Tunable, Flexible, and Resilient Robots Driven by an Electrostatic Actuator

Congran Jin, Jinhua Zhang,* Zhe Xu, Ian Trase, Shicheng Huang, Lin Dong, Ziyue Liu, Sophie E. Usherwood, John X. J. Zhang,* and Zi Chen*

Robustness, deformability, maneuverability, and ease of fabrication are among the most desirable features of soft robots that can adapt to various working environments and complex terrains. Herein, polymeric thin-film-based flexible robots are designed, prototyped, and examined that use mechanical instability and electrostatic force actuation for locomotion. An electrostatic actuator is first developed using a buckled beam that can deform by up to 68% of its height under an applied voltage. A centimeter-scale robotic bug is then designed that shows superb flexibility, adaptability, and maneuverability by incorporating origami structural elements. For instance, the robotic bug can be completely smashed and still recover its mobility, walk on various terrains, slopes (up to 30°), narrow spaces, overcome hurdles, make turns, and even move backward with a crawling (linear) and turning (rotation) speed up to 40 mm s⁻¹ and ≈45° s⁻¹, respectively. Such remarkable characteristics are controlled by a set of parameters such as the amplitude and frequency of the input voltage and/or the origami geometries. The facile and tunable design and the actuation principle can potentially enable ample opportunities for the development of the next-generation soft robotics.

1. Introduction

Conventional robots are rigid, powerful, and robust, and hence they have been serving as trustworthy tools to assist humans in a variety of activities ranging from manufacturing parts in a streamline to exploring a dangerous place. However, due to their rigid body, they lack flexibility to cope with situations where space is confined, terrain is complex, or the environment is constantly changing. To solve these problems, researchers have focused on developing soft and flexible robots that can adapt to different environments. Soft robots made from soft materials with Young’s modulus close to that of soft tissues have enhanced flexibility and environmental adaptability compared with rigid robots. They can roughly be classified into either gripping or locomotive robots which can be further grouped into swimming robots and land-based robots that walk, climb, or crawl.

Multiple actuation mechanisms have been developed for soft locomotive robots. For example, pneumatics can easily elongate, contract, bend, and twist driven by changes in fluid pressure. A semisoft pneumatic actuator built by slit tubes can be turned into a grasper or a walker. A pneumatically actuated multigait soft robot that could perform sophisticated locomotion, which was then improved by Tolley et al., who untethered this robot by implementing a miniature air compressor. Hawkes et al. invented a soft pneumatic robot that navigates its environment through shape transformation. With pneumatic being the most popular mechanism for soft robots, other materials such as shape memory alloy (SMA) and electroactive polymers have also been widely used for actuation using temperature and electric field, respectively. For instance, worm and caterpillar soft robots that were fabricated using SMA are ideal for detection and inspection in narrow spaces. Most recently, Wu et al. used a piezoelectric polyvinylidene fluoride film to build a remarkable insect-scale soft robot that is robust and fast moving, can carry loads, climbs up a small slope, and exhibit forward galloping-like gaits. In addition, engineers have fabricated electric-, motor-, magnetic-, light-, and humidity- and even living tissue-driven robots designed to function in limited space or on complex terrains.

Despite the advantages over rigid robots, there is still plenty of room to improve the locomotive performances of current soft robotics. For example, pneumatic robots made of soft elastomers are extremely deformable, and in the meantime, they usually require complex fluid tunnels and pressure manipulation to
control their movement that could make them slow crawlers. While large deformation can be induced by SMAs in response to applied voltage, SMA-based robots are relatively vulnerable to fatigue and yield a slow locomotion due to the thermal cycling process. Electromagnetic field is an excellent external source to power untethered robots and produce fast locomotion; nonetheless, it requires a preprogrammed electromagnetic stage on which the robot moves. Although the insect-scale robot with piezoelectric actuators\[19\] is major advancement with the robots being small, lightweight, fast, and robust, it remains challenging to make improvements so as to maneuver over rough surfaces, overcome hurdles, or move backward. Electrostatic actuation is an ideal candidate for lightweight and small mechanisms. It has long been utilized for actuation in micro- and nanoelectromechanical systems (MEMS/NEMS),\[28–31\] An electrostatic force-controlled microrobot was made by Donald et al.\[31\] Other engineers have incorporated electrostatic force for centimeter-scale robots\[32–34\] and decimeter-scale wall climbers\[35,36\] and electrostatic forces have been used to actuate soft robotics such as the muscle-like electrostatic actuator for gripping objects\[37,38\] and untethered inchworm-like robots.\[39\]

Herein, we designed a highly flexible and maneuverable robot with rigid materials such as Kapton films—in fact, this method is suitable for a vast variety of materials as we do not resort to specific material properties such as piezoelectricity. Specifically, a thin-film-based electrostatic soft actuator with extremely simple geometric design is used to build a centimeter-scale and lightweight soft robot with common materials and an extremely easy fabrication process. The actuator is a 75 mm-long, multilayer structure composed of Kapton (polyimide) films with a prebuckled top layer which will rapidly deform in response to an applied alternating current (AC) voltage. Next, a soft and flexible robot was built using this actuator which showed good locomotive performance and excellent maneuverability. Therefore, our devices, compared with traditional soft actuators/robots made of soft materials, are built flexible via structural design. Once this type of robot becomes untethered by incorporating portable, ultralightweighted power source, and electronic components, it will be potentially suitable for missions that require small, fast, and easily maneuverable robots.

2. Result and Discussion

2.1. Electrostatic Soft Actuator

Inspired by the theoretical studies on bistability and buckling of a symmetrical, initially curved microbeam actuated by electrostatic forces,\[40–42\] we designed a flexible actuator composed of polyimide films that utilize electrostatic force ($f_e$) to create large deformation. The conceptual schematic of the actuator is shown in Figure 1A. It is a five-layer structure where the top, middle (insulation), and bottom layers are thin polyimide films and the inner sides of the top and bottom films are coated with ultrathin gold electrodes ($\approx 10$ nm). The length of the top film is longer than that of the bottom one and is buckled upward to form an arch-shape gap, as shown in Figure 1A. To illustrate the distribution of electrostatic distribution along the longitudinal direction of the actuator, the following theoretical analysis is made. In Figure 1B (top), the length of the bottom film is non-dimensionalized to 1, and the ratio of the apex height of the top film to the bottom film length is set to be 0.15 to present a general geometry of the actuator. This buckled shape yields an extremely simple yet effective configuration for the actuator and the robot that we developed in this work. With the bottom film anchored, as both films are charged oppositely, the top film will be pulled downward due to electrostatic force. This force has the following qualitative relationship with the input voltage ($V$) and the distance between the top and bottom layer ($y$):\[43\]

$$f_e \propto \frac{V^2}{y^2}$$

From Equation (1), we note that under a constant voltage and assuming a constant dielectric constant, the electrostatic force is proportional to $\frac{1}{y^2}$, and its profile along the length of the actuator is visualized quantitatively in Figure 1B (bottom), where the vertical axis is also a dimensionless quantity $\frac{1}{y}$. As the voltage is applied to the actuator, the electrical energy is converted to the kinetic and elastic energies of the top film. Upon removal of the voltage, the electrostatic force vanishes, and the deformed top film bounces back, recovering its original shape. In this process, the stored elastic energy in the deformed configuration is transferred to kinetic energy. The actuation process was simulated with finite element analysis (FEA) using COMSOL Multiphysics (Note S1, Figure S1, Supporting Information). Figure 1C shows the deformation process of the actuator when an increasing voltage is applied. In the simulation, the bottom film is electrically grounded, and the voltage gradually increases from 0 to 2000 V, as shown by the color contour which represents the voltage field, forcing the top film to be attracted downward. To quantify the deformation of the top layer in the simulation, we plotted the displacement of the center point of the top layer in response to an increasing voltage (Figure 1). We first compared the deformation performance of devices with two different thicknesses. Figure 1D shows that a 51 $\mu$m-thick top layer undergoes a larger displacement than a 127 $\mu$m-thick one, which can be explained by the fact that a thinner layer has a lower bending rigidity and therefore bends more significantly when subjected to the same amount of force compared with a thicker one. In addition, the thinner film starts to deform at a lower voltage and its displacement increases more rapidly than the thicker one. Next, we compared the simulated device of different initial buckling heights (i.e., 5, 8, 11, and 14 mm), which is defined as the vertical distance between the center point of the top layer and the bottom layer before actuation. In Figure 1E, all devices show a turn-on voltage, below which there is no displacement, and the larger the initial height, the higher the turn-on voltage. Past this point, the displacement rises, and it rises more rapidly with taller devices. It is also observed that a taller device has larger deformations at a high voltage (in the range of 1500–2000 V). Moreover, in relative terms, the shorter devices can displace a larger percentage of their overall heights. For instance, at 2000 V, the relative traveling distance of the top film’s center point (center point displacement/device height) for heights 5, 8, 11, and 14 mm are 40%, 30%, 26%, and 24%, respectively, suggesting that the shorter devices more efficiently use their geometry and has a larger relative deformation.
After verifying the feasibility of using such an electrostatic buckling structure as a soft actuator via the finite element method (FEM), we proceeded to experimentally evaluate the electromechanical performance of the fabricated sample. To quantify the actuator’s real performance, we chose the center point (A) and measured its displacement ($d = |AA'|$) while a sinusoidal AC voltage was applied, as shown in Figure 2A. $h_0$ and $L_e$ are the initial height of the film and the effective length of the actuator, respectively. Again, sinusoidal AC voltage is used to actuate the device, and the schematic depicts the proposed mechanism of the actuation which contains four processes within each period of the applied AC voltage. Opposite charges accumulate on the top and bottom electrodes in processes 1 and 3, leading to the top film to be pulled downward, whereas the charges are neutralized in processes 2 and 3 that allow the top film to buckle back up. We tested the actuator with different peak voltages ($V_p$), frequencies ($f$), top film thicknesses ($t$), and initial gap height ($h_0$) and measured the displacements ($d$). Figure 2B shows a typical displacement curve of the top film’s center point in response to an applied AC voltage at 1 Hz. Note the asymmetry of the displacement curve for each voltage period: the displacement increases slower than it drops. This asymmetry can also be seen from the hysteresis curve of displacement over voltage in Figure 2C and is verified qualitatively using FEM (Figure S2, Movie S1, Supporting Information). In this work, only sinusoidal wave functions were used as they produced larger and smoother deformations than other wave forms (e.g., square, triangular, and so on) provided by our function generator. Intuitively, a higher...
input frequency limits the time required for the top film to return to its original position and therefore restrain the maximum displacement. In other words, the higher the frequency, the smaller the film deformation, as shown in Movie S2, Supporting Information. In Figure 2D, the test result with a 51 μm-thick top film shows that the displacement dropped from 1.48 mm at 10 Hz to 0.21 mm at 100 Hz with an average slope of −1.4 μm/Hz (Figure 2D) which matches our intuition. However, when the top film is thicker (i.e., 127 μm, red and blue curves), the displacements become much smaller and do not decline over the same frequency range. Moreover, it is interesting to notice that taller (i.e., larger initial buckling height) devices (black and red curves) showed a constantly larger displacement than the shorter one (blue curve) across the entire tested frequency range. These observations lead us to speculate that the thickness and the initial gap height each individually play an important role in determining the deformation of this actuator.

To further investigate the role of film thickness and initial buckling height, we measured the displacements of the top film with different thicknesses and heights (Figure 2E) and initial heights (Figure 2F) at a peak voltage ranging from 0 V to 1 kV. First, as we expected, increasing voltages always result in larger displacements as a result of larger-induced electrostatic force between the two films (Figure 2E) at a peak voltage ranging from 0 V to 1 kV. Next, as shown in Figure 2E, thinner films yield larger deformations than thicker ones. This is because thinner films have a smaller bending rigidity, $E \cdot I$, where $E$ is the Young’s modulus of the film, and $I$ is the second moment of inertia, which make them more vulnerable to bend under the same electrostatic force. Next, it is observed that thinner films have lower actuation thresholds: 127, 51, and 25 μm films start...
to deform at 700, 500, and 200 V, respectively, and their displacements rise faster (i.e., steeper voltage–displacement slopes in Figure 2E). For all devices, displacements level off at a certain displacement and voltage (25 μm film: at 2.7 mm/500 V; 51 μm film: at 2.1 mm/800 V; 127 μm film: at 0.1 mm/700 V). In Figure 2F, we compared the displacements of films with different initial buckling heights. First, smaller initial heights show lower actuation thresholds as seen previously. Second, the maximum displacement (\(d_{\text{max}}\)) of the top layer at 1 kVp also depended on its initial height: it is constraint below 4 mm when the initial height is either too large (e.g., 20 mm) or too small (e.g., 5 mm), because a large initial height reduces the electrostatic force acting on the top film, whereas a small initial height allows for insufficient space for large deformations. Only when the initial heights are within the middle range (\(h_0 = 8–17\) mm), the displacement is large and increases as \(h_0\) increases. Finally, we emphasize that the actuator can create large deformation compared with its own size. For \(h_0 = 5, 8, 11, 14, 17, \) and 20 mm, the deformation percentages (defined by maximum displacement divided by height of the actuator or \(d_{\text{max}}/h_0\)) were 57%, 68%, 61%, 54%, 52%, and 30%, respectively, and the actuator showed high durability through a fatigue test, which was conducted by measuring the displacement of the oscillating top film before and after running one million cycles, as shown in Figure 2G. The displacement is measured using a vibrometer, and the test setup is shown in Figure S3a and b, Supporting Information.

2.2. Electrostatic Soft Robotic Bug

Next, we designed, prototyped, and tested a small, lightweight, and flexible bug-like robot (75 mm × 10 mm × 10 mm. Weight: ≈450 mg) built upon the actuator. The robotic bug was fabricated by facing the buckled top film downward to form a “belly” and attaching two “legs” to it (Figure 3A). We started with the simplest leg by creating a single fold on a piece of paper, which gives our robot extra flexibility and deformability (Figure S3C, Supporting Information). The legs move along with the bug’s “belly” which deforms under applied voltage. The gait of each step of the walking bug has three major stages. As shown in Figure 3B, in stage 1, both the top and bottom films are free of electrical charge and thus in a release stage. Both legs are in contact with the ground and the rear leg forms an angle of electrical charge and thus in a release stage. Both legs are free to deform at 700, 500, and 200 V, respectively, and their displacements rise faster (i.e., steeper voltage–displacement slopes in Figure 2E). For all devices, displacements level off at a certain displacement and voltage (25 μm film: at 2.7 mm/500 V; 51 μm film: at 2.1 mm/800 V; 127 μm film: at 0.1 mm/700 V). In Figure 2F, we compared the displacements of films with different initial buckling heights. First, smaller initial heights show lower actuation thresholds as seen previously. Second, the maximum displacement (\(d_{\text{max}}\)) of the top layer at 1 kVp also depended on its initial height: it is constraint below 4 mm when the initial height is either too large (e.g., 20 mm) or too small (e.g., 5 mm), because a large initial height reduces the electrostatic force acting on the top film, whereas a small initial height allows for insufficient space for large deformations. Only when the initial heights are within the middle range (\(h_0 = 8–17\) mm), the displacement is large and increases as \(h_0\) increases. Finally, we emphasize that the actuator can create large deformation compared with its own size. For \(h_0 = 5, 8, 11, 14, 17, \) and 20 mm, the deformation percentages (defined by maximum displacement divided by height of the actuator or \(d_{\text{max}}/h_0\)) were 57%, 68%, 61%, 54%, 52%, and 30%, respectively, and the actuator showed high durability through a fatigue test, which was conducted by measuring the displacement of the oscillating top film before and after running one million cycles, as shown in Figure 2G. The displacement is measured using a vibrometer, and the test setup is shown in Figure S3a and b, Supporting Information.

2.2. Electrostatic Soft Robotic Bug

Next, we designed, prototyped, and tested a small, lightweight, and flexible bug-like robot (75 mm × 10 mm × 10 mm. Weight: ≈450 mg) built upon the actuator. The robotic bug was fabricated by facing the buckled top film downward to form a “belly” and attaching two “legs” to it (Figure 3A). We started with the simplest leg by creating a single fold on a piece of paper, which gives our robot extra flexibility and deformability (Figure S3C, Supporting Information). The legs move along with the bug’s “belly” which deforms under applied voltage. The gait of each step of the walking bug has three major stages. As shown in Figure 3B, in stage 1, both the top and bottom films are free of electrical charge and thus in a release stage. Both legs are in contact with the ground and the rear leg forms an angle \(\alpha\) (≈31°) with the ground which is also the angle when the robot is at rest. Entering stage 2, as the voltage is applied and increased to peak magnitude, the belly of the robot contracts and brings the rear leg upward through the belly–leg connecting point A. The tip of the rear leg, point B, remains on the ground and has slid forward a small distance. Now, the rear leg forms an angle \(\alpha\) (≈39°) with the ground. Meanwhile, the front leg is slightly lifted and swings forward due to the contracting belly. Next, upon release of the voltage, the bottom film returns to its original shape and the gait enters stage 3. The releasing belly expands downward and attempts to move the rear leg backward. However, the frictional force in the forward direction is large enough to prevent the rear leg from sliding backward. As a result, the body of the robot is being “pushed” forward by the supporting force \(f_s\) that is acting on point B. The front leg swings forward and is back in contact with ground again. Finally, at the end of stage 3, both legs have moved forward, a short distance of \(\Delta X\). Sinusoidal AC voltage drives the bug to take many small consecutive steps like the one demonstrated earlier with preset frequency, resulting in a smooth forward motion. Our experiments showed that the rear leg is the dominating leg that drives the robot forward. Therefore, the moving mechanism of the robot can be interpreted using a simple model of the rear leg, assuming it is a rigid body, as shown in Figure 3C, with the three stages labeled. To better observe and analyze the detailed locomotion and gait of the robot, we took a slow-motion video of a moving robot (Figure 3D, Movie S4, Supporting Information) and tracked the path of points A and B, as the robot moves forward. In Figure 3D, the wavy path (blue) of point A shows that the belly of the robot is continuously oscillating due to the applied voltage, whereas the straight path (orange) of point B shows that the rear leg is always moving forward while in contact with the ground. To show how the vertical contraction–expansion of the belly transforms into the horizontal movement of the robot, we plotted the vertical and horizontal displacements of points A and B as well as the angle \(\alpha\) over time under a 1 kVp, 20 Hz signal (Figure 3E). Theoretical curves are obtained by applying the simple model in Figure 3C and solving trigonometrical equations (Note S2, Figure S4, Supporting Information). It is shown that the belly (point A, second row) is moving up and down periodically with a displacement of ≈1 mm in each period in response to the applied sinusoidal voltage. Point B remains on the ground (no vertical displacement). This vertical movement is transformed into a forward, horizontal motion of the robot which can be represented by the horizontal displacement of both points A and B with the displacement in each period ≈1 mm, as shown in the third row of Figure 3E. Moreover, the angle \(\alpha\) between the rear leg and the ground also changes sinusoidally between ≈31° and ≈39° (Figure 3D, fourth row) corresponding to the vertical displacement of point A. Overall there is good agreement between the experiments and theoretical predictions, with the exception of the horizontal displacement of the two points. This discrepancy is probably due to the assumption in our simplified model that the motion solely originates from the movement of the rigid rear leg, hence neglecting the effects of the front leg and the elasticity of the rear leg on the locomotion.

To evaluate the robot’s locomotive performance, we examined its speed at different frequencies and voltages. Figure 4A shows that the speed of the robotic bug (S) can be controlled by the frequency of the input voltage, and it continuously increases until 30 Hz and then starts to drop. To understand the shape of this speed versus frequency curve, we measured the average vibrational velocity (V) of front and rear legs which is computed as \(4df\) (Figure 4B), where \(d\) is the measured displacement at each leg–belly joint, and \(f\) is the frequency (Note S3, Figure S3c, Supporting Information). It is found that the speed curve of the robotic bug (Figure 4A) matches the curve of the average vibrational velocity (V) of the legs (Figure 4B) in a way that both increase in the range of 5–30 Hz and decrease in the range of 30–40 Hz. In fact, it is the vibrational velocity that controls the robot’s speed. Moreover, we define the velocity transfer efficiency as speed of the robot divided by the average velocity of the legs (S/V), which keeps in the range between 10% and 20%, as shown in Figure 4C. In addition, the electrical power of the robot in the 5–40 Hz operating frequency range is estimated to be
36–122.8 mW (Figure S5, Supporting Information), showing a relatively low power consumption. Furthermore, as we expected, the magnitude of the input AC voltage also has a nearly linear relationship with the speed of the bug (Figure 4D) in that at a given frequency, a higher voltage induces a larger deformation and thus a bigger step size and faster movement. An excessive voltage (>1 kV_p) may require a thicker insulation layer or otherwise it could potentially lead to an electric breakdown. As this study mainly focuses on examining the tunability of the robot’s mobile performance through changing the controlling parameter

Figure 3. The robotic bug’s locomotion. A) 3D model of the robotic bug (top) and its side view (bottom). B) Schematic of the gait of the robotic bug walking forward one step with three stages (left) and the corresponding snapshot in the slow-motion video (right). C) The model of the moving mechanism of the rear leg. D) Snapshot of a walking robotic bug with the paths of point A where the leg is attached to its belly (white line), and point B where its leg is in contact with ground (yellow line). E) First row: a 20 Hz sinusoidal voltage generated by a function generator applied to the robotic bug. Second row: the vertical displacement (Y) of points A and B over time. Third row: horizontal displacement (X) of points A and B over time. Fourth row: the angle α over time. The data points were obtained for the slow-motion video.
(i.e., voltage and frequency of the applied voltage), voltages larger than 1 kVp are not tested here. Furthermore, not only can the robot walk on flat smooth surfaces, but it can also climb slopes, survive from harsh pressing that results in maximum compression of the body in the vertical direction, adapt to different terrains, and crawl through narrow spaces. First, we tested its ability to climb slopes of different tilting angles (Figure 4E). With a 50 Hz frequency and 1 kVp voltage, the robotic bug climbed a nearly 30° slope, with higher slopes causing lower speeds. Second, the flexible robotic bug showed remarkable resilience to external impact (Figure 4F and Movie S5, Supporting Information). A moving robotic bug was completely compressed for 2 s (4–6 s) and was allowed to recover its shape for 4 s, after which it continued moving on without loss of mobility. Next, the robotic bug was able to move on different terrains made by common materials ranging from cardboard to print paper (Figure 4G) that have different surface roughness, and we observed that it moved faster on relatively smoother surfaces. This tendency is confirmed by testing the robotic bug on sandpaper of different grit numbers from 80 to 600, which quantify their surface roughness. Finally, the robotic bug, mimicking a cockroach by wearing an origami outfit, crawled underneath a narrow space, thanks to the incredibly flexible body, as shown in Figure 4H and I and Movie S6 and S7, Supporting Information. The cockroach-like robot was able to passively and gradually compress its body in the vertical direction and pass the narrow space that is ≈55% of its height.

Figure 4. Various performances of the robotic bug. A) Speed of the robotic bug as a function of frequency. Vp = 1 kV. B) Average vibrational velocities of the film at the front and rear legs as a function of frequency. Vp = 1 kV. C) Efficiency (Vr/Vavg) at different frequencies. D) Speed of the robotic bug as a function of peak voltage. Vp = 1 kV. E) Vr versus upward ramp angle (θ). Sandpaper grit #240 was chosen for the surface to provide adequate traction. f = 50 Hz. Vp = 1 kV. F) Recovery of the robotic bug after maximum body compression. f = 30 Hz. Vp = 1 kV (Movie S5, Supporting Information). G) Speed of the robotic bug on surfaces of different roughness. f = 30 Hz. Vp = 1 kV. H) The robot mimicking a cockroach with an origami outfit. I) Illustration of the cockroach robot crawling through under a narrow space (Movie S6 and S7, Supporting Information).
The robot’s mobility can be easily enhanced by adopting paper-based legs using simple origami design and cutting patterns. By folding the paper following the simplest origami pattern with a mountain and valley fold (Figure 5A), a bistable paper-based leg is obtained that can be triggered into two mechanically stable states (SSs) (Movie S8, Supporting Information). As illustrated in Figure 5B and C, SS 1 and SS 2 tilt the legs forward and backward, driving the robotic bug in respective directions (Movie S9, Supporting Information). Inspired from Kirigami, where cuts are made on a piece of paper to form aesthetic design in art, we enhanced the robot’s mobility through making simple parallel cutting patterns on its legs and body to allow it pass through obstacles and change directions, respectively. In the obstacle test (Movie S10, Supporting Information), it is observed that the robotic bug with the original leg design was inevitably tripped by small obstacles (Figure 5D) and consequently either detoured or completely stopped. The simple cutting pattern on the robot’s legs (Figure 5E) is to increase the flexibility of the leg as each beam in the leg becomes more vulnerable to bending when hitting the obstacle (Figure 5F), and as a result, the robot passed through a series of obstacles with similar sizes. In addition, the robotic bug can thus far only move forward. To add maneuverability to it, we cut a simple “H” shape configuration with two legs attached to each of the parallel unit (Figure 5G and S6, Supporting Information). By individually controlling the voltage frequency of each unit, directional control was realized. To test its maneuverability, we challenged the robot to park into a “garage” (Figure 5G, Movie S11, Supporting Information). It successively accomplished a series of maneuvers, including a counterclockwise (CCW) turn, a forward move, a clockwise (CW) turn, another forward move, and finally a controlled stop with precision in the “garage” over a distance of \( \approx 236 \text{ mm} \) in \( \approx 12.5 \text{ s} \). In the process, forward motion and turning maneuvers were achieved by pacing the left and right units independently. To simplify the control protocol and maximize the turning effectiveness, frequencies (left/right) of 20/25, 0/25, and 20/0 Hz were used for forward motion, CCW turns, and CW turns, respectively, as shown in Figure 5H, that provides.

![Figure 5. Enhanced mobility of the robot through origami and cutting pattern designs. A) The origami design of the robot’s leg that can be triggered into two mechanically SSs: B) SS1 making the robot move forward and C) SS2 making the robot move backward (Movie S9, Supporting Information). D) The robot tripped by an obstacle and stopped moving. E) The robot’s leg with simple cutting pattern helped F) the robot pass through small obstacles (Movie S10, Supporting Information). G) The H-shaped robot successfully completed a series of maneuvers including forward and turning motion and parked into a designated space (Movie S11, Supporting Information). H) The kinematic analysis of the “parking” process with each maneuver highlighted by a modulated frequency.]

© 2020 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
a kinematic analysis of the “parking” process. Note that the angular velocity when the robot turns can reach up to $\approx 45^\circ \text{s}^{-1}$ (between 0 and 1 s). The prototype robot tended to turn CW; thus, there is a need to prescribe the asymmetry in the driving frequencies (20/25 Hz) to counteract that tendency, which was likely due to an asymmetrical dragging force by the electrical wire or a geometrical flaw in fabrication.

In this work, we designed a soft electrostatic actuator and a soft robot integrated with origami/cutting structures using relatively stiff materials such as Kapton. For the actuator, we demonstrated its capability of quick reaction and large deformation compared with its own size. The soft robot is lightweight and highly deformable and has excellent locomotive performance, maneuverability, and resilience. Table 1 shows a comparison of some key parameters that are used to evaluate soft robots including the size, weight, speed, deformability, the capability of steering, climbing, overcoming obstacles, and moving on different surfaces among major terrestrial locomotive soft robots developed since 2010. The robot developed in this work has comprehensively strong performances in all aspects listed in this table. Instead of using traditionally soft materials with Young’s modulus close to that of soft tissues, we used a hard material (polyimide) on which the electrostatic force can be applied. Using this strategy, we have created soft robots that are superior in many aspects to traditional soft robotics and that can be fabricated using a wide variety of materials.

The bending rigidity, $EI$, is the criterion that differentiates soft robots from rigid ones. However, as the second moment of inertia ($I$) is not an intrinsic quantity (it depends on the geometric parameters of the material and the direction of load), normally only Young’s modulus ($E$) is used to classify soft robots. Conventional soft robots are flexible, thanks to the composed materials with low Young’s moduli between 10 kPa and 1 GPa.[1,2] The Kapton film in our robot has a Young’s modulus of 2.5 GPa which is above the defined range. Yet, it can create a flexible robot because (1) the film has micrometer thicknesses, leading to a small second moment of inertia ($I$) and therefore rigidity ($EI$), and (2) the buckling design as well as the origami-inspired legs are resilient structures. This relatively high bending rigidity requires high voltages to actuate the robot. One way to reduce the voltage is by replacing the Kapton film with softer films (a lower elastic modulus). However, softer pre-buckled films will lead to a slower recovery to its original arch shape once the applied charges are removed and less force to support the weight of the robot, both of which could undermine its mobile performance. Hence, further studies will be required to explore an effective way to reduce the required magnitude of the voltage while maintaining the robot’s maneuverability.

In addition to advantages in weight, size, flexibility, adaptability, and speed, the robot responds quickly to driving source or stimuli when compared with pneumatic and SMA actuators. We define the response time as the time interval between the voltage being turned on and the film completing one cycle of deformation. As the movement of electrical charges occurs at extremely small timescales, the response time solely depends on the frequency of the applied voltage. For example, at 100 Hz, the response time is 5 ms (one period of sine wave voltage creates two periods of film deformation). This work opens ample venues for future research, e.g., efforts can be made on 1) preventing the electrical components of the robot from being exposed so that it can work in moist atmosphere or wet environments, 2) making an untethered robot, 3) lowering the voltage required for actuation, and 4) improving its mobility on rough environments. Solving the tethering problem will dramatically enrich the range of applications. Finally, more advanced origami[23] and kirigami[44,45] structural elements can be incorporated into this or other soft

Table 1. Major terrestrial locomotive soft robots developed since 2010.

| Reference       | Belding et al.[3] | Verma et al.[3] | Shepherd et al.[3] | Tolley et al.[7] | Gu et al.[11] | Cao et al.[39] | Umedachi et al.[18] | Jayaram and Fuji[22] | Wu et al.[19] | Shin et al.[20] | This work |
|-----------------|-------------------|-----------------|-------------------|-----------------|--------------|--------------|-------------------|-------------------|--------------|---------------|-----------|
| Year            | 2018              | 2017            | 2011              | 2014            | 2018         | 2018         | 2016              | 2016              | 2019         | 2018          | 2019      |
| Actuation method| Pneumatic         | Pneumatic       | Pneumatic         | Pneumatic       | Dielectric   | Dielectric   | SMA               | Motor             | Piezoelectric | Humidity      | Electrostatic |
| Material        | Elastomer         | Silicone        | Elastomer         | Elastomer       | Dielectric   | Elastomer    | Dielectric        | 3D printing material | Polyether      | Polyvinylene fluoride | Polymeric |
| Length [cm]     | 25                | 59              | 25                | 65              | 85           | 20.8         | 80                | 85                | 50           | 0.024         | 0.035     | 0.45       |
| Weight [g]      | 227               | 98              | n/a               | 2240            | n/a          | n/a          | n/a               | 50                | n/a          | 0.024         | 0.035     | 0.45       |
| Speed [mm s$^{-1}$] | 4                 | 25.6            | 5                 | 88.5           | 4.16         | 2.1         | 112              | 140              | 200          | 6            | 200       | 40        |
| Full body compression | No             | No              | No                | No              | No           | No          | No                | No                | Yes          | n/a           | Yes       |
| Steering        | Yes$^a$           | Yes$^b$         | Yes$^b$           | Yes$^b$         | Yes$^b$      | Yes$^b$     | Yes$^b$           | Yes$^b$           | No           | No            | Yes$^b$   |
| Climbing ability | n/a              | Up to 90$^c$    | n/a               | n/a             | Up to 90$^c$ | n/a         | n/a               | n/a               | Up to 15.6$^d$ | n/a          | Up to 30$^e$ |
| Overcoming hurdles | No               | No              | Yes$^f$           | Yes$^f$         | Yes$^f$     | No          | No                | No                | No           | No            | Yes$^f$   |
| Multiterrestrial | n/a              | n/a             | Yes$^g$           | Yes$^g$         | Yes$^g$     | n/a         | Yes$^g$           | Yes$^g$           | n/a          | Yes$^g$       | Yes$^g$   |

$^a$The performance is better or equal to that of this work in terms of miniaturization, speed, flexibility, etc.
3. Conclusions

Electrostatic attraction is a ubiquitous phenomenon in daily life; yet, except for being used for actuation in MEMS/NEMS, it is often undervalued in larger-scale engineering applications. Although limited in magnitude, electrostatic forces can create fast responsive reactions with low energy consumption. Herein, we designed a centimeter-scale soft electrostatic actuator and easily maneuverable soft robots by integrating a prebuckled thin-film actuator with origami and simple cutting features. The actuation can be easily achieved and tuned by the amplitude and/or frequency of the applied voltage. Moreover, the buckled shape, together with simple origami and cutting pattern design, allows the robot to be highly robust, deformable, and maneuverable. We showed that the electrostatic actuator can result in up to 68% instantaneous deformation in height in response to an applied voltage. Furthermore, we demonstrated the robot’s remarkable adaptability and flexibility, as well as outstanding maneuverability, including making turns, climbing up a 30° slope, overcoming hurdles, and moving backward. Our facile and tunable design strategy for the actuator can potentially enable the development of the next generation of soft miniature robots that can be used on complex terrains or in confined space to conduct various tasks.

Supporting Information

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

Acknowledgements

The authors thank the support from the startup funds from the Thayer School of Engineering at Dartmouth College. J.Z. acknowledges the support by the National Natural Science Foundation of China (no. 51675413). X.J. Zhang thanks the support by National Science foundation (no. ECCS-1509369). Z.C. acknowledges the Branco Weiss Society in Science fellow and Biomimetic, ROBIO, IEEE, Piscataway, NJ 2007, pp. 330–335.

Conflict of Interest

U.S. Provisional Application entitled “Electrostatic-actuator-based soft robotics” (no. 62/773,009) filed on 11/29/2018.

Author Contributions

C.J. and Z.C. conceived the idea and designed the experiments. C.J., J.Z., and Z.X. performed the experiments. I.T. conducted the computer simulation. C.J., J.Z., Z.X., I.T., S.H., L.D., Z.L., and S.U. contributed to data collection. J.Z., X.J.Z., and Z.C. supervised the research and contributed to data analysis and interpretation. C.J., J.Z., and Z.C. wrote the article with feedback and edits from all authors.

Keywords

electrostatic actuators, flexible robots, origami structural elements, soft robotics

[1] C. Majidi, Soft Robot. 2014, 1, 5.
[2] D. Rus, M. T. Tolley, Nature 2015, 521, 467.
[3] L. Belding, B. Baytekin, H. T. Baytekin, P. Rothenmund, M. S. Verma, A. Nemirovski, D. Sameoto, B. A. Grzybowski, G. M. Whitesides, Adv. Mater. 2018, 30, 1.
[4] J. Lim, H. Park, S. Moon, B. Kim, in 2007 IEEE Int. Conf. on Robotics and Biomimetics, ROBIO, IEEE, Piscatway, NJ 2007, pp. 330–335.
[5] M. S. Verma, A. Ainla, D. Yang, D. Harburg, G. M. Whitesides, Soft Robot. 2017, 5, 133.
[6] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, Proc. Natl. Acad. Sci. 2011, 108, 20400.
[7] M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, G. M. Whitesides, Soft Robot. 2014, 1, 213.
[8] E. W. Hawkess, L. H. Blumenschein, J. D. Greer, A. M. Okamura, Sci. Robot. 2017, 2, eaan3028.
[9] Y. Tang, Q. Zhang, G. Lin, J. Yin, Soft Robot. 2018, 5, 1.
[10] Y. Bar-Cohen, Electroactive Polymer (EAP) Actuators as Artificial Muscles, SPIE, Bellingham, WA 2004.
[11] G. Gu, J. Zou, R. Zhao, X. Zhao, X. Zhu, Sci. Robot. 2018, 1284, 1.
[12] R. Pelrine, R. D. Kornbluh, Q. Pei, S. Stanford, S. Oh, J. Eckerle, R. J. Full, M. A. Rosenthal, K. Meijer, Proc. SPIE. 2002, 4695, 126–137.
[13] Q. Pei, M. Rosenthal, S. Stanford, H. Prahlad, R. Pelrine, Smart Mater. Struct. 2004, 13, N86.
[14] B. Kim, M. G. Lee, Y. P. Lee, Y. Kim, Sens. Actuators, A 2006, 125, 429.
[15] S. Kim, E. Hawkess, K. Cho, M. Jolda, J. Foley, R. Wood, in 2009 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IROS 2009, IEEE, St. Louis, MO 2009, pp. 2228–2234.
[16] K. Zhang, C. Qiu, J. S. Dai, ASME. J. Mech. Robot. 2015, 7, 021014.
[17] C. A. Daily-Diamond, A. Novelia, O. M. O’Reilly, Bioinspiration Biomimetics 2017, 12, 056005.
[18] T. Umedachi, V. Vikas, B. A. Trimmer, Bioinspiration Biomimetics 2016, 11, 025001.
[19] Y. Wu, J. K. Yim, J. Liang, Z. Shao, M. Qi, Z. Luo, X. Yan, M. Zhang, X. Wang, R. S. Fearing, R. J. Full, Lin. Sci. Robot. 2019, 4(32).
[20] Y. Hu, J. Liu, L. Chang, L. Yang, A. Xu, K. Qi, P. Lu, G. Wu, W. Chen, Y. Wu, Adv. Funct. Mater. 2017, 27, 1704388.
[21] V. Vikas, E. Cohen, R. Grassi, C. Sozer, B. Trimmer, IEEE Trans. Robot. 2016, 02155, 1.
[22] K. Jayaram, R. J. Full, Proc. Natl. Acad. Sci. 2016, 113, 950.
[23] S. Felton, M. Tolley, E. Demaine, D. Rus, R. Wood, Science 2014, 345, 644.
[24] S. Miyashita, S. Guirton, M. Ludersdorfer, C. R. Sung, D. Rus, in Proc. – IEEE Int. Conf. on Robot. Autom., 2015, pp. 1490–1496.
[25] H. Zeng, O. M. Wani, P. Wasylczyk, A. Primagi, Macromol. Rapid Commun. 2018, 39, 1.
[26] B. Shin, J. Ha, M. Lee, K. Park, G. H. Park, T. H. Choi, K. J. Cho, H. Y. Kim, Sci. Robot. 2018, 3, 1.
[27] B. Xu, X. Han, Y. Hu, Y. Luo, C. H. Chen, Z. Chen, P. Shi, Small 2019, 15, 1.
[28] G. Duan, K.-T. Wan, J. Appl. Mech. 2007, 74, 927.
[29] H. Conrad, H. Schenk, B. Kaiser, S. Langa, M. Gaudet, K. Schimmanz, M. Stolz, M. Lenz, Nat. Commun. 2015, 6, 1.
[30] S. Yang, Q. Xu, J. Micro-Bio Robot. 2017, 13, 1.
[31] B. R. Donald, C. G. Levey, C. G. McGarvy, I. Paprotyn, D. Rus, J. Microelectromech. Syst. 2006, 15, 1.
[32] M. A. Graule, P. Chirarattananon, S. B. Fuller, N. T. Jafferis, K. Y. Ma, M. Spenko, R. Kornbluh, R. J. Wood, Science 2016, 352, 978.
[33] H. Shigemune, S. Maeda, V. Cacucciolo, Y. Iwata, E. Iwase, S. Hashimoto, S. Sugano, IEEE Robot. Autom. Lett. 2017, 2, 1001.
[34] A. S. Chen, H. Zhu, Y. Li, L. Hu, S. Bergbreiter, in Proc. – IEEE Int. Conf. on Robotics and Automation, IEEE, Hong Kong 2014, pp. 5038–5043.
[35] R. Liu, R. Chen, H. Shen, R. Zhang, Int. J. Adv. Robot. Syst. 2013, 10, 1.
[36] H. Wang, A. Yamamoto, T. Higuchi, Int. J. Adv. Robot. Syst. 2014, 11, 1.
[37] E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, C. Benjamin, M. King, M. Radakovitz, C. Keplinger, Science 2018, 359, 61.
[38] M. Taghavi, T. Helps, J. Rossiter, Sci. Robot. 2018, 3.
[39] J. Cao, L. Qin, J. Liu, Q. Ren, C. C. Foo, H. Wang, H. P. Lee, J. Zhu, Extrem. Mech. Lett. 2018, 21, 9.
[40] L. Medina, R. Gilat, S. Krylov, Int. J. Solids Struct. 2012, 49, 1864.
[41] L. Medina, R. Gilat, B. Robert Ilic, S. Krylov, Appl. Phys. Lett. 2016, 108, 073503.
[42] X. Chen, S. A. Meguid, Proc. R. Soc. A Math. Phys. Eng. Sci. 2015, 471, 20150072.
[43] F. E. H. Tay, X. Jun, Y. C. Liang, Y. J. Logeeswaran, Y. Yufeng, J. Micromechanics Microengineering 1999, 9, 281.
[44] A. Rafsanjani, Y. Zhang, B. Liu, S. M. Rubinstein, K. Bertoldi, Sci. Robot. 2018, 3, 1.
[45] N. Hu, D. Chen, D. Wang, S. Huang, I. Trase, H. M. Grover, X. Yu, J. X. J. Zhang, Z. Chen, Phys. Rev. Appl. 2018, 9.