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Multistable wireless micro-actuator based on antagonistic pre-shaped double beams

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Abstract

This paper presents a monolithic multistable micro-actuator based on antagonistic pre-shaped double beams. The designed micro-actuator is formed by two rows of bistable micro-actuators providing four stable positions. The bistable mechanism for each row is a pair of antagonistic pre-shaped beams. This bistable mechanism has an easier pre-load operation compared to the pre-compressed bistable beams method. Furthermore, it solves the asymmetrical force output problem of parallel pre-shaped bistable double beams. At the same time, the geometrical limit is lower than parallel pre-shaped bistable double beams, which ensures a smaller stroke of the micro-actuator with the same dimensions. The designed micro-actuator is fabricated using laser cutting machine on medium density fiberboard (MDF). The bistability and merits of antagonistic pre-shaped double beams are experimentally validated. Finally, a contactless actuation test is performed using 660 nm wavelength laser heating shape memory alloy (SMA) active elements.

Keywords: multistable, micro-actuator, bistable pre-shaped beam, shape memory alloy (SMA), contactless actuation

(Some figures may appear in colour only in the online journal)

1. Introduction

The development of micro-electro mechanical system technology leads to micro-actuators with smaller dimensions. As a consequence, integrating additional sensors (e.g., position sensors) and a power supply unit without disturbing the micro-actuators' degrees of freedom becomes more difficult. In this situation, the multistable micro-actuators (or digital micro-actuators) have attracted the attention of researchers. A multistable micro-actuator has multiple discrete stable output positions by coupling several bistable modules. Each stable position is well known and self-maintained, thus can be controlled with the open-loop method. Furthermore, due to the bistability of each bistable module of the multistable micro-actuator, energy consumption only happens during the switching cycle (from one stable position to another stable position). Therefore, the power-consuming ratio can be limited to a low level, which will largely reduce the dependency of the power supply for multistable micro-actuators, especially for scenarios when the micro-actuators are not actuated frequently.

The maximal number of stable positions for a multistable micro-actuator is 2^n, where n is the number of bistable modules. By serial coupling two bistable modules, Pham and Wang [1] developed a quadristable mechanism that has four stable positions distributed over a single axis. In this design, one inner bistable module is surrounded by another outer one and each is based on curved beams. These two modules were designed with different maximal output force; when the switching force is applied on the quadristable mechanism, the outer bistable module, which has a smaller output force, will be switched firstly. If the switching force continues to increase, the inner bistable module will be also switched. In addition, if the direction of switching force is reversed, the outer and inner bistable module will be switched back in a sequence. Different from the design in [1], Han *et al* [2], reported a quadristable mechanism with *x*- and *y*-directional bistable curved beams. It is capable of 2D output, with four stable positions that are the four vertices of a rectangle.

Another strategy to get a 2D workspace lead Chalvet *et al* [3] to design a planar digital robot by coupling six bistable modules in parallel. This device proposes 64 output positions uniformly distributed in a square workspace.

Bistable curved beams are used as the bistable mechanism in previously mentioned multistable micro-actuators because of performance, including factors such as self-stability, relative big output force, etc. These bistable curved beams can be classified into three groups: pre-compressed bistable beams, pre-stressed bistable beams, and pre-shaped bistable beams. In [4–6], a contactless bistable micro-actuator using pre-compressed bistable beam was developed by Zaidi *et al.* A straight beam was compress to a cosine curved shape with the help of a precise linear stage (used to compress one of the two ends of the beam) and a force sensor fixed on a linear motor (used as a contact probe to set the stroke of the bistable beam). In [7], a pre-compressed beam was used as an approach for vibrational energy harvesting. The pre-compressed beam has the advantages of symmetrical output force and adjustable stoke. But the pre-compress operation is relatively complex and difficult to control. Furthermore, due the pre-compress operation, the position of the beams' ends will change, which leads to the difficulty of coupling several bistable modules in case of multistable micro-actuators design. Different from pre-compressed beam, a pre-stressed beam is curved by artificially creating stress during the fabrication process. In [8–10], Pane and Asano fabricated a bistable micro-actuator by patterning the active silicon (Si) layer of SOI (silicon-on-isolator). The pre-stress was introduced by the difference in thermal expansion between Si and SiO_2 layers during the oxidation process. However, the depth of oxidation is difficult to control. A solution to avoid the need of pre-load operation (pre-compress or pre-stress) is a pre-shaped bistable beam that is designed and fabricated with a certain curved shape without residual stress. In [2, 11], parallel pre-shaped double beams were used as the bistable mechanism. In [11], a bistable mechanism based on a pair of central clamped parallel pre-shaped bistable beams with a cosine shape was fabricated on silicon wafer using the deep reactive-ion etching (DRIE) technique. Although, the designs' choice of pre-shaped beams avoids the pre-load operation, the pre-shaped design introduces some issues at the same time, e.g., due to the pre-designed shape, the strains at two stable positions are not equal so the force output is not symmetrical in the forward and backward directions. Additionally, the bistability is limited by a geometrical factor Q (the proportion between the half stroke and the thickness of the beam). In detail, the half stroke should be more than several times the thickness of the beam to achieve the bistability. According to [11], the critical value is 2.31 and to have the beam well bistabled, Q should be bigger than 6. Due to this limit, the stroke would be bigger than the one of bistable micro-actuators with same dimensions using the pre-compressed beams, which is not suitable for micro-applications that require small strokes.

In this work, a bistable mechanism based on antagonistic pre-shaped double beams and a multistable micro-actuator using this mechanism will be presented. The antagonistic pre-shaped double beams will be compared with pre-compressed beam and parallel pre-shaped double beams. A prototype of the multistable micro-actuator was fabricated and tested. The experimental results will be presented and discussed. Finally, the study of wireless actuation, using laser-heated SMA elements, of the multistable micro-actuator will be presented.

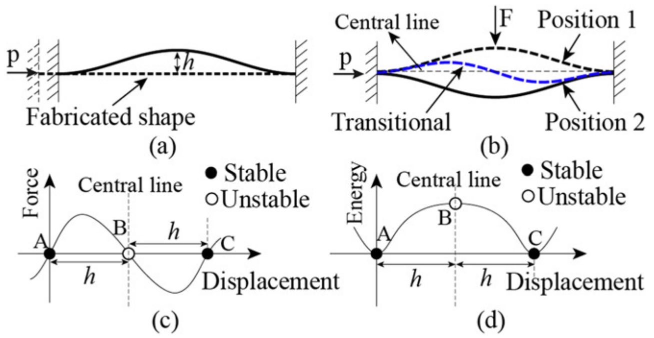

Figure 1. (a) Pre-compressed beam; (b) transitional buckling mode (s-shaped) of pre-compressed beam; (c) force-displacement chart of pre-compressed beam; and (d) energy-displacement chart of pre-compressed beam [6].

2. Modeling

2.1. Bistable mechanisms based on pre-compressed and pre-shaped beams

A pre-compressed beam is one of the most commonly used bistable mechanisms. A pre-compressed beam is fabricated with the straight form and then axial force is applied to achieve a cosine shape (figure 1(a)). A single pre-compressed beam has two stable positions, with the shape of buckling mode 1. When the switching force F is applied to the midpoint, the beam will be deflected from stable position 1 to stable position 2 (figure 1(b)). For the single pre-compressed beam, the rotation of the midpoint is not constrained, so the transitional buckling mode is buckling mode 2 (figure 1(b)).

As shown in figure 1(c), the force-displacement curve of a single pre-compressed beam is symmetrical with respect to the displacement axis [5], i.e., the beam generates the same force in the forward and backward directions. As we see, there are three equilibrium positions (indicated as A, B, and C) where the force is zero. Among them, A and C are stable equilibrium positions, because if there is a small disturbance at position A or C, according to the force-displacement curve, the beam could reset itself to position A or C after the disturbance is gone. However, if there is a disturbance around B, the beam will snap to position A or C instead of recovering to position B; therefore, B is an unstable equilibrium position.In an energy view, the transitional buckling mode (mode 2) stores more energy than the stable buckling mode (mode 1) [11]. As shown in figure 1(d), buckling mode 2 created an energy barrier between two stable positions and the two stable positions are two local minimal energy points. Therefore, a single pre-compressed beam is bistable.

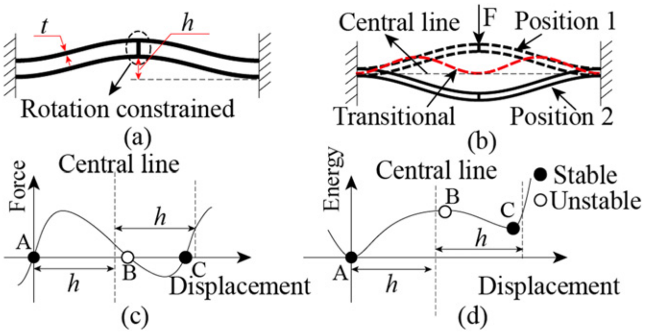

Figure 2. (a) Centrally clamped parallel pre-shaped double beams; (b) transitional buckling mode of centrally clamped parallel pre-shaped double beams; (c) force-displacement of centrally clamped parallel pre-shaped double beams; and (d) energy-displacement of centrally clamped parallel pre-shaped double beams.

However, the pre-load operation for pre-compressed beam is difficult to control, especially for the configuration that contains multiple beams. Pre-shaped beams are fabricated with a curved shape (cosine shape), thus, no pre-load is necessary. Due to the fact that a single pre-shaped beam could not be bistable, the central clamped parallel pre-shaped double beams [2, 11, 22] (figure 2(a)) were used as the bistable mechanism. Two parallel pre-shaped beams were clamped at the midpoints. The central clamp constrained the rotation of the midpoint during the switching cycle, so that the transitional buckling mode would be buckling mode 3 (figure 2(b)). Buckling mode 3 stores more energy than mode 2, so the energy barrier is high enough to create two local minimal energy points (A and C) for each stable position. The force-displacement and energy-displacement curves are shown in figures 2(c), (d). Similar with figure 1(c), the part (between B and C) of the force-displacement curve is negative and there are two stable equilibrium positions (A and C). So, the centrally clamped parallel pre-shaped double beams are bistable.

Although the bistability is achieved by centrally clamping parallel pre-shaped double beams, there is a geometrical limit $Q = h/t$ [11]. The original rise h should be more than 2.31 [11] times the beam's thickness t or it will not be bistable. To have the beam well bistabled, Q should be more than 6 [11]. So the stroke, $2 \times h$ (in real case, the stroke is slightly smaller than $2 \times h$), is bigger than the stroke of a pre-compressed beam with the same dimensions. This is not suitable for applications that need precise position output. Furthermore, as we see in figure 2(c), the force-displacement curve is not symmetrical with respect to the displacement axis, which is not good for applications that need symmetrical force-displacement behavior, such as the mechanical memory cells.

2.2. Antagonistic pre-shaped double beams

A bistable mechanism based on centrally clamped antagonistic pre-shaped double beams was designed (figure 3(a)). The designed bistable mechanism will simplify the pre-compression operation for the pre-compressed beam, so it can be efficiently produced in bulk fabrication. Furthermore, it could lower the geometrical limit Q and have symmetrical force-displacement behavior.

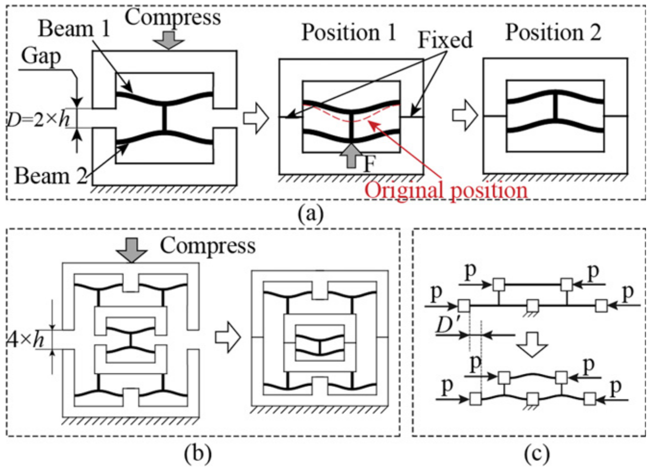

Figure 3. (a) Pre-load of bistable micro-actuator based on antagonistic pre-shaped double beams; (b) pre-load of quadristable micro-actuator based on antagonistic pre-shaped double beams; and (c) pre-load of quadristable micro-actuator based on pre-compressed beams.

The realized structure consists of two pre-shaped beams, with the same dimensions, that are configured to be antagonistic to each other. They are clamped at the midpoints. Between the support parts of each beam, a gap equal to $2 \times h$ is defined. After the structure is fabricated, it will first be pre-loaded until the gap disappears and then the two parts will be fixed together.

Because of the fabrication defects, these two beams are not the same strength as designed. During the pre-load operation, the force on two beams is increased by the same magnitude. Since the beam used in our design is also pre-shaped, the force-displacement behavior will be similar with the one shown in figure 2(c). Therefore, the beam that is relatively weaker (beam 2 in figure 3(a)) will first reach its maximal force tolerance. Then it will be pushed by the stronger one (beam 1 in figure 3(a)) to the position near its second extreme position. At the same time, the force tolerance of beam 2 will be largely decreased, so that beam 1 will recover to the position near its original position and the two beams will reach an equilibrium state. This state will act as stable position 1 for the entire bistable structure and it can be switched to the stable position 2 by an external force F (figure 3(a)).

The bistable mechanism based on centrally clamped antagonistic pre-shaped double beams can lower the difficulty of pre-load operation (especially for multiple rows beams) (figures 3(b), (c)) for the pre-compressed beam. The distance needed to compress during the pre-load operation is defined by the gap between two support parts, so the pre-load can be realized without help from an external instrument (e.g., linear stage or force sensors used in [4]). The pre-load for a multi-stable micro-actuator can be finished in one operation with one compressing force (figure 3(b)). It is simpler than a

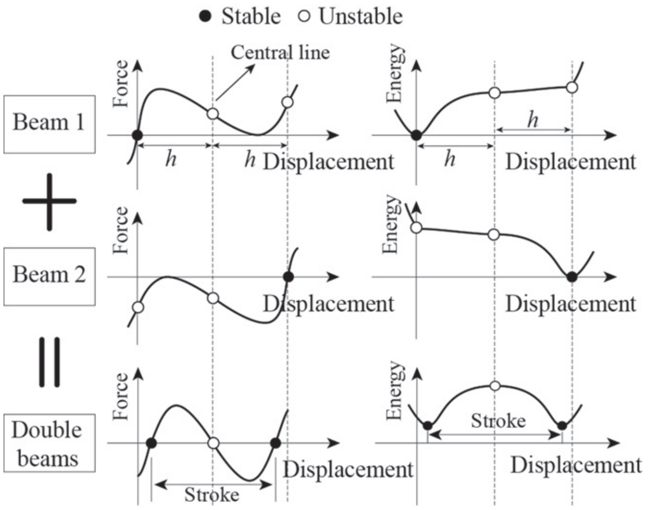

Figure 4. Force-displacement and energy-displacement curves of antagonistic pre-shaped double beams (when $Q < 2.31$).

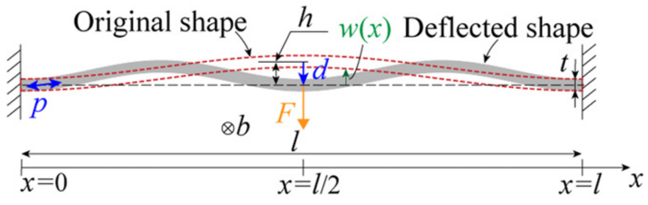

Figure 5. Model of a single pre-shaped beam with rotation of midpoint constrained.

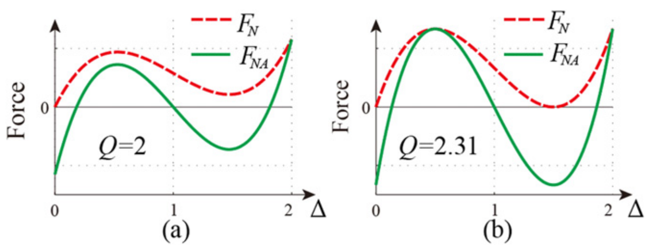

Figure 6. Force-displacement curves from Matlab with different value of Q: (a) $Q = 2.0$; (b) $Q = 2.31$.

multistable micro-actuator based on pre-compressed beams (figure 3(c)), which needs multiple compressing forces.

Moreover, the pre-load operation is less sensitive to errors. If take a beam with a length of $l = 25$ mm and a half stroke $h = 500\,\mu$m as an example. The gap $D = 2 \times h$, which is also the stroke, would be $1000\,\mu$m. For the pre-compressed beam with the same length, the distance (D' in figure 3(c)) needed to be compressed to get a same h ($500\,\mu$m) would be $32.9\,\mu$m. Due to the error of fabrication or compression, there can be a variation of $10\,\mu$m for D and D'. For antagonistic pre-shaped double beams, the stroke error introduced by the variation of D would have the same value of this variation, i.e., $10\,\mu$m. But for the pre-compressed beam, the stroke error would be $114\,\mu$m, which is much larger.

As mentioned previously, after the antagonistic pre-shaped double beams are pre-loaded and fixed, beam 1 stays near its original position, so the force-displacement behavior of beam 1, during the switching process from position 1 to position 2, (figure 3(a)) should be similar to the behavior of parallel pre-shaped double beams (figure 4). During the same process, beam 2 will recover from the position near its second extreme position to the position near its original position. Thus, the force-displacement behavior of beam 2 is the mirror of beam 1 with respect to the central line. Moreover, the two beams are antagonistically configured, so the force of beam 2 should be reversed to below the displacement axis, as shown in figure 4. Then, the total force-displacement behavior for entire bistable mechanism is the sum of beam 1 and beam 2. To be clear, the chart shown in figure 4 is for the state when $Q < 2.31$. Although both beam 1 and beam 2 are not bistable, the entire structure is bistable and the force is symmetrical. In the energy-displacement chart, it is also obvious that there are two local minimal energy points for both two stable positions and the energy amount at these two points would be the same. Additionally, we can see that the two stable positions are moved for a small distance to the central line, which means the final stroke would be slightly smaller than $2 \times h$.

2.3. Mathematical model

To calculate the force generated by the designed micro-actuator, a model for a pre-shaped beam is constructed as shown in figure 5. Where l is the length, t is the thickness, h is the original rise of the central point, d is the displacement of central point, p is the axial load, and b is the depth of beam.

During the deflection, the shape of the beam can be expressed as a superposition of a set of infinite buckling modes. Using the minimal energy principle, the switching force F during the deflection process for centrally clamped parallel pre-shaped beam can be calculated by following equations [11, 12, 22]:

$$F_N(\Delta) = \begin{cases} \dfrac{3\pi^4 Q^2}{2}\Delta\left(\left(\Delta - \dfrac{3}{2}\right)^2 - \left(\dfrac{1}{4} - \dfrac{4}{3Q^2}\right)\right) & p_1 \leqslant p < p_2 \\ 4.18\pi^4 - 2.18\pi^4\Delta & p_2 \leqslant p < p_3 \\ 8\pi^4 - 6\pi^4\Delta & p \geqslant p_3 \end{cases} \quad (1)$$

Where $F_N = Fl^3/EIh$ is the normalized switching force, $\Delta = d/h$ is the normalized deflection, E is Young's modulus, $I = bt^3/12$ is the inertia moment with respect to the axis of deflection, p_2 and p_3 are the critical axial load for buckling mode 2 and mode 3, and $Q = h/t$ is the geometry factor. If we define the switching force for the antagonistic pre-shaped double beams as F_A, the normalized switching force $F_{NA} = F_A l^3/EIh$, then:

$$F_{NA}(\Delta) = F_N(\Delta) - F_N(2 - \Delta) \quad (2)$$

The normalized force-displacement curves of central clamped parallel pre-shaped beam (F_N in figure 6) and antagonistic pre-shaped double beams (F_{NA} in figure 6) are calculated in a Matlab environment. As we see in figure 6, the antagonistic pre-shaped double beams need much smaller Q to be bistable (critical value is $Q = 1.16$), when $Q = 2$, the

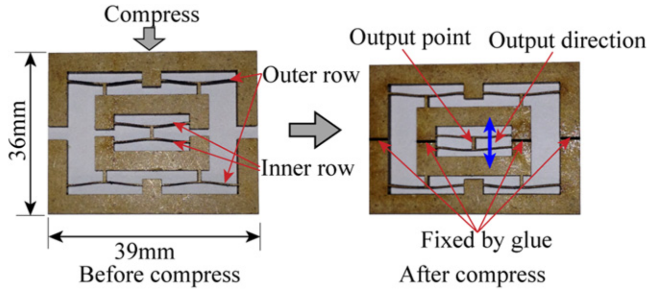

Figure 7. Quadristable structure fabricated using a laser cutting machine on MDF ($l = 15$ mm, $b = 3$ mm, $t = 250\ \mu$m, $h = 500\ \mu$m; review figure 5 for the meanings of these parameters).

antagonistic pre-shaped double beams are already well bistabled, while the parallel pre-shaped beam just reaches the critical state when $Q = 2.31$. So, with a given fabrication condition, we can get smaller stroke; for example, in our laboratory, if the minimal thickness t we get is about 250 μm, the theoretical minimal stroke for our design could be 580 μm ($2 \times Q \times t$ when $Q = 1.16$), while the minimal stroke for parallel pre-shaped beams would be 1155 μm ($Q = 2.31$). Furthermore, the force generated by antagonistic pre-shaped double beams is symmetrical in the forward and backward directions.

3. Fabrication and test

3.1. Fabrication

A quadristable micro-actuator was fabricated using a laser cutting machine (Trotec Speedy 400 with CO_2 laser) on medium density fiberboard (MDF). It is a combination of two rows of central clamped antagonistic pre-shaped double beams (figure 7).

3.2. Switching with linear motor

To test the multistability of the designed micro-actuator, an experimental setup was arranged, as shown in figure 8. In order to verify the bistability of the designed bistable mechanism based on antagonistic pre-shaped double beams, a linear motor (Newport MFA 25 CC), instead of SMA elements, was used to switch the micro-actuator between its stable positions. An optical fiber distance sensor [14] is used to measure the output movement at the output point. With the aim of improving the sensitivity of optical fiber distance sensor, a small mirror is glued on the output point. The test results are shown in figure 9.

In figure 9, it is obvious that, in one switching cycle, four stable positions are separate: two for the inner row and two for the outer row (since the stroke for inner and outer rows is designed with the same value, stable position 2 and 4 are almost at the same position). Thus, the multistability of the designed micro-actuator is proved. The measured strokes for both inner and outer rows are 970 ± 1 μm over 100 cycles. As

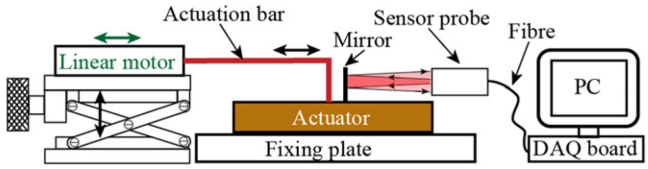

Figure 8. Schematic of the experimental setup for multistability test.

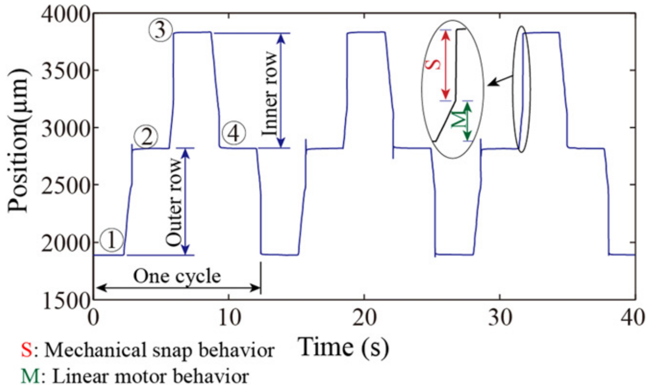

Figure 9. Multistability and response time tests of the designed multistable micro-actuator switched by linear motor ($l = 15$ mm, $b = 3$ mm, $t = 250\ \mu$m, $h = 500\ \mu$m; review figure 5 for the meanings of these parameters).

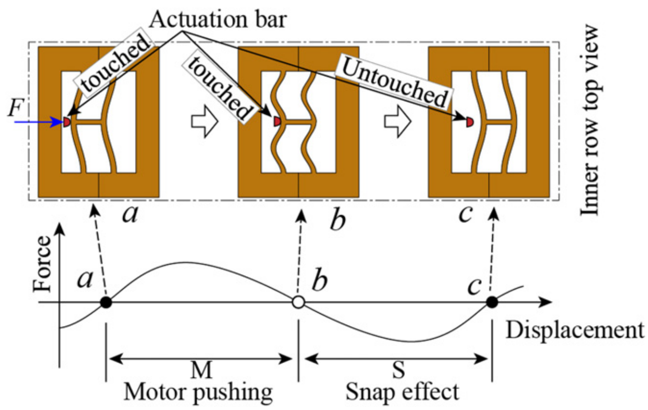

Figure 10. Snap effect during switching.

predicted, the strokes are slightly smaller than $2 \times h = 1000\ \mu$m.

If we take the inner row as an example, the zoomed step response (figure 9) can be divided into two parts. The part indicated by M corresponds to the pre-shaped double beams pushed by the linear motor through the actuation bar (a top view of the switching process for inner row is shown in figure 10). Limited by the maximal speed of linear motor, the gradient of part M is relatively small. After the double beams are pushed across point b (figure 10), which is an equilibrium point, the force needed to switch the double beams becomes negative, which means they can reach point c automatically. This is called the 'snap effect', which is indicated as S in figures 9 and 10. The duration of the part S is 14 ms, which leads to a big gradient of part S in figure 9. Theoretically, the length of the part M should equal to the length of part S along the position axis. However, due to the limit of fabrication precision, the two antagonistic beams are not cut exactly the same, which results in part S being longer than part M in the zoomed view of figure 9.

3.3. Switching with SMA active elements

As mentioned in previous section, the multistable micro-actuator has low level power consumption, which leads to the possibility of being actuated with contactless method using laser-heated SMA active elements. Due to a reversible diffusionless solid-to-solid transformation that results in large reversible strains, SMAs are suitable for a wide range of micro-actuators, energy absorption, and vibration damping applications [15–21]. A nitinol (nickel and titanium alloy) sheet was chosen for the SMA active elements due to its better thermomechanical properties, as compared to the other commercially available shape memory alloys [13]. The nitinol sheet was purchased in annealed state from Johnson Matthey Co. Its chemical composition is 55% Ni–45% Ti (wt%). The austenitic warm form is flat.

The switching of the inner row of the multistable micro-actuator was realized using two antagonistic SMA elements heated by a red laser (wavelength $\lambda = 660$ nm, power $p \approx 100$ mW). The experimental setup for switching the inner row using laser-heated SMA active elements is presented in figure 11. In this setup, two SMA active elements, each having dimensions $3 \times 1 \times 0.1$ mm, were used. These active elements were fabricated using a laser cutting process as discussed in [4]. The heat affected zone was less than 10 μm, which is small compared to the dimensions of SMA elements. Thus, the shape memory effect was mainly preserved.

Figure 11(b) shows the top view (left side) and cross section view (right side). At state 1, the bistable double beam is at an upper stable position, SMA 1 is bent by the beams. Then laser 1 is turned on to heat SMA 1 to the final temperature of the austenite phase. Due to the shape memory effect, a force is exerted on the beams that pushes them toward the lower stable position (i.e., state 2). When the double beams reach the central position (see point b in figure 10), the snap effect starts pushing SMA 2. Finally, SMA 2 is bent. After SMA 1 is cooled down, the beams can be switched back to the upper stable position by turning on laser 2 to heat SMA 2.

During the switching process, the movement of the output point, where a mirror is glued, is measured by an optical fiber distance sensor. The results are shown in figure 12. The stroke between the two stable positions is 681 ± 4 μm over five cycles. It is smaller than the stroke when the micro-actuator is switched by a linear motor. This is because one of the SMA active elements is acting as a load during the switching process, e.g., SMA 2 is the load when the double beams are switched from the upper stable position to the lower stable position. One of the solutions to eliminate this load effect is to use a biasing spring that could bend the SMA active elements back to its initial position once cooled down. The integration of a biasing spring will be part of the future work.

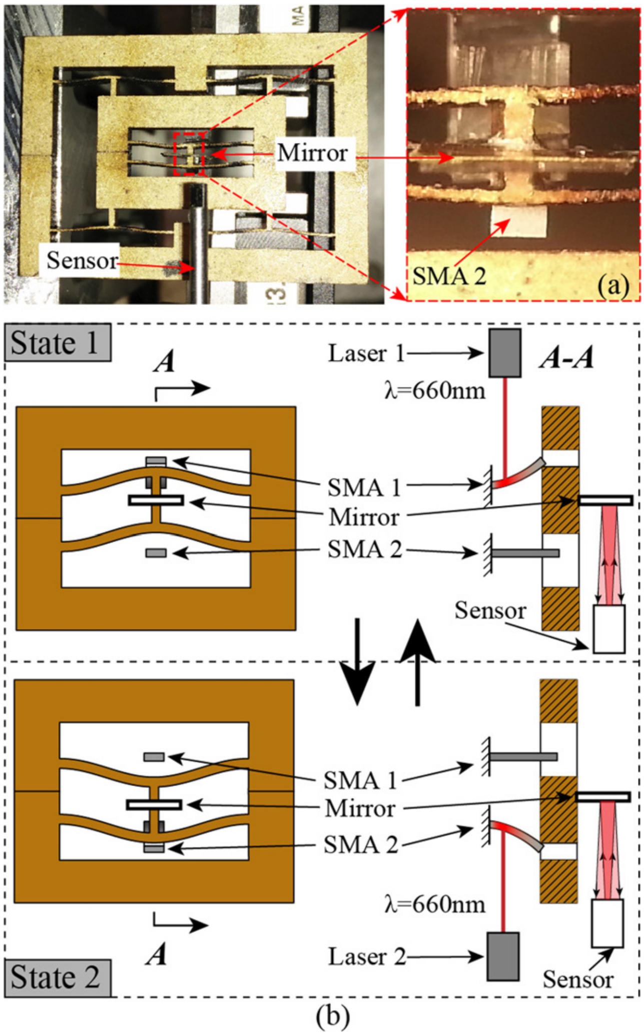

Figure 11. Experimental setup. (a) Real photograph and (b) schematic of the inner row switching using laser-heated SMA sheets.

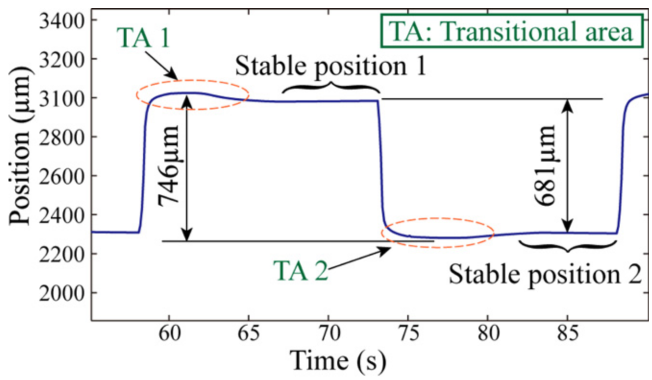

Figure 12. Test of switching with laser-heated SMA active elements ($l = 15$ mm, $b = 3$ mm, $t = 250$ μm, $h = 500$ μm, $\lambda = 660$ nm).

In the future, the designed micro-actuator will be fabricated on an SOI wafer using the DRIE technique as a perspective of this work to minimize the designed micro-actuator to get smaller stroke. Moreover, the beams could be more precisely fabricated and have more symmetrical output. Furthermore, smaller SMA active elements with an automatic spring back mechanism will be used to actuate the micro-actuator without causing the load effect.

4. Conclusion

A bistable mechanism using antagonistic pre-shaped double beams was designed. It has simplified the pre-load operation, especially for multistable micro-actuators as compared to pre-compressed beam strategy. At the same time, it is less sensitive to pre-load errors. Moreover, with this new design, the geometry limit is much lower than the one of parallel pre-shaped double beams and the generated force is symmetrical in the forward and backward directions. The bistability was experimentally validated. Based on the designed bistable mechanism, a wireless multistable micro-actuator with four stable positions was designed, fabricated, and tested. The multistability has been verified by actuating with a linear motor. Additionally, a contactless actuation of the inner row has been realized with laser-heated SMA active elements. The stroke of the micro-actuator is shorter than in the 'free case' (actuated with motor) because of the load effect of the SMA elements.

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