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A Self-switching Bistable Artificial Muscle Actuator

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Abstract: We present a self-motivating and self-switching bistable structure using bending actuators or artificial muscles. By exploiting the inherent bi-stability in buckled beam and buckled plate structures we have designed a bistable actuator that requires no energy to maintain either of the two stable states. In addition to bistable characteristics we show how such a structure, if constructed from a bending actuator (artificial muscle) such as ionic polymer metal composites (IPMC), may actively switch itself between stable states. Thus the self-switching bistable actuator is an extremely simple and elegant design that requires none of the external actuating mechanics traditionally used. In the analysis we consider the nature of bistable buckled beams and their internal stresses and we propose actuating schema for the movement from one stable state to another. We show how segmentation of a strip actuator can be matched to the desired bistable structure and the intended switching motion. We consider the characteristic buckling modes of axially compressed beams and show how these can suggest efficient control and switching mechanisms. We also present some example applications from the micro-scale upwards, including a tactile display device.

Keywords: bending actuator, bistable, buckled beam, self-switching, artificial muscle, IPMC.

1. INTRODUCTION

Much research is currently underway into the materials and basic properties of bending actuators and artificial muscles [1-3]. At the same time researchers are working towards the application of these materials to real world problems. Unfortunately these new actuator materials are not without their problems when it comes to practical use. Such problems include relaxation after actuation [2], low repeatability [3], and the need for energy to maintain a constant actuated state. Approaching these problems from the viewpoint of smart structures we observe that there are some fundamental structures that are missing or under-developed in the link between materials and applications. The bistable actuator presented here is just such an important building block that may help expand application areas and help realize practical devices.

In this paper we exploit the ability of some types of actuators, such as ionic-polymer metal composites (IPMCs) and smart memory alloys (SMAs), to bend upon electrical stimulation. This characteristic unleashes a huge potential for building active structures, including actuators and muscles, that were previously impractical. In this paper we configure IPMC bending actuators as bistable buckled beams, but it is clear from the outset that the principles are equally applicable to other materials that bend under electrical stimulation.

The bistable buckled beam structure is well known in mechanics [7][8] and has been used in many devices requiring a stable structure when power is removed. Such devices typically use a simple switching event to open or close a valve or relay. Unfortunately these devices are lacking in flexibility [5] and most commonly require external mechanical actuation to change state [4].

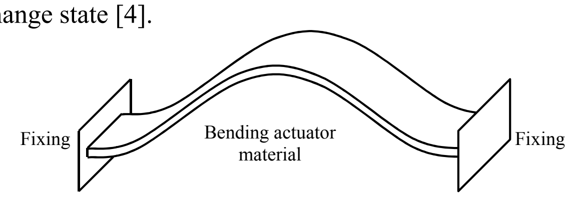

Fig. 1 The basic buckled beam actuator shape

In this paper we propose the use of bending actuators to form bistable buckled beams (Fig. 1,) plates and diaphragms. By controlled electrical stimulation the actuator can bend itself from one stable state to another, thus mitigating the need for an external actuator. The actuator can therefore be termed ‘self-switching.’ When in a stable state the actuator requires no energy to maintain its shape. The stable states also provide known reference shapes between which to move, thus increasing repeatability and reducing, or even eliminating, post-actuation relaxation.

In this paper we also show how a bending actuator beam can be divided into a number of electrically independent segments. We propose a number of methods for firstly, determining the number and size of these segments, and secondly, selectively activating these segments in order to change state. This new ability to control the shape and actuating motion of bistable structures is the enabling factor for a whole new family of devices that were not previously possible.

In the analysis we consider the classic model for a passive buckled beam and especially focus on the natural buckling modes. We show how movement between these buckling modes results in state switching. By selecting one of the higher order buckling modes (or another shape as required) as an intermediate shape through which to actuate we show that bistable state switching can be optimized with respect to some quantity such as time, energy or space.

We also give examples of applications of such self-switching bistable structures ranging from the micro (MEMS) scale to much larger actuators.

2. BUCKLED BISTABLE BEAMS

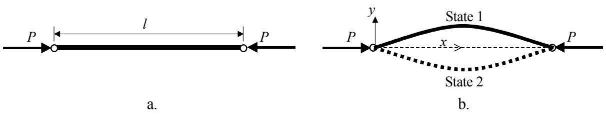

Fig. 2 Buckling of a pinned beam

2.1 Buckling modes in clamped beams

Consider the pinned beam of length l as shown in Fig. 2 [7]. Under axial loading P the beam initially deforms axially (Fig 2a.) Once the critical load is exceeded, the beam deforms sideways into the buckled "bow" shape (Fig 2b,) characterized by the equation,

$$\frac{d^2y}{dx^2} = -\frac{P}{EI}y, \qquad (1)$$

where E is the Young's modulus, I is the moment of inertia, and y is the deflection along length x. In this case the boundary conditions are, $y=0|x=0$ and $y=0|x=l$. The resulting deflection equation of the buckled beam has the form:

$$y = A\sin(kx) + B\cos(kx), \qquad (2)$$

where, $k^2 = P/EI$

In Fig. 2b we can clearly observe the two stable buckling states for a beam with rectangular cross section. The disadvantage of the pinned beam is the difficulty of mounting such a beam to ensure free end rotation. In order to develop a more convenient, mountable, bistable structure we now consider the double clamped beam in Fig 3. Here the ends are fixed such that rotation is eliminated.

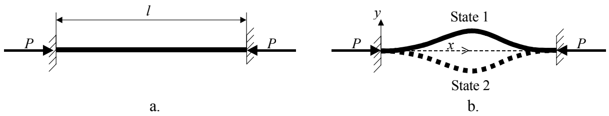

Fig. 3 Buckling of a clamped beam

Equation (1) still applies, but boundary conditions now become, {y=0,y'=0}|x=0 and {y=0,y'=0}|x=l. Now (1) results in the deflection equation of the clamped buckled beam of the form,

$$y = A\sin(kx) + B\cos(kx) + \frac{M_0}{P}, \qquad (2)$$

where M_0 is the bending moment at the clamps.

In order to obtain non-zero solutions to this equation we must satisfy the following restriction:

$$\sin\left(\frac{kl}{2}\right)\left(\tan\left(\frac{kl}{2}\right) - \frac{kl}{2}\right) = 0, \qquad (3)$$

This yields two families of solutions for the displacement equation [2],

$$y = C\left(1 - \cos\left(\frac{(j+1)\pi x}{l}\right)\right) \qquad (4)$$

$$j = 1, 3, 5, \ldots$$

$$y = C\left(1 - 2\frac{x}{l} - \cos(kx) + \frac{2\sin(kx)}{kl}\right) \qquad (5)$$

$$kl = 2.86\pi,\ 4.92\pi,\ 6.94\pi,\ 8.95\pi,\ 10.96\pi, \ldots$$

Equation (4) defines symmetric buckling shapes and (5) defines asymmetric shapes. Fig. 4 shows the first three solutions from (4) and (5), commonly referred to as buckling modes 1, 2 and 3. Note the reflexive symmetry of modes 1 and 3.

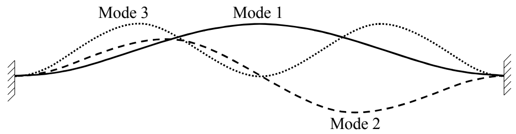

Fig. 4 The first three buckling modes

By constraining movement at various key points along the length of the beam, or by applying specific critical loads, the different buckling modes can forced to develop.

2.2 Restricting buckling modes

Traditional applications of bistable beams restrict movement to a small subset of these modes [6], and most usually only one [4][5]. This is a constraint imposed by the fairly rigid materials used and the inflexibility of the actuation method. It is clear that, while such mode restrictions may be necessary for passive beam structures they would unnecessarily constrain the active self-bending structures proposed in this paper. Further, it may be advantageous to utilize such alternative buckling modes since they can provide pointers to low-energy state transition paths. Indeed, the ability of bending actuators to change the shape of the buckled structure means that it may be possible to move through more optimal paths than are possible with the best-designed passive structures.

In the next section we discuss the switching of state through intermediate shapes, including alternate buckling modes.

3. SELF-BENDING BISTABLE BEAMS

Given a pre-stressed (or at least pre-deflected) bending actuator that exhibits the simplest buckling mode (mode 1) we now consider movement paths from one state to the complimentary state. Figs. 5 and 6 show two possible actuation paths that pass through alternative buckling solutions. In Fig. 5 the actuator in state A bends under electrical stimulation until is resembles the mode 2 buckle B. This is the snap-through region of a passive bistable beam and only a little further actuation is required to force the actuator into state C, again in buckling mode 1. Likewise, the same state switching may be achieved by passing through buckling mode 3 as shown in Fig 6.

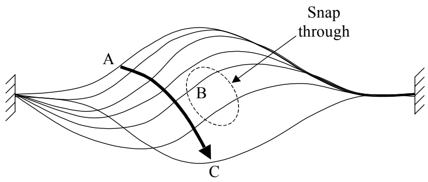

Fig. 5 State change via intermediate buckling mode 2

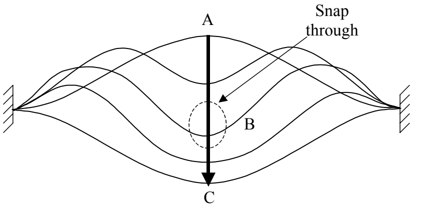

Fig. 6 State change via intermediate buckling mode 3

There are advantages in choosing each of these transition paths. For example, the mode 2 shape has a lower potential energy and is therefore a more suitable intermediate shape for applications requiring lower energy actuation. The mode 3 shape, on the other hand, is characterized by the vertical motion of the center of the structure. This vertical motion may be extremely important in applications where the beam contacts another object.

Another actuation strategy is shown in Fig 7. The right hand side shows the activation path of a buckled actuator from state 1 to state 2. The left side shows this actuator reduced to an articulated two- or three-beam model. Here we see that by elongating the center region of the actuator we change the structure from a two-beam model to a three-beam model. The introduction of this morphology greatly reduces the moment required to force state transition

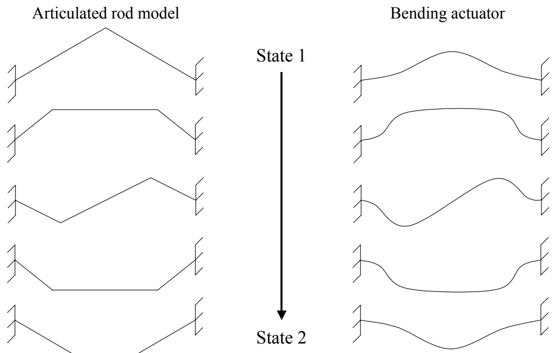

Fig. 7 An alternative state switching mechanism

Fig 8 shows one of the test Nafion-based ionic polymer metal composite beams in both of the bistable states. Notice that the shapes in the two states are very slightly different. This is due to natural imperfections in the structure resulting from the polymer material and the manufacturing process.

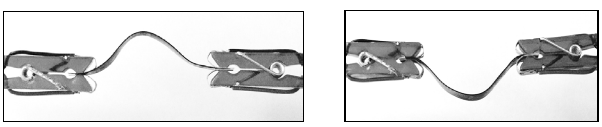
Fig. 8 Nafion-based IPMC in the two buckle states

4. ACTUATOR SEGMENTATION

Consider the typical bending actuator, such as an IPMC, that bends under electrical stimulation. Typically the actuator bends with constant curvature r, as shown in Fig. 9.

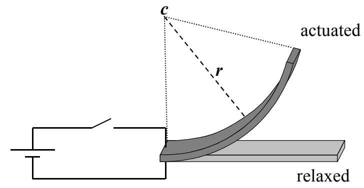

Fig. 9 IPMC bending with constant curvature

When a beam of uniform material is forced into the first buckle mode shape (Fig. 3) the structure does not have constant curvature. Crucially there are three distinct regions where the curvature has the same direction, i.e., $0 \le x \le l/4$, $l/4 < x \le 3l/4$, $3l/4 < x \le l$, as shown in Fig. 10. The boundary points $x = l/4$ and $x = 3l/4$ coincide with the points of zero stress in the structure where,

$$\frac{d^2 y}{dx^2} = 0 \qquad (6)$$

If we superimpose three curves with constant radius r and with centers at C_1, C_2 and C_3 onto the buckled beam in Fig. 10 we can see that there is a very close correspondence between the bending of three IPMC actuators represented by these curves and the natural curvature of the bistable beam. Thus it is natural to consider this buckled structure as three joined, but electrically independent, bending actuators.

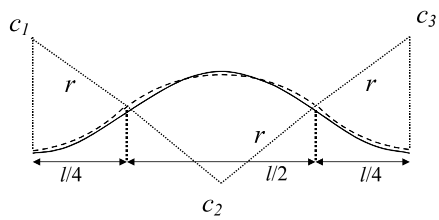

Fig. 10 Distinct bending regions in a buckled beam

Actually we need only to electrically segment a single actuator strip to achieve the same effect. Segmentation of a polymer actuator can be achieved by cutting or etching the electrodes upon one or both sides of the actuator. The base polymer material (e.g. Nafion) is unaffected and provides the necessary mechanical linkage from one segment to the next. Segmentation is therefore an electrical construct that has a consequent mechanical effect through the actuator transduction mechanism.

To enable self-actuation between states we desire that the actuator bend efficiently in the region of the stable state. This is possible only if we supply the same polarity voltage to sections of the buckled structure that have bending moments in the same direction. The worst case exists when part of the region is bent one way and part of the region is bent in the opposite direction, such as in an ‘s’ shape. These observations give us some valuable information about how and where to segment a single bending actuator to make a buckle beam actuator that can change state effectively.

Our initial approach is to segment the actuator electrodes at the points of minimal internal stress (i.e. minimum bending) such as the $x=l/4$ and $x=3l/4$ points in Fig. 10. Unfortunately, during actuation these points are not stationary along the length of the actuator. That is, the points of minimum stress move and change number. If we determine, however, that actuation should involve transition through, for example, the mode 2 buckle shape we can use this known shape as a further indicator as to where to segment the actuator.

4.1 Segmentation of a 6-segment beam

Let us assume that we have a buckled beam made out of bending actuator material that naturally falls into the mode 1 buckle shape (labeled A in Fig. 5.) We now desire that the actuator switch state to the complimentary stable state (labeled C in Fig. 5.) We also wish (due to application requirements) to actuate the structure through the path shown in Fig. 5 that passes through the mode 2 buckle shape (labeled B.) What is a reasonable segmentation scheme for this actuator?

Evaluating the second derivative of the displacement equations for both mode 1 (stable shape) and mode 2 (intermediate shape) yields the following two sets of points of minimum stress along the actuator, where l is the length of the actuator.

mode 1: $\{0.25l, 0.75l\}$
mode 2: $\{0.15l, 0.50l, 0.85l\}$

We can now use these points as reasonable first approximations of where to segment the actuator. Fig. 11 shows a strip actuator that has been segmented into six segments using the five points above. Note that the first, third and last segmentation points do not correspond to the zero stress points in the mode 1 shape shown, but in the intermediate mode 2 buckle shape.

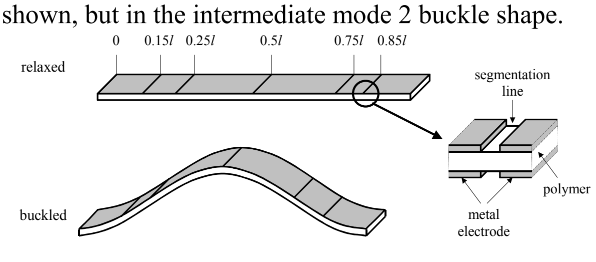

Fig. 12 Segmentation at minimal static stress points

Of course, along with this segmentation we need a sufficient set of control signals for the stimulation of individual segments in order to achieve the desired actuation.

4.1 Actuation of a 3-segment beam

It may be that in many applications the optimum number of segments and their precise segmentation is not required. This may be, for example, in order to simplify the control strategy or the manufacturing process. As such, a simple segmentation schema may provide the needed actuation.

Consider, for example, the three-segment beam in Fig.12. Here the beam has been split into three segments at the previously discussed positions of $l/4$ and $3l/4$. When forced into the mode 1 buckling its shape resembles that in Fig. 10. Now let us actuate this structure with a single varying voltage Vs. For simplicity of control we connect the drive signal Vs as shown in Fig. 12 where the middle segment is connected in reverse polarity with respect to the end segments. This reverse polarity connection scheme matches the natural polarity of bending in each segment. That is, the end segments bend in the opposite direction to the middle section.

In actuation this structure will bend into a symmetric intermediate shape resembling the mode 3 buckle. State transition thus substantially resembles that shown in Fig. 6.

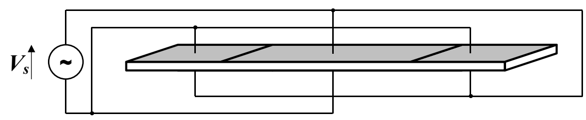

Fig. 12 a three-segment test beam

An actuator with this structure was manufactured from gold plated IPMC material with a base of Nafion 117 and dimensions 4mm × 38mm × 0.175mm. The beam was clamped at both ends and given a slight axial load to force the formation of a mode 1 buckle shape. The voltage signal Vs in Fig. 13 was applied to each segment using the connections shown in Fig. 12. At the same time the displacement of the center of the buckle beam was recorded using a Keyence laser displacement meter. Displacement of the center point D is also show in Fig.13.

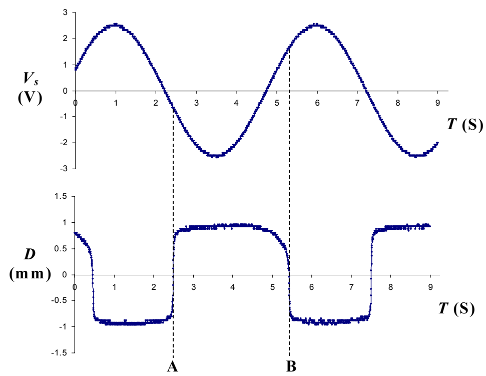

Fig. 13 Driving voltage and Displacement signals

We can clearly see that the displacement of the actuator is a near square wave in response to the sine wave input. This is a typical displacement response for a bistable buckled beam. Note the switching events at A and B. As time T approaches point A the input voltage falls below zero but structural stability keeps the actuator in its stable shape. At point A the input is sufficient to cause the structure to rapidly change state to the complimentary shape, as shown by the very high gradient of displacement. The structure stays in this stable state until a half cycle of the input has passed when, at point B, the reverse state-switching event occurs.

If we plot displacement *D* against input *Vs* we have a clearer illustration of the state switching action. Fig. 14 shows this graph with an inset showing the direction of progress with time. Fig. 14 shows the classic hysteresis plot of a bistable device. Note the asymmetry resulting mainly from imbalance in the end clamps but also partly from manufacturing effects.

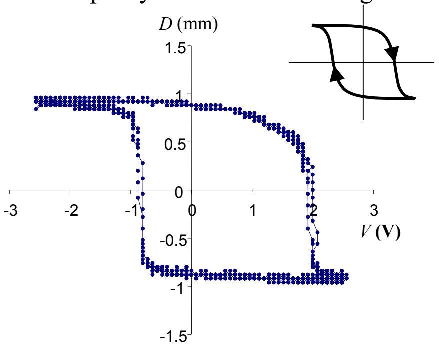

Fig. 14 Voltage vs. Displacement hysteresis graph

5. RELATIVE ACTIVATION

An important feature of buckled beams made from bending actuators such as IPMCs is that they can be made to actuate around a stable state. This results in local motion and the consequent ability to generate a local force. For example, Fig. 15 shows a buckled beam actuator that is actuated symmetrically about the mid point such that the center of the structure moves in the vertical axis. This activation can be used to apply a force upon a contacting object.

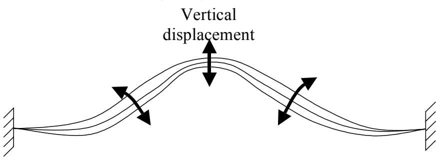

Fig. 15 Actuation resulting in vertical motion

Fig. 16 shows another example of relative motion about a stable state. Here the actuator is caused to flex laterally as well as vertically. The resulting motion of a point fixed to the center of the structure (marked with a diamond) is circular. Clearly there are many applications for such a motion generating structure, including a simple micro-motor where a shaft is attached eccentrically to the center point, or as part of a conveyer system somewhat similar in nature to the ultra-sonic motor drive mechanism.

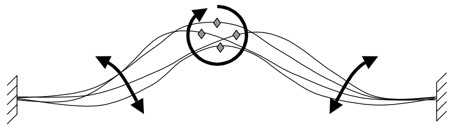

Fig. 16 Actuation resulting in circular motion

One important potential of this self-actuating bistable structure is that it can be actuated around one state to provide a working force and then switched to the complimentary state where it is mechanically de-coupled. Take the example of the conveyer system mentioned above. In this application we can construct a base plate into which are mounted a number of bistable beams. A load can be supported by these structural elements and transported laterally using a coordinated circular motion of the type show in Fig. 16. The conveyer system is shown moving an object towards a goal position in Fig. 17a. When the load reaches the desired goal position the bistable structures can be switched to their complimentary down state thus lowering the load onto a firm and stable bed, as shown in Fig. 17b.

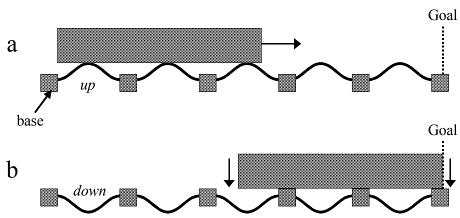

Fig. 17 conveyor action

6. SENSING AND ACTUATION

It is well known that some bending actuators, such as IPMCs can act as sensors as well as actuators. This is a particularly useful feature that can be exploited in the buckled beam actuator as a means to determine the current state of the actuator. By dedicating a small section of the actuator to the role of sensor we can monitor the state transition progress of the actuator in real time. Thus we can verify the success or failure of any state transition actuation. Additionally the whole buckled beam can be used as a sensing element where, for example, the structures are initially actuated into the "up" position and then switched to sensor mode so that they can detect when they are pushed into the complimentary state by an external force.

6. APPLICATIONS

It is clear that the simple bistable beam actuator can be a building block for more complex multi-stable structures. For example, combining two beams in a cross shape results in the three-dimensional structure in Fig. 18 with consequent increased opportunities for local movement and alternative state transition paths.

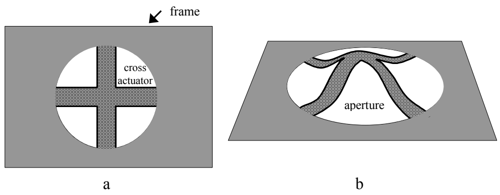

Fig. 18 A two-strip bistable structure

A natural extension of this composite structure is the segmented bistable buckled diaphragm made from bending actuator material as shown in Fig. 19. Here the diaphragm is shaped and mounted such that it protrudes above a fixing or frame. Controlled activation of segments across the diaphragm causes the structure to flex and pass through an aperture into the complimentary state. Such a simple yet versatile structure can form the basic actuation element (or *actel* for short) for larger structures and devices.

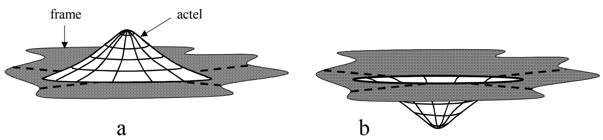

Fig. 19 A bistable diaphragm *actel*

A very simple but practical application is that of a tactile output device, such as needed for Braille displays. Fig. 20 shows a self-actuating buckled bistable beam which acts upon a shaft. Activation of the bistable beam results in movement of the shaft along a channel. The top of the shaft is formed into a dome that the finger can feel. The two states of the bistable beam (*up* or *down*) correspond to the two states of the tactile display (*on* or *off*.) Of course, the *actel* described above can also be used as a tactile display element on its own, but the structure in Fig. 20 offers more lateral strength whilst still being a simple device. Additional possibilities include using the bistable actuator in Fig. 20 to sense the current position of the finger from slight changes in pressure upon the shaft. It is then a short step to realize a Braille display that automatically updates the text as the reader's finger passes over the display. Note also that this tactile display will maintain its display pattern even when all power is removed from the device.

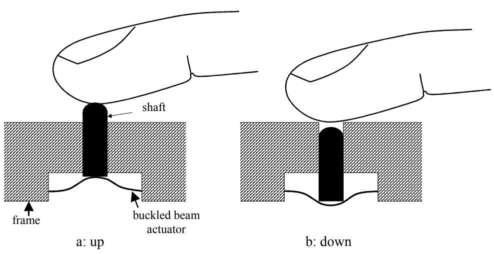

Fig. 20 a tactile output device

CONCLUSIONS

We have presented a new self-switching bistable actuator based on the buckled beam structure. We have shown how the structure can self-bend from one stable state to another through a path that can be optimal in some quantity such as energy, speed or space. This actuator overcomes some of the problems with state-of-the-art actuator materials, such as relaxation, repeatability and energy needed to maintain activation.

We have also shown how to determine suitable points for the segmentation of actuator electrodes depending on the desired state transition path. Finally we have given examples applications using this structure.

Future work will involve further characterization of the self-switching bistable structure, its segmentation and its control. We will also turn to the dynamic behavior of the device and its coupling to loads.

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