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SOFT ACTUATORS AND THEIR FABRICATION FOR BIO-INSPIRED MOBILE ROBOTS

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ABSTRACT: Dielectric elastomer actuators (DEA), which are capable of muscle-like actuation, have potential to drive insect-inspired flapping-wing robotfly. There have yet been successfully used to drive flapping wings due to various limitations. This paper revisits their use and integration in a thoracic mechanism as either indirect or direct muscles. Three forms of DEA, i.e. folded, rolled, and pre-stretched membrane, were evaluated and integrated in different thoracic mechanisms. The pre-strained membrane of dielectric elastomer was found capable of generating a large rotation. On the other hand, the folded and rolled ones with either no or little pre-strain performed modestly in this flapping-wing application. Pre-strain was found to be important to maximize the actuator performance. In addition, this paper reviewed manufacturing processes for multi-layered DEAs and possibility of introducing pre-strained in the multi-layered layup.

INTRODUCTION

Recently, various mobile robots have been developed to move like animals: swimming like a fish (Ashley, 2003), crawling like a spider (Pei *et al*, 2002), flying like a bird (Lentink *et al*, 2010). These man-made mobile robots are commonly powered by electro-magnetic motors, which are attractive for producing high continuous power per unit mass (Madden, 2007). Yet, the electro-magnetic motors are not as good and efficient as natural muscles to drive the animal-like locomotion (Dickinson *et al* 2000). For example, a Honda's humanoid robot ASIMO, which is powered by servomotors, cannot run or jump like human does though it can jog slowly (Madden, 2007). At a smaller scale, motor-power micro air vehicles (Lentink *et al*, 2010) are not energetically efficient to stay aloft by flapping wings, as enduring as natural flyers. Indeed, animal-like locomotion could be very demanding to the existing electro-magnetic actuators. Jumping requires high instantaneous force generation (Dickinson *et al* 2000), while wing flapping requires elastic energy storage to recover wing inertial power (Alexander *et al*, 1977).

In comparison to man-made actuators, skeletal muscles are very attractive for locomotion due to their large strain of 20-30%, high work density (150J/kg on average) and scalability across various animal sizes, from as small as a fly to as big as an elephant (Mirfakhrai *et al*, 2007; Brochu and Pei, 2010). Skeletal muscles are more than a simple actuator, acting simultaneously as a spring, a strut, and fuel storage (Alexander *et al*, 1977). In the applications to mobile robots, man-made actuators are highly desirable to act as good as and even better than the natural muscles. As inspired by natural muscles, electro-active polymers have recently been investigated to produce muscle-like actuation upon electric stimulus. Among various electro-active polymers, dielectric elastomeric actuators offer the best muscle-like actuation, in terms of large strain, high work density, and speed (Brochu and Pei, 2010). They produce large actuation upon high voltage activation. They had been applied to various bio-inspired robots, such as crawling and jumping robots (Pei *et al*, 2002).

Dielectric elastomer actuators (DEAs) are basically a soft membrane capacitor, which has a pair of compliant electrodes sandwiching a dielectric elastomer membrane (Pelrine *et al*, 2000). When activated, the electrostatic force (Maxwell stress) is induced to compress the membrane, causing thickness reduction and areal expansion simultaneously. Pre-stretch helps the dielectric elastomer membrane sustain high dielectric strength and consequently help it produce a large actuation. A rolled dielectric elastomer actuator (Pei *et al*, 2002) with high axial pre-stretch can produce up to 40% axial actuation strain and high work density, comparable or even better than those of natural muscles. Though the active elastomeric membrane itself has high work density, the actuator system using it has a lower work density due to passive weight of the external frame, which is added to keep the dielectric membrane pre-tensioned (Lau *et al*, 2014). Moreover, to effectively drive mobile robots, the soft elastomeric actuators need to have matched stiffness with those of the load and flexural mechanism.

This paper will review the challenges of integrating the soft actuator to bio-inspired mobile robots and concerns for their manufacturing. A case study of insect-inspired robofly will be reviewed here to illustrate the use of dielectric elastomeric actuators as indirect muscles. Another case study showed that the agonist-antagonist DEAs can be applied as direct muscles to produce a large swing. Finally, this paper will review techniques to manufacture multi-layered dielectric elastomer actuators and with possibility of integrated pre-strain to maximize the actuator performance.

CASE STUDY 1: INDIRECT MUSCLES FOR ROBOFLY

Insect's thoracic mechanism is a ring of elastically connected rigid plates, on which wing pair is attached, as shown in Figure 1 (Mackean, 2014). There are two sets of insects' flight muscles, alternately activated to change the thorax's shape and consequently oscillate wings. When the vertical muscles contract, the thorax roof is pulled down, causing the wings to move up about the elastic fulcrum. When longitudinal muscles contract, the thorax bulges up and moves the wings down.

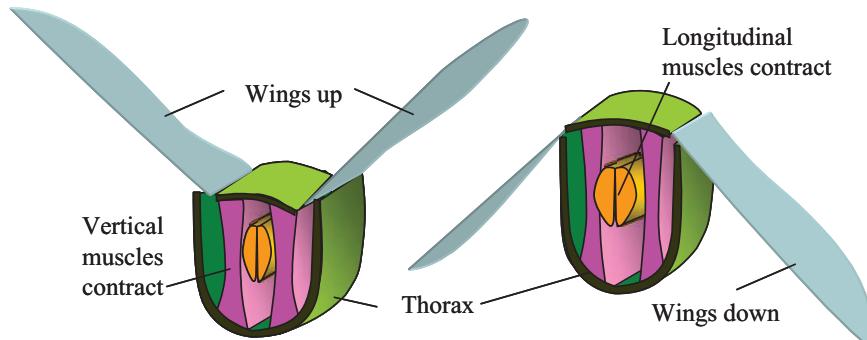


Figure 1. Indirect flight muscles act on the thorax and deform it to beat wings up and down (Adapted from D. G. Mackean)

Folded Dielectric Elastomer Actuator

With high work density, DEAs can potentially act as artificial muscles to drive an insect-like thoracic mechanism. Thickness change of membrane DEA is usually small, without pre-stretching the membrane (Carpí et al, 2007). To accumulate the contractive strain in the thickness direction, a DEA membrane can be folded and adhesively bonded between free interfaces into a stack as shown in Figure 2. Activation by compressive electrostatic force at high voltage causes a height decrement to the folded elastomeric stack. Such folded elastomeric actuator could be integrated in an insect-like thoracic mechanism, which consists of carbon-fibre-reinforced polymer plates and polyimide film hinge. Contraction of the elastomer actuator pulls down the thorax roof, causing wings up.

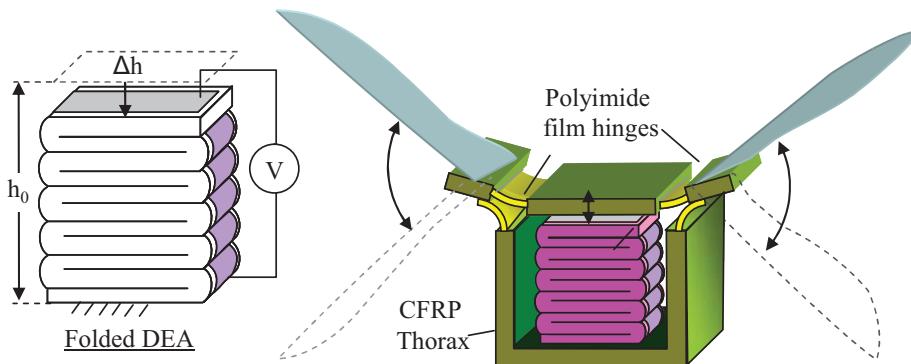


Figure 2. A folded dielectric elastomer actuator acts vertically on a thoracic mechanism

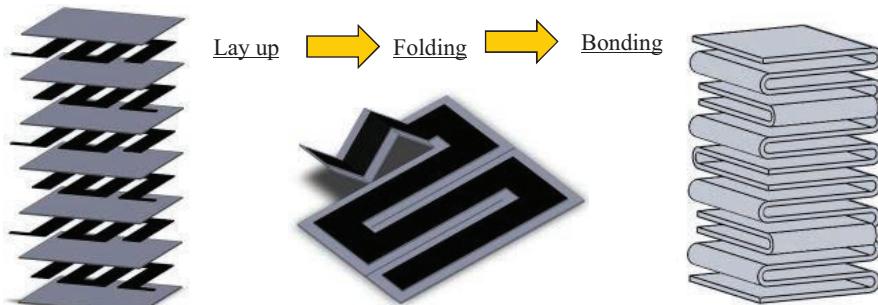


Figure 3. Lay-up, folding, and bonding process to make multi-layered folded actuator

Typically, elastomeric membrane is prepared by spin coating and curing of liquid pre-polymer of silicone (BJB 5005) on a 100mm square acrylic substrate. A spun-cast membrane typically has a 100 μm cured thickness. For the purpose of folding, the square membrane needs to be cut into a long strip of meander shape as shown in Figure 3. Graphite powder electrodes are smeared through a meander-shae Teflon stencil. Lay up of two electrode-coated silicone membranes yield a simple unit of membrane DEA. As such unit of membrane DEA is thin, its folding results in a low actuator stack, which could only produce a limited stroke. A higher stack can produce a larger stroke. Use of multiple DEA layers for folding can achieve a larger height with the same number of fold.

Figure 4 shows a 32 mm-high and 25mm-wide stack, which were obtained by folding a 7-layer silicone dielectric elastomer membranes interleaved with 6 graphite-powder electrodes. The folded actuator has an axial stiffness of 3.847kN/m. It generated a small stroke of 0.2 mm at the driving voltage of 3kV. The effective axial strain is merely 0.625% due to 50% passive height of overcoat layers and low dielectric strength. Such actuator stack was integrated in a compliant thoracic mechanism, which consists of CFRP plates and polyimide film hinges. A 0.2 mm axial contraction of the folded actuator could induce a 3-degree wing stroke. A 10-fold larger actuation is needed to beat the wings for a 30-degree stroke.

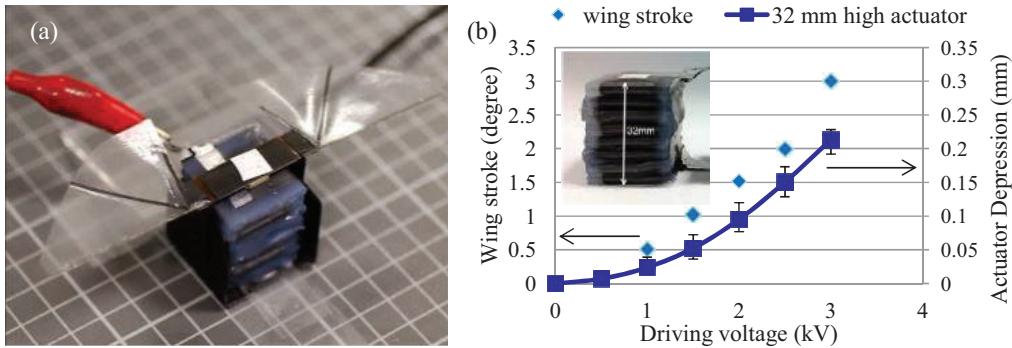


Figure 4. Integration of folded dielectric elastomer actuator for flapping wing

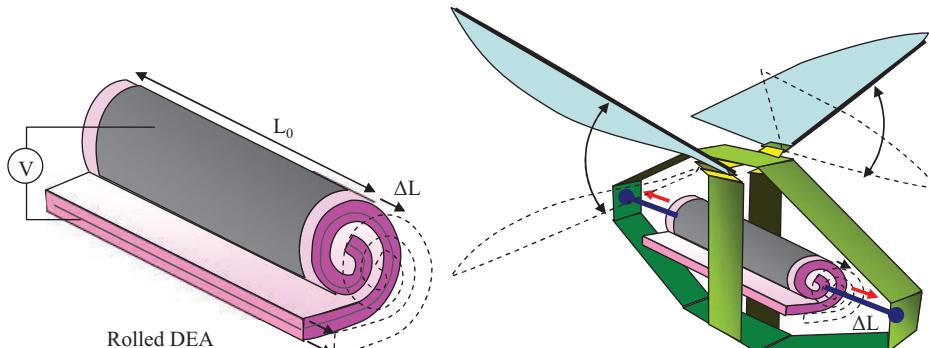


Figure 5. A rolled dielectric elastomer actuator acts longitudinally on a thoracic mechanism

Rolled Dielectric Elastomer Actuator

Dielectric elastomer actuators can also be configured into a roll to produce longitudinal actuation as shown in Figure 5. The rolled actuator is pre-stretched in order to prevent membrane buckling (Pei et al, 2002). Hoop stretch is bound by end caps, while the axial stretch is kept by a sturdy external frame. In this work, a diamond-shape frame of carbon-fibre reinforced polymer (CFRP) has been developed to pre-stretch longitudinally the roll actuator. When activated, the rolled actuator elongates and relaxes, flattening the initially compressed frame. In turn, the DEA activated frame can drive the thoracic mechanism similar to that Figure 2, moving wings up.

A rolled DEA is a roll up of multiple layers of dielectric elastomer membranes, interleaved with compliant electrodes. To be wound into a roll, dielectric membrane needs to be a long strip. Long Elastomeric film is prepared by draw casting liquid pre-polymer over a flat Mylar substrate using a film applicator as shown in Figure 6. Room temperature curing yields on a solid film. The free solid film is pre-stretched bi-axially and subsequently transferred to another plastic sheet so that the graphite-powder electrode can be smeared on it. Lay-up of two identical electrode-clad elastomeric membranes and an overcoat layer yields a unit of laminated capacitor. When rolled up, the overcoat layers, which appear to be passive, are sandwiched by opposite electrodes and make another unit of capacitor. In other words, there are no passive dielectric layers left after the rolling, except non-electrode areas.

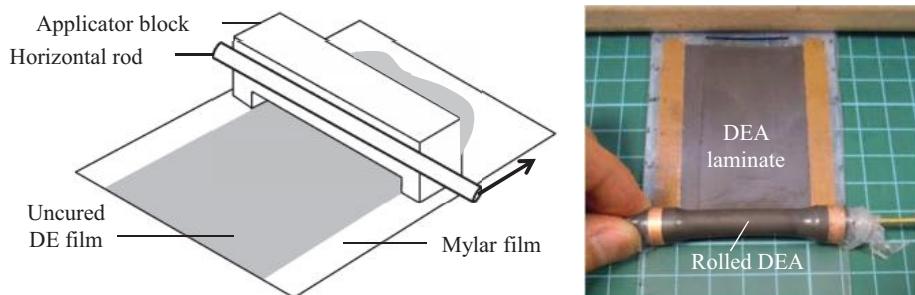


Figure 6. Draw casting of wet liquid pre-polymer film and rolling of laminate capacitor.

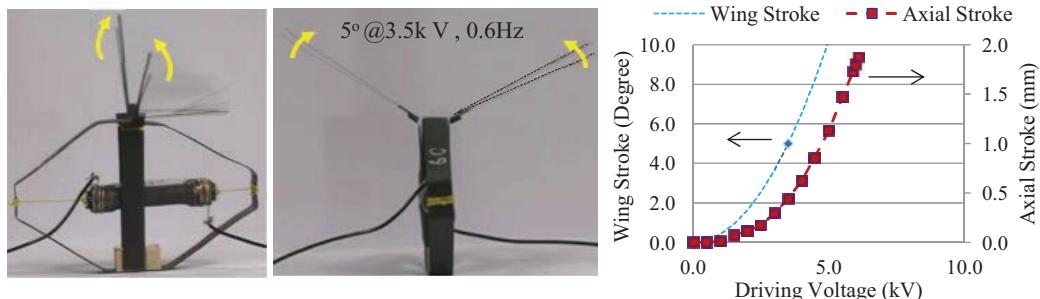


Figure 7. Integration of rolled actuator and thoracic mechanism for flapping wings

A 11-mm diameter and 61 mm long rolled actuator was obtained by rolling 3 dielectric elastomeric layers, interleaved with 2 graphite electrodes. The roll has axial stiffness varies with pre-stretch. A 15% equi-biaxial pre-stretch is found to maximize the dielectric strength of the rolled actuator. At this pre-stretch, the roll has an axial stiffness of 305N/m, which is 3 times stiffer than the diamond-shape pre-tensioning frame. This 61mm long actuator produced a 1.87 mm stroke at a maximum driving voltage of 6kV. This yields merely 3.1% axial strain due to low dielectric field of the lightly-pre-stretched silicone membrane. This rolled actuator can indirectly drive a thoracic mechanism as shown in Figure 7 to beat a 5-degree wing stroke at 3.5kV and 0.6Hz as shown in Figure 7

CASE STUDY 2: DIRECT MUSCLES FOR SWING ARM

For elbow flexion, tricep and bicep muscles contract alternately. This inspired the antagonist-agonist configuration of DEAs to swing a rotary arm as shown in Figure 8. Each of the membrane DEAs is pre-stretched in the pure-shear boundary condition such that it can elongate axially upon activation while clamped with a constant width as shown in Figure 9. When activated by Maxwell stress, the membrane pre-tension relaxes. Voltage-control tension in the DEA membrane can adjust tilting of the rotary arm. When subjected to equal un-activated membrane tensions, the swing arm is positioned vertically. When one of the two DEAs is activated, a net unbalanced tension is induced to tilt the arm away from the activated side. Such antagonist-agonist pair of DEAs induced a large rotation up to 20 degrees at 7kV as shown in Figure 10.

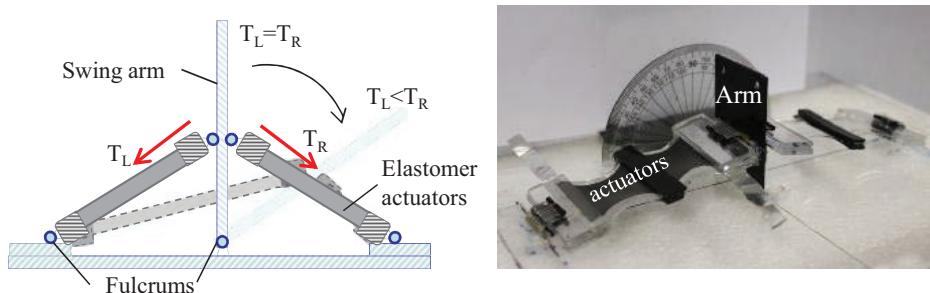


Figure 8 A rotary swing arm subjected to tensions of left and right dielectric elastomer actuators

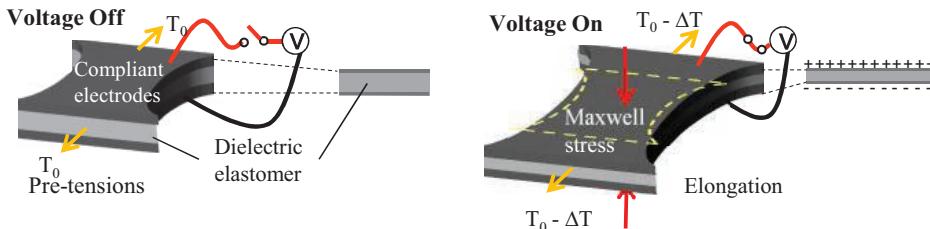


Figure 9. Shape change of the membrane DEA subjected to pure-shear pre-stretch.

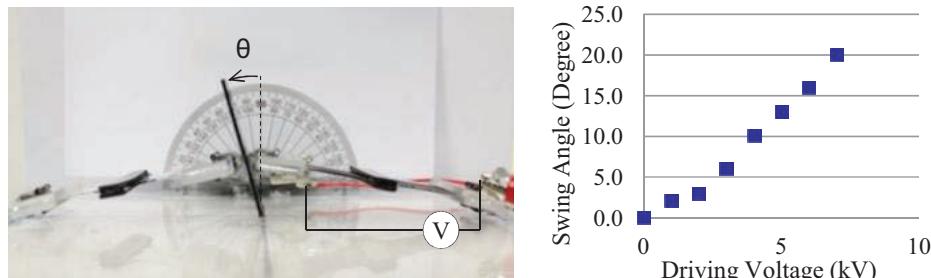


Figure 10. Arm swing under activation of one of the two DEAs.

FABRICATION AND INTEGRATION ISSUES

Review of the two case studies suggests that multi-layered DEAs are good to for maximizing the capacitance and actuation. Yet, fabrication of the multi-layered DEAs is tedious and time consuming, involving layer by layer lay-up of electrode coating and pre-stretched dielectric elastomer membranes. Manual fabrication for multi-layered DEAs are prone to weak interface between layers, for example existence of air voids and poor adhesion between the elastomer and graphite powders. Such non-ideal interfaces could cause moisture trapping and partial discharge, weakening mechanical strength and causing pre-mature electrical failure. Recently, multi-layered DEA has been automated manufactured using spin-coating of dielectric elastomer membrane and spray coating of graphite electrodes (Schlaak *et al*, 2005). By optimized process, good thickness uniformity was attained for 50 μm thick silicone elastomer membrane and 5- μm thick graphite electrodes. Yet, this multi-layered DEA do not produce as large actuation without pre-strain in the dielectric elastomeric membranes.

Pre-stretch is important to maximize the dielectric elastomer actuation and dielectric strength. Low pre-stretch can integrated to multi-layered dielectric laminate by transferring and laying-up the pre-stretched membrane from a plastic sheet to a base plate. To prevent spring back, the pre-stretched membrane should be bonded strong onto the base plate or underlying layer on the base plate when being pelt from the transfer sheet. Such transfer technique to freeze the pre-stretch is good for tacky or adhesive elastomer membrane at low pre-stress. Too much pre-stress in the dielectric elastomer membrane may cause warping of the transfer sheet.

For example, a multi-layered DEA stack with integrated pre-strain was prepared by 32 times folding a 100% equi-biaxial prestretched VHB tape with graphite electrodes. The pre-strain is largely fixed by the base plate and thin adhesive borders. However, interfaces between the graphite electrodes are not bonded well to the underlying layer and consequently the electrode region of the elastomer membrane may spring back and thicken. As a result, the top surface of the folded elastomeric stack is warped, even though reinforced by a Mylar sheet. Such transfer technique to hold the pre-stretch is prone to variation during manual folding. A possible solution is to deposit a stretcher layout of hard plastic to hold the pre-strain in the pre-stretched dielectric elastomeric membrane. As such, multiple pre-strained layers with stretcher layout can be layup readily.

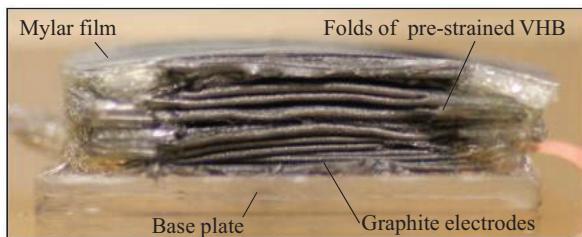


Figure 11. Folded VHB dielectric elastomer actuator with integrated pre-strain

CONCLUSIONS

Though promised to act as artificial muscles, the present designs and materials for dielectric elastomer actuators still fall short in producing the required force and stroke to beat wings, like insect's flight muscles does. This investigation found that actuation performance of dielectric elastomer varies with design, boundary condition, material, and pre-strain. Pre-strain is important for maximizing the dielectric strength and actuation. Highly pre-stretched membranes in the agonist-antagonist configuration is found be good to swing a large rotation to the rotary arm. On the other hand, the multi-layered DEAs, such as folded and rolled, are modest in producing strain even though the multi-layered design can accumulate forces and strokes. Future work will explore possibility of integrating hard plastic layout in the pre-stretched elastomeric membrane and ease the layup process for multi-layered DEAs with pre-strain.

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