Peano-Hydraulically Amplified Self-Healing Electrostatic Actuators Based on a Novel Bilayer Polymer Shell for Enhanced Strain, Load, and Rotary Motion

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1. Introduction

The last few decades have witnessed the emergence of soft body technologies. Due to their flexible and adaptable bionic performance, soft robotic systems are able to employ mechanically flexible, and appropriately shaped gripping devices and actuators to interact with objects or living beings without leading to potential damage. As a key component of a soft robot, the ideal soft actuator should be able to act as fast as biological muscles and output a range of forces.[1]

At present, soft actuators in robotic systems include thermally responsive polymers,[2] flow actuators,[3–9] and dielectric elastomer actuators.[10–13] Fluid-driven actuators include pneumatic and hydraulic modes, where pneumatic actuators can realize a large stroke and high output power, similar to natural muscle, thus making its application highly universal and useful for surgical procedures on the human body[14–16], however, its output efficiency, response speed, and portability continue to be limited.[17]

Dielectric elastomer actuators are rapidly developing soft...
actuators with the advantages of high strain\cite{18,19}, rapid response time,\cite{10-13} and the ability to self-repair.\cite{10-13} These can be applied in soft robots for different forms of motion, including wall-climbing, swimming, crawling, and flying.\cite{20-23} However, dielectric elastomer actuators require high driving voltages and electric fields to operate, which can often lead to dielectric breakdown of the materials or device.\cite{11} In addition, a new type of self-healing actuator was recently reported, which could be rapidly actuated by temperature and humidity control.\cite{24-27}

Hydraulically amplified self-healing electrostatic (HASEL) actuators have been recently developed that consist of a flexible polymer shell which is filled with a liquid dielectric and is partially covered with conductive electrodes; these include the quadrant donut HASEL actuator, curly HASEL actuator, Peano-HASEL actuator, high strain Peano-HASEL actuator, and the crimped HASEL actuator. The HASEL exploits the Maxwell stress generated by the applied electric field that acts on the liquid to generate a hydraulic pressure and achieve actuator motion.\cite{17,28} This approach has attracted significant interest because it combines the advantages of both the dielectric elastomer actuator and fluidic actuator, and has demonstrated high versatility\cite{29} and performance. As an example, quadrant donut HASEL actuators have exhibited a larger linear expansion and generated higher forces at lower drive voltages compared to elastomeric donut actuators.\cite{10} The curly HASEL actuator has been used to simulate the attack action of the scorpion tail, showing a bionic attack speed of 1.26 m s\(^{-1}\).\cite{29}

The Peano-HASEL actuator, designed by Niiyama et al.\cite{6} and Sanan et al.\cite{7} combines the advantages of a linearly contractible Peano-fluidic actuator with the electrostatic principle of a resilient HASEL actuator. The actuator architecture generally consists of a thermoplastic shell, flexible electrodes, and a liquid dielectric. When a voltage is applied to the flexible electrodes located on the sides of the thermoplastic shell, the two electrodes are attracted to each other due to Maxwell stress generated by the applied electric field,\cite{31} and the electrodes are then completely closed, like a zipper, from the edge. With an increase of the drive voltage and Maxwell stress, the liquid dielectric located between the electrode and shell is then squeezed toward the other end of the device, so that the actuator develops a strain. Such an actuator configuration has been shown to realize rapid linear contraction and relatively large deformation.\cite{17} As the Maxwell stress between the electrodes leads to “zipping” of the shell to produce a strain, the dielectric strength and permittivity of the thermoplastic shell have a direct impact on actuator performance.

To improve the HASEL actuator performance, in this article, we have designed a Peano-HASEL actuator equipped with a bilayer polymer shell (Figure 1A) that improves the dielectric strength, stiffness, and permittivity of the actuator shell. Unlike the single-layer shell of a conventional Peano-HASEL actuator, a bilayer polymer film is used for the shell material, which is composed of a layer of biaxially oriented polypropylene (BOPP) and an additional layer of thermoplastic polyurethane (TPU), as shown in Figure 1B. This bilayer architecture has been...
chosen because it combines the high dielectric strength and high elastic modulus of BOPP with the high permittivity of TPU. This article will demonstrate that the actuator with the bilayer polymer shell demonstrates improved performance compared to those based on a traditional single-layer shell. The majority of soft robots require complex architectures, and more complex motions beyond simple expansion and contraction.\(^{[25]}\) To demonstrate its potential, the new actuator was therefore applied to drive a ratchet system, which converted the reciprocating motion of the new actuator into a rotating motion and a flexible output torque.

2. Experimental Validation

2.1. Materials and Equipment

The actuator shell was prepared from a bilayer film of BOPP and TPU, in which the BOPP film was provided by Meideli Co. Ltd. (China) and has a relatively low relative permittivity of \(\varepsilon_r/C_0 \approx 1.9\), a high dielectric strength of \(E_d = 320 \text{ kV mm}^{-1}\), and a high elastic modulus of 466 MPa. The TPU film provided by Xintai Plastic Company (China) has a high relative permittivity of \(\varepsilon_r/C_0 \approx 4.9\), and a relatively low dielectric strength of \(E_d = 100 \text{ kV mm}^{-1}\), and a low elastic modulus of 5.07 MPa. The liquid dielectric (PMX-200) in the actuator is selected from the Dow Corning Company (USA), with a viscosity of 50 cs. Hydrogel sheets were used as working electrodes,\(^{[32]}\) which was provided by JIJISHUN Co. Ltd. (Shenzhen, Baoan, China), with a thickness of 0.8 mm and a square resistance of \(\approx 30 \Omega\). A plastic film heat sealer provided by XINGYE Machinery Equipment Co. Ltd. (Zhejiang, Wenzhou, China) was used to package the shell for the actuator.

2.2. Fabrication of Actuator with a BOPP/TPU Bilayer Polymer Shell

The BOPP film and TPU film are hot-sealed together to make the bilayer film shell in Figure 1. However, it was found that wrinkles and defects were often formed when heat-sealing the as-received BOPP film with the TPU film, which led to reduced mechanical properties and low dielectric strength. In this work, we therefore first created surface patterns on one side of the BOPP film using the process of roller embossing to increase the surface roughness to \(Ra \approx 1.6 \mu m\), as shown in Figure 2A, imaged by laser microscopy LEXT OLS4500 (Olympus). This roughened surface microstructure provides an effective pathway for exhaust gases to escape between the laminated films during hot-sealing. The increased surface area of the microstructured BOPP film can also more closely attach to the TPU film and achieve a strong degree of lamination by increasing the contact area, as shown in Figure 2B.

The fabrication process of a HASEL actuator with the BOPP/TPU bilayer polymer shell is shown in Figure 2C. The two

![Figure 2. A) Surface microstructure of BOPP film, with a surface roughness of \(Ra \approx 1.6 \mu m\). B) The cross-sectional view of the heat-sealed BOPP and TPU films; C) manufacturing process of actuators with bilayer shell; D) injection of a liquid dielectric; and E) heat-seal the final side and attachment of the hydrogel electrodes.](file.png)
laminated BOPP–TPU bilayer films were stacked together, with the BOPP layers placed inward. Three sides of the actuator were then sealed with a heat sealer, with one side kept open to allow infilling of the device with the liquid dielectric. A specific amount of liquid dielectric was then injected into the opening, and the air was then removed (Figure 2D). Finally, the last side was then heat-sealed, and hydrogel conductive electrodes were applied to both sides of the actuator capsule (see Figure 2E).

In this study, three actuators with different shell structures were fabricated: 1) a BOPP–TPU bilayer film (25 μm + 30 μm); 2) a single BOPP film with a thickness of 25 μm; and 3) a BOPP film with a thickness of 55 μm; the single BOPP films acted as a control to assess the degree of improvement in using a bilayer construction. The overall dimension of the actuator was designed to be 88 mm in length, 68 mm in width, and 7.2 ± 0.1 mm in center thickness. The volume of filled liquid dielectric was 30 mL. According to the previous actuator manufacturing experience and the research results of Kellaris et al. on the influence of electrode area proportion on actuator performance,[33] we controlled the ratio of electrode area to actuator area to be slightly less than 50%. The hydrogel electrodes were rectangular with rounded corners, 60 mm in length and 40 mm in width, and their area accounts for ≈50% of the total effective area of the actuator.

3. Results and Discussion

3.1. Starting Voltage of the Actuator

First, the starting voltage, defined as the minimum voltage that causes the actuator to generate strain under no-load conditions, is evaluated. The starting voltage of the actuator with a thicker BOPP film of 55 μm was 12 kV, while the actuators with the 55 μm bilayer BOPP–TPU film and thinner 25 μm BOPP film could be driven at a lower voltage of 3 kV. Movie S1, Supporting Information shows the working states of the three actuators with their respective starting voltages.

3.2. Capacitance of Actuator

When the actuator electrode is closed, its two electrodes can be regarded as two plates of a parallel plate capacitor, and the electrostatic force generated by the electrodes at this time is

\[ F = \frac{CU^2}{2d} \]  

(1)

where \( U \) is the voltage applied to the capacitor, \( C \) is its capacitance, and \( d \) is the distance between the two plates of the capacitor. According to Equation (1), when the voltage and the distance between the electrode plates are constant, the electrostatic force of the plates is proportional to the capacitance. In order to compare the capacitance of the three actuators when fully actuated, an experiment was designed to test the charge storage capacity of the actuator when fully driven, as shown in Figure 3A. First, the actuator with its electrodes connected in series with a resistor of known resistance (1 MΩ) was subjected to a test voltage. Then an oscilloscope was used to capture the voltage waveform applied to the resistor during the power-on process. As the total amount of charge that is charged into the system is equal to the integral of current and time during charging, and the waveform area of oscilloscope is the integral of voltage and time on resistor during charging, the total charge applied to the actuator can be obtained by \( Q = \frac{S}{R} \), where \( S \) is the area of the voltage waveform and \( R \) is the magnitude of series

Figure 3. A) Circuit diagram of capacitance testing system. B–D) Voltage waveforms of resistors in bilayer BOPP–TPU film actuator, 25 μm BOPP actuator and 55 μm BOPP actuator.
resistance. Then, the capacitance of the actuator can be obtained from $C = Q / U$, where $U$ is the working voltage of the actuator.

Figure 3B–D shows the waveform of the three kinds of actuators when the applied test voltage is 500 V. It can be concluded that the actuator with a bilayer polymer BOPP–TPU film shell (55 μm) has a charge of 98.8 nC and a capacitance of 197.6 pF (Figure 3B). However, the actuator with a thin BOPP film (25 μm) has a charge of 69.2 nC and has a lower capacitance of 138.4 pF (Figure 3C). The actuator with the thick BOPP film shell (55 μm) has a charge of 36.2 nC and exhibits the lowest capacitance 72.4 pF (Figure 3D). These results indicate that the BOPP–TPU bilayer shell actuator has a larger capacitance than the BOPP shell actuator of the same thickness. Compared with the other two actuators, the actuator with a thick BOPP shell (55 μm) has poor performance because the capacitance is small, which leads to an extremely high voltage drive; as a result, this configuration is not suitable for further testing. The thin BOPP shell (25 μm) actuator shows similar performance as the BOPP-TPU bilayer shell (55 μm) actuator, although with a lower capacitance. The electrostatic force is inversely proportional to the electrode distance, and although the smaller capacitance of a 25 μm BOPP shell actuator will make its electrostatic force smaller, the distance between its electrodes may be shorter due to its thin shell, which, in turn, will make the electrostatic force larger. Therefore, its small capacitance does not mean that the electrostatic force of its electrodes is smaller than that of the bilayer membrane actuator. As the actuator with a thick BOPP shell (55 μm) has poor performance, due to its low capacitance, the load performance of BOPP shell (25 μm) actuator and bilayer BOPP-TPU film (55 μm) actuator is compared in the following sections.

3.3. Load Testing at a Fully Driven State

A load test for a fully driven state (defined here as when most of the electrodes are closed and flat) was developed to compare the load performance of the actuators. An actuator with a bilayer BOPP–TPU shell (55 μm) and a thin single-layer BOPP shell (25 μm) could be fully driven at 3 kV; therefore, the maximum load at 3 kV in the fully driven state is evaluated. First, the actuator was placed flat on an insulating plane, and a voltage applied to its electrodes until the actuator reaches the fully driven state. After that, a load was applied to the actuator using a thrust probe of a dynamometer, and the maximum load that detached and severed the state of complete electrode adhesion was recorded (Figure 4A and Movie S2, Supporting Information). The experimental results show that both actuators can achieve their fully driven state at 3 kV, and the bilayer BOPP–TPU shell actuator can bear a greater load compared to the BOPP shell (25 μm) actuator in the fully driven state. For the same voltage increase, the load of the bilayer BOPP–TPU shell actuator increases more than the BOPP shell actuator. The fully driven load characteristics of the actuator with the bilayer BOPP-TPU shell were significantly increased to 620 mN at 6 kV when compared with the single-layer BOPP shell (25 μm), with an average increase of $\approx 151\%$ (Figure 4B).

3.4. Displacement Output with Load

The displacement output of the actuators with a specific load is also an important factor to measure actuator performance. We tested the strain in the thickness direction of the two actuators at different drive voltages, under an applied load of 15 and 25 g (see Figure 5A). After the actuator was placed horizontally, a mechanical load was applied to the strained surface, and then a range of voltages were applied and the strain in the thickness direction was measured as an output; these results are shown in Figure 5B.

It can be seen from the results that the actuator with the bilayer BOPP–TPU shell (55 μm) is easier to operate and the strain changes more smoothly with applied voltage, with a greatly improved strain and load-bearing performance compared with the thin BOPP shell (25 μm). With a load of 15 g (Figure 5B), the average strain in the thickness direction increases by approximately 40.4%. Movie S3 shows the working state of the two actuators with a 15 g load and 7 kV voltage. With a load of 25 g (Figure 5C), the strain in the average thickness direction increases by $\approx 62.9\%$, and reaches up to 74.76% at a drive voltage of 6 kV. When there is no mechanical load, the strain in the thickness direction can reach 164% at 5 kV, as shown in Figure 6A. In addition, the threshold value for an applied load that cannot induce any strain of the bilayer actuator (defined as the blocking load) reached 115 g.

![Figure 4](image-url). Load test in a fully driven state. A) Schematic of load test process in a fully driven state. B) Fully driven load–voltage profile of the actuator.
3.5. Performance and Simulation of Bilayer Actuator

To better understand the quasistatic behavior of the bilayer actuators, we derived an electromechanical model using the COMSOL 5.5 to analyze its motion state and compare it with the experimental results. According to the side view of the bilayer actuator in its initial state (see Figure 1A), its geometry was modeled as a 2D ellipse with a major axis of 88 mm and a minor axis of 8 mm. The 2D ellipse geometry consists of the upper and lower electrodes with a thickness of 0.8 mm, a shell with a thickness of 80 μm, and a fluid enclosure domain, as shown in Figure 7A. The entire bottom surface of the actuator is placed on a spring foundation to simulate the condition that the bottom surface is in contact with the ground due to gravity. An electric field is applied on the top electrode, while the bottom electrode is grounded. The electrodes are assumed to be in direct contact with the shell. A time-dependent solver was used to simulate the large deformation of the bilayer actuator. The time step is controlled by the software and the time range is from 0 to 2 s. Only the final time step situation was analyzed.

A Laplace smoothing equation is used in the fluid domain. The boundary between the shell and the fluid domain is defined as the fluid–solid interaction surface; thus, the velocity of the shell can be effectively transmitted to the fluid domain. The electrode materials and shell materials are considered as linear elastic materials to simplify the finite elements methods.

Figure 5. Displacement output with load: A) working state of polymer shell actuator with 15 g load at working voltage of 7 kV; B) strain in thickness direction with different voltages with 15 g load; C) strain in thickness direction with different voltages with 25 g load.

Figure 6. Displacement output with load. A) Strain–load characteristics of the actuator. The strain decreases with an increase of load, and the change of strain is smooth and linear. B) Strain–voltage characteristics of the actuator. The strain increases with voltage and has a tendency to be more linear with increasing load.
(FEM) model for higher computational efficiency. The elastic modulus of the electrodes and shell is 1 and 466 MPa, while the viscosity of the fluid is 0.05 Pa s. The relative permittivity of the shell and fluid is $\varepsilon_r = 4.9$ and $\varepsilon_r = 2.7$, respectively. The pressure distribution of the flow domain, driven by an electrical voltage of 8 kV, is shown in Figure 7B and Movie S4, Supporting Information. The ellipse geometry represents the original position of the bilayer actuator. After applying the electric field, the left-side fluid is driven to the right side of the actuator, and the bilayer actuator displacement increased. The average pressure is $\approx 100$ Pa at a drive voltage of 8 kV.

To analyze the load effect on the bilayer actuator, the upper right surface of the shell is placed on a load ranging from 0 to 15 g, with a step change of 1 g. We found that the critical load of the model is 15 g, as when the load is larger than 15 g, the provided electrical force will be insufficient to drive the HASEL actuator. This phenomenon is different to the experimental results, which can achieve a maximum load to 25 g. We analyzed and summarized that the reasons can be 1) the difference of the fluid volume in the simulated and actual HASEL. The original geometry of the bilayer actuator indicates that the maximum inner volume of the HASEL is $\approx 40$ cm$^3$, while 30 cm$^3$ of dielectric liquid was injected into the actual HASEL. Using the analytical 2D ellipse assumption, the simulated volume of the HASEL is $\approx 30$ cm$^3$, functioning as a fully liquid-injected actuator. This results in the flow resistance of the simulated HASEL being larger than the actual one. Therefore, a higher electric field is required to drive the simulated HASEL for higher load. It is challenging to model a partially dielectric liquid injected HASEL due to the complexity of the fluid–solid interaction surfaces and the uncertain motion responses of the liquid inside the HASEL. Further research directions can include investigation of the characteristics of the HASEL liquid motion response and the effect of the liquid volume. 2) To achieve reasonably fast computational speed of the models and avoid unstable conditions, a boundary condition was applied between the simulated upper and lower electrodes, which resulted in a small amount of dielectric liquid remaining in the left-hand side of the HASEL when it was actuated. This predicted amount might be different to the real experimental condition. However, it is difficult to measure the amount of the remaining dielectric liquid when the HASEL is actuated in experiments. The remaining dielectric liquid may reduce the loading capability of the actuator. Therefore, the relationship between the load (15–25 g) and strain was estimated by using linear extrapolation. The simulated and experimental relationships between the load (0–25 g), strain, and driven voltage of 3, 4, 6, and 8 kV are shown in Figure 7, where the model can effectively predict the relationships of the strain and load of the actuator, in comparison to the experimental results.

According to the results of our experimental and simulation analysis, the strain output of the bilayer actuator has a fairly

![Figure 7. A) HASEL geometry modeled as a 2D ellipse geometry in FEM models. B) The pressure distribution of the flow domain, driven by an electrical voltage of 8 kV. C) Simulated and experimental relationship of HASEL strain and load, driven by the electrical voltage of 3, 4, 6, and 8 kV. D) Simulated and experimental relationship of HASEL strain and voltage, with a variety of loads from 0 to 25 g.](image-url)
linear and regular relationship with the drive voltage, which can be beneficial to controlling the performance of the artificial muscle by voltage. The bilayer actuator achieves a greater strain up to 165% compared to the maximum strain (117%) produced by the donut actuator,[30] which also uses a thickness output.

3.6. Design of Actuator with Bilayer BOPP–TPU Films

3.6.1. Electrostatic Force of the Actuator

In a conventional Peano-HASEL, when a starting voltage is applied, its electrodes are close to each other and in contact, as in a zipper, due to the electrostatic force that presses the liquid contents, thereby driving the actuator to work, as in Figure 8A. Clearly, the greater the electrostatic force exerted on the liquid at the electrodes during actuator operation, the larger is the output performance of the actuator.

When the actuator is completely strained, its driving part can be regarded as a parallel plate capacitor to explore the stress state of its electrodes.[10] The two working electrodes of the actuator are the positive and negative plates of the capacitor; the shell and liquid material inside become the dielectric between the polar plates, as shown in Figure 8B.

Under the condition of a consistent electrode distance and electrode area, the electrostatic forces on the two electrode plates are expressed as Equation (2)

\[ F = \frac{QE}{2} = \frac{QU}{2d} \]  

(2)

where \( Q \) is the total charge of the capacitor, \( E \) is the electric field intensity, \( U \) is the voltage applied to the capacitor, and \( d \) is the distance between the two plates of the capacitor. The relationship between \( Q \) and capacitance \( C \) follows Equation (3)

\[ Q = CU \]  

(3)

where the capacitance is equal to

\[ C = \frac{\varepsilon_r \delta s}{4\pi kd} = \frac{\varepsilon_0 \delta s}{d} \]  

(4)

where \( \varepsilon_r \) is the relative permittivity of the material between the two plates, \( k \) is the electrostatic force constant, \( d \) is the distance between the two plates of the capacitor, \( \delta \) is the vacuum permittivity, and \( s \) is the plate area. From Equation (2) and (4), it can be concluded that \( F \) can be expressed as

\[ F = \frac{\varepsilon_0 \delta s U^2}{2d^2} \]  

(5)

Then, in the condition when the plate distance and electrode area are consistent, the electrostatic force generated by the two plates during operation is directly proportional to the permittivity of the dielectric.[31] As a result, increasing the permittivity of the dielectric can increase the electrostatic force generated by the two plates. According to the actuation of the structure, in Region 3 shown in Figure 8C, there is a large distance between the electrodes due to the presence of the liquid dielectric; as a result, the electrostatic force is initially weak and does not play a significant role in driving the actuator. Therefore, it is required that the slightly opened region of the electrodes, Region 2 in Figure 8C, can initially generate a relatively large electrostatic force due to the smaller spacing to drive electrodes close to each other.

The electrostatic force generated by the electrodes at Region 2 is therefore an important factor in driving the actuator. The electrode state at Region 2 is similar to that of a fully closed electrode, with a small plate distance, and the shell acts as the interplate dielectric. Therefore, the permittivity of the shell becomes one of the key factors affecting the driving performance of the actuator, which is also shown in high-strain Peano-HASEL actuator.[1]

It should be noted that as the BOPP material has a higher dielectric strength and can withstand a higher operating voltage than TPU, the increase in \( U^2 \) will lead to an increase in \( F \) (see Equation (5)). Therefore, when the operating voltage of the actuator is breakdown critically, the electric field induced
force generated by the BOPP actuator is greater than that generated by the TPU actuator. However, an extremely high operating voltage should be avoided as it causes safety risks and more energy consumption, requires complex antbreakdown protection measures (for actuator operation, the covering electrodes and the contacts between the cable and the electrode and even the surrounding air are also susceptible to breakdown), and higher specification requirements for power supply, cables, and the working electrode. In this work, the BOPP–TPU bilayer actuator achieved the same output performance as the BOPP actuator at a lower voltage, therefore safer operation.

3.6.2. Calculation of the Thickness of Each Layer in the Bilayer Films

The dielectric strength of BOPP film is generally between 200 and 700 kV mm$^{-1}$,[34] but its relative permittivity is as low as $\varepsilon_f \approx 1.9$. In comparison, TPU film has a relative permittivity of about 2–3 times higher than BOPP film ($\varepsilon_f \approx 4.9$). Therefore, for the same specifications, except shell material and thickness, the electrostatic force of actuator with a high permittivity TPU shell will be larger in the initial state, and the actuator can be driven more easily, therefore an actuator with a TPU shell will generate a larger strain under a low load. However, the dielectric strength of TPU film is relatively low, typically $\approx 100$ kV mm$^{-1}$, which requires a thicker film to resist the common working voltage when a TPU film is used as the actuator shell. This may cause a decrease in the electrostatic force of the electrode when the actuator is completely strained. In addition, the lower elastic modulus of TPU film does not allow it to maintain a strain under conditions of high load. Therefore, lamination of BOPP and TPU films to create a BOPP–TPU bilayer allows us to exploit the excellent electrical breakdown resistance and higher stiffness of the BOPP materials, and the higher relative permittivity and output performance of TPU for improving the bilayer actuator performance.

After a comprehensive consideration of ease of processing and the need for electrical breakdown resistance up to 15 kV, the total thickness of the BOPP–TPU bilayer film was selected to be 55 µm, and the performance difference due to the change in the thickness ratio of the two films is calculated and analyzed. As shown in Figure 9, a higher proportion of BOPP in the bilayer film results in a higher overall dielectric strength, while a higher proportion of TPU leads to a higher relative permittivity of the bilayer film. If the bilayer film shell needs to withstand a 15 kV drive voltage, the overall dielectric strength of the shell should be greater than 136.4 kV mm$^{-1}$, and the thickness of the BOPP in the bilayer film should be at least 11.7 µm. Therefore, the proportion of TPU can be increased to increase the permittivity of the bilayer film (the total thickness is 55 µm) and improve the electrostatic force of the actuator.

When the working voltage is applied to the actuator, the enclosure between the electrodes can be considered as a dielectric capacitor in series, and the strength of the electric field distributed across the series capacitance is inversely proportional to the magnitude of the capacitance. As a result, when a voltage is applied to a 55 µm-thick bilayer enclosure, the strength of the electric field to which the BOPP film is subjected to is given by

$$
E_B = \left(\frac{C_T}{C_B + C_T}\right) \frac{U}{d_B}
$$

where $U$ is the total voltage applied on the shell, $C_B$ is the capacitance of BOPP film, $C_T$ is the capacitance of TPU film, and $d_B$ is the thickness of BOPP film. The strength of the electric field to which the TPU film is subjected should be

$$
E_T = \left(\frac{C_B}{C_B + C_T}\right) \frac{U}{d_T}
$$

where $d_T$ is the thickness of BOPP film. $D_{SB}$ and $D_{ST}$ are the dielectric strengths of BOPP film and TPU film, respectively, where $D_{SB} = 320$ kV mm$^{-1}$ and $D_{ST} = 100$ kV mm$^{-1}$, then if the electric field applied to the BOPP ($E_B$) layer is larger than $D_{SB}$ or the electric layer applied to the TPU layer ($E_T$) is larger than $D_{ST}$, then one of the films will be unable to bear the electric field and will experience dielectric breakdown.

In Figure 9 it can be seen that the bilayer shell will not be able to bear the predetermined voltage of 15 kV (applied field 136.4 kV mm$^{-1}$) when the thickness of BOPP film is less than 11.7 µm, because the TPU will breakdown, so the overall dielectric strength of the bilayer shell is determined by the maximum electric field strength of the TPU. According to the electric field strength of TPU, the dielectric strength of the whole bilayer polymer film is as follows

$$
D_{EB} = \frac{\frac{C_B}{\varepsilon_f \pi R_2^2}}{d_T}
$$

If the bilayer film shell is considered as dielectric, its capacitance ($C_P$) should be
\[
\frac{1}{C_P} = \frac{1}{C_B} + \frac{1}{C_T}
\] (9)

In which \( C \equiv \varepsilon_\delta S/d \). Therefore, the effective relative permittivity of the polymer film is
\[
\varepsilon_P = \frac{\varepsilon_B \varepsilon_T}{\varepsilon_B + \varepsilon_T}
\] (10)

where \( \varepsilon_P \), \( \varepsilon_B \), and \( \varepsilon_T \) are the relative permittivity of bilayer polymer film, BOPP film, and TPU film; \( d_B \) and \( d_T \) are the thickness of BOPP film and TPU film, respectively, in the shell, and \( d_P \) is the total thickness of the shell \( d_P = 110 \mu m \), and \( d_T = 110 \mu m - d_B \).

In order to measure the Maxwell stress and the driving force of the actuator with different polymer shells under different voltages, we developed a Maxwell stress-measuring device, as shown in Figure 10. The hydrogel electrodes were fixed in the center of two identical polymethyl methacrylate (PMMA) sheets, and different films were used as dielectrics between the hydrogel electrodes. Then, the PMMA sheets were aligned so that the two electrodes were fully aligned and naturally closed, and then electrified to simulate the working state of the actuator and therefore test the electrostatic force.

As shown in Figure 10C, the electrostatic force or the actuation force of the BOPP–TPU bilayer film as the dielectric interlayer was \( \approx 54\% \) higher than that with the same thickness of BOPP film as the interlayer. Even compared with the single-layer BOPP film with a thickness of 25 \( \mu m \), the electrostatic force of the BOPP and TPU bilayer film is increased by approximately 31\%. In summary, the bilayer configuration provides a balance between the dielectric strength, permittivity, and stiffness to provide higher strain, force, and load-bearing capability.

### 4. Application in Rotating Mechanism

We now apply the new bilayer actuator design to achieve rotatory motion. Today, structures based on the principle of hydraulic amplification driver such as the flexible gripper,\(^{28}\) scorpion tail, and jumping donut muscle mainly include zipper linear actuator,\(^{17,29}\) curling actuator, and elastic donut actuator.\(^{29}\) They can provide linear and bending motions but seldomly realize rotary motion. Here, the hydraulic amplification electrostatic driver is innovatively used to drive the ratchet mechanism. In this way, the linear output of the electrostatic driver is converted into a torque output.

Unlike the rigid output of a traditional motor, the output of the HASEL actuator is smoother and softer (see Figure 11C). As a result of the actuator’s soft shell and flow of internal liquid dielectric, its output is also soft and can bear the external strain. When the actuator operates, excess energy will be stored as hydraulic energy of the liquid. When it is applied to the drive of ratchet mechanism, it can provide a flexible driving force for the ratchet and make the ratchet output a flexible torque (see Figure 11Ab), thus avoiding the torsional fracture of the ratchet shaft and reducing the loss of the ratchet pawl. Movie S5, Supporting Information, shows the working state of the ratchet system driven by the actuator.

In addition, the corresponding strain of the actuator according to different electrostatic forces allows the output of the ratchet system to be controlled by the load voltage of the actuator. If the electrical signal is used to control the load voltage of the actuator, the output of the ratchet system can be flexibly controlled. Figure 11Aa,b,c, respectively, illustrates the state of the actuator with different drive voltages and in Figure 11Ab, the pawl pushes the ratchet to rotate by one ratchet tooth angle, while in

![Figure 10](image-url)

**Figure 10.** A) Schematic diagram of electrostatic force test in the state of electrode closed. B) Test state of electrostatic force in the electrode closed state. C) Test results of three different shells in different voltages.
Figure 11. Application in rotating mechanism A) a, b, and c are the state of the ratchet system with different voltages applied to the actuator. B) Simple ratchet system in operation, which is output of a flexible moment by the actuator as the motive force. C) Thrust output curve of voice coil motor-driven ratchet and actuator-driven ratchet; the output curve of actuator is gentle, and there is no rapid impact.

Figure 11Ac, it rotates by two ratchet tooth angles. Movie S6 shows the change of output of ratchet system with different voltages.

5. Conclusion and Prospects

A new type of linear contraction HASEL actuator is designed, fabricated, modeled, and evaluated. The new actuator shell architecture is based on a bilayer film of BOPP and TPU, which combines the advantages of high dielectric strength and high elastic modulus of the BOPP layer with the high permittivity of the TPU layer, so that the performance of the actuator is highly improved compared with a traditional monolayer actuator design.

Compared with the electrostatic attraction between a conventional single-layer BOPP (55 μm) shell, the electrostatic force of attraction between the BOPP–TPU bilayer film (55 μm) is increased by ≈54% when the actuator electrodes are partially closed. In addition, compared with a thin BOPP single-layer film (25 μm), the electrostatic force of the BOPP–TPU bilayer film (55 μm) is increased by 31%. In comparison with traditional shell actuators based on single-layer shells, the complete strain–load behavior of the bilayer shell actuator was increased by 151%, on average. In addition, it is also easier to drive the bilayer shell actuator with the same load and it can lead to a lower drive voltage for a higher strain. The new bilayer film used for the actuator shell has been demonstrated as an effective approach to improve the performance of the actuator because the relative permittivity, dielectric strength, and elastic modulus of the polymer shell can be tailored by the type, thickness, and proportion of the selected polymers to form the bilayer.

The new form of soft actuator is innovatively applied to the ratchet system, so that the linear strain output of the actuator can be converted into rotary motion to realize a flexible torque output. In addition, the output of the whole ratchet system can be flexibly controlled by controlling the electrical signal of the actuator loading voltage. The high strain and load characteristics of the new bilayer configuration and the flexible and easy-to-deform characteristics of the soft actuator make it an attractive approach to fabricating actuators of complex geometry to achieve a variety of motion modes in future soft systems.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.
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