Dielectric elastomer actuators with zero-energy fixity

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ABSTRACT

Although dielectric elastomer actuators (DEAs) are becoming more powerful and more versatile, one disadvantage of DEAs is the need to continuously supply electrical power in order to maintain an actuated state. Previous solutions to this problem have involved the construction of a bistable or multi-stable rigid mechanical structure or the addition of some external locking mechanism. Such structures and mechanisms add unwanted complexity and bulk. In this paper we present a dielectric elastomer actuator that exhibits zero-energy fixity. That is, the actuator can be switched into a rigid state where it requires no energy to maintain its actuated shape. This is achieved without any additional mechanical complexity. This actuator relies on changes to the elastic properties of the elastomer material in response to a secondary stimulus. The elastomer can be switched from a rigid glass-like state to a soft rubber-like state as required. We present a dielectric elastomer actuator that utilizes shape-memory polymer properties to achieve such state switching. We call this a dielectric shape memory polymer actuator (DSMPA). In this case control of the elastic properties is achieved through temperature control. When the material is below its glass transition temperature (T_g) it is in its rigid state and dielectric actuation has no effect. When the temperature is elevated above T_g the material becomes soft and elastic, and dielectric actuation can be exploited. We present preliminary results showing that the necessary conditions for this zero-energy fixity property have been achieved. Applications are widespread in the fields of robotics and engineering and include morphing wings that only need energy to change shape and control valves that lock rigidly into position.

Keywords: dielectric elastomer actuator, DEA, dielectric shape memory polymer actuator, DSMPA, zero energy, fixity, shape memory polymer.

1. INTRODUCTION

Electroactive polymers (EAPs) are highly suited to applications involving the interaction of humans and robots. A soft-soft interface of compliant EAP and biological tissue is much safer and more comfortable than the soft-hard interface most commonly encountered in conventional human-robot interactions. EAPs are the ideal technology for applications including naturalistic prosthetics, implantable medical devices, and active ergonomics. The compliant nature of EAPs, although a highly attractive feature, can be a disadvantage in that EAPs remain soft and compliant both when actuated and when at rest. Active biological mechanisms overcome this by using muscular actuation to graduate stiffness (e.g. along the length of carangiform swimmers such as the pumpkinseed sunfish) [1] or to effectively lock a loose mechanism (e.g. antagonistic control of the elbow joint) [2]. These approaches can be replicated using EAPs by actively controlling their actuation against a spring or against another, antagonistic, EAP. Unfortunately, although providing an element of controllable stiffness both the biological and artificial mechanisms require energy to maintain position under any load. An alternative is to mechanically lock or 'fix' the actuated structure, hence enabling a step change in compliance from a soft, deformable state to a rigid state. We refer to the property whereby a soft structure such as an EAP actuator can be fixed in a rigid shape as 'shape fixity.' The characteristic of shape fixity, and especially zero energy fixity, is therefore a desirable property which is lacking in existing EAPs. On the other hand the addition of an external mechanical fixing mechanism to an EAP is highly undesirable. Such an addition would add complexity and weight, and in applications such as mobile robotics or medical devices may make the complete device unusable. It would be far better to engineer the property of fixity into the EAP material or compliant EAP composite such that minimal additional weight or complexity were introduced.

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This paper introduces a solution to the problem of EAP fixity where dielectric elastomer actuators (DEAs) can be fabricated such that their rigidity can be simply controlled. Crucially the rigidity, and hence fixity, of the actuator can be maintained at zero energy cost. This is achieved through the use of a dielectric elastomer which has the property of controlled elasticity, and which exhibits shape memory properties. The use of dielectric shape memory polymers in these configurations opens up completely new areas of research exploiting variable-stiffness, zero-energy fixity and controlled and reversibly shape recovery. Applications which are set to immediately exploit this development include binary robotics, surgical tools, variable stiffness actuators and stroke rehabilitation tools. These technologies have further applications as kinetic energy storage devices.

In the next sections we will describe the property of zero-energy fixity and how it can increase the versatility of DEA actuators. We will then describe how shape memory polymers can be used as DEA actuators with variable stiffness and controllable fixity. Finally we describe a simple experimental setup and the subsequent results which verify this property.

2. FIXITY IN DIELECTRIC ELASTOMER ACTUATORS

2.1 Zero-energy fixity

Fixity is the property that actuators and actuated structures exhibit when they can be locked into a fixed, rigid configuration. For example, a robot arm needs to move when commanded but also needs the ability to remain rigid in a fixed position. Fixity in conventional robotics is achieved through either electrical or mechanical means, for example by energizing antagonistic pairs of actuators or by mechanically locking a gear or shaft. This is shown in Fig. 1 where a simple arm is mobile in Fig. 1a as two motors work in cooperation to move the arm. In Fig. 1b and Fig. 1c the arm is fixed, either by applying mechanical lock X or by energizing both of the motors to act against each other.

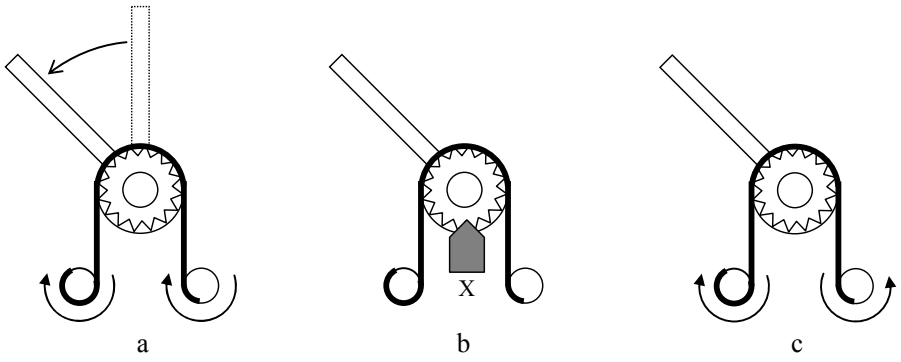

Figure 1. Controlling fixity in a simple robot arm

Zero-energy fixity is achieved when the actuated structure can maintain its fixed state with the expense of zero energy. Fig. 1b shows zero-energy fixity whereas Fig. 1c shows fixity at the expense of energy used in powering the motors.

2.2 Dielectric elastomer actuators

Dielectric elastomer actuators are triple-layer composites with a soft compliant polymer material sandwiched between two compliant electrodes[3]. When an electric potential is applied to the two electrodes they are attracted by Coulomb forces. The polymer undergoes a compressive deformation in the direction normal to the electrodes. Since the polymer is incompressible it expands in a direction parallel to the electrodes and this results in stresses that can be utilised in application. If the polymer undergoes a deformation within its elastic region, and is chemically unaltered by the applied electric field, its material properties remain unchanged. In other words an elastomeric polymer with a low modulus of elasticity will have the same low modulus even when actuated. The consequence of this is that any change in load during either the actuated or unactuated state will result in a similar deformation. The corollary of this is that since low modulus is desirable to maximize strain response in a DEA, the actuator is more easily deformed and distorted from small external forces than a structure made from a higher modulus elastomer. There is clearly a trade-off between the ability to maintain a mechanically strong actuated state (high modulus) and the need for a large actuation strain (low modulus.) This property is shown in Fig. 2a where state S_1 is the unactuated state of a DEA actuator where both applied electric field E and induced strain e are zero, and state S_2 is the actuated state where applied electric field E is large and

where strain *e* is non-zero. Here the actuator has the same low modulus M in both states, and hence both states undergo large deformations in response to any change in loading.

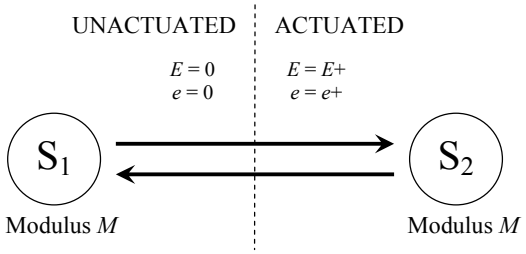

Figure 2. Actuated and unactuated states of a conventional dielectric elastomer actuator.

To overcome this compromise we need to be able to dynamically change the modulus of the elastomeric material. This will enable the fixing of the electrically induced actuation such that the actuator is rigid and strongly resists external forcing. In many cases binary stiffness control is sufficient. For example, Fig. 3 shows the two states of a binary variable-stiffness elastomeric material. In state S_a the material has a high modulus M_1. When a suitable stimulus is applied the material switches to state S_b and modulus reduces significantly to M_2. The state switching is reversible either by the removal of the previously applied stimulus or by the application of some other counteracting stimulus.

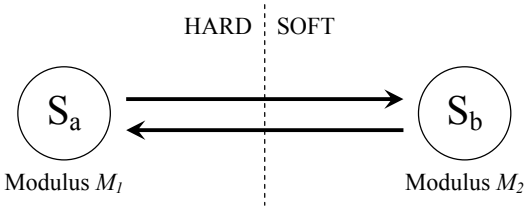

Figure 3. Two states of a variable stiffness elastomer.

Fig. 3 shows controllable fixity in an ideal elastomeric material. To achieve fully controllable fixity in a dielectric elastomer actuator the states and transitions in Fig. 2 and Fig. 3 must be combined. This is shown in Fig. 4. Here, for example, a DEA starts in hard, unactuated state S_0. An appropriate stimulus is applied which reduces elastic modulus of the actuator's elastomer from M_1 to M_2 and the actuator moves to state S_1. Now the DEA is soft enough to be actuated under an applied potential E+ and it moves to state S_2. In this state the DEA has exhibited some strain e+ but is still soft and deformable. To fix the structure in its actuated shape the stimulus that was first applied to reduce the elastic modulus is removed. Now the elastomeric material returns to its high modulus M_1 (state S_3) but still retains the strain e+ that was electrically induced. S_3 is a state exhibiting fixity but since the electric field is still applied it does not exhibit zero-energy fixity. To achieve zero-energy fixity the electric field is now removed and the actuator enters state S_4. In state S_4 no electric field is applied and no energy is being consumed in maintaining the fixed shape, but, as in state S_3, the strain e+ is retained. To recover the original, unactuated shape, the usual path would involve the return state transitions $S_4 \rightarrow S_3 \rightarrow S_2 \rightarrow S_1$. To achieve the same result with minimal cost the actuator in state S_4 can also return directly to state S_1 by switching it back to its low modulus state M_2 without reapplying the electric field. If the elastomer material retains sufficient restorative elastic energy it will return directly to it's unactuated shape. The release of this stored elastic energy through conversion into kinetic energy opens up the interesting possibility of using these materials as kinetic energy storage devices.

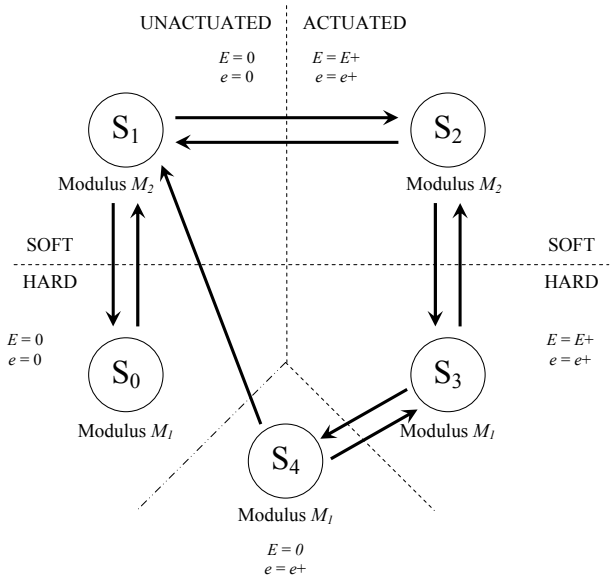

Figure 4. Combined states and transitions for a variable stiffness dielectric elastomer actuator.

3. SHAPE MEMORY POLYMERS

Shape memory polymers have responsive properties that set them apart from other materials [4]. When appropriately stimulated a shape memory polymer (SMP) will undergo a change in elastic modulus. This typically occurs in a very narrow range of stimulation. For example the majority of SMPs are thermo-responsive, that is, they respond to temperature change. These SMPs change their modulus around a glass transition temperature T_g. When the temperature T of this SMP is below T_g the material is in its high modulus state, often referred to as the glassy state. When the temperature of the SMP rises above T_g the material markedly softens and it enters a low modulus state, often referred to as the rubbery state. This is illustrated in Fig. 5 which shows the change in modulus in response to temperature change.

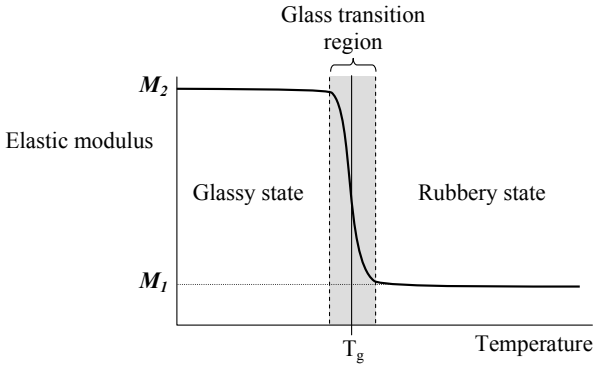

Figure 5. Effect of temperature change on elastic modulus of a shape memory polymer.

Equally important in this paper is the property of shape recovery, the so-called memory effect. If an SMP is deformed in its soft state and this deformation is maintained as it undergoes a soft → hard transition (i.e. temperature is changed from $T>T_g$ to $T<T_g$) the deformation is 'frozen' or fixed into the rigid material. The polymer will hold this deformed shape indefinitely, or until the next time it enters the soft, low modulus state. When the deformed SMP is next transitioned into its soft state ($T<T_g \rightarrow T>T_g$) it will spontaneously return to its pre-deformation shape. Since the polymer is exhibiting a kinetic effect triggered, but not driven, by the stimulation (temperature change in this case) it is releasing elastic energy

that had been induced when it was last in its low modulus state. Shape memory polymers can recover from large induced strains in the order of 300% [5]. Fig. 6 shows the transition states for a shape memory polymer under temperature control and external forcing F. Note that the state transitions are isomorphic to those in Fig. 4 for an ideal variable stiffness dielectric elastomer. These two characteristics; large rapid change in modulus and shape recovery, mean that shape memory polymers are finding use in applications ranging from mould making to implantable medical devices [6][7].

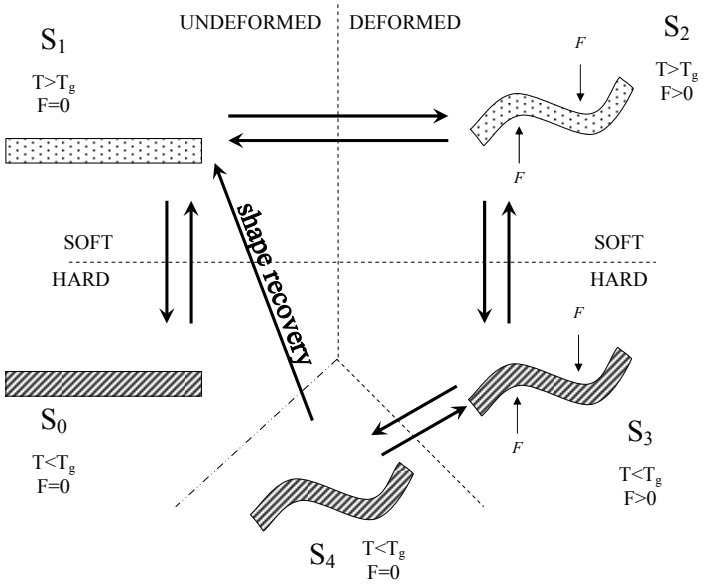

Figure 6. State transitions of a shape memory polymer.

The hard-soft transitions shown in Fig. 4 (i.e. $S_0 \leftrightarrow S_1$ and $S_2 \leftrightarrow S_3$) match the property of controllable modulus in shape memory polymers. It is natural therefore to conclude that SMPs have the potential to provide the dynamic, controllable modulus needed to realize the complete set of state transitions, and hence zero-energy fixity, in Fig. 4.

One important transition in Fig. 6 is from S_4 to S_1. This provides a direct route for the return of a rigid deformed structure to its soft, undeformed state. As mentioned previously this can only occur if there is sufficient elastic energy stored in the deformed material to force it back to its initial undeformed state upon transition to low modulus. This is precisely the property that SMPs have in their shape recovery, or shape memory, effect.

4. DIELECTRIC SHAPE MEMORY POLYMER ACTUATOR

We can see clearly from Fig. 4 and Fig. 6 that the combination of a shape memory polymer and a dielectric elastomer actuator can be used to realize a zero-energy self-fixing actuator. There are two ways in which this can be achieved; 1. by forming a composite structure of a conventional DEA actuator and a separate SMP element, or 2. by utilizing SMP materials to replace the dielectric polymer within the DEA. The latter is preferred for reasons of cost, efficiency and simplicity. Fig. 7 shows the configuration of two possible DEA/SMP actuators, where T represents the stimulus (e.g. temperature) applied to the SMP which changes its elastic modulus. Fig. 7a shows a relatively unchallenging sandwich composite structure and Fig. 7b shows a more pleasing structure where the SMP is used as the dielectric element and hence is labeled DSMP (for dielectric shape memory polymer.) Composite actuators along the lines of Fig. 7a have clear potential as variable stiffness actuators, for example as configurable bimorph structures. Unfortunately the SMP here may act as an unnecessary load, even when it is in its lowest modulus state, and reduce the performance of the DEA actuator component. The actuator in Fig. 7b is far more attractive since only one active layer is used and this performs the role of both the dielectric elastomer for actuation and the controllable stiffness element for self-fixity. From here we will only consider actuators of the form shown in Fig. 7b, where the SMP is also a dielectric elastomer. We refer to a DEA/SMP actuator of this type as a *dielectric shape memory polymer actuator* (DSMPA.)

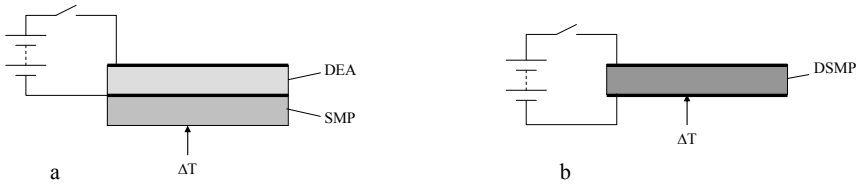

Figure 7. Configurations for a DEA/SMP actuator

Let us now consider how the DSMPA actuator in Fig. 7b could be controlled. Here we are assuming that electrical actuation is independent of modulus control stimulus. Although many different shape memory polymers exist which undergo modulus change in response to different stimulus (chemical, thermal, optical, etc.)[4] we will use thermo-responsive shape memory polymers for all subsequent illustrations and experiments. Fig. 8 shows the actuation states for the proposed DSMPA which are derived from the controlled application of both voltage V and temperature T. We illustrate here using a simple DSMPA structure for clarity, though any conventional DEA configuration can be used, such as membrane, spring roll, bow-tie, etc. Note that Fig. 8 is isomorphic with both Fig. 4 (an ideal actuator) and Fig. 6 (a shape memory polymer.)

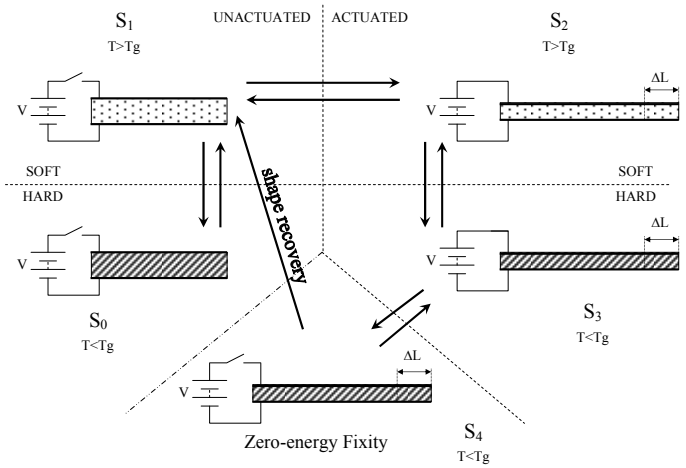

Figure 8. Actuation states for the dielectric shape memory polymer actuator (DSMPA)

The typical actuation process for a DSMPA starts in the rigid, unactuated state S_0. First the temperature is raised above T_g to ensure the polymer transitions to its low modulus state (S_1). Electrical actuation can be achieved by applying voltage V which generates strain $\Delta L/L$ (state S_2). This strain can be fixed by lowing the temperature of the polymer below T_g to force it into its high modulus state (S_3). To achieve zero-energy fixity the voltage V is now removed (S_4) but the previously induced strain $\Delta L/L$ is retained. To recover the original, unactuated state the temperature is raised one more time above T_g with no applied voltage. This final step returns the actuator from state S_4 to state S_1 and involves the spontaneous release of stored elastic energy. Note that all the state transitions in Fig. 8 are shown as reversible, except the transition between S_1 and S_4. Clearly the direct transition $S_1 \rightarrow S_4$ is not possible without some external mechanical forcing.

4.1 Electrical and mechanical requirements of DSMPA

For a DSMPA to work effectively and to have the property of zero-energy fixity the shape memory polymer must have the following properties:

1. High modulus when $T<T_g$ (for rigid fixity.)
2. Low modulus when $T>T_g$ (for effective strain generation under dielectric actuation.)
3. High dielectric constant (for effective conversion of electrical to mechanical energy.)

It has been shown that polynorbornene [14], a thermo-plastic shape memory polymer marketed under the name Norsorex by Astrotech, has a elastic modulus of approximately 900MPa when $T<T_g$ [8]. This value falls to approximately 3MPa when $T>T_g$. The glass transition temperature T_g of polynorbornene is approximately 35°C [9]. The high modulus below T_g results in a rigid material, similar in elasticity to acrylic, which is suitable for many applications requiring a fixed zero-energy state. The low modulus above T_g is similar to some silicone polymers which have already been used in dielectric elastomer actuators[10]. Polynorbornene therefore is mechanically compatible with the proposed DSMPA actuator.

To determine the dielectric constant ε_r of polynorbornene we performed impedance tests on a sheet of the material and calculated its value through the capacitance equation (1).

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{1}$$

A flat sample of polynorbornene d=760μm in thickness was clamped between two electrodes with surface area $A=2.4\times10^{-4}m^2$. A digital impedance meter operating at 100Hz measured a capacitance of C=200pF. Using (1) we calculate a value of $\varepsilon_r=7.15$. These tests were conducted at room temperature (approx. 20°C) and hence the shape memory polymer was in its high modulus state and well below the glass transition temperature. Although this figure is higher than the value of $\varepsilon_r=2.2$ calculated by [11] where impedance was measured at 10kHz, it does indicate that polynorbornene has a high enough dielectric constant for use in a dielectric elastomer actuator. Indeed the dielectric constant of VHB-4910, a common dielectric elastomer material, is approximately 4.7 in it's non pre-strained state, but has been shown to reduce to as low as 2.6 when prestrained [12]. This value is close enough to that in [11] to suggest that polynorbornene would be a suitable dielectric material. Note that we assume the dielectric constant of polynorbornene does not change significantly as temperature increases. It is not yet established how temperature affects dielectric constant in this shape memory polymer.

5. EXPERIMENTAL SETUP

In order to demonstrate the feasibility of a dielectric shape memory polymer actuator, and hence to realize the property of zero-energy fixity, a prototype DSMPA was constructed as shown in Fig. 9. A polynorbornene sheet of approximately 200μm thickness formed the dielectric membrane, which was coated on both sides with silver grease to form the compliant electrodes. The membrane was fixed over an opening using a silicone sheet and a 10mm diameter o-ring. To ensure that actuation was in one direction only, the membrane was pre-strained by a slight air pressure P on the underside, thus creating a slight bias to actuation towards the top side of the membrane. The silver electrodes were connected to an Emco F121 high voltage amplifier which was driver through a power amplifier by a National Instruments DAQ card. Air pressure was measured using a Keyence AP-43/AP-C40 air pressure meter and displacement of the DSMPA membrane was measured using a Keyence LK-G150/LK-GD500 laser displacement meter (LDM). Temperature just above the DSMPA membrane was measured using a digital thermometer with micro thermocouple element. Heating was performed by a hand held heat gun. Cooling was performed using an aerosol can of compressed air at room temperature.

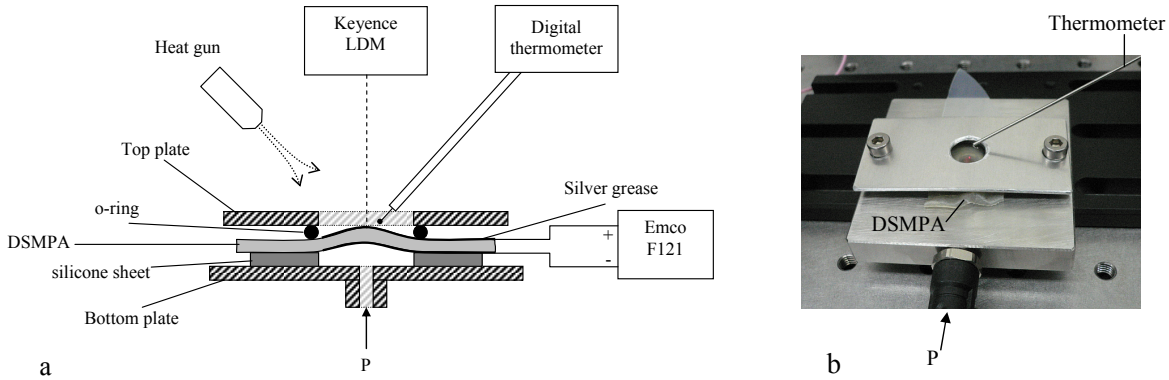

Figure 9. Experimental setup for testing the DSMPA; a. setup, and b. top view of actuator mounting.

Fig. 10 is derived from Fig. 9 and shows the state transitions and actuation modes for the test DSMPA. To confirm dielectric actuation we performed the following experiment:

5.1 Confirmation of different dielectric actuation results when $T<T_g$ and when $T>T_g$.

According to Fig. 10 when the DSMPA is in a low modulus state ($T>T_g$) we would expect repeatedly switching of the voltage V to result in a vertical membrane displacement varying between 0 and d. This corresponds to the state transitions $S_1 \leftrightarrow S_2$. On the other hand, when $T<T_g$ no direct state transition exists between S_0 and S_3 so we would expect to see no changes in membrane displacement in response to switching voltage V. The test procedure for this experiment involves the following steps:

1. Test start (state S_0, $T<T_g$.)
2. Apply a 6kV square wave actuation voltage to the DSMPA and record displacement.
3. Heat the DSMPA above T_g (state S1.)
4. Apply a 6kV square wave actuation voltage to the DSMPA and record displacement.
5. Test end.

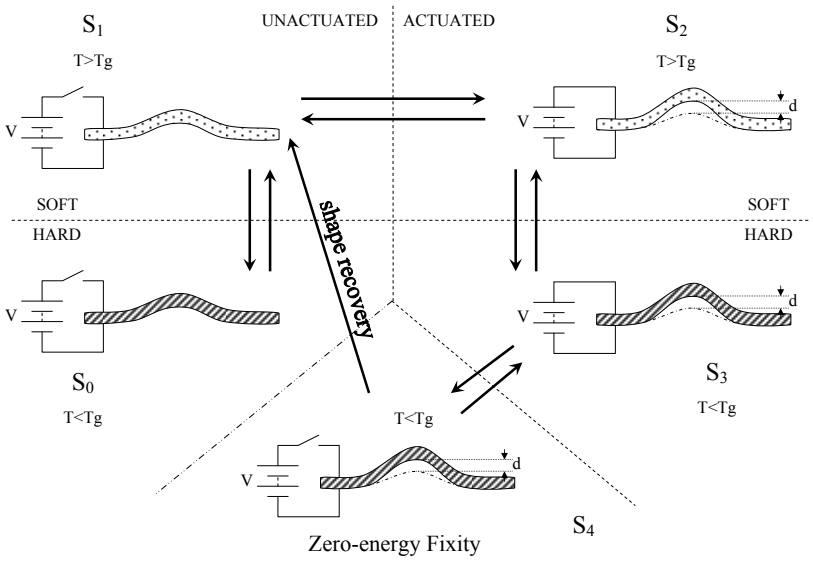

Figure 10. Testing procedure for DSMPA.

This experiment is sufficient to demonstrate that all the properties that are required for DSMPA realization (as identified in section 4.1) are present and hence that a zero-energy self-fixing dielectric elastomer actuator is practical.

6. RESULTS

Fig. 11 shows experimental results using the setup in Fig. 9. Here the effects of electrically stimulating the DSMPA at different temperatures are shown. It is clear that at low temperatures ($T<T_g$) the actuator produces almost zero strain (approx 1μm). When the temperature is raised above T_g the strain increases 2400% to approx. 24μm. This is shown more clearly in Fig. 12 which shows significant actuator displacement (dashed line) when $T>T_g$ and in Fig. 13 which shows almost zero displacement when $T<T_g$. From these results we draw the following conclusions:

1. The actuator has high enough modulus below T_g to enable rigid fixity.
2. The actuator has low enough modulus above T_g to generate effective strain.
3. The dielectric constant of the DSMPA is high enough to realize effective dielectric actuation.

These match the requirements for an effective zero-energy self-fixing dielectric shape memory polymer actuator identified in section 4.1. Confirmation of these properties means that all the crucial state transitions in Fig. 8 can be achieved, thus enabling the fabrication of a zero-energy self-fixing dielectric shape memory polymer actuator.

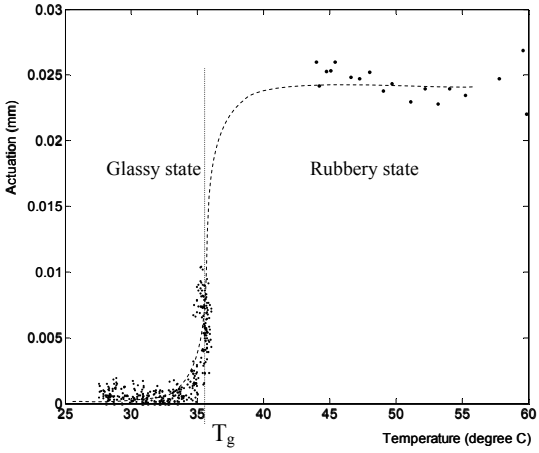

Figure 11. Effects of temperature on dielectric actuation of a DSMPA.

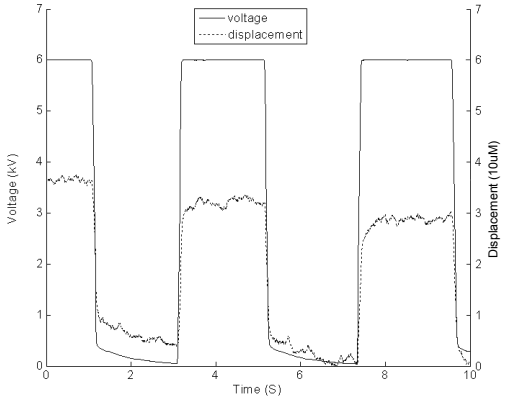

Figure 12. Actuation response of a DSMPA, $T>T_g$.

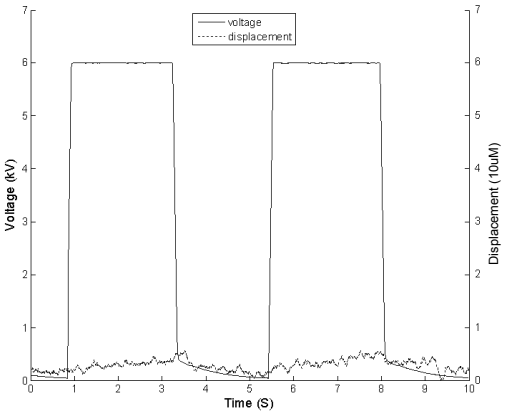

Figure 13. Actuation response of a DSMPA, $T<T_g$.

7. CONCLUSIONS

In this paper we have identified the need for a soft electroactive actuator that can exhibit zero-energy self-fixity and we have shown that this cannot be achieved using conventional dielectric elastomer actuator technologies. We have shown that shape memory polymers offer the crucial ability to modify their elastic modulus in response to some controllable stimulus. We have proposed that, if a number of electrical and material requirements are satisfied, including elastic modulus range and dielectric constant, a dielectric shape memory polymer actuator (DSMPA) can be fabricated which will have the characteristics of conventional DEA actuators but will also have the additional property of zero-energy self-fixity. The dielectric constant of polynorbornene, a common shape memory polymer, was calculated from impedance measurements and shown to meet the electrical requirements for an effective DSMPA. A simple experimental setup was presented which was used to show that the thermo-active and material properties of a polynorbornene DSMPA also meet the requirements previously identified. This experimental verification proves the validity and versatility of the proposed DSMPA actuator.

Applications likely to benefit from this new zero-energy self-fixity actuator include reversible shape memory polymer devices for medical applications, valve control mechanisms and morphing surfaces for aircraft wings [13].

Future work will investigate and characterize the material and dynamic properties of the new DSMPA actuator and investigate alternate mechanisms for inducing modulus change in the shape memory polymer. This will include optical stimulation and thermal stimulation via resistive heating of the compliant electrodes.

REFERENCES

1 McHenry, M.J., Pell, C.A., Long, J.H., "Mechanical control of swimming speed: stiffness and axial wave form in undulating fish models," The Journal of Experimental Biology, **198**, 2293–2305, (1995)

2 Lochmatter, P., Kovacs, G., Ermanni, P., "Design and characterization of shell-like actuators based on soft dielectric electroactive polymers," Smart Materials and Structures, **16**.1415, (2007)

3 Pelrine, R., Kornbluh, R., Pei, Q., Joseph, J., "High-speed electrically actuated elastomers with strain greater than 100%," Science, **287**.5454:836-839, (2000)

4 Behl, M., Lendlein, A., "Shape-memory polymers," Materials Today, **10**, pp20–28, (2007)

5 Lendlein, A., Kelch, S., "Shape-memory polymers," Angewandte Chemie International Edition, **41**.12: 2034-2057, (2002)

6 Baer, G., Wilson, T.S., Matthews, D.L., Maitland, D.J., "Shape-memory behavior of thermally stimulated polyurethane for medical applications," Journal of Applied Polymer Science, **103**, pp3882–3892 (2007)

7 Lendlein, A., Langer, R., "Biodegradable, elastic shape-memory polymers for potential biomedical applications," Science, **296**, pp1673–1676, (2002)

8 Galperin, I., Carter, J.H., Hein, P.R., "Poly(norbornene): Tensile and dynamic-mechanical properties," Journal of Applied Polymer Science, **12**.7:1751-1754, (1968)

9 Sakurai, K., Takahashi, T., "Strain-induced crystallization in polynorbornene," Journal of Applied Polymer Science, **38**.6:1191-1194, (1989)

10 Kofod, G., Sommer-Larsen, P., "Silicone dielectric elastomer actuators: Finite-elasticity model of actuation," Sensors and Actuators A: Physical, **122**.2:273-283, (2005)

11 Grove, N.R., Kohl, P.A., Allen, S.A.B., Jayaraman, S., Shick, R., "Functionalized polynorbornene dielectric polymers : Adhesion and mechanical properties," Journal of polymer science. Part B, **37**.21:3003-3010, (1999)

12 Wissler, M., Mazza, E., "Electromechanical coupling in dielectric elastomer actuators," Sensors and Actuators A, **138**, pp384–393, (2007)

13 Thill, C., Etches, J., Bond, I., Potter, K. Weaver, P., "Morphing skins", The Aeronautical Journal, **112**.1129:117-139, (2008)

14 Bhowmick, A.K., Stein, C., Stephens, H.L., "Polynorbornene rubber," in Handbook of Elastomers, Bhowmick, A.K., and Stephens, H. (eds), pp775-784, CRC Press, (2000)