opposite direction and then embedded. As shown in the graph in Fig. 5 (b), the actuators are balanced at 360° in the flat state of the folding joint. To plot the graph of both actuators (TSW1, TSW2), the opposite actuator, TSW2, starts at 720° and is twisted in the opposite direction compared to TSW1. When TSW1 is activated, its torque follows the solid line of Au, and the torque of TSW2 follows the dotted line of Mar. The angle then decreases to the angle at which the two lines meet. The two lines meet at approximately 100°, but it is impossible to fold more than 180°. Therefore, it is fully folded, as shown on the left side of Fig. 5 (b). Conversely, when the TSW2 is activated at that time, the torque of TSW1 follows the solid line of Mar, and the torque of TSW2 follows the dotted line of Au. The angle starts to increase to the angle at which the two lines meet. This is approximately 620°, as shown in the graph, but the folding joint cannot be folded more than 540°, which is shown as fully inverse folding on the right side of Fig. 5 (b).

Figure 5 shows the result of the modeling with the designed parameter that satisfies the above requirements. The radius of the wire (r) is 200 µm, and the length of the torsion part (L) is 12 mm.

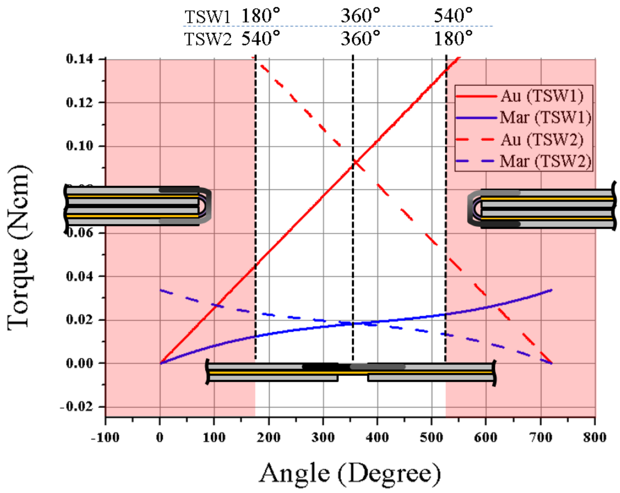


(a) (b)

FIGURE 4. (a) DESIGN PARAMETERS OF THE TSW ACTUATOR AND (b) ANTAGONISTIC PAIR OF TSW ACTUATORS



(a)



(b)

FIGURE 5. RELATION BETWEEN TORQUE AND ROTATION ANGLE FOR THE TSW ACTUATOR. (a) SINGLE TSW ACTUATOR AND (b) TWO ANTAGONISTIC TSW ACTUATORS

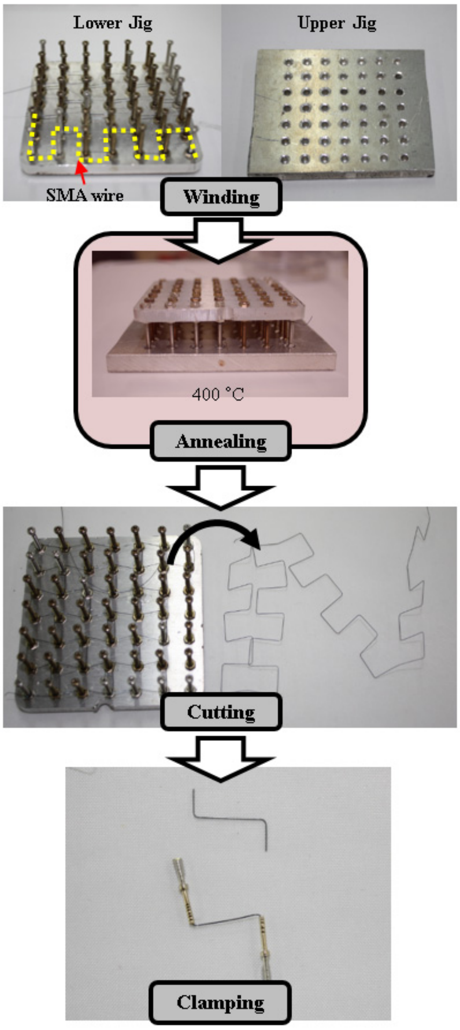


FIGURE 6. FABRICATION OF THE TSW ACTUATORS

FABRICATION

Torsion SMA Wire (TSW) Actuator

The TSW actuator is fabricated using the shape-memory process of SMA as shown in Fig. 6. The SMA wire is wound in a zigzag shape along the jig, which is an array of bolts that are driven onto the aluminum plate and are positioned at regular intervals, as shown by the "Lower Jig" in Fig. 6. The "Upper Jig" holds the bolts to prevent them from bending while annealing. The jig is put into the furnace and annealed at 400 °C for 1 h. After annealing, the shape of the wire is programmed into the zigzag shape, as shown in the lower-left picture in Fig. 6. We obtain multiple TSW actuators by cutting the array of the zigzag wire. Finally, two arms of the TSW actuator are clamped by pin clamps, which are commonly used as pin connectors of electrical wires.

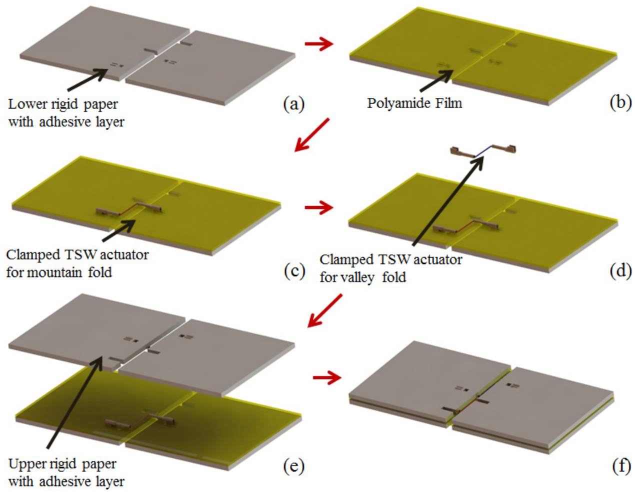


FIGURE 7. LAYUP OF THE FUNDAMENTAL SELF-FOLDING JOINT USING THE TSW ACTUATORS

Self-folding Hinges

The fundamental unit of the self-folding hinge is composed of the rigid sheet, the flexible film for the flexure joint, and the pair of antagonistic TSW actuators. Figure 7 shows the fabrication process of the fundamental unit of the self-folding hinge. The origami structure has a sandwich-like shape. The polyimide flexible film is positioned between the two rigid papers. There are small holes in the rigid papers for holding the clamps of the TSW actuators. The layers are cut by precise laser machining and bonded to each other by double-sided adhesive layers. Figure 2 (d) shows the self-folding motion of the fundamental self-folding hinge.

SELF-FOLDING ORIGAMI

One of the possible applications of the TSW actuator is to construct a self-folding origami sheet that can fold from a single sheet into various shapes. The TSW actuator is low-profile and easily controlled by an electric current. It is suitable as an origami-sheet actuator because it can be embedded between thin planar materials and actuated by electric current without manual folding.

By using this origami-inspired design, we can make complicated 3-D structures from simple 2-D patterns. Therefore, origami structures, which feature a planar fabrication process that is straightforward, cheap, and scalable, may replace traditional robotic elements. They may be utilized

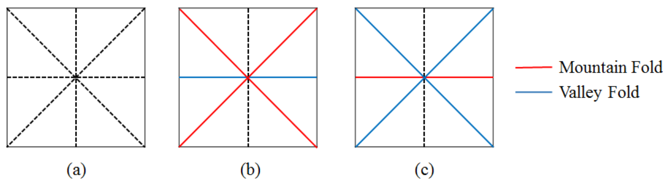


FIGURE 8. BOX-PLEAT FOLDING PATTERN. (a) EIGHT FOLD LINES. (b) AND (c) TWO TYPES OF MOUNTAIN AND VALLEY FOLD LINES PROGRAMMED IN THE EXAMPLE.

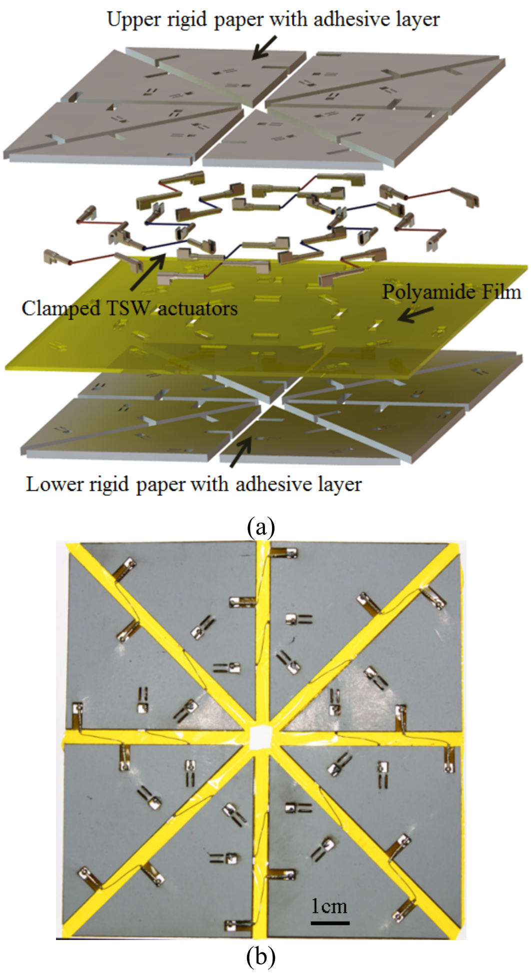


FIGURE 9. (a) LAYUP FOR THE FABRICATION OF THE SELF-FOLDING BOX-PLEAT ORIGAMI AND (b) PROTOTYPE

for designing micro-scale robots or self-folding structures [12, 13].

To verify the adaptability of the TSW actuator, we applied a single-hinge design to construct a single box-pleat pattern, which will verify the TSW actuator's universality in forming various 3-D structures by folding a sheet with box-pleat patterns. In a single box-pleat, there are eight fold lines, as shown in Fig. 8 (a).

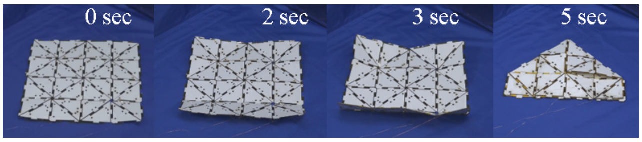


FIGURE 11. SEQUENTIAL STOP-MOTION FIGURES OF HOUSE-SHAPE SELF-FOLDING VIDEO OF THE 2 × 2 BOX-PLEAT ORIGAMI

We aimed to fold a triangular shape and to fold it reversely by using the single box-pleat origami. Its fold lines are illustrated in Fig. 8 (b), and its reverse fold pattern is shown in Fig. 8 (c). For the mountain fold, TSW actuators were fixed to the lower layer, and for the valley fold, TSW actuators were fixed to the upper layer. Six TSW actuators were connected serially by enamel wire, and the antagonistic pairs were connected in the same way for reverse folding.

In our self-folding sheet, at each fold line, there were two antagonistically embedded TSW actuators, which were prestrained 360° reversely so that they were able to rotate 180° in the opposite direction, as described in the previous modeling section. The layup for the lamination process of the single pox-pleat sheet is shown in Fig. 9 (a). The facet of the origami was made of rigid papers, and the fold lines were made of polyimide flexible film. Between them, the TSW actuators were inserted after twisting by 360°. The self-folding box-pleat prototype is shown in Fig. 9 (b). The thickness of the structure was 1 mm, and there were no projecting parts on the surfaces.

The sheet was folded as shown in Fig. 10. First, we delivered the current of 0.8 A to the six actuators configured as shown in Fig. 8 (b), and a triangular shape was formed in the range of 0–4 s. After we cut off the current to the six actuators and delivered the current to their antagonistic pair actuators, the sheet unfolded and returned to its original flat shape (4–8 s) and reverse-folded into a triangular shape during the next 2 s (8–10 s). Total bidirectional actuation required only 10 s, and only 1.6 W was required for actuation.

DISCUSSION

The TSW actuator has a simple structure and can be made using a comparatively easy fabrication process; it does not

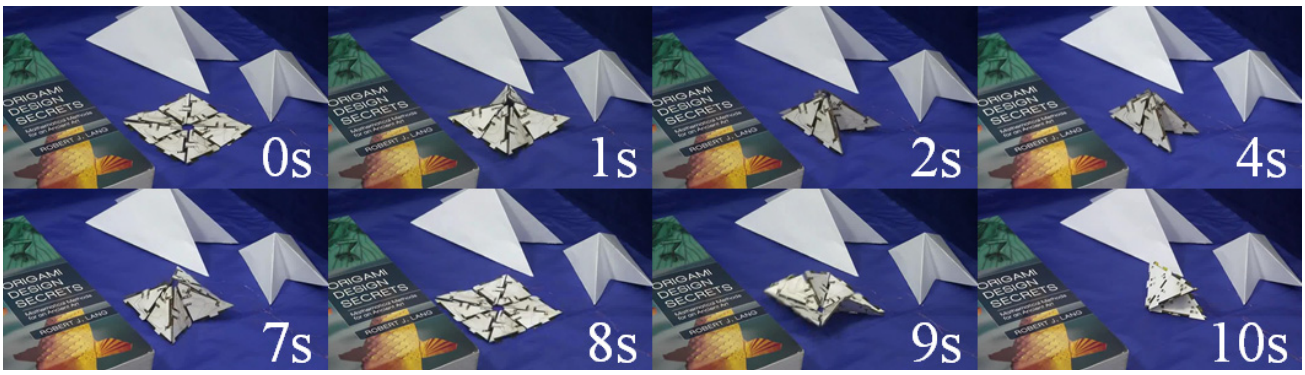


FIGURE 10. SEQUENTIAL STOP-MOTION PICTURES OF SELF-FOLDING, UNFOLDING AND REVERSE FOLDING VIDEO

require complex machining. Regarding actuation performance, it performs fast actuation to fully fold, unfold, and reverse fold the single box-pleat origami structure within 10 s. The box-pleat pattern may be a basic pattern to be expanded infinitely. Various shape changes are possible by programming the fold lines of the large array of the box-pleat pattern. As shown in Fig. 11, the planar sheet changes in shape from a square to a house-like shape by self-folding 2 × 2 box-pleat patterns.

In terms of fabrication of the self-folding structure, there remain laborious lamination steps to align the actuators and layers. Although the TSW actuator has a simple shape and requires the attachment of only two arms on the folding joints, large numbers of actuators increase the working time. By applying the printed circuit technique, the electrical wires are hidden inside the composites, and the routing of the wire can be designed to generate various shape changes by using various programming input signals.

CONCLUSION

We have developed torsion SMA coil and wire actuators for self-folding origami hinges. The SMA changes its shape because of thermally induced stress and strain and has high power density. Being embedded at the self-folding hinge, the TSW is low-profile and unobtrusive. The TSW produces torque by pure torsional stress, and the TSC induces normal stress and strain by bending. The TSW produces much higher torque per unit weight than the TSC. Furthermore, the TSW actuator performs faster folding than other self-folding mechanisms. It can fold an origami structure in less than 5 s, and unfolding and reverse folding are performed in less than 5 s. In less than 10 s, the self-folding origami structure can be folded into a specific shape; the shape can be changed by programming the fold lines. Although the proposed self-folding mechanism must be improved to expedite the fabrication process, it is a promising actuation mechanism because of the simplicity of its design and implementation.

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