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Proceedings of SPIE -- Volume 6524
Electroactive Polymer Actuators and Devices
(EAPAD) 2007, Yoseph Bar-Cohen, Editor, 65241B

A Linear Actuator from a Single Ionic Polymer-Metal Composite (IPMC) Strip

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ABSTRACT

We present a novel linear actuator made from a single Ionic Polymer-Metal Composite (IPMC) strip. In its simplest form the device activates into the shape of a double-clamped buckled beam. This structure was chosen following observation of the buckle failure modes of axially compressed beams. The practical realization of this device is made possible by the development of new manufacturing techniques also described. The benefit of this buckled beam structure is that bending moments in the two halves of the beam cancel each other out. As a result, only one bending actuator is needed to form a single linear actuator and there is no need for mechanical joining of separate actuators - a disadvantage of previous linear actuator designs. The non-rotating nature of the end fixing in the double-clamped buckled beam also means that joining multiple elements to increase displacement or force is trivial. We present initial experimental results of a single linear actuator and a balanced, pair-connected linear actuator.

Keywords: polymer composite, IPMC, linear actuator, buckled beam

1. INTRODUCTION

Ionic polymer-metal composites (IPMC) and other bending actuators have a number of important characteristics that make them suitable for use as artificial muscles and actuators [1]. These include low weight and low driving voltage. At the same time application areas such as robotics are demanding more compact linear motion actuators. Unfortunately, although IPMC actuators bend effectively through angular paths, they must be mechanically reconfigured to generate linear motion. This requires the canceling of multiple bending moments in order to resolve a single linear component. Previous approaches have involved combining multiple bending actuators to create a single linear actuator [2][3][4]. These approaches have, by necessity, included mechanical features such as sliding arrays, flexible tape joints, rotating end fixings and so on. These mechanical features are undesirable because they introduce mechanical weakness, add weight, or make manufacturing more difficult.

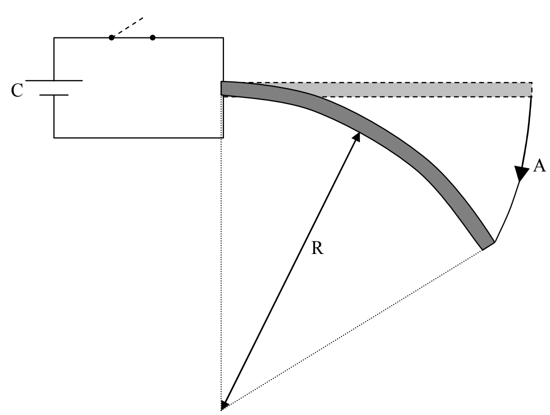

Fig. 1 Simple activation of a bending actuator

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Take the typical IPMC as shown in relaxed state in Fig. 1. When stimulated by a small DC voltage it bends uniformly into the curved shape of radius R as shown. It is clear from line A that any point on the actuator moves through a curved path. This makes the actuator eminently suitable for applications where a curved actuation path is desired, for example as flapping wings. Unfortunately, in applications where a linear actuation is required, the curved path is undesirable. The problem lies in the fact that a curved path necessarily involves motion (or force) components that are non-zero in two dimensions. Conversely, linear motion requires that motion or force components resolve into only one direction.

In order therefore to convert a curved motion into a linear motion we require that the force or motion components in undesired directions are reduced to zero. The simplest way to achieve this is to ensure the actuator is configured or mounted such that unused components are cancelled. Fig. 2 shows three mounting systems where horizontal components cancel, leaving only vertical components [1][2][3]. The great disadvantage of these approaches is that they involve special fixings or bonding (Fig. 2a, 2b) or introduce undesired mechanical effects such as friction and wear (Fig. 2c.)

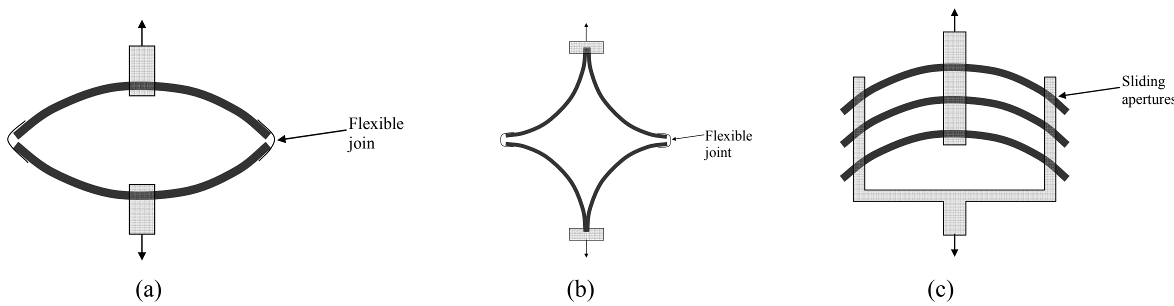


Fig. 2 Examples of previous linear actuator structures

The need therefore is for a modified actuator or mounting configuration that cancels undesired components without the disadvantages of special mechanical or electrical fixings, or mountings involving friction or wear. In this paper we present a novel approach to this problem which results in a linear actuator that is made from a single strip of bending actuator material. While we have used IPMC material in this study, the principles are equally applicable to other bending actuators such as PZT materials.

The basis for the proposed actuator structure is the buckled beam. Here we actuate the initially unstressed beam into a shape that almost exactly corresponds to the buckled beam under axial compression. The novelty of this approach is that it is the reverse of conventional buckled beam analysis. This is rather an inspirational step in design since we mimic a natural physical consequence of *mechanical failure* (beam buckling) to make a more effective *non-failing* activating structure.

2. THE BUCKLED BEAM

The conventional approach to buckling is to view it as a form of failure. This is quite natural when considering supporting structures such as steel girders and concrete columns. In the context of failure we would typically study an axially loaded beam and analyse the buckle shape as the critical load is exceeded [4].

2.1. Simple buckling

Let us now consider the simplest form of buckling that occurs in a beam where the end points are free to rotate. Fig. 3a shows such a simple beam. Here the beam is axially compressed with force F, and F is less than the critical load F_c. When $F>F_c$ the beam buckles into the shape in Fig. 3b.

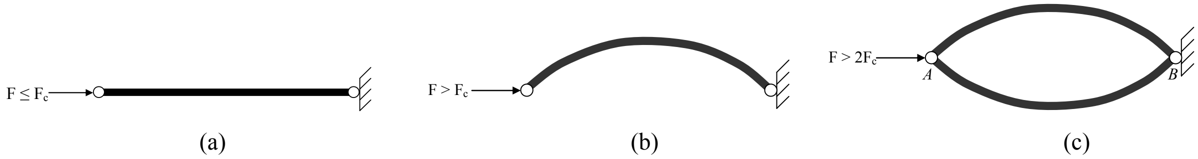


Fig. 3 Forced buckling in a simple beam

Immediately from these figures we can see the similarity to the activation of a bending actuator. Where the buckled beam is forced into the buckled shape by an axial force and subsequent buckling failure, the bending actuator naturally activates into this curved shape. It is also clear that the linear actuator in Fig. 2a is composed of two of the buckled beam shapes of Fig. 3b, and we have redrawn this paired structure in Fig. 3c for illustration.

It is clear from Fig. 3c that this structure, whether representing a pair of axially compressed simple beams or a pair of activated bending actuators, relies on rotational fixings at end points A and B. This poses a problem with practical implementations since rotational end fixings typically exhibit one or more of the following failings:

- Complexity, e.g. hinged structures.
- Restriction of the movement of the structure, e.g. flexible, but restrictive joints.
- Introduction of mechanical weakness, e.g. in weak flexible materials or at bonding points.
- Cost, e.g. in the manufacture of low friction hinges.

A laudable goal therefore is to reconfigure the simple actuator in Fig. 2a such that there is no need for rotational end fixings. If this can be achieved we may be able to circumvent all the above failings.

2.2. Buckling with clamped ends

A first step towards this goal is to consider a simple beam with *clamped ends*. Such a beam is shown in Fig. 4a.

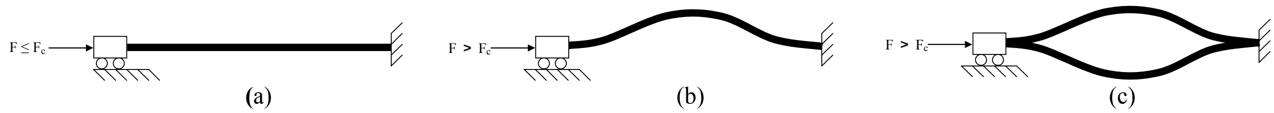


Fig. 4 Forced buckling in a double-clamped beam

When axially loaded with a force F the beam will initially undergo elastic deformation. When F exceeds F_c, the critical loading force, the beam will buckle into the classic double-clamped buckle shape shown in Fig. 4b. It is simple to extend the single beam case in Fig. 4b to the double beam case as shown in Fig. 4c. Now we have the pair of buckling beams much like Fig. 3c, but with one crucial difference: the ends undergo no rotation.

In the previous section we observed that the simplest buckling pair in Fig. 3c resembles the bending actuator pair in Fig. 2a. Working in reverse we may now use Fig. 4c as the basis for designing a simple bending actuator that can activate effectively with clamped ends.

2.3. A bending actuator with clamped ends

Unfortunately we cannot simply clamp the ends of a simple uniform bending actuator strip and expect it to operate effectively. The problem lies in the property of these materials to bend with a uniform curvature. That is, the relative bending moment along the length is constant. By casual observation of Fig. 4b we see that this structure does not bend with uniform curvature. In fact, we can isolate two points along the length where the curvature actually reverses polarity. A uniform bending actuator, when configured with fixed ends, will therefore have two distinct regions where actuation moments will be acting in opposition to the stress-induced moments of the natural buckling shape. The natural effect of this is to move the points where curvature reverses polarity towards the ends of the beam. Yet, as these points move towards the ends of the beam, the counteracting moments deriving from the material stresses increase until the moments are balanced. The gross effect of this is that the actuator settles into an equilibrium shape some way between the uniform curve of Fig. 3b and the natural buckle shape of Fig. 4b. Fig. 5 illustrates this equilibrium shape and the two points (marked with arrows) where curvature reverses. Notice that these points are much closer to the ends of the structure than the equivalent points in Fig. 4b.

An added effect of this activation is evident at the end points. Here the balancing moment M_R that acts against the actuating moment M_E is provided by the end fixing. Clearly this is not ideal since this moment represents an energy loss. Ideally we would want there to be no bending moment at the ends and the force against the end fixings would be linear in a line directly between fixings.

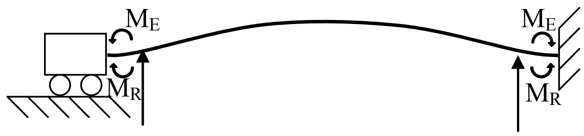


Fig. 5 A double-clamped uniform actuator

2.4. Buckling analysis

Consider the pinned beam of length l as shown in Fig. 3a [4]. Under axial loading F the beam initially deforms axially. Once the critical load is exceeded, the beam deforms sideways into the buckled "bow" shape (Fig. 3b,) characterized by the equation,

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

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:

$$y = A\sin(kx) + B\cos(kx), \tag{2}$$

where, $k^2 = P/EI$

Now let us consider the double-clamped beam in Fig. 4a where the ends are fixed such that rotation is eliminated. 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,

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

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 condition:

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

This yields two families of solutions for the displacement equation [5],

$$y = C\left(1 - \cos\left(\frac{(j+1)\pi x}{l}\right)\right)$$
$$j = 1, 3, 5, \ldots \tag{4}$$

$$y = C\left(1 - 2\frac{x}{l} - \cos(kx) + \frac{2\sin(kx)}{kl}\right)$$
$$kl = 2.86\pi,\ 4.92\pi,\ 6.94\pi,\ 8.95\pi,\ 10.96\pi, \ldots \tag{5}$$

Equation (4) defines symmetric buckling shapes and (5) defines asymmetric shapes. Fig. 6 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.

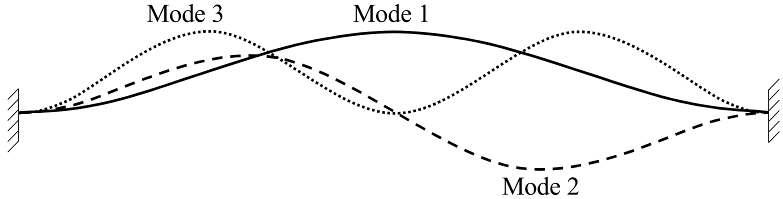


Fig. 6 The first three buckling modes

By constraining movement at various key points along the length of the beam, or by applying specific critical loads, the different buckling modes can be forced to develop. In this paper we are focusing on an actuator that mimics the mode 1 buckle shape. Of course, it is possible to design an actuator that activates into one of the higher order bucking modes, and that may prove necessary for some applications.

Crucially there are three distinct regions where the curvature has the same polarity, i.e., $0 \le x \le l/4$, $l/4 < x \le 3l/4$, $3l/4 < x \le l$, as shown in Fig. 7. The boundary points $x=l/4$ and $x=3l/4$ coincide with the points of zero stress in the structure where,

$$\frac{d^2 y}{dx^2} = 0 \tag{6}$$

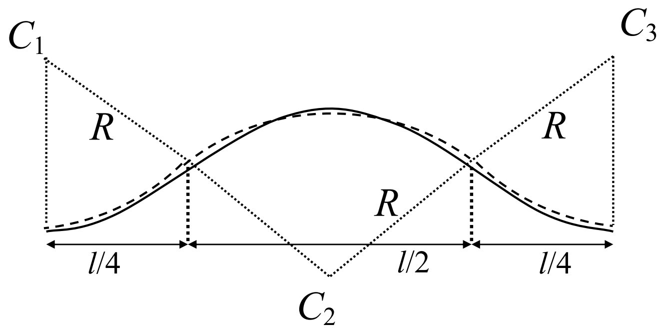


Fig. 7 Three distinct sections in a buckled beam

The three distinct sections in Fig. 7 can be approximated by three circular segments with centers at C_1, C_2 and C_3, and with radius R (shown as dashed lines.)

The premise of this paper is that a linear actuator can be made from three segments of bending actuator material if the mechanical and electrical configurations are chosen such that the activated shape resembled the double clamped buckled beam in Fig. 7. For more information on buckled beam structures in polymer actuators see [6][7].

3. THE BUCKLED BEAM LINEAR ACTUATOR

We propose that a three segment actuator can be configured as a linear actuator if the three segments are independently controlled. In this way different segments can be made to bend in different directions and the whole structure would then resemble the double-clamped buckled beam structure.

3.1. Segmentation

A three-segment bending actuator can be achieved by either joining three separate pieces of actuator material or by modifying a single piece of material such that three independent segments are created. Segmentation of a single strip of bending actuator material is achieved typically by patterning the electrodes upon the surface of dielectric actuator material and this method will be used subsequently in this paper. These segmentations are placed at positions $l/4$ and $3l/4$, corresponding to the points of zero bending stress as shown in Fig. 7. Fig. 8 shows a three segment bending actuator in relaxed state (a) and in activated state (b) where the polarity of the potential across each segment is indicated by +/-. Note that in each subsequent segment the polarity is reversed.

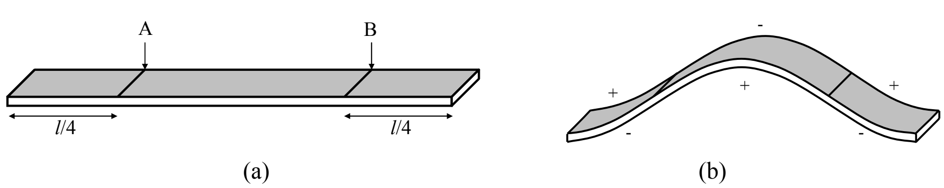


Fig. 8 A three segment bending actuator

3.2. Supplying power connections

Since the polarity of connections is reversed in adjacent segments we can simplify the activating power supply as shown in Fig. 9. Here a single voltage source Vs is connected such that adjacent segments have opposite polarity. Activation of this device is simply a case of controlling Vs.

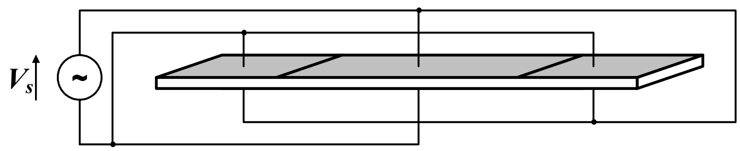


Fig. 9 Electrical connections to a three segment bending actuator

To achieve this design we can either deliver the control signal to each segment independently, i.e. with wires and clips, or we can try to design an actuator that has inter-segment connections which perform the same function.

3.3. Inter-segment connections

Since adjacent segments have reverse polarity, and a bending actuator is typically a dielectric device with conducting electrodes on two sides, we simply need a mechanism for connecting opposite electrodes between segments. This is shown more clearly in Fig. 10 where the dotted and dashed lines indicate the crossover connections.

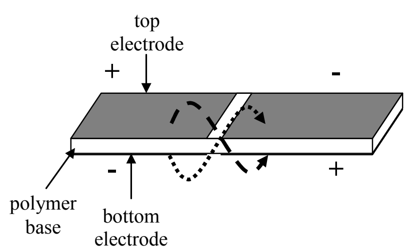
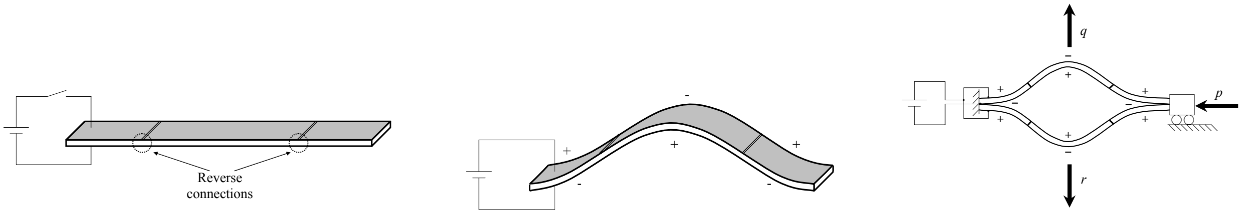


Fig. 10 Reverse connections schema for adjacent segments

The great advantage of this reversing connection is that the control signal to the entire actuator need only be applied to one end of the device. The control signal is propagated, and its polarity is reversed, from one segment to the next via this reversing connector.

Now the schema for the entire linear actuator strip can be shown in Fig. 11. Fig. 11a shows the un-activated strip with two reverse connections indicated. Fig. 11b shows the activated strip and the local bending within each segment. Fig. 11c shows two strips mounted together to give a more versatile actuator. Here, activation causes contraction in the direction p and expansion in the directions q and r.



(a) (b) (c)

Fig. 11 Three segment linear actuator element

4. MANUFACTURING TECHNIQUES

In order to realize the single-strip linear actuator we need to consider how current technologies constrain manufacturing and how we need to develop new techniques to overcome these limitations. Our goal in manufacturing is to create a simple and robust reversing connection that can electrically connect adjacent segments such that polarity is reversed. Below we present a new method for manufacturing a metal-polymer composite actuator whereby the reverse connection is formed as part of the main manufacturing process. This has the great advantages of simplicity, robustness and low cost.

Fig. 12a shows the general process of making a metal-coated polymer composite. The process involves treating a single sheet of polymer material (I), such as Nafion or Flemion, and chemically depositing gold or platinum electrodes on the surface (II). Finally the surface electrodes are cut, for example by knife, laser, or hot iron, to create isolating gaps (III). Note that these metal electrodes are actually fused into the surface polymer as they are deposited.

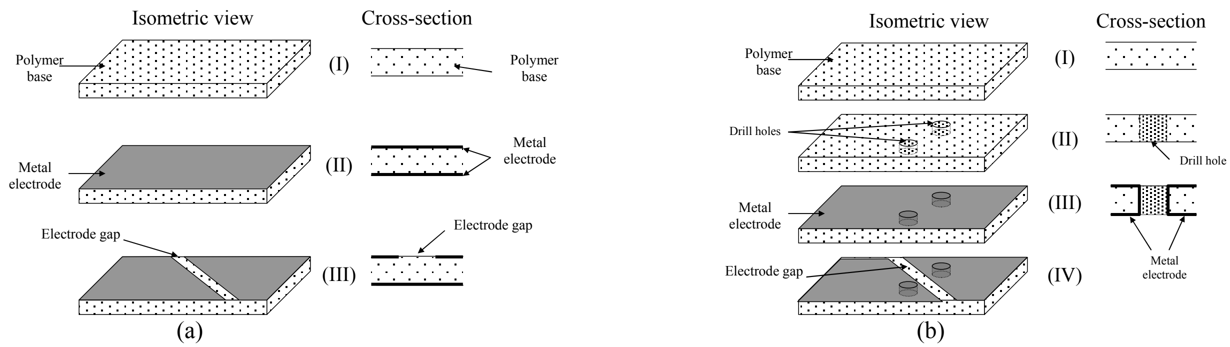


Fig. 12 Manufacturing a polymer-metal composite actuator

Now we modify this manufacturing technique to create a through-hole connector as shown in Fig. 12b. It can be seen that the main difference between this technique and the previous technique is the introduction of two holes before the electrode coating stage. Holes are introduced at this stage in order that their inside surfaces are also coated, thus creating a conducting through-hole from one electrode to the other. The final stage is to cut the electrode insulating gaps. Fig. 13 shows a magnified picture of a through-hole made using this method. It is clear that the light coloured gold extends from the top electrode down the inner surface of the hole to connect with the bottom electrode. The electrical conductivity of the through hole is the same as the conductivity of the surface electrodes.

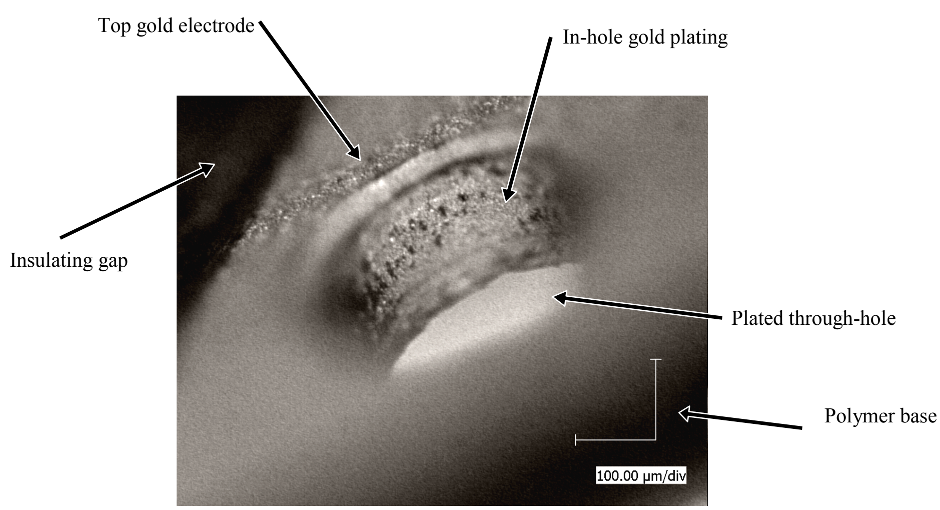


Fig. 13 Microscope picture of plated through-hole

By making suitable holes and cutting suitable electrode patterns we can create a complete reversing connection which is both simple and robust. Fig. 14 shows the hole arrangement and appropriate electrode cuts that are needed to make the reverse connection. Fig. 14a shows the top view of the two-segment actuator strip with two through-holes and two electrode cuts (the dotted line shows the insulating cut on the underside of the strip.) This is shown in decomposed profile in Fig. 14b, which also shows the regions of positive and negative polarity swapping from top to bottom (and vice versa) across the reverse connection. Fig. 14c shows an alternative reverse connection using square, rather than diagonal, cuts. This square-cut connection shows that the reverse connection can be tailored to match the requirements of specific applications.

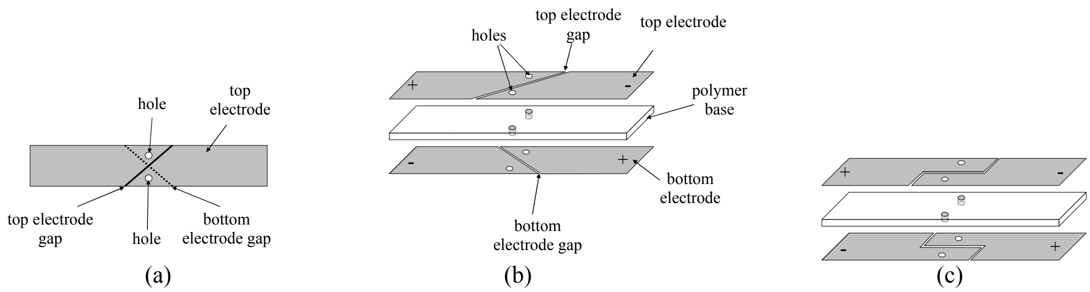


Fig. 14 The reverse connection

Of course, a reverse connector can also be made after the metal-polymer composite actuator strip has been manufactured. This may be achieved by drilling holes and filling them with some suitable conducting material. Experiments using silver conducting paint have verified that this is possible. The disadvantages of this approach include the incompatibility of the conducting filler and the metal electrodes, the mechanical weakness of a material that has been bonded to the actuator after manufacture, and the extra time required to make the connector. For more information about the polymer through-hole connector and the reverse connector see [8].

5. EXPERIMENTAL VERIFICATION

As an initial experiment we sought to verify the operating principle of the simple linear actuator. First we verified the activating shape and the conditions of the end points, then we measured the blocking force generated by a two leaf actuator pair.

5.1. Single strip actuation

A single three-segment, reverse connected, ionic polymer-metal composite actuator strip of 40mm×4mm was manufactured by chemically coating Nafion 117 with gold following the method in the previous section. This strip was then connected to a potentiostat/galvanostat through a clip which also served as the mechanical mounting. The experiment was conducted with the polymer actuator suspended horizontally in purified water. A step input of 2.5V amplitude was applied to the device and its motions were recorded by video camera.

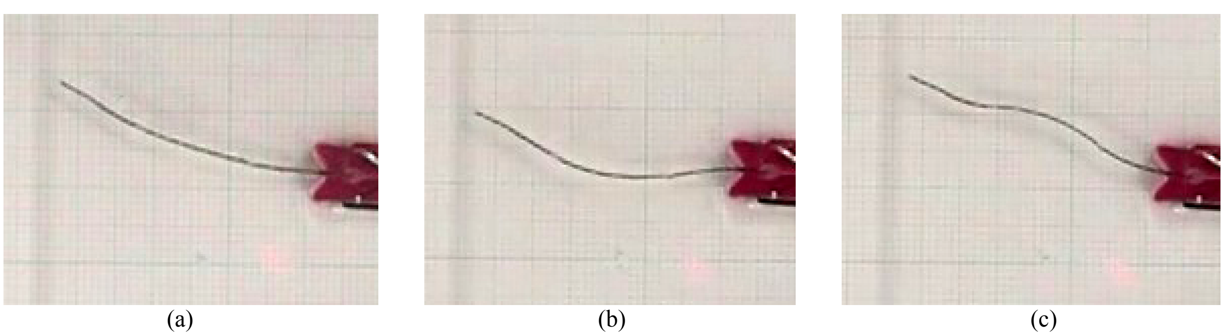


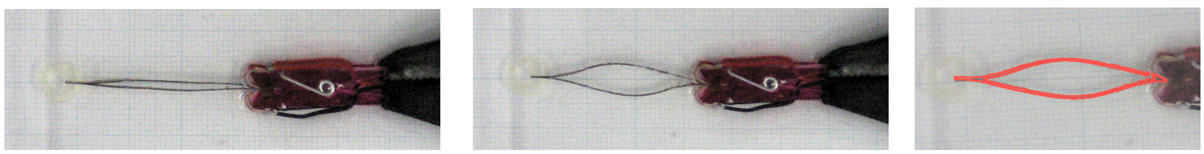
Fig. 15 Activating a single linear actuator strip

Fig. 15 shows the rest position (a) and two activated states (b and c) of the three segment linear actuator. Notice how the activated shapes resemble the double-clamped buckled beam. Notice also that the free end undergoes almost zero rotation throughout the activation. The slight translational movement of the free end is a result of the clamping where, by necessity, a small length of the strip must be held by the clip. This results in a slight shortening of this segment and the consequent introduction of slight bending just at the clamp. This can be easily circumvented by manufacturing slightly longer end sections to cater for the end fixings.

5.2. Paired actuation

Next we examine the activation of a pair of these actuators in the configuration shown in Fig. 11c. Two identical actuator strips of the same dimensions as the one used in the previous experiment are clamped together at one end such that the outside electrodes are electrically connected and the inner electrodes are electrically connected. A small rubber clip is used to clamp together the free end. We then applied the same 2.5V step voltage and observed the actuation shapes.

Fig. 16a shows the inactivated pair and Fig. 16b shows the pair under actuation. Notice that the actuated shapes of the two double-clamped strips closely match the shapes of the free actuator in Fig. 15, suggesting that the clamping of the free end has negligible effect on the activation of each individual strip. Notice also there is no vertical deflection at the free end when actuated. This evidence strongly confirms the validity of our proposed linear actuator.



(a) (b) (c)

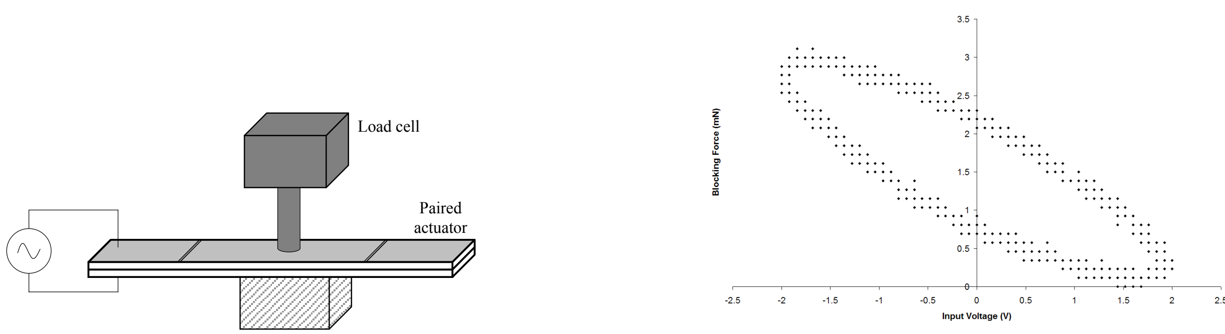
Fig. 16 Activating a pair of linear actuator strips

As a further support for this buckling actuator as a natural actuating structure we compared the activated shape in Fig. 16b with the same actuator in non-activated state, but axially compressed by hand through gently pushing on the end clamp. Fig. 16c shows the shape of the manually compressed actuator overlaid on the activated shape on Fig. 16b. We can see that the two shapes are almost identical. This adds further weight to the proposal that a double-clamped buckled beam is a natural structure for a linear actuator.

Note that the vertical movement of the mid section is much larger than the horizontal movement of the end. This characteristic enables the device to be used in a wide variety of applications. For example, where a small force is required over a large stroke the load should be mounted at the mid point, whilst a larger force but shorter stroke is achieved by mounting the load at the end point.

5.3. Blocked force

Blocked force was measured using the pair of linear actuator strips from the previous experiment. The strips were mounted with a fixed block under the mid point and a load cell positioned above the same point, as shown in Fig. 17a. A 2V sine wave was supplied to the actuator pair and the blocking force at the load cell was recorded. The load cell was calibrated such that the measured force was zero then the input voltage was maximally positive and maximum when the input voltage was maximally negative.



(a) (b)

Fig. 17 Measurement of blocking force

Fig. 17b shows the measured blocking force as voltage is varied. The graph shows a maximum blocking force of approximately 3mN. The hysteresis in this graph is typical of many polymer metal bending actuators.

6. ADDITIONAL APPLICATIONS AND MODIFICATIONS

Because the linear actuator strip presented in this paper was designed specifically for easy mounting and implementation it is a trivial matter to increase the force and/or stroke of the device by combining multiple actuators. In fact, multiple actuators can even be made from a single very long strip of material. In this case no bonding is required between each of the buckled sections of the strip. There are many other configurations possible for combining strips of these linear actuators. Some examples are described below.

6.1. A 2d actuator array

Fig. 18a shows three long strips of linear actuator material, each of which has been manufactured as a series of four linear actuators. The strips have then been bonded together at key points. Actuating the structure simply involves applying a voltage to the structure at any point. This results in large vertical displacement with low force and small horizontal displacement with large force. Fig. 18b shows one method of joining these strips with a single conducting rivet such that electrical connections are carried from one strip to another in the appropriate configuration.

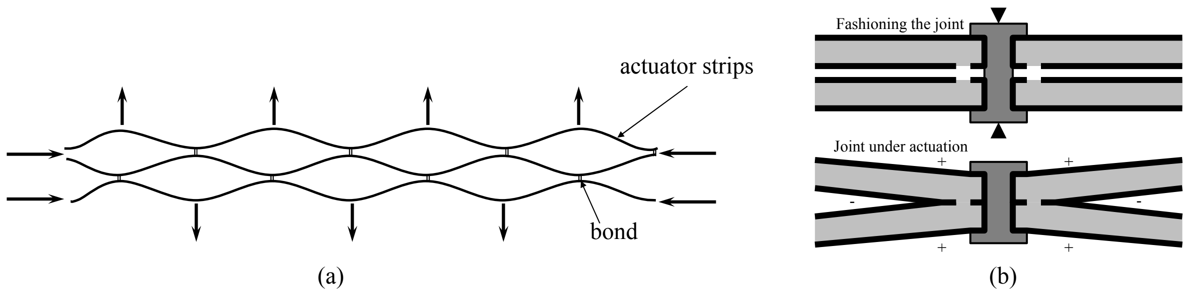


Fig. 18 A 2d actuator array

6.2. A cylindrical linear actuator

Fig. 19a shows a structure made from a preformed sheet of linear actuator material that has been rolled into a cylinder. The single sheet of material is manufactured such that a multitude of linear actuator strips are produced when thin slits are cut out of the material. When actuated, all the linear actuator strips bend outward into the buckle shape and the ends of the cylinder contract together. This structure is very easy to manufacture, requiring little extra effort above the basic actuator strip. Such a cylindrical structure naturally forms the basic building block for a range of serial- and parallel-connected actuators. Fig. 19b shows a serially connected structure where displacement is increased and Fig. 19c shows a combined serial and parallel structure where both displacement and force are increased.

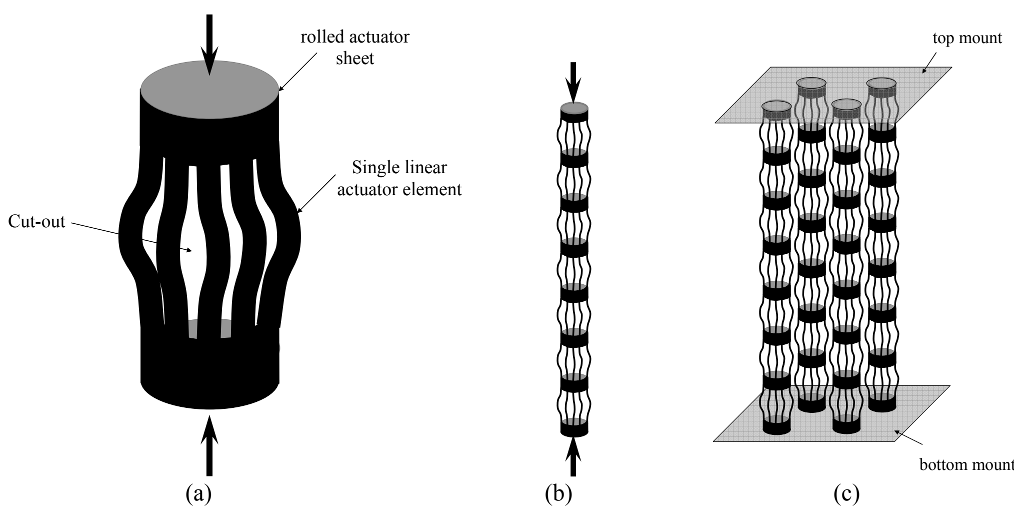


Fig. 19 A cylindrical linear actuator

7. CONCLUSIONS

In this paper we have presented a new linear actuator structure made from a single strip of ionic polymer metal-composite actuator material. Important characteristics include the non-rotation of end fixings and the ready ability to be combined into large and more effective actuator structures. The simplicity of manufacture also lends to the strength of the design, where no bonding or joining is required to achieve the required actuation.

The next stage in this research will involve more detailed investigations into the strength and displacement profiles of the actuator and the modeling of stresses in the actuated device. Practical implementation of some of the more interesting parallel and serial structures is also planned.

ACKNOWLEDGMENTS

Dr Jonathan Rossiter is currently the holder of a Royal Society Research Fellowship and this research is has been made possible by the generous support of the Royal Society.

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