A Spring – Loaded Actuator Developed By DC 3481 Silicone / Polyaniline – Based Dielectric Polymer Film

D.M.N.T. Dissanayake[1], W.D.C.C. Wijerathne[1], S. Shakaf[1], M.A.R.L. Samaraweera[1]*, A.U. Asela[1], A.K.C.P. Premarathna[2]
[1]Department of Science and Technology, Faculty of Applied Sciences, Uva Wellassa University, Sri Lanka.
[2]School of Engineering, University of Greenwich, United Kingdom

ABSTRACT

Dielectric polymer films play a significant role in soft robotics in actuator development. Silicone and acrylic materials are commonly used for creating dielectric polymer films with superior properties compared to other potential materials such as PVDF and Polyurethane. Published literature reports applying different fillers to enhance the electromechanical response of dielectric polymers. Starting with an already-reported novel dielectric polymer based on polyaniline/DC 3481 silicon, we report the fabrication and characterization of a spring-loaded actuator. Here we developed a simple spring-loaded actuator, and three different designs were used to optimize the actuator design. As per research outcomes, it can be concluded that paper tie-based clamping provides the best configuration for the actuator in terms of high deflection and low tendency to short-circuit. The developed actuator renders the maximum deflection of 4.19 mm at 2 kV voltage, and the actuation time is approximately 115 s. The proposed actuator is superior to many reported actuators in terms of maximum deflection and corresponding voltage. The proposed actuator and the corresponding dielectric polymer thus have potential applications in developing actuators for haptics with comparatively high deflection.

KEYWORDS: *actuators, dielectric polymers, haptic technology, DC 3481 silicon, spring-loaded*

1 INTRODUCTION

Haptic devices produce a sense of touch during human-computer interaction, and they connect users with virtual environments. Today, haptics technology has been widely applied in diverse sectors such as education, cinema, health, etc. As a sub-category of haptics, tactile displays, which are comprised of actuators, deliver cutaneous feedback (Pacchierotti et al., 2015). Here, the actuator stimulates signals to the fingertip as the friction between the fingertip and the tactile display is generated. Dielectric polymer usually increases the tactile display's wearability by reducing the unit's weight significantly, resulting in improved deflection, flexibility, power saving and degrees of freedom of the actuator (Boys et al., 2018). In an actuator setup, the dielectric polymer is mounted between two compliant electrodes where Coulombic attractions occur across the thickness of the polymer film. Compliant electrodes can be made by blending or dispersing conductive fillers (e.g., carbon black powder, graphite powder) in the insulating polymer matrix (Skov & Yu, 2018; Aradhana et al., 2020). The conductivity, simplicity, and flexibility of compliant electrodes significantly influence the performance of actuators in published works (Park et al., 2015; Boys et al., 2018). The activation mechanism of dielectric polymer-based actuators can be described via Maxwell stress and electrostriction force concepts, which outline how the alignment of dipoles and the application of Coulombic forces result in the deformation of the polymer. Moreover, the strain achieved by dielectric polymers depends on both Young's modulus and the dielectric constant.

Several commercially available dielectric polymers, such as silicone, acrylic, PVDF, and polyurethane, are used to make different actuators. Out of these, the acrylic material is difficult to modify because of its irreversible solid phase and thus, recent focus has been on the development of liquid-based dielectric polymers such as polyurethane and silicone. In this regard, silicone shows superior electromechanical properties compared to polyurethane. Furthermore, the dispersion of conductive fillers in dielectric polymers can be identified as a novel technique to enhance the polymer’s electromechanical properties. Accordingly, metal fillers, ceramic fillers, carbon fillers, and metal-

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coated fillers are dispersed in the dielectric matrix to increase the dielectric constant (Liu et al., 2012, Paul et al., 2016, Nawaka & Putson, 2020; Aradhana et al., 2020).

As evident in the above discussion, silicone is a robust candidate for making dielectric polymers and it also possesses several useful properties such as low shore hardness or higher softness and the capability of making very thin polymer films. In actuator applications, silicone elastomers usually possess fast response times (around 3 s), higher efficiency, excellent viscoelastic properties, and a wide range of thermal stability than acrylic. Also, silicone dielectrics respond approximately 1000 times faster and exhibit lower mechanical losses and viscosity creep than acrylic materials. The Dow corning (DC 3481) silicone shows a larger electroactive strain out of silicone polymers. Nevertheless, its maximum strain is around 10%, which is a key limitation of using silicone elastomers in actuators (Michel et al., 2010). To address this research gap, a novel dielectric polymer was developed in our previous work by incorporating Polyaniline (PANI) fillers in a silicone matrix (Dissanayake et al., 2021), and the optimum material composition to develop the polymer was discussed. However, as described previously, it is vital to investigate the application of a polymer in an actuator, and therefore, this research work aims to fabricate a simple prototype actuator that is made of the proposed silicone dielectric polymer. In this manuscript, the materials used for dielectric polymer development and then the development strategy of the actuator are briefed initially to provide an overview of the actuator material. The characterization techniques for the polymer and the actuator are detailed next, followed by the outcomes and conclusions of the study.

2 MATERIALS AND METHODOLOGY

2.1 Preparation of the dielectric polymer film

The Dow corning or DC 3481 silicone (Siliconesandmore, Netherlands) and spherical particles (particle size: 3-100 µm) of Polyaniline (Sigma-Aldrich, Germany) were used to prepare the polymer film, while carbon conductive grease (846-80G, M.G. Chemicals, Canada) was employed to make the compliant electrode. DC 3481 and polyaniline (PANI) particles were mixed first according to the ratios in Table 1 and five samples (A-E) were obtained.

Table 6: The Weight Percentage of Polyaniline Particles in Five Samples

Sample	**Weight of DC 3481 silicone (g)**	**Weight of Polyaniline (PANI) (g)**	**Weight percentage of PANI particles**
A	10.00	0.00	0.0
B	10.00	0.05	0.5
C	10.00	0.10	1.0
D	10.00	0.15	1.5
E	10.00	0.20	2.0

During the experimental design as outlined in (Dissanayake et al., 2021), the maximum mixing percentage was limited to 2% (w/w) as larger mixing percentages resulted in poor curing with the hardener (i.e., DC 3481R). The mixed polymer blends were then stirred at 1000 rpm for 6 h, using a magnetic stirrer (Model: VELP SCIENTIFICA). The hardener material (i.e., DC 3481R) was then added according to the ratio DC 3481: hardener = 1:20. The dielectric polymer films with a thickness of 125 µm were then prepared using the Doctor Blade technique on polyvinylchloride (PVC) sheets following the reported works (Boyadzhieva, 2018). The optimum thickness of 125 µm was selected considering the stretchability of the polymer film and the supply voltage range. The dielectric polymer films were removed from respective PVC sheets after 24 h when the crosslinking process was completed. Carbon conductive grease was finally applied on both sides of the polymer film to make them compliant electrodes.

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2.2 Electromechanical Characterization of the Dielectric Polymer Film

A dielectric polymer film is usually characterized by electromechanical measurements: dielectric constant and Young’s modulus. In this context, the capacitance of samples A-E were first measured using an LCR meter (Model: Proskit MT-5110) at a test frequency of 800 Hz. The dielectric constant (κ) for each sample was then computed by using the equation $\kappa = C_p \times d / A\mathcal{E}_0$, where A, d, C_p, $\mathcal{E}_0$ are cross-sectional area (m^2), the thickness of the polymer film (m), capacitance (F), and permittivity of free space, respectively. Young's modulus of each sample was calculated at the first 10% elongation of stress vs. strain curves.

2.3 Fabrication of the Actuator

The spring-loaded actuator consisted of a dielectric polymer film that was attached to a plastic ring, two copper strips to connect with the power supply and a sensitive vertical spring that was placed below the polymer film. One end of the spring was fixed to a metal base while a hollow plastic ball (diameter < 5 mm) was loosely kept on the other end. The top surface of the ball was placed in such a way that it slightly made contact with the polymer film. As shown in Figure. 01, three clamping designs were tested to clamp the polymer film to the ring: (a) nut and bolt, (b) paper clips and (c) paper tie.

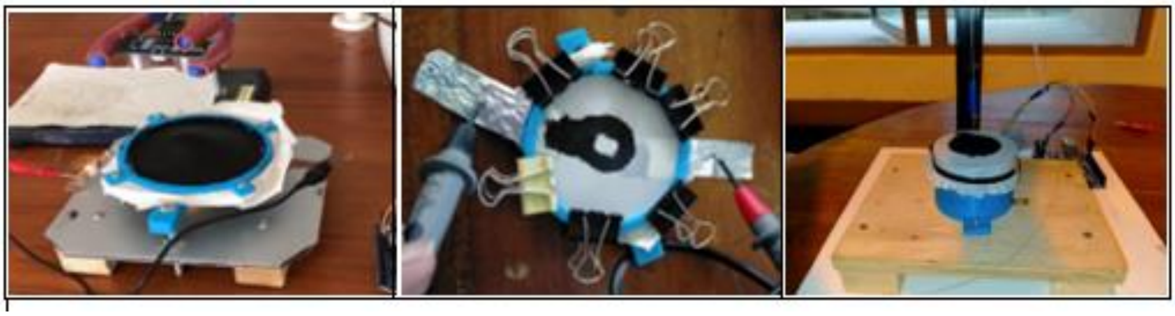

Figure. 01. Designs proposed for the clapping of the dielectric polymer film (from left to right) (a) Design I (nut/bolt) (b) Design II (paper clips) (c) Design III (cable-tie)

In Design I (Figure. 01 (a)), the actuator was stretched and placed between two rings with similar radii (10.0 cm diameter each) and clamped using a nut/bolt system. These rings were fixed to the metal base. Due to the larger radius of the ring, the energy loss was high, and the expansion was insufficient to actuate the mechanism. Furthermore, the clamping using nut/bolt assembly damaged the dielectric film and led to the film's burning due to short-circuiting even at very low voltages. In Design II (Figure 01 (b)), the ring's diameter was reduced to 7.5 cm and clamped using paper clips. This Design reduced the damage to the polymer film to some extent and still faced issues in damaging the polymer film. In Design III, as shown in Figure. 01 (c), one ring with a diameter of 5.0 cm was used and the polymer film was clamped to the ring using a cable tie. This setup was more effective than the previous designs in enabling the actuation and distinct reduction of short-circuiting.

Figure 02 illustrates the optimized actuator based on Design III. Figure 02 (a) and (b) show the stretched dielectric polymer film placed on top of the ball, which was secured using a cable tie. A layer of grease was applied on the outside of the polymer film and, that end of the electrode was extended using a copper strip. The other end of the electrode was extended by connecting the copper strip underneath the dielectric polymer film. The configuration of the spring, ball and polymer film is further elaborated in Figure 02 (c).

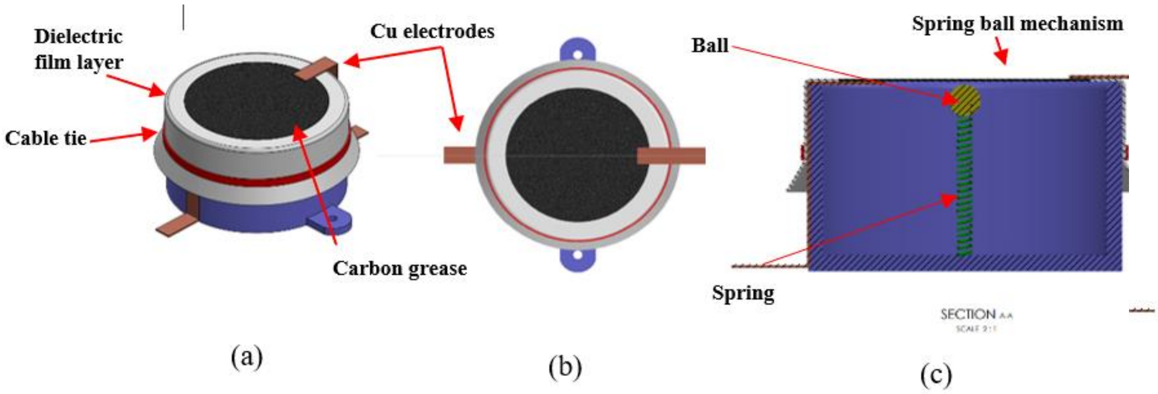

Figure 02: The schematic of the spring-loaded actuator (a) front view (b) top view (c) cross-sectional view

Figure 03 depicts the motion of this spring-loaded actuator during actuation (i.e., when an electric field is applied).

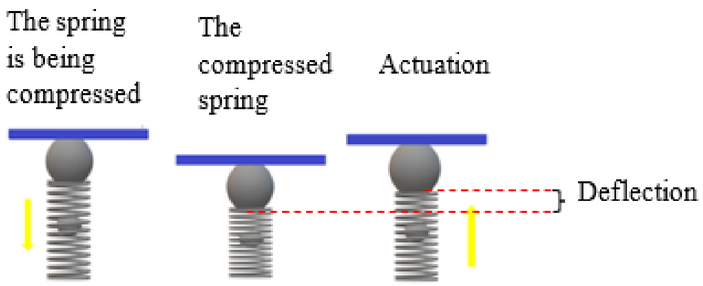

Figure 03: Schematic diagram of the working mechanism of the spring-loaded actuator

When a high voltage (usually in the kV range) is applied across the dielectric polymer film, it expands due to Maxwell stress and electrostriction (Nawaka & Putson, 2020). As a result, the spring is released from the compressed position while moving the polymer film upwards. The difference between the initial and the actuated states was taken as the deflection of the actuator, as shown in Figure. 03. When the potential difference across the polymer film reaches zero, the polymer film returns to its initial state, reducing the expanded area to the initial value. As a result, the spring compresses and the polymer film moves downwards.

2.4 Deflection of the actuator

The overall setup to measure the deflection of the actuator is shown in Figure. 04. Here, a pulsed high-voltage supply was developed by appropriately combining a series of capacitors (100 µF, 450 V) for respective experiments. Here, voltages starting from 0.68 kV were used, and the maximum voltage was recorded when the dielectric polymer film started to burn. A Lidar sensor (type: VL53L0XV2) was used to detect the deflection of the ball, and Arduino Uno was used for data processing. The noise associated with each recording was reduced using a Kalman filter (Boys et al., 2018).

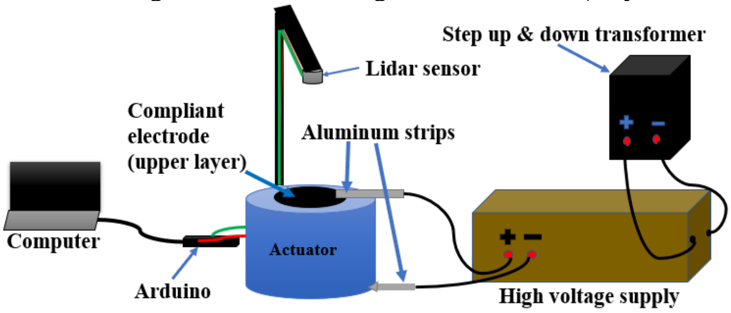

Figure 04: Setup to measure the deflection of the actuator

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3 RESULTS AND DISCUSSION

3.1 Electromechanical Measurements

Figure 05 shows the variation of the dielectric constant (κ) and Young's modulus (Y) with the percentage of PANI added to the polymer film. Accordingly, κ increases with the percentage of PANI and the maximum value for κ (i.e., 1.65) is achieved at 2% of PANI. The published literature using acrylic material reports the same variation of κ with the corresponding binder composition. This phenomenon can be attributed to the orientation of dipoles in the dielectric polymer film (i.e., PANI particles) towards the applied electric field, which increases the net charge while increasing κ (Nawaka & Putson, 2020).

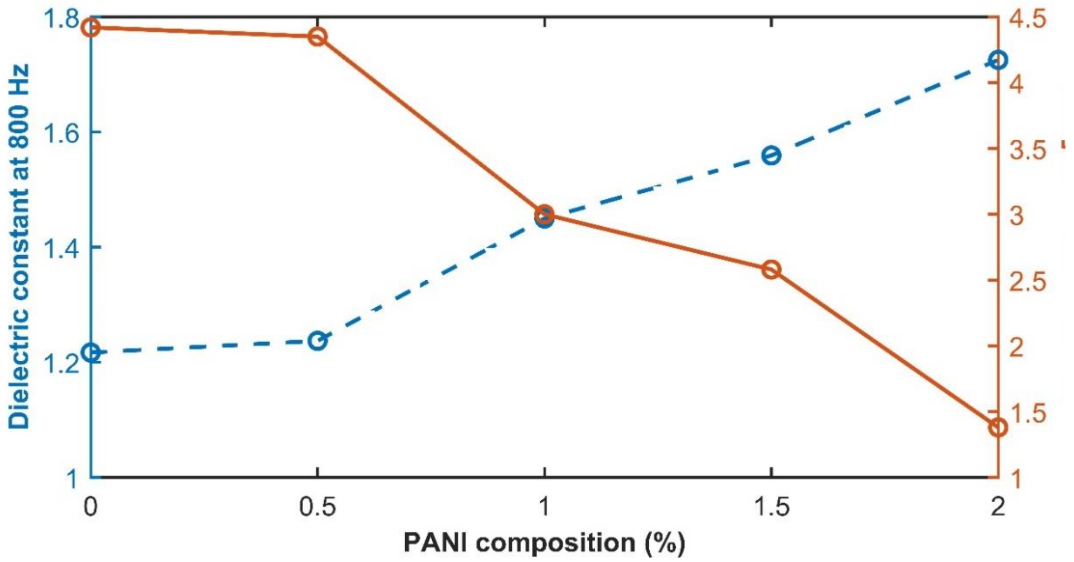

Figure 05: Variation of dielectric constant and Elastic modulus (or Young's modulus) with PANI composition

The above phenomenon can also be used to describe the observed increase of κ, where dipoles are dispersed in the DC 3481 matrix. Compared with published works (Nawaka & Putson, 2020), our results report lower values for κ. One possible reason could be the frequency of the electric field, for which our study was conducted at 800 Hz while the reported work was conducted at 1 Hz. Furthermore, Young's modulus (Y) decreases with the percentage of PANI, and the lowest value was obtained at 2% (w/w) composition. This variation of Young's modulus (Y) also agrees with the reported findings (Nawaka & Putson, 2020). As lower Young's modulus and higher dielectric constant values promote the applicability of dielectric polymer films for haptics, the best composition for the polymer film is identified as 2% (w/w) of PANI.

3.2 Deflection of the Actuator

Figure 06 shows the actuator deflection with time at different voltage values. The experimental voltage-supply setup generated 0.68 kV, 1.36 kV, and 2.0 kV voltage, and the maximum voltage was identified when the polymer film started to burn. For 0.68 kV and 1.38 kV, the actuator deflection is less than 0.5 mm and a significant increase in deflection is not detected throughout the inspected period. However, at 2 kV, the deflection is around 1 mm for the first 95 s and then increases drastically to 4.19 mm within about the next 20 s.

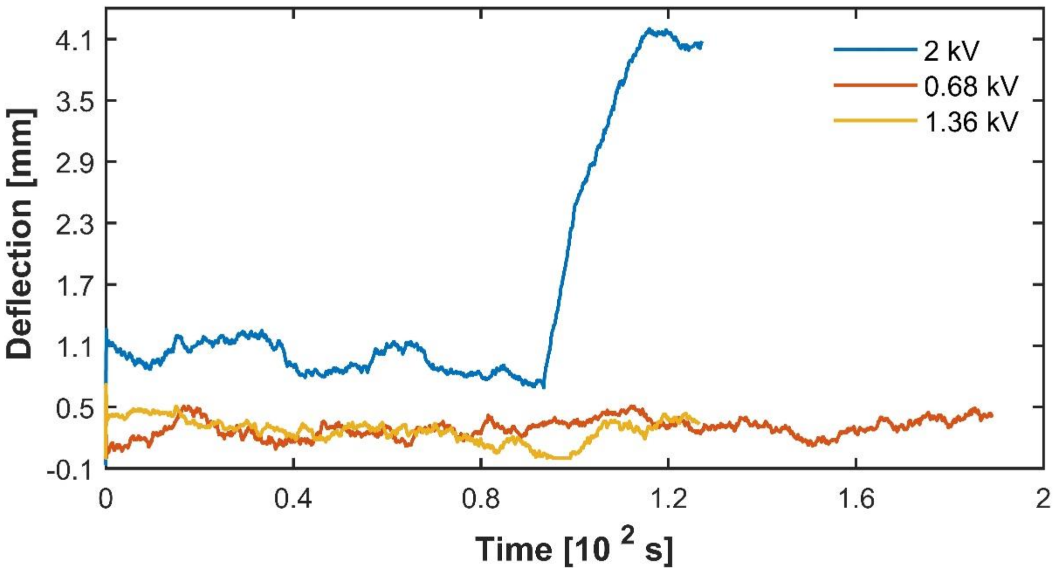

Figure 06: The variation of actuator deflection with time at different voltages

The deflections rendered by several reported actuators made from distinct dielectric polymers are shown in Figure. 07 to further highlight the performance of the developed actuator. Accordingly, most polymers result in actuator displacement in mm scale and the displacement tends to increase with voltage. Furthermore, the highest displacement (i.e., 6.0 mm) is recorded from the actuator made of Terpolymer and 2-(ethylhexyl) phthalate. This actuator requires approximately 1 kV to yield such displacement. On the other hand, the lowest displacements (in µm scale) correspond to actuators made from polyurethane. In this regard, the proposed actuator shows a 4.19 mm displacement at 2 kV. Thus, the actuator displacement of this work is only inferior to dielectric polymers made of Terpolymer and 2-(ethylhexyl) phthalate.

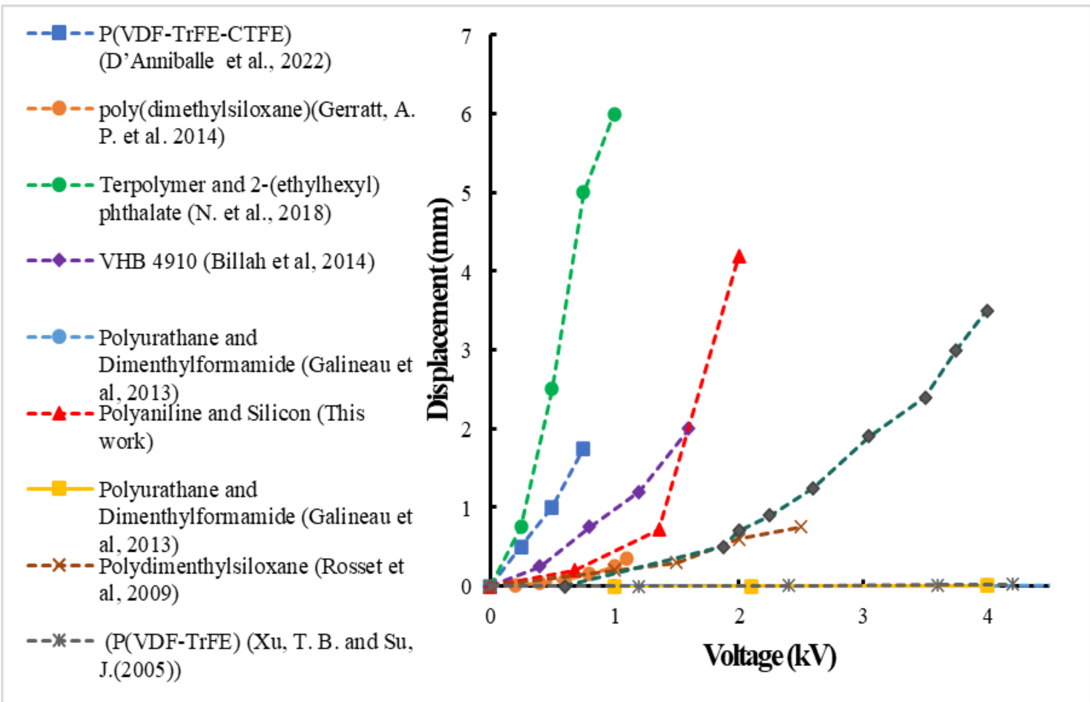

Figure 07: Comparison of deflections generated by different actuators

4 CONCLUSION

This work investigated the extension of a newly developed dielectric polymer to fabricate a spring-loaded actuator composed of a plastic ring, dielectric polymer film and a spring/ball unit. The following conclusions can be drawn from this study.

1. Cable-tie clamping design for the polymer film and plastic ring works best to develop the actuator.
2. The actuator deflection reaches a maximum of 4.19 mm within 115 s at 2 kV actuation voltage.
3. The deflection of the actuator is superior to most reported actuators.

In future, by using a suitable numerical model, the force and vibratory stimulations of the actuator will be investigated to identify unexplored electromechanical and thermal features of the dielectric polymer. Accomplishing a considerable deflection is also targeted as future work which may be done through fabricating stacked later actuators. Moreover, the introduced actuator could be miniaturized and extended for wearable tactile displays while modifying the insulation technology of the actuator as a safety measure.

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