Strong dielectric-elastomer grippers with tension arch flexures

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ABSTRACT

Soft grippers based on dielectric elastomer actuator (DEA) are usually too flimsy to perform the task of pick and place on a heavier object given their low payload capacity. This work developed a new design of DEA unimorph consists of a flexible frame holding at a DEA on the discrete support by a stiffer spine-like flexure of 380μm thick Polyvinyl chloride (PVC) sheet. It finds an equilibrium of curling up when the DEA's pre-stretch is partially released; it can electrically unfolds upon a voltage application. This dielectric elastomer unimorph of 3 grams produced a maximum voltage induced bending of close to 90° and a maximum voltage-induced blocked force of up to 168mN. Given their higher stiffness and large actuation, these 3-D shaped and strengthened DEA unimorphs can make stronger grippers for passive grasping and active pinching.

Keywords: Dielectric elastomer actuator, flight muscles, flapping wing, compliant mechanisms

1. INTRODUCTION

Soft robotic grippers are good for handling fragile objects as delicate as an egg or a tender fruit. The materials used in the making of soft grippers are often soft, yielding and compliant. These mechanical attributes of soft materials give soft gripper the potential for a more gentle interaction with fragile object when grasping them while allowing the grippers to be more tolerant to potentially damaging forces, such as an impact. In addition to being made of soft and flexible materials, soft grippers are also capable of large retracting motion without the need of complex joints.

Different soft grippers driven by various means of actuators, includes vacuum pressure,[1,2] compressed air,[3,4] shape memory actuator[5,6] and dielectric elastomer actuators (DEA)[?,7–13] have been developed. Among them, DEA-based grippers are attractive for being lightweight, having notably low elastic modulus with large strain capability, and their actuation motion can be carefully controlled by the application of an electrical voltage.[7,8,12] The means to operate them simplifies the infrastructure necessary for their actuation, eliminating the need of compressor and gas valves typically found in pneumatic-based grippers or the need of heating element for the actuation of heat sensitive shape memory-based grippers. Because of its simplicity in controls, DEA-based gripper is capable of untethered gripping motion while maintaining the overall compliance of the structure.

In most designs of DEA-based grippers, the DEAs are either reinforced with stiff fibres or bonded onto flexible frames to form dielectric elastomer minimum energy structures (DEMES)[7–10] or bi-layered grippers[12,13] which consist of one active DEA layer and inactive layer that can undergo shape change when deformation of active layer was induced by electrical fields. Those reinforcements or supporting frames are responsible to direct the actuation shape of the soft grippers to perform the task of pick and place. The practical use of DEMES gripper is currently limited by its low lifting capacity and grip force.[7–9,14] Most DEMES gripper uses flexible frame that is too flimsy to provide enough grip force to hold and lift an object.

In order to achieve a stronger grasp, the grippers based on dielectric elastomer DE unimorphs need further reinforcement. Although the adoption of a stiffer frame can readily increase the DEMES gripper's overall stiffness, the amount of folding or bending of the unimorphs into its resultant three-dimensional configuration will be significantly reduced given the same amount of pre-compressive force exerted by the pre-stretched DEA layer. If the frame is over stiffened, the pre-stretched DEA layer may not even have enough pre-compressive force to buckle the stiffer frame into the required three-dimensional shape suitable for gripping function.

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A conventional method for converting the lateral expansion of DEA into a flexural bending is based on a bi-layer design of minimum energy structure.[7,8,14] The bi-layer design of dielectric elastomer minimum energy structure (DEMES) consists of a pre-stretched DEA bonded on top of a flexible frame of higher stiffness, as compared to dielectric elastomer's. On release of the elastomeric pre-stretch, the frame buckles out of plane, and bends with the relaxed dielectric elastomer membrane in a complex three-dimensional shape due to the equilibrium of internal forces. Bending of the minimum energy structure depends on the frame stiffness and elastomeric pre-tension. Application of voltage shifts the system's minimum energy state, resulting in the uncurling of the buckled frame.

A bilayer design of minimum energy structure requires a high critical pre-compressive force to buckle the frame due to the small offset between the force centre and the frame's neutral plane. Given the initially planar structures, a larger curling by buckling under a critical load is at the expense of the decreased stiffness.[15] This trade-off between bending and strength presents an obstacle to the development of versatile DEA grippers.

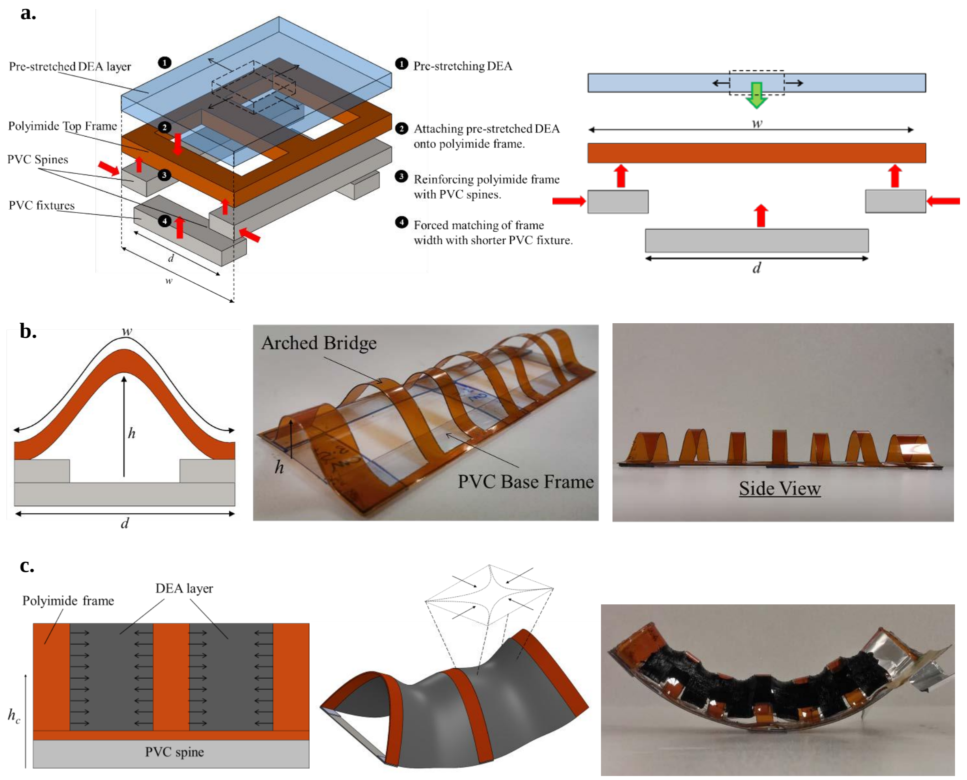


Figure 1. Formation of spine-like DEMES structure - a) pre-stretched DEA layer is adhesively attached to the polyimide frame that is reinforced with stiffer PVC spines and fixtures. b) Arched bridge is formed by forcefully matching the wider polyimide top frame to a narrower PVC width fixture. c) The resultant configuration forms the spine-like structure when bent under pre-compression force from pre-tensioned DEA layer

2. NOVEL PRINCIPLE AND DESIGN

In this study, we develop novel dielectric-elastomer fingers' with strength for firm grip by using a tension arch structure (see Figure 1). The tension arch flexure is inspired by the architectural designs of metal arched frames that keep fabric based roof in tension support. These structures provide extreme flexibility and are lightweight. Unlike the common bi-layer design, this three-dimensional tensioned arch flexure shapes a pre-stretched acrylic DEA such that the high elastomeric pretension is de-leveraged to produce a large bending. Voltage activation of the arched membrane of dielectric elastomer reduces the pre-tensions and actively undoes the bending.

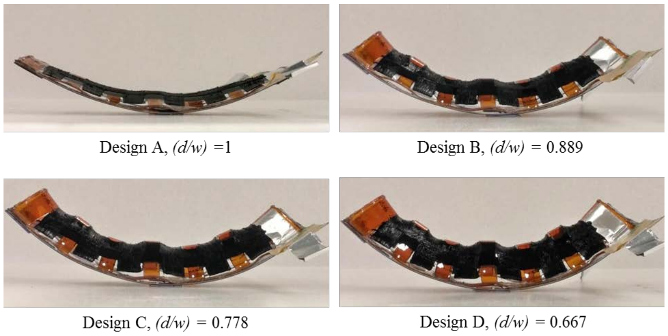


Figure 2. Samples of Spine-like DEMES designs with different width mismatch ratio d/w

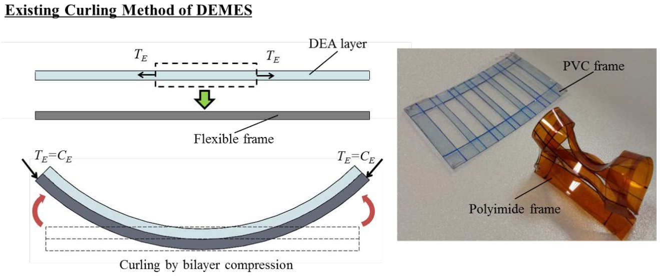


Figure 3. Bending principle of existing DEMES gripper using a bilayer unimorph consistsing of a pre-stretched DEA on a passive structrual layer.

For each dielectric elastomer finger of a 2.5 gram total weight, the composite tensioned flexure comprises of base spines, arch bridges, and a pre-stretched dielectric elastomer membrane (see Fig. 2). The components of this composite structure are initially flat (see Figure 1a): a base frame of 0.38mm thick Polyvinyl chloride (PVC) and a flexible frame of 0.127mm thick polyimide. The flexible frame of width w holds an initially flat pre-stretched DEA before it is bonded at discrete point onto the PVC base frame of narrower width d. Due to the width mismatch ($d/w < 1$), cross bars of the polyimide frame buckle into arch bridges, elevating the DEA into a roof with height h (see Figure 1b). This asymmetric loading of elastomeric pre-tensions can induce a larger moment and thus readily bends the base frame of higher stiffness. When released, the composite tension structure undergoes a large bending (see Figure 1c).

3. FABRICATION

To vary the buckled height of this built-up frames, we have four base frames of different widths (45mm, 40mm, 35mm, and 30mm) bonded separately to a common polyimide frame of $w = 45mm$ wide and 103mm long. When compressed by a biaxially pre-stretched dielectric elastomer membrane, the spines of PVC frame bends and subtends a large residual angle. The DEA is a VHB 4910 tape is pre-stretched for 5 times longitudinally and 6 times transversely.

Figure 2 shows the four designs of DE unimorph with different width mismatch ratios, namely Design A with d/w=1, Design B with d/w=0.889, Design C with d/w=0.778, and Design D with d/w=0.667.

It is observed that a large width mismatch (i.e. $d/w < 1$) heightens the arched bridge, help increasing the stress-induced moment generation. The Design A with matched flexure width (d/w=1) bends much less at 46.6° due to a light saddle formation given the inter-layer freedom. The Design B (d/w = 0.889) with a 8mm high arch bridges bends for 85.5°. The Design C (d/w = 0.778) with a 12mm high arched bridges bends for a 110° residual angle. The Design D (d/w = 0.667) with a 14mm high arched bridge bends for 105°. The overheightend arch bridges does not help produce more bending due to the extra membrane relaxation at the height during a bending.

In comparison (see Figure 3), a flimsy frame made of a 0.127mm thick polyimide film with no strength simply rolls up under pre-compression by the same DEA pre-stretches. A stiff frame made of 0.38mm thick polyvinylchloride (PVC) sheet remains nearly flat under the pre-compression by the pre-stretched dielectric elastomer membrane.

4. EXPERIMENTAL METHODS

To evaluate the actuation uncurling performance of the spine-like DEMES, the following data from an experiment are required: Voltage-induced strain quantified in terms of tip angle ? and actuation blocked force produced. For tip angle measurements, incremental voltage steps were supplied to the actuator at 1kV intervals in the range of 0 to kV for static tip angle measurement. The input voltages were supplied by TREK (Model 610E) High-Voltage Supply and the inputs were transformed into square-wave by Agilent 3120A function generator before transmitting to the actuators. Agilent 34410A digital multi-meter detects the voltage and current in real-time. Still images were taken at each voltage step using DSLR camera for static tip angle measurements a few seconds after application of the voltage increment to allow the actuators to reach the steady state. The images were subsequently postprocessed in Kinovea Motion Tracker software to determine the tip angle.

For blocked force measurements, a load cell was used to measure the block force exerted by the actuator as a function of an imposed linear displacement of load cell and voltage change in the strain rosette (see Figure 12). The linear displacement of load cell was converted to change in voltage potential difference in strain rosette. This change can be translated to the amount of force acting on the load cell. The voltage change of the strain rosette are captured by Labview and converted into force magnitude. All measurements were conducted at the actuator tip and displacements made normal to the actuator tip surface. The actuator was held in place at an exact height such that the tip was merely in contact with the load cell and tangent to it.

5. RESULTS AND DISCUSSIONS

5.1 unimorph characteristics

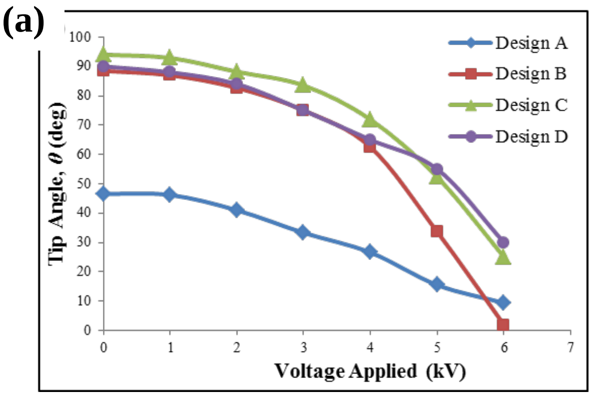
Figure 4 shows that voltage activation of the dielectric elastomer membrane can partially or fully undo the bending of different DE unimorphs. For Design A (d/w=1), the 6kV activation induced a higher electric field (127.7MV/m) across the thin DEA membrane, but can only electrically unbend for 37.2°. For Design B (d/w=0.889), the 6kV activation of DEA (with an electric field of up to 109MV/m) can fully undo the 86.6°. For Design D (d/w=0.667), the electrical unbending is 60° at 6kV activation (48.8MV/m) due to the membrane thickening for the large residual bending.

A voltage-induced blocked force of the DE unimorph is a release of elastic force of base frame upon DEA activation. Figure 5 shows that the blocked force generated increases with the increase in the applied voltage across the DEA layer. As the tension in activated DEA reduces, the curled-up DEMES unfolds. This allows more elastic energy stored in the frame to be released and greater blocked force to be exerted on the load cell.

It is noted that the unimorph designs subjected to a large residual bending can produce a higher blocked force, as compared to that subjected to small residual angle. For example, Design A, which is subjected to 60° residual bending, produces a lesser force of 55.5mN, despite a higher field activation at 6kV due to its smaller release of spring force. Designs B, C, and D are subjected to a larger residual bending angle ranged from 90° to 110°. Given the same driving voltage at 6kV, design B produces the largest blocked force (168.7mN) due to higher electric field across the not-so-relaxed DEA membrane.

5.2 Grippers in action

Figure 6 shows normally close grippers based on three dielectric elastomer unimorphs. Such grippers have mechanical strength to grasp and lift an object of several times the gripper weight, thanks to the benefit tension arch flexures on a stiff PVC base frame. For example, they are use to pick and place a mandarin orange of 47 gram weight. The unimorphs open upon 5.4kV activation, to envelop around the orange. They curl up and hold the orange with their passive strength, upon the voltage removal.



(b) Design C

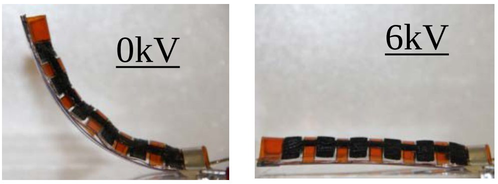


Figure 4. Voltage-induced bending of the unimorphs with spine-like structures

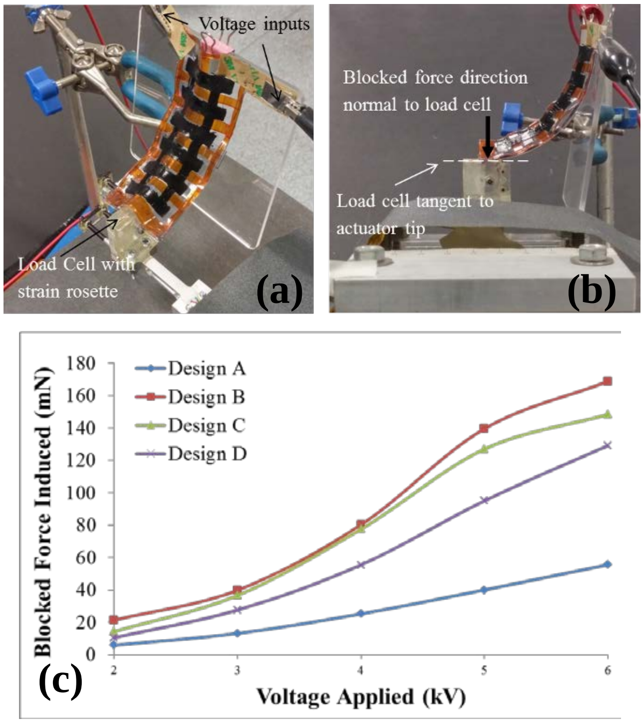


Figure 5. a) Isometric view - Blocked force measurement set-up. b) Side view - Load cell measures the blocked force at the actuator tip as the load cell is linearly displaced downwards. Linear displacements of load cell translate to change in voltage potential difference in strain rosette which equates to force. c) Overall blocked force measurements for various widths mismatch designs.

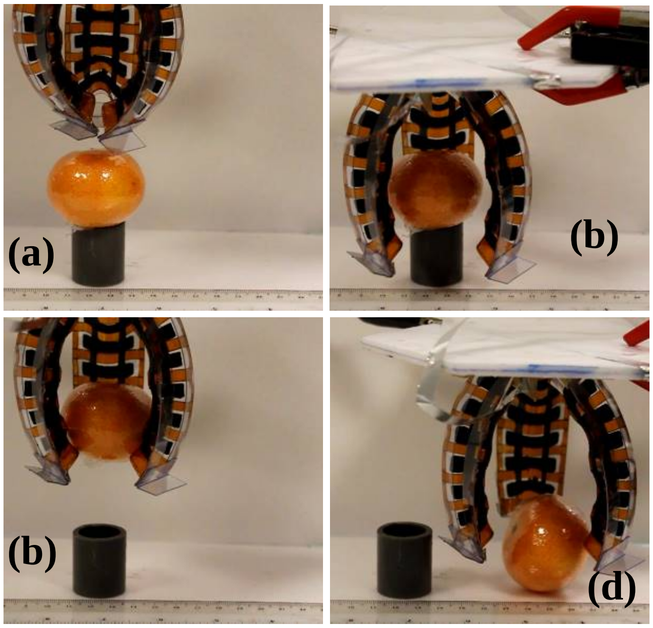


Figure 6. Action of 'pick-and-place' by 3 spine-like grippers arm

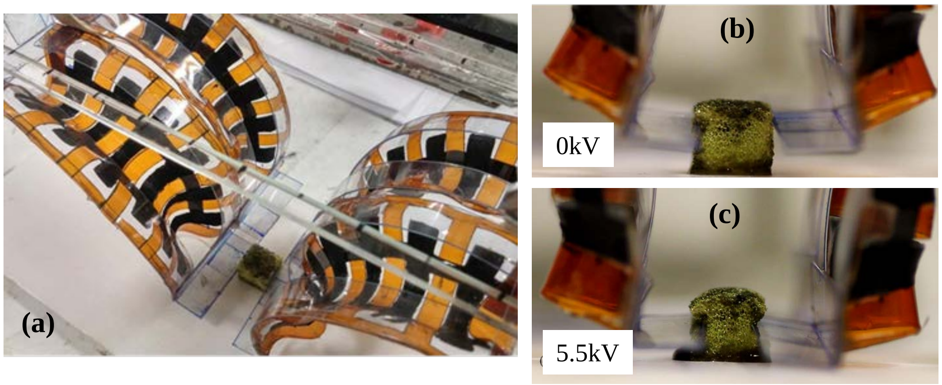


Figure 7. Demonstration of squeezing a sponge

Figure 7 shows that normally open grippers can pinch an object by applying the voltage-induced grip force. The grippers are made of two pairs of dielectric elastomer unimorphs, which are orientated opposite to the normally close ones. They can squeeze a 1 cm^3 sponges at 20 gram grip force (as measured from the blocked force) upon 5.5kV activation.

6. BENCHMARKING WITH PREVIOUS WORKS

The current DEMES is able to produce an impressively large amount of blocked force as compared to other works mainly because the frame used in the fabrication of spine-like DEMES is made of PVC material (380m thick). PVC has a comparatively higher elastic modulus than Polyethylene terephthalate (PET) sheet which was largely used in previous works. Both DEMES from Kofod et al. [8] and O'Brien et al. [11] are made of 100m thick of PET sheet for the flexible supporting frame which are rather flimsy, allowing lesser elastic energy to be stored and released when bent and uncurled.

Table 1. Comparison with other previous works

	O'Brien et al (2008)[9]	Araromi et al (2015)[14]	**This work**
Actuator mass	1.2 g	0.65 g	3 g
Actuator length	45 mm	100 mm	103 mm
Dielectric elastomer (pre-stretch ratios)	VHB 4905 (3,5)	Silicone (1.3,1)	VHB 4910 (5,6)
Base frame (thickness)	PET (100μm)	PET (100μm)	PVC (380μm)
Maximum Operating voltage	2.5 kV	3.8 kV	6kV
Maximum angular stroke	65°	63°	86.6°
Maximum blocked force	12 mN	2.2 mN	168 mN
Grip force/actuator mass	10mN/g	3.38 mN/g	57.2 Nm/g

7. CONCLUSION

This work developed a novel design of dielectric elastomeric unimorph, with strength for generating a large grip force of close 6 times its own weight (3gram) while undergoes a large bending/unbending for close to 90°. These great improvement in the actuation performance is attributed to the elevated roof of DEA, on the support of tension arch flexures, that magnifies the membrane-stress induced moment generation to bend a stiffer base frame. Such dielectric elastomeric unimorphs make normally close grippers capable of grasping a payload 5-6 times the gripper weight. They also makes normally open pinchers to squeeze a sponge.

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