Electronically Innervated Adaptive Fully Soft Robots

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Introduction

Unlike traditional robots, which are made from rigid materials and components to fulfill the requirements of high precision, rapid movement, high force, and easy control, soft robots, an emerging class of robots, are designed in a largely soft fashion for the purposes of increased safety, adaptability, and complex motions, which can be very difficult, if not possible, to achieve in traditional counterparts\(^1\). Nature offers a great deal of inspiration for the development of soft robots. Loopers, spanworms, inchworms and other caterpillars of insect larvae exhibit amazing capabilities in fully soft body locomotion through the conjugation of neural control processes and biomechanics\(^2\)-\(^5\). Different from vertebrates, which have stiff skeletons and joints and whose motions have limited degree of freedom (DOF), caterpillars feature distributed deformation over their bodies and can deform into very complex shapes with virtually unlimited DOF. Accumulative understanding in biology and recent advances in novel materials and manufacturing technologies have led to fast development in construction of artificial soft robots actuators and machines\(^6\)-\(^16\). However, the development of soft robots, especially solely from soft materials that mimics the biology, is still nascent. Soft robots could harvest the deformation from pneumatically actuated elastomers structures\(^1,7,11,13\), and stimuli responsive soft materials, such as electroactive polymers (EAPs)\(^15\)-\(^18\), shape memory polymers (SMPs)\(^19\), and hydrogels\(^20\)-\(^22\). Nevertheless, none of the synthetic machine shows the analogic mimicry of local deformation and soft bodied locomotion of a caterpillar. In addition, the ability to sense and react to environmental change or stimuli has never been achieved in existing synthetic soft robots; yet it is vital for the survival and societal activities for animals and also for the future synthetic machines.

The results reported here show that soft electronics, i.e. sensor and actuator, innervated
soft responsive artificial muscles as the fully soft robots provide a solution to achieve effective soft bodied locomotion based on programmable body bending and friction induced anchored motions, similar to that of an inchworm. The demonstrated soft robots capable of sophisticated shape adaptation and two-way gait locomotion in programmable and adaptive sensing-actuating manners involve soft Joule heating electronic meshes, ultra-thin Si optoelectronic sensors, and thermal responsive liquid crystal elastomer (LCE). By combining the merits of the mechanical softness, sensing and local actuating from the soft electronics and the responsiveness from the artificial muscle, the soft robot exhibits abilities in sensing and autonomous actuation and locomotion. The findings encompass a complete set of materials, components, and design strategies to enable the adaptive soft robots. Systematic experimental, computational and analytical studies of the mechanical, thermal, and electrical properties reveal the fundamental aspects of the synthetic soft robot design, fabrication and operation, and also provide quantitative design guidelines that are applicable to future scaled systems.

**Results and Discussion**

For inchworms, innervated neurons and muscles are among the most important organs responsible for their locomotion\(^4\). As mimicry, our synthetic robot employs soft sensing and actuating electronics and LCE based thermal responsive artificial muscles. Specifically, LCE is chosen owing to its compliant nature (modulus 0.5 MPa at 25 °C) and reversible shrinking-elongating attribute upon thermal stimulus. Near the temperature of 75 °C, the LCE undergoes reversibly transition from anisotropic phases with ordered and aligned mesogens (elongated) to isotropic phase with disordered mesogens (shrunk)\(^{23,24}\), as sketched in Extended Data Fig. 1a. Carbon black nanoparticles were doped into LCE (LCE-CB) to enhance its thermal conductivity.
thus to fasten thermal-response and to improve structural stability\textsuperscript{25}. The details of the preparation of LCE-CB are described in the Methods. Extended Data Fig. 1b displays the reversible shrinking-releasing deformation of the LCE-CB strip along its longitude direction when it is heated up (80 °C) and cooled down (25 °C). The measured maximum shrinking ratio is \( \sim 24\% \) when the temperature reaches 95 °C, as shown in Extended Data Fig. 1c.

The open mesh shaped stretchable heater is employed to actuate the LCE-CB once integrated together. The design criteria are that 1) the heater should be able to generate enough joule heat to effectively actuate the LCE-CB, 2) the heater and LCE-CB can deform currently, 3) the heater remain functional while deformed, 4) the heater does not impose significant mechanical constrain on the LCE-CB, 5) the arrayed heaters can be activated sequentially, and 6) the LCE-CB can be actuated locally. A free-standing ultra-thin (\( \sim 2.6 \) µm thick) open mesh serpentine shaped heater structured as polyimide-Au-polyimide through multiple steps of deposition and patterning is therefore designed and fabricated. The detailed fabrication processes of the heater are described in Methods. The serpentine layout is designed to achieve uniform heat across the LCE-CB while enabling mechanical deformability. An anisotropic conductive film (ACF, Elform) cable connects the bonding pad of the heater and a printed circuit board that can interface with external circuits, as shown in Supplementary Fig. 1. The left images of Fig. 1a, b show optical images of a fabricated integrated device before and after the heater is powered on, respectively. The resistance of the heater is 281.8 \( \Omega \). By applying a voltage of 8.2 V, the generated Joule heat (\( \sim 0.237 \) W) from the heater conducts to the LCE-CB, resulting in shrinkage along longitudinal direction, as shown in Fig.1b. The measured shrinking ratio (\( \sim 24\% \)) is almost identical with that from heating on a hotplate as presented in Extended Data Fig. 1c. The temperature of the LCE-CB material on both front and back sides are captured by an infrared
camera (FLIR SC7000), as shown in Fig.1c. Finite element analysis (FEA) was performed to confirm the experimental findings. The details are included in the Supplementary Information. The FEA results of the temperature mapping (Fig.1d) match well with the experiment observations. In addition, FEA also confirms that the heater can deform concurrently with the LCE-CB and does not constrain the LCE-CB to deform. The overall shrinking ratio from FEA agrees well with the experiment, as shown in Fig. 1a, b. The very low stress in the heater resulted from the deformation indicates that the heater can function normally when deformed.

To mimic the “wavy” configuration of an inchworm’s body during locomotion, bimorph structures are employed. The bimorph constructs from a kapton film (polyimide, 50 µm thick, Dupont), an LCE-CB (500 µm thick) strip, and an ultra-thin heater, as shown in Fig. 1e. The kapton film is chosen because of its mechanical softness, low thermal expansion coefficient, physical adhesion, and low friction coefficient. Upon electrical stimulation, thermal induced mechanical mismatch between the LCE-CB and kapton film drives the bending deformation. It is noted that the temperature at which the bimorph is effectively actuated can be just slightly above the transition temperature. In this study, we exploit the bimorph actuation at the temperature of around 80 °C. Figure 1f presents the optical images of the bimorph before and after electrical stimulation. The bending direction is determined by the kapton film owing to the unidirectional nature of the bimorph. After retrieving the electrical stimulation, the temperature decreases and the bilayer structure will return to its initial configuration attributing to the elongation of the LCE-CB and also the release of the mechanical energy stored in the kapton film. A simplified thermo-mechanical model, as described in details in the Supplementary Information and Supplementary Fig. 2, is established to analyze the bimorph bending upon electrical stimulation. The resulted bending radius from the analysis agrees reasonably well with the experiment, as
indicated in Extended Data Fig. 3.

By introducing multiple bimorphs into a soft structure, its shapes can be programmed. Figure 2a, b display the schematic and optical images of a structure with two bimorphs, where the two heaters (I and II) can be individually addressed. Upon electrical stimulation (applying a power of 0.069 W), originally flat structure (the insert of the left image in Fig. 2c) achieves different bent shapes, as shown in Fig. 2c. As indicated from the IR temperature mapping (Fig. 2d) and also the FEA simulations (Fig. 2e), the heat is localized, thus the bimorph can be effectively actuated and the shape of the structure can be locally programed. The experimental observations on the local deformation (Fig. 2c) and FEM simulations (Fig. 2f) agree with each other very well. The local shape programming cannot be easily achieved in other reported responsive materials based soft actuators and robots which heavily rely on global stimulation or environmental change.\(^{20,22,26}\)

More complex shape programming can be easily achieved based on the number of innervated heaters, their distribution, and the activation sequences. Three independently addressable heaters and associated bimorphs are prepared to sever as an example to illustrate the distributed deformation and complex shapes. Figure 3a shows an optical image of a fabricated device with three distributed heaters on the LCE-CB. The location of the attached kapton film determines the bending direction of the bimorphs and thus the resulted programmable shapes. For this case of three different heaters, eight possible variations of the bimorph distribution exist. Here we demonstrate two representative examples, as schematically illustrated in Fig. 3b, c. Selectively activating specific heaters results in different programmable shapes without changing the environment temperature globally. Figure 3d shows the programmed shapes from a flat configuration upon activating the heater I (left), heaters I and II (middle), and all the three
heaters (right). Such “S” shape is also observed when the whole structure is uniformed heat to ~80 °C without any electrical stimulation (Fig. 3e). Similar outcomes of a rolling shape, as exhibited in Fig. 3f, g have also been achieved with all three bimorphs bend downward. Since the bimorph defines the overall shapes, the results clearly show that shape morphing from electrical stimulation is as effective as that from other thermal means. Fully soft bodied structures can be programmed into desired shapes with simple combination of soft electronics and soft artificial muscle. The results demonstrated the distributed deformation and complex shape programming by actuating the LCE-CB locally through joule heat from the innervate heaters.

Soft-bodied inchworms have unique crawling locomotion patterns through contracting their longitudinal muscle fibers to bend the body and alternating the immobilization of their legs. It typically performs four sequential steps to complete one stride, i.e. one cycle of crawling locomotion, as schematically illustrated in Supplementary Fig. 3. To mimic such locomotion, our synthetic robot employs two electrically programmable bimorphs, of which one bends upwards and the other bends downwards, as illustrated in Fig. 4a of a schematic construct in exploded view. Figure 4b shows an optical image of the ultra-thin heater innervated LCE-CB strip. The soft robot has a size 28.6×7.7×0.5 mm³ (length × width × thickness) with a total light weight of 0.29 g. It is noted that the size can be easily scaled up to achieve faster locomotion speed.

Based on functions of each element, the soft robot can be divided into three major components: the front leg, the rear leg, and the body, as indicated in the image I in Fig. 4c. The locomotion experiment is performed on a glass plate. The lengths of the front and rear legs are 0.5 and 4.3 mm, respectively. Extended Data Fig. 4 shows the measured static friction forces between the LCE-CB and glass plate and also the friction force between the kapton film and
glass. The friction force between the LCE-CB and glass plate at 25 °C and 80 °C are 3,094 μN/mm² and 12,042 μN/mm², respectively. Owing to much higher friction force between the LCE-CB and glass comparing with that between the kapton film and glass (Extended Data Fig. 4), once resting on the glass, the front leg serves as a grip and lead to anchor-pull or anchor-pulling motions, as described below. By sequentially activating and deactivating the bimorphs, the soft robot achieves two-way gait locomotion. Figure 4c, d illustrate one locomotion stride moving forward and backward, respectively. In each stride cycle, four sequential steps are involved, which is similar as that of an inchworm. In the first step, the heater I is activated and the corresponding bimorph is actuated and thus bent downward. Due to much higher friction from the front leg comparing with the rear one, the rear leg and body of the robot are pulled forward, i.e. an anchor-pull step. Such deformation takes ~15 s to complete. The image II in Fig. 4c illustrates the resulted shape configuration. The second step involves bending the robot by activating other bimorph upwards to release the front leg from the glass plate, as presented in the image III in Fig. 4c. In the third step, the heater ‘I’ is deactivated while the heater II is kept activated to flatten the bimorph I, as shown in the image IV in Fig. 4c. Finally, after powering off both heaters, the robot becomes flattened with the body and front leg move forward by one stride length, i.e. anchor-push, as illustrated in image V in Fig. 4c. Continuous crawling locomotion is achieved by iterating the steps II-V. Each step takes about 15 s to stabilize and each stride cycle takes 60 s to complete, owing to the thermal characteristics of the structures. The average stride length is about 1.91 mm by averaging 6 cycles, where a total locomotion distance of 11.46 mm in 364 s is achieved. Supplementary Video 1 shows the forward crawling of the robot. The axial displacement of the robot along the travel direction is plotted in Fig. 4e. The calculated average speed is 1.91 mm·min⁻¹. Similar backward locomotion at similar speed from anchored motions is
illustrated in Fig. 4d and Supplementary Video 2. The axial displacement over time appears in Fig. 4f. These results verify that the soft robots from soft heaters innervated LCE-CB can effectively perform locomotion functions.

The adaptiveness is an important feature for live soft animals to survive and interact\textsuperscript{27}. By innervating soft deformable sensors together with the heaters on the artificial muscle, soft adaptive robots have been created. We exploit ultra-thin Si optoelectronics as one example of sensing organ in the synthetic soft adaptive robot to illustrate the autonomous light sensing and actuation/motion capability. The Si optoelectronics is accomplished by transfer printing ultra-thin Si from a silicon-on-insulator (SOI) wafer with pre-defined optoelectronic properties onto a thin polyimide (PI) substrate followed by metallization and passivation. The detailed fabrication process appears in Methods, Supplementary Fig. 4, 5. Since the soft robot experiences bending during locomotion, the photodetectors in thin open mesh networked format is employed thus not to constraint the mechanical motion. Figure 5a shows a schematic illustration of the soft adaptive robot in exploded view. Two photodetector arrays sit on the surface of the soft robot. The optical image of the fabricated robot is presented in Fig. 5b. The structure of the photodetector and its optoelectronics characteristics are shown in Fig. 5c, d. The detailed designs and geometries of the soft adaptive robot are shown in Supplementary Fig. 6. While the robot has the same locomotion capability as previously described, the adaptive actuation of the bimorphs follows the photo responses of the photodetector arrays. Two photodetector arrays are involved and the response from each control the on/off of the heaters correspondingly. We used laser pointers (green and red) to shining on the photodetector array. Once the photodetector array I senses the laser light, the heater I will be activated. Likewise, the heater II will be activated upon the photodetector array II senses the light. Figure 5e shows the sequential steps of autonomous
sensing and actuation of the soft robot. The left and right columns are the schematic and optical images, respectively. After photodetector array I sense the laser light (green), the bimorph I bend upward and stabilize after 15 s, as indicated by the image II in Fig. 5e. Then shining the red laser onto the photodetector array II will active the bimorph II to bend downward, as indicated by the image III in Fig. 5e. Switching off the green laser, the bimorph will become flat and thus the front leg contact with glass substrate and form a grip owing to high friction. Finally, turning off the red laser will result in an anchor-push motion backward as the bimorph II becomes flat. The movie of adaptive locomotion appears in Supplementary Video 3. The sequential actuations are triggered based on the response of photodetectors, in an autonomous manner. The results demonstrated here reveal that the soft robots can sense the environment and respond or locomote adaptively, close to what nature creatures do.

**Conclusion**

The soft robots demonstrated in this study have numerous advantages over existing synthetic systems. The capabilities in programming the shapes locally in a controllable manner for soft structures and enabling their motions are very unique and have been achieved through simple structures. The locomotion patterns in the synthetic system closely mimic those in inchworms. The electronically innervated soft robots that can sense the environment and respond through actuating the muscles yet not confining their motions, is unprecedented. While LCE-CB is an example artificial muscle material utilized in this study, other responsive materials is broadly applicable. Although photo sensing capabilities is only demonstrated in this context, other sensing capabilities such as temperature, chemical, mechanical, etc. once designed properly can be implemented and enrich the smartness of adaptive robots. The soft robot presented in this
study is a tethered system; but it can be implemented to be fully untethered with the recent advances in soft energy harvester$^{28}$, energy storage$^{29}$, sensors$^{30}$, circuits$^{31}$, etc. The strategy of innervating the soft artificial muscle with distributed soft sensors and actuators establish foundation in addressing the key challenges in emulating soft animals and suggest a feasible approach to develop smart soft autonomous robots.
**Experimental Section**

**LCE-CB preparation**

The materials, including Anhydrous toluene, dichloromethane, 4-methoxyphenyl 4-(3-butenyloxy)benzoate, poly(methylhydrosiloxane), 11-bromo-1-undecene, hydroquinone, 1-butanol, (dichloro(1,5-cyclooctadiene)-platinum(II) and carbon black nanoparticles, were purchased from commercially available suppliers and used as purchased. The crosslinker, 1,4-di(10-undecenyloxybenzene), and the LCEs were prepared as previously reported. The LCEs were made by stirring a solution of 4-methoxyphenyl 4-(3-butenyloxy)benzoate (166.23 mg), poly(methylhydrosiloxane) (40 mg), and 1,4-di(10-undecenyloxybenzene) (12.8 mg) (for conductive LCEs, 4.38 mg of carbon black was also added) in anhydrous toluene (0.6 ml) at 35°C until fully dissolved. 30 μL of a 1 wt% solution of dichloro(1,5-cyclooctadiene)-platinum(II) in dichloromethane was stirred into the solution and then poured into a custom made PTFE mold (3 cm × 2 cm × 1 cm). The mold was placed into a heating oven at 60 °C for 30 min with a loose glass covering. Any bubbles were removed by gently shaking the mold during the first 15 min. Next, the mold was removed and was cooled by contacting the bottom of the mold with liquid nitrogen for 2 s. Then the LCE was carefully removed from the mold and cut into desired sized strips. These strips were hung vertically with a weight attached to one end to align the sample over 7 days at room temperature. The amount of weight used to align samples scales linearly with the size of the sample. For a 2.7 cm × 0.5 cm strip 4.4 g (2.2 g for conductive LCEs) of weight was used.

**Distributed open mesh based Heater fabrication**

To prepare the open mesh based heater, a glass slide was cleaned and then baked it at 110 °C for 2 min on hotplate for dehydration. The PI precursor solution (PI-2545, HD Microsystems) was
then coated on the glass by spin-casting (3000 rpm for 30 s, 1.2 µm) and the film was cured at 250 °C for 1 hr. To form heater, metal layers (Cr/Au; 3 nm/200 nm) were deposited on the PI by e-beam evaporation. The electrodes were patterned through photolithography and wet chemical etching. Thereafter another PI layer as encapsulation was formed and patterned by RIE under O₂ plasma. The fabricated heater was released from by immersed in buffer oxide etchant (BOE, 6:1) and hold by a temporary holding substrate. Finally, an ACF cable was thermally (200 °C for 1 min) bonded to the exposed electrode pads of the released device at one side and to a PCB at the other side, serving as electrical connections for external data acquisition and power supply.

**Integrated heater and Si photodetector fabrication**

To fabricate the ultrathin heater and photodetector device, an SOI wafer with 1.25 µm thick top single crystal silicon and 400 nm thick buried oxide was cleaned with acetone, IPA, DI water and then dehydrated on hotplate at 110°C for 2 min. A layer of SiO₂ (~600 nm thick) was formed on the SOI wafer by spin-on-glass (700B, Filmtronics) and then patterned with standard photolithography and etching process to create a hard mask for selective n-type doping. Since the SOI wafer is slightly doped as p-type (resistivity: 11.5 Ω·cm), commercially available phosphorous based spin-on-dopant (P510, Filmtronics) was used for the n-type doping and annealed at 950 °C for 4 min to form the n-p-p-n junction. The topmost doped Si device was patterned into 200 µm × 200 µm square arrays by photolithography and reactive ion etching (RIE) with sulfur hexafluoride (SF₆) gas and then immersed in buffer oxide etchant (BOE) for ~2 min to remove the exposed SiO₂. Subsequently, photoresist anchors near the edge of the Si squares were formed to hold the photodetector array during the following hydrofluoric acid (HF, 49%) etching to remove the buried SiO₂. The photodetector array was peeled off from the SOI wafer using a PDMS based elastomer stamp and printed onto a partially cured PI substrate. To form
interconnects for the photodetector and heater device, layers Cr/Au (3 nm/200 nm thick) were deposited on the top of the Si squares and PI substrate and then patterned by photolithography and wet etching. The whole device was encapsulated with another layer of PI film and patterned by RIE to finish the device fabrication.

**Supplementary information**
Supplementary information is available from the online or from the author.

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Figure Legends

Figure 1. Electrical Stimulation of LCE-CB and its bimorph. a, b, A free-standing LCE-CB strip with bonded ultrathin deformable heater mesh before (a) and after (b) the heater is activated. The optical images are on the left, and the FEA results are on and right. c, The IR temperature mapping of both the front and back surfaces. d, FEA simulation results of the temperature mapping of both the front and back surfaces from FEA simulation results of the LCE-CB under joule heat from ultrathin deformable heater, respectively. The applied power of the heater is ~0.237 W. e, Optical image of a bimorph with a heater sandwiched between the LCE-CB and kapton film. The inset shows the schematic in exploded view. f, Optical image of the bimorph with the heater before (left image) and after ON (right image) activation.

Figure 2. Local actuation and shape programming. a, Schematic illustration of a soft structure with two bimorphs. b, Optical image of the fabricated device. c, Shape programming locally in the soft structure through activating the individual heaters. The inset illustrates the initial flat configuration. d, e, The IR (d) and FEA simulations (e) of temperature mapping of the structure showing local temperature increase. f, FEM simulation results of the shape change which matches well with the experiment in (c).

Figure 3. Complex shape programming. a, Optical image of an LCE-CB with three independently addressable heaters, marked as I, II, and III, respectively. b, c, Schematic illustrations of the structure with the kapton film located at different positions for constructing “S” shape (b) , and rolling shape (e), respectively. d, f, Sequential optical images of the programmed shapes upon activating the heater I (left), heater I and II (middle), and all the three heaters (right) for constructing “S” shape (d) and rolling shape (f). e, g, The shapes of structure upon uniformly
heated (~80 °C) for constructing “S” shape (e) and rolling shape (g).

**Figure 4. Crawling locomotion of an inchworm inspired soft robot.** a, b, The schematic illustration (a) and optical image (b) of the designed soft robot to mimic the crawling locomotion behavior of an inchworm. c, d, The sequential steps during one crawling stride moving forward (c) and backward (d). e, f, Plots of the soft robot locomotion displacement during crawling forward (e) and backward (f) for 6 cycles.

**Figure 5. Sensing and responding of an adaptive soft robot.** a, Schematic illustration in exploded view of an adaptive soft robot. b, Optical image of the fabricated adaptive soft robot. c, Optical microscopic image of an Si photodetector. d, Dynamic photo-electrical response of the Si photo detector array. e, The sequential steps of the soft robot to sense and locomote autonomously. The left and right columns are the schematic illustrations and corresponding snap short images, respectively.
Extended Data Figures Legends

**Extended Data Figure 1. The shrinking-elongating of the LCE-CB.** a, Schematic illustration of the LCE-CB shrinking mechanism induced by phase transition. b, Images of the LCE-CB shrinking and elongating when heated and cooled. c) The shrinkage ratio of the LCE-CB at different temperature.

**Extended Data Figure 2. FEA simulation result of stress distribution in the heater and LCE-CB.**

**Extended Data Figure 3. The bimorph bending from electrical stimulation.** a, Optical images and FEA results of the bimorph’s shape configurations before (left) and after (right) electrical stimulation. b, The FEA simulation result of the strain distribution in the bimorph while bent.

**Extended Data Figure 4. The measured friction forces.** The measured static friction forces between the LCE-CB and glass plate at different temperatures. The friction force between the kapton film and glass marked in the chart is based on technical datasheets from the vendor.
Supplementary Figure Legends

Supplementary Figure 1. Interconnected heater interfacing with external circuit. a, Optical image of a heater connected with a printed circuit board through an ACF cable. b, The equivalent circuit diagram.

Supplementary Figure 2. Simplified thermo-mechanical model for bimorph bending analysis.

Supplementary Figure 3. A schematic illustration of the key steps to complete one crawling locomotion stride.

Supplementary Figure 4. The fabrication process flow of the Si photodetector array based on an SOI wafer.

Supplementary Figure 5. The fabrication process flow of the heater with photodetector array.

Supplementary Figure 6. The detailed designs of the heater and photodetector. a, The overview size of the device. b, The geometrical details of the heater. c, The geometrical details of the photodetector. d, Schematic illustration in cross-sectional view of a Si photodetector. e, Optical microscopic image of an fabricated Si photodetector array.
Electronically Innervated Adaptive Fully Soft Robots

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**Finite element analysis**

A three-dimensional thermo-mechanical model is established in ABAQUS\(^1\). The C3D8RT element is used to discretize the structures. The gold heater is modeled as a volume heat source, as verified by the experimental findings, i.e. IR temperature mapping. The free surfaces have a natural convention boundary with the coefficient of nature convection of 12 Wm\(^{-2}\)K\(^{-1}\) (ref. 2). The ambient temperature is 25 °C. The Young’s modulus, Poisson’s ratio and thermal conductivity are 79 GPa, 0.44, and 317 Wm\(^{-1}\)K\(^{-1}\) for gold\(^3\), 0.5 MPa, 0.5, and 0.4 W m\(^{-1}\)K\(^{-1}\) for LCE-CB\(^4\), 2.5 GPa, 0.34 and 0.12 W m\(^{-1}\)K\(^{-1}\) for kapton tape\(^5\), respectively. The coefficients of thermal expansion for gold and kapton tape are 15.4 × 10\(^{-6}\)°C\(^{-1}\) (ref. 6) and 17.0 × 10\(^{-6}\)°C\(^{-1}\) (ref. 7), respectively. For simplification, the constitutive relation of LCE-CB is modeled as a material with temperature-dependent orthotropic thermal expansion as indicated in Extended Data Fig. 1c. When the power is turned on, the temperature increase induces the shrinking of LCE-CB, which corresponds to the loading process. When the power is retrieved, the temperature decreases and the LCE-CB returns back to its original configuration, which corresponds to the unloading process.

**Thermo-mechanical model for bimorph bending**

A simple thermo-mechanical model is established to predict the bending of the bimorph. A one-dimensional thermal model, schematically shown in Supplementary Fig. 2, is established since the in-plane dimension of the gold heater (17 mm×9.4 mm) is much larger than total thickness of the bimorph (~0.55 mm). The gold heater is modeled as a planar heat source with the total power \(Q\) at the interface between LCE-CB and Kapton tape since its thickness is very thin (~2.6 µm). The natural convection boundaries are applied at both the top and bottom.
surfaces of the bimorph. The temperature increase from the ambient temperature, $\Delta T = T - T_0$, satisfies

$$\frac{\partial^2 \Delta T}{\partial z^2} = 0,$$

which gives the temperature increase in LCE-CB and Kapton tape as

$$\Delta T_{\text{LCE}} = A_{\text{LCE}} z + B_{\text{LCE}},$$
$$\Delta T_p = A_p z + B_p,$$

(2)

where the subscripts LCE and P denote the LCE-CB and kapton film, respectively. The coefficients $A$ and $B$ are obtained from the natural convection boundaries and continuity conditions at the interface as

$$A_{\text{LCE}} = -\frac{Q(k_p + ht_p)}{2k_p k_{\text{LCE}} + h(k_{t_{\text{LCE}}} + k_{t_p})},$$
$$B_{\text{LCE}} = \frac{2k_p k_{\text{LCE}} + h(k_{t_{\text{LCE}}} + k_{t_p})}{Q} \left[ (k_{\text{LCE}} + ht_{\text{LCE}}) t_p + (k_p + ht_p) t_p + \frac{k_p (k_{\text{LCE}} + ht_{\text{LCE}})}{h} \right],$$
$$A_p = \frac{Q(k_{\text{LCE}} + ht_{\text{LCE}})}{2k_p k_{\text{LCE}} + h(k_{t_{\text{LCE}}} + k_{t_p})},$$
$$B_p = \frac{Qk_p (k_{\text{LCE}} + ht_{\text{LCE}})}{h[2k_p k_{\text{LCE}} + h(k_{t_{\text{LCE}}} + k_{t_p})]}$$

(3)

where $k$ is the thermal conductivity, $h$ is the coefficient of natural convection, and $t$ is the thickness. For a temperature increase of 70 °C, the thermal expansion of Kapton tape is on the order of 0.07 %, which is much smaller than the shrinking of LCE-CB (~24 %). Therefore, the bending from mechanical mismatch mostly attributes to the shrinking of LCE-CB. The radius of bending curvature under the mechanical mismatch of $\varepsilon_{\text{LCE}}$ is given by

$$8$$
\[
R \approx \frac{E_p}{E_{LCE} t_{LCE}} \left( \frac{t_p}{E_{LCE}} \right)^2 + \frac{E_{LCE}}{E_p t_{LCE}} \left( \frac{t_p}{t_{LCE}} \right)^2 + 2 \left( \frac{2}{t_{LCE}} + \frac{2 t_{LCE}}{t_p} + 3 \right) \frac{1}{6} \left( 1 + \frac{t_{LCE}}{t_p} \right) \varepsilon_{LCE},
\]

where \( E = E(1 - \nu^2) \) is the plane-strain modulus with \( E \) as the Young’s modulus and \( \nu \) as the Poisson’s ratio, \( t \) is the thickness. The shrinkage of LCE-CB, \( \varepsilon_{LCE} \), can be obtained from Extended Data Fig. 1c through its dependence on the temperature, which is given by the averaging \( \Delta T_{LCE} \) over the thickness as

\[
\Delta T_{LCE} \approx \frac{Q t_{LCE}}{k_{LCE}} \left[ 2 + \frac{h t_{LCE}}{k_{LCE}} \right]^{-1} \left[ \left( 1 + \frac{h t_{LCE}}{k_{LCE}} \right) \frac{k_{LCE}}{k_p} \frac{t_p}{t_{LCE}} + \frac{k_{LCE}}{h t_{LCE}} + \frac{1}{2} \right],
\]

where \( k_p \gg h t_p \) is adopted since \( k_p/(h t_p) \sim 100 \) in experiments. The normalized radius of bending curvature inversely proportional to the shrinking strain in LCE-CB layer, and depends also on the two non-dimensional parameters: the normalized modulus ratio and the normalized thickness ratio. For the experimental values of, \( t_{LCE} = 500 \mu m \), and \( t_p = 50 \mu m \), the predicted radius of bending curvature from Eq. (4) is 3.76 mm, which agrees reasonably well with FEA (3.29 mm). Equations (1) and (2) establish the design basis for LCE-CB bimorph soft robots.

References

4. Torras, N. *et al.* Tactile device based on opto-mechanical actuation of liquid crystal


Figure 1

(a) Power OFF LCE-CB
(b) Power ON LCE-CB
(c) Front Back
(d) Front Back
(e) kapton film LCE-CB Heater
(f) Power OFF Power ON

Temperature (°C)
Figure 2
Figure 3
Figure 4
**Figure 5**
Extended Data Figure
Extended Data Figure 1

(a) Schematic representation of the crosslinking and shrinking ratio of the mesogen at different temperatures. 

- **T < 75 °C, Nematic:**
  - Backbone
  - Crosslink
  - Mesogen

- **T > 75 °C, Isotropic:**

(b) Photographs showing the shrinking ratio of the mesogen at different temperatures:

- **25 °C**
- **80 °C**
- **25 °C**

(c) Graph showing the shrinking ratio (%) vs. temperature (°C):

- Shrinkage ratio increases with temperature from 25 °C to 110 °C.

**Extended Data Figure 1**
Extended Data Figure 3
Extended Data Figure 4
Supplementary Information
Supplementary Figure 1
Supplementary Figure 2
Supplementary Figure 3
a. Prepare SOI wafer
Si substrate

SiO₂

Si, 1.25 μm thick

b. SiO₂ formation

SiO₂

c. Pattern SiO₂ for mask

SiO₂

d. n⁺ doping and remove SiO₂ layer

n⁺ doping region

SiO₂

e. Isolate Si PD array using Photolithography & RIE

SiO₂

f. Partially etch SiO₂ using BOE

SiO₂

g. Form photoresist anchors for holding

Photoresist anchors

h. Undercut etching SiO₂ using HF

SiO₂

Supplementary Figure 4
a. PI spin casting on glass

b. Transfer printing photodetector array on PI

c. Metallization for heater and interconnection

d. Forming PI encapsulation by spin casting

e. Pattering by RIE

f. Releasing the device using BOE

Supplementary Figure 5
Supplementary Figure 6