Visible and infrared three-wavelength modulated multi-directional actuators

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In recent years, light-guided robotic soft actuators have attracted intense scientific attention and rapidly developed, although it still remains challenging to precisely and reversibly modulate the moving directions and shape morphing modes of soft actuators with ease of stimulating operation. Here we report a strategy of building a multi-stimuli-responsive liquid crystal elastomer soft actuator system capable of performing not only multi-directional movement, but also different shape morphing modes. This strategy is based on the selective stimulation of specific domains of the hierarchical structured actuator through the modulation of three wavelength bands (520, 808, 980 nm) of light stimulus, which release the actuation system from light scanning position/direction restriction. Three near-infrared dual-wavelength modulated actuators and one visible/infrared tri-wavelength modulated multi-directional walker robot are demonstrated in this work. These devices have broad application prospects in robotic and biomimetic technology.

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n recent years, soft actuators as one kind of the most exciting and attractive soft matter materials, have emerged as a signif-
ificant and extensive research area, and dramatically accel-
erated the development of biomimetic devices, manipulators,
sensors, and robotic technology, owing to their advantageous
features, such as multiple degrees of freedom, strong adaptability
to changing surroundings, inexpensive raw materials, diversiform
actuations, and integration of multi-functionality, etc. How-
ever, despite considerable progress in the research of stimuli-
responsive soft actuators, it still remains challenging to preci-
sely and reversibly modulate the moving directions and even the
shape morphing modes of soft actuators with robust macroscopic
motions, fast responsive rates, and in particular ease of stimu-
lation operation.

To control the moving directions of robotic soft actuators, light
as a wireless remote control, is undoubtedly the most effective
and predominant stimulus. Up till now, most of light-guided
robotic soft actuators could only execute one-way directional or
two-way bidirectional moving. Few four-way (multi-direc-
tional) actuators relied on meticulously controlling the spatial
distribution of light on the sample surfaces to reversibly modulate
the moving directions of soft actuators. In another word, scien-
tists had to precisely adjust the scanning position/direction/
intensity of light, to induce the local asymmetric shape deforma-
tions of actuators and consequently realize the macroscopic
directional moving changes, such as turning left and right,
coming forth and back, etc. For example, to produce a bidirec-
tional moving, researchers shined the laser light on the rear part
of the actuator to generate thermal gradient stress and force it to
come forward; and shined the laser light on the head part to force
it to go backward. In another approach, scientists waved the laser
from one side to the other side of the actuator to force it to go left,
and waved the laser in the opposite direction to force the actuator
to go right, etc. However, this commonly used light modulation
strategy seriously lacks ease of operation, in particular when
handling microscale robotic soft actuators. It is hard to imagine a
scenario that doctors used an extremely thin beam of light,
located it through skin tissues accurately on a micron-sized
specific region of a microscale soft robot planted inside organ-
isms, and hoped it would move along a designed pathway to
perform medical treatments. To remove the operation and con-
figuration restriction of light stimuli is an important and urgent
subject in soft actuator research area.

The integration and modulation of diversified shape morphing
modes (such as shrinking, bending, curling, etc.) within a same
soft actuator, is another intriguing challenge. One effective
strategy was to build multi-stimuli-responsive soft actuators with
hierarchical architectures possessing different functionalities
towards different stimuli. For example, several multi-stimuli-
responsive liquid crystal elastomers (LCEs)-based bilayered
soft actuators that could undergo bending and chiral twisting,
right-handed and left-handed helical curlings in response to
ultraviolet (UV) and near-infrared (NIR) light stimuli, have been
fabricated by incorporating azobenzene chromophores and NIR
photothermal conversion dyes into the top-layer and bottom-
layer LCE matrices respectively. Another similar strategy took
advantage of the difference of shape deformations induced by
photochemical conversion and photothermal conversion effects
to modulate the deformation degrees of soft actuators. Nonetheless, all the above light-modulated multi-motion-mode actuators must involve both the visible/infrared (vis/IR)-triggered
photothermal-induced phase transition effects and UV-induced trans-cis isomerization of azobenzene chromophores. However,
due to the very limited light penetration capability, UV-guided
soft actuator systems have strict scanning direction restriction.
Moreover, UV light can only efficiently drive the actuations of
thin polymeric films, while the applications of several hundred-
micrometer-thick soft actuators are severely plagued by the very
slow UV-responsive rates. Thus, exploration of UV-
alternative light-guided multi-motion-mode soft actuator sys-
tems becomes the second objective of this work.

To address the above two challenges, we report in this
manuscript a strategy of constructing a multi-stimuli-responsive
hierarchical structured LCE soft actuator system capable of per-
forming not only multi-directional moving, but also different
shape morphing modes. This strategy is based on the selective
stimulation of specific domains of the hierarchical structured
actuator through the modulation of three-wavelength bands (520
nm vs. 808 nm vs. 980 nm) of visible/NIR light stimulus, which
help the LCE actuation system free of light scanning position/
direction restriction. Three NIR dual-wavelength modulated
actuators including a two-way switch, a dual-motion-mode shape
morpher and a two-way walker, and one vis/NIR tri-wavelength
modulated multi-directional walker robot are demonstrated
herein.

Results

Design and preparation protocol. The logic of this design is to
build multiple independent and non-interfered photothermal
conversion systems responding to different wavelength bands of
light, in separate regions of a hierarchical structured LCE mate-
rial. In such a design, the local asymmetric shape deformations
of the LCE actuators will not be influenced by the varied scanning
position/direction/intensity of light, but the photon energy
absorption difference between different regions.

The detailed chemical components used in this work are shown in
Fig. 1a, we chose the classical polysiloxane-based LCE system
including poly(methylhydrosiloxane) (PMHS), a mesogenic monomer
4-but-3-enoxy-benzoic acid 4-methoxy-phenyl ester (MBB), Karstedt catalyst and two crosslinkers (11UB and VBPB)
which were mixedly used for tuning the LC-to-isotropic phase
transition temperature ($T_c$) of the LCE material. Most impor-
tantly, three organic NIR absorbing dyes, YH79648, commer-
cially available Dye1002 and Disperse Red169,70 were selected as
three independent photothermal conversion fillers, which had
sharp and almost non-interfered absorptions (around 796 nm,
1005 nm, and 512 nm respectively) in the vis/IR region as shown in
Fig. 1c.

The fabrication protocols of the LCE actuators are schemati-
cally illustrated in Fig. 1b. In general, four kinds of fundamental LCE films, LCE1002, LCE796, LCE512, and LCE0 were prepared. The LCE1002, LCE796, and LCE512 films, designated as the photo-responsive functional parts, were uniaxial-stretched monodomain LCE films doped with three organic dyes (Dye1002, 0.03 wt%; YH796, 0.03 wt%; Disperse Red1, 0.11 wt%) respectively, whereas LCE0 was a polydomain
LCE film without mechanical alignment nor incorporation of
any photothermal conversion fillers. Meanwhile, the mole percentages of two crosslinkers VBPB and 11UB in the three
LCE matrices were different. In LCE0, we applied 8 mol% of
VBPB and 2 mol% of 11UB as the crosslinkers; in LCE512, we
used 10 mol% of 11UB solely; while LCE1002 and
LCE796 systems had 1.7 mol% of VBPB and 8.3 mol% of
11UB instead. The addition of more VBPB was used for
achieving a higher $T_c$ (88.3 °C, Supplementary Fig. 1a) than
those (74.5–71.5 °C, Supplementary Fig. 1b–d) of LCE796,
LCE1002, and LCE512 films, to ensure that LCE0 film could
preserve enough mechanical strength to support the actuator
system when LCE1002 or LCE796 or LCE512 film was heated to
above its $T_c$. The dye-doped LCE1002, LCE796, and LCE512
films, compared with three neat organic dyes, had broader
optical absorption peaks which slightly red-shifted to 806 nm, 1025 nm, and 513 nm respectively, as demonstrated in Fig. 1c.

With these four fundamental LCE films in hand, we could synthesize bilayer- or trilayer-structured LCE actuators by adopting the classical two-step hydrosilylation crosslinking method. As shown in Fig. 1b, the corresponding chemical reagents of LCE1002, LCE796, LCE512, and LCE0 dissolved in toluene were poured into four polytetrafluoroethylene (PTFE) rectangular molds (4.0 cm long x 2.0 cm wide x 1.5 cm deep) respectively, followed by ultrasonic treatments for 1.5 min. After heating in an oven at 60 °C for 2 h, these pre-crosslinked LCE films were removed from molds, and then cut into ribbons, dried for several hours. The pre-crosslinked LCE1002, LCE796, and LCE512 strips were uniaxially stretched along the longitudinal
direction to obtain a monodomain alignment of mesogens, whereas LCE0 was used without any mechanical treatment so that its LC molecules remained in a polydomain state as shown in Supplementary Fig. 2. Subsequently, the pre-crosslinked LCE1002 or LCE796 or LCE512 strip was stuck on the top of the pre-crosslinked LCE0 film, to provide bilayered LCE material (named as BLCE1002 or BLCE796 or BLCE512). The trilayered LCE material (TLCE) was prepared by stamping one LCE796 strip on one side, and one LCE1002 strip on the reverse side of the pre-crosslinked LCE0 film. Eventually, the bilayer- or trilayer-structured LCE material would be formed through a further heating in the oven at 60 °C for 2 days to complete the second-step hydrosilylation crosslinking procedure, which could not only lock the monodomain/polydomain mesogenic alignment of each LCE layer, but also spontaneously glue all the LCE layers together due to the covalent bonding of residual unreacted vinyl groups and Si–H groups on the interfaces of the pre-crosslinked LCE samples94, as demonstrated in Supplementary Fig. 3. The thickness of the TLCE film was ca. 500 μm (Supplementary Fig. 4).

Vis/IR wavelength-selective response. The vis/IR wavelength-selective responsive behavior of this LCE system was first investigated. As shown in Fig. 1d, BLCE796, BLCE1002, and BLCE512 films were placed side by side on the table, the right end of each sample was fixed, and vis/NIR light was illuminated on both samples at the same time. Under the irradiation of 808 nm NIR light (0.18 W cm⁻²), the temperature of BLCE796 film quickly jumped to 74.5 °C in 32 s (Fig. 1e), which exceeded the Tg of the upper LCE796 layer, and triggered the upward bending of the BLCE796 film, whereas the temperatures of BLCE1002 and BLCE512 films reached to ca. 48 °C and 40 °C only. On the contrary, when exposed to 980 nm NIR light (0.19 W cm⁻²), the temperature of BLCE1002 film quickly rose to above the Tg (74.5 °C) of the upper LCE1002 layer in 26 s, which induced the macroscopic upward bending motion of BLCE1002 film, while BLCE796 and BLCE512 films kept almost motionless since their surface temperatures were slightly raised to around 39 °C and 33 °C, as shown in Fig. 1f. Compared with YHD796 and Dye1002, Disperse Red1 had much weaker photothermal conversion efficiency, thus the concentration of Disperse Red1 in LCE512 was increased from 0.03 to 0.11 wt%. As shown in Fig. 1g and Supplementary Movie 1, under the illumination of 520 nm light (47 mW cm⁻²) for 23 s, the surface temperatures of BLCE1002, BLCE796, and BLCE512 films appeared as 44 °C, 42 °C, and 71.5 °C, which only caused the upward bending motion of BLCE512 film. The photo-responsive bending rates of BLCE796, BLCE1002, and BLCE512 films were evaluated by recording the included angle a between line l₁ (tangent line to the left endpoint of the arc bending sample) and the horizontal line l₀, against the light illumination time, as plotted in Fig. 1h–j. It could be seen that all BLCE796, BLCE1002, and BLCE512 films performed a continuous bending motion, and achieved their maximum bending angles at 111°, 103°, and 115°, after 33 s stimulation of 808 nm NIR light, 26 s stimulation of 980 nm IR light, and 23 s stimulation of 520 nm visible light respectively.

Two-way soft actuator demonstrations. Encouraged by the vis/IR wavelength-selective actuation results, we started to use this hierarchical structured LCE system to fabricate diverse multi-wavelength modulated actuators. The first example was a two-way switch based on a trilayer-structured LCE material. As schematically illustrated in Fig. 2a, when a TLCE actuator was stimulated by one NIR light (808 nm or 980 nm), either the corresponding longitudinally aligned LCE796 or LCE1002 layer would respond and shrink when the photothermal energy was accumulated enough to raise its temperature to above the Tg, whereas the middle LCE0 layer would not actuate since its mesogens were arranged in a polydomain manner. Meanwhile, LCE0 with low thermal conductivity (ca. 0.28 W m⁻¹ K⁻¹, measured by using the laser flash analysis method92, Supplementary Fig. 5) acted as a soft thermal insulating layer preventing the transmission of the heat generated from the top layer to the bottom layer, to some extent, so that the bottom LCE796 or LCE1002 layer could not obtain enough thermal energy to trigger the LC-to-isotropic transition-induced actuation, and the soft thermal insulating layer thickness should be at least twice of the surface layer thickness, as demonstrated in Supplementary Figs. 6 and 7. Overall, the gradient stress generated between the top layer and middle/bottom layers would induced upwards/downwards bending.

A demonstration was shown in Fig. 2b and Supplementary Movie 2, such a TLCE film could be stimulated by two NIR sources to execute opposite bending modes. Under the irradiation of 808 nm NIR light, TLCE film would bulge and bend downwards, and further recover back to the original linear structure after the removal of NIR light. When the same TLCE film was scanned by 980 nm NIR light, an opposite upward bending was found. The surface temperature variations of the bottom LCE796 and top LCE1002 layers of TLCE film during the two NIR light irradiation process were further measured by using a thermal imager instrument (FLUKE Ti90) which always showed the highest temperature, and a thermocouple thermometer (CEM DT-610B) which was adopted to detect the temperature of the low-temperature layer at the same time. As indicated in Fig. 2c,d, under the irradiation of 808 nm NIR light (0.18 W cm⁻²), the surface temperature of the bottom LCE796 layer was always increasing more quickly than that of LCE1002 layer, reached to its Tg (74.5 °C) in 33 s and stabilized at a saturated temperature of ca. 91 °C, whereas the surface temperature of the upper LCE1002 layer could just rise to ~66 °C. When stimulated by 980 nm NIR light (0.19 W cm⁻²), the surface temperature of LCE1002 layer was always higher than that of LCE796 layer, reached to its Tg (74.5 °C) in 26 s and stabilized at ca. 87 °C while the LCE796 layer could only go up to 69 °C.

A circuit of two light-emitting diode (LED) lights, using this TLCE film coated with conductive material as a two-way switch control, is schematically illustrated in Fig. 2e. Stimulating the TLCE switch with 980 nm NIR light, led to a rightward bending, and closed the right circuit to turn on the blue light. After the removal of 980 nm NIR light, the rightward bending switch recovered back to its original state, the right circuit opened and the blue light went out. A subsequent stimulation of 808 nm NIR light forced the TLCE switch to bend leftwards, closed the left circuit to turn on the green light. After the removal of 808 nm NIR light, the left circuit opened and the green light was turned off, as shown in Fig. 2f and Supplementary Movie 3.

The second example was a dual-motion-mode shape morpher. As demonstrated in Fig. 3a, a TLCE actuator was fabricated with a crossed angle of 45° between the alignment directions of LCE796 and LCE1002. Such a TLCE actuator could execute a right-handed helical twisting when it was irradiated by 808 nm NIR light and preform a bending motion under the stimulation of 980 nm NIR light respectively, as shown in Fig. 3b and Supplementary Movie 4. To quantitatively characterize the helical rotation and bending motions of this TLCE ribbon, the twist angle a which was defined as a 360° rotation between line OM and line ON of the ribbon (Fig. 3c), and the bending angle θ which was defined as the angle between line l₁ (tangent line to the right endpoint of the arc bending sample) and horizontal line l₂, were measured respectively, as presented in Fig. 3d, e. It could be
seen that the twist angle $\alpha$ increased slowly during the beginning 4 s, then grew rapidly in the next 29 s, and eventually achieved a maximum angle $\alpha$ of 450° under the stimulation of 808 nm NIR light (0.18 W cm$^{-2}$). When exposed to 980 nm NIR light (0.19 W cm$^{-2}$), the bending angle $\theta$ kept almost constant in the original 7 s, and then sharply increased to ca. 54° in the next 20 s. Compared with the previously reported dual-motion-mode shape morphers built on azobenzene LCE system which required tens of minutes for actuating, this TLCE ribbon could efficiently perform both motion modes in seconds timescale.

The third example was a two-way inchworm-mimic walker capable of performing reversible bidirectional moving. The fabrication design is schematically illustrated in Fig. 4a, the two-way walker was a bilayered LCE film of which the first layer was a LCE0 ribbon and the second layer was a head-to-head joint of LCE1002 and LCE796 ribbons with both alignment directions parallel to the ribbon’s longitudinal orientation. Under the stimulation of 980 or 808 nm NIR light, the inchworm-like walker could selectively undergo asymmetric downward bending as shown in Fig. 4b. When stimulated by 808 nm NIR light, the right BLCE796 part acted as the inchworm body, bulged and bent downwards, whereas the left BLCE1002 part acting as the inchworm head, was passively dragged towards the BLCE796 part. Although, both BLCE1002 and BLCE796 parts moved towards the center, the asymmetric shape deformation provided the BLCE796 part a larger inclination which was fundamental in producing moving result. According to Amontons’ law, the friction force $F = \mu N$, where $\mu$ is the friction coefficient, $N$ is the normal force component. After the removal of 808 nm NIR light, the right BLCE796 part would obtain a bigger friction than that of
As shown in Fig. 4d, when the light source was placed at a spot in stimulating light intensity were two crucial parameters way from the sample, the maximum moving speed of the 16-mm-long inchworm-like walker would decrease from $V_{\text{left}} = 5.26 \text{ mm min}^{-1}$ and $V_{\text{right}} = 5.88 \text{ mm min}^{-1}$ to $V_{\text{left}} = 0.81 \text{ mm min}^{-1}$ and $V_{\text{right}} = 1.33 \text{ mm min}^{-1}$, along with the $W/L$ ratio increasing from 29% to 75%, under the stimulation of 808 and 980 nm NIR light respectively. It indicated that the actuator with smaller $W/L$ ratio would obtain faster moving speed. Meanwhile, the moving speed of the inchworm-like walker was plotted in relation to the stimulating light intensity which could be simply tuned by varying the linear distance ($d$) between the sample and the light source, and accurately measured by using an optic power meter. As shown in Fig. 4e, the moving speed was observed to decrease almost linearly with the increasing of $d$ value. At $d = 5 \text{ cm}$, the speeds of $V_{\text{left}}$ and $V_{\text{right}}$ were 3.90 and 5.15 mm min$^{-1}$, respectively, and decreased to 0.71 and 1.43 mm min$^{-1}$ when the $d$ value increased to 8 cm. Obviously, weaker light intensity would slower the moving speed of the two-way walker.

Three-wavelength modulated multi-directional actuator. Eventually, we prepared a vis/IR three-wavelength modulated multi-directional walker robot, as schematically illustrated in Fig. 5a. The multi-directional walker was a bilayered LCE film of which the top layer was a Y-shaped three-legged LCE0 film, and the bottom layer was consisted of LCE002, LCE796, and LCE512 ribbons which were glued onto one of the three legs each and assigned as the front leg, left rear leg, and right rear leg respectively. Under the stimulation of 980 nm NIR light, the front leg of the walker could selectively undergo asymmetric downward bending and forced the three-legged robot to move backward. When stimulated by 808 and 520 nm light simultaneously, the two rear legs of the walker bulged together, bent downwards and pushed the three-legged robot to move forward. If either 808 nm NIR light or 520 nm green light was irradiated on the robot, only one rear leg would perform downward bending and make the walker turn to the opposite direction.

To investigate the robot moving statistically, the real-time position coordinate of the midpoint A of the three-legged walker under light stimulation (Supplementary movie 6) was analyzed by Tracker software, and plotted in Fig. 5e–h. We set (0, 0) in $x$–$y$ plane as the starting point of the midpoint A of the LCE walker, and recorded its position coordinate once after every on/off light illumination cycle. It could be seen in Fig. 5f that when the walker robot was stimulated by the repeating on/off illumination cycles of either simultaneous 808/520 nm light (40 s per cycle, including
12 s light on and 28 s light off) or 980 nm NIR light (81 s per cycle, including 60 s light on and 21 s light off), the location distribution of the midpoint A of the robot in one round trip was almost in a straight line. When exposed to the repeating on/off illumination cycles of 520 nm light (34 s per cycle, including 15 s light on and 19 s light off), the midpoint A would first turn left-forward to position C, whereat the walker could continue to move forward after the light source was replaced with both 808 and 520 nm light (Fig. 5g). Similarly, when the wavelength of light was changed to 808 nm (27 s per cycle, including 7 s light on and 20 s light off), the walker robot would first move right-forward to position D, followed by moving forward in a straight line under the repeating on/off illumination cycles of 808 and 520 nm light simultaneously (Fig. 5h).

In addition, the walker robot was able to realize more complex moving mode, such as the parallel parking of a vehicle as schematically illustrated in Fig. 6a, b. It could be seen from Fig. 6c, d and Supplementary movie 7 that the walker robot could move horizontally from position A to the parallel right position D in three steps: (1) moving right and forward to position B under the repeating on/off illumination cycles of 808 nm light; (2) turning left and forward from position B to position C under the repeating on/off illumination cycles of 520 nm light; (3) reversing backward from position C to the destination D under the repeating on/off illumination cycles of 980 nm light. These experiments demonstrated that the modulation of the wavelength bands of light stimulus could effectively control the multidirectional moving of such a vehicle-like LCE walker robot.

**Discussion**

In conclusion, we describe in this manuscript a series of multi-wavelength modulated soft actuators capable of performing reversible multi-directional moving and dual-motion-mode shape morphing. Integration of multiple independent and non-interfered photothermal conversion systems in a hierarchical structured LCE material, would generate gradient stress inside the LCE matrices and induce the consequent asymmetric shape deformations of the macroscopic actuators, under the stimulation of different wavelengths of light.

This multi-stimuli-responsive actuator design has one obvious advantage: the multi-directional moving and dual-motion-mode shape morphing of these multi-wavelength modulated soft actuators are induced by the photon energy absorption difference between multiple independent and non-interfered photothermal conversion regions, and thus are free of light scanning position/direction restriction. For example, as shown in Fig. 2f, the two NIR light sources which were both set at the same spot, could effectively drive the TLCE switch to bend either leftwards or rightwards. The two walker robots are another striking example.
Fig. 5 Photo-modulated multi-directional bilayered LCE walker. **a** Schematic illustration of the fabrication protocol and the moving mechanism of a multi-directional bilayered LCE walker. Photographs showing the multi-directional walker (b) moving either forward or backward upon on-off irradiation of 808/520 nm or 980 nm light, (c) moving left and then forward upon on-off irradiation of 520 nm and then 808/520 nm light, (d) moving right and then forward upon on-off irradiation of 808 nm and then 808/520 nm light. (e) The definition of the starting position coordinate of the LCE walker in x-y plane. The real-time position coordinate of the midpoint A of the LCE walker recorded in (f) moving forward and backward manner, (g) moving left and then forward manner, (h) moving right and then forward manner. Scale bar = 1.0 cm. Source data are provided as a Source Data file.

Fig. 6 Photo-guided parallel parking of LCE walker robot. Schematic illustration of **a** the parallel parking of a vehicle and **b** how a vehicle accomplishes such a horizontal movement. **c** Photographs showing the process of such a vehicle-like walker robot moving horizontally from position A to position D under the stimulation of 808 nm, 520 nm, and 980 nm light (scale bar = 1.0 cm). **d** The real-time position coordinate of the midpoint A of this LCE walker recorded in parallel parking manner. Source data are provided as a Source Data file.
As long as light was irradiating on the sample, the walkers could freely change the moving direction by just tuning the wavelength of the stimulating light, and required no further meticulous arrangement of the incident angle or scanning position of the incoming light source (Figs. 4c, 5b–d). Furthermore, since the vis/IR light stimuli possessed high tissue penetration capabilities, these light-guided robotic soft actuators have broad application prospects in biomedical technology.

We believe that this strategy could be further adopted to build four or even more independent photothermal conversion systems in hierarchical structured polymeric matrices to synthesize multi-wavelength modulated soft actuators with more functionalities, as long as we could find more organic photothermal conversion dyes which had non-interfered optical absorptions in the visible and infrared light regions. We hope this work would pave the way for multi-stimuli-responsive soft actuators with robust macroscopic motions, fast responsive rates and ease of stimulating operation.

Preparation of the trilayered LCE material. In general, two pre-cross-linked LCE1002 and LCE796 films (2 cm long × 1 cm wide) were uniaxially stretched to ca. 130% of their original lengths. Then, the pre-crosslinked LCE1002 film was stamped on the top of a pre-cross-linked LCE0 film, whereas the pre-crosslinked LCE796 film was stuck on the reverse side of the pre-cross-linked LCE0 with a crossed angle of either 0° or 45° between the alignment directions of LCE796 and LCE1002. The trilayered LCE sample was placed on an oven and heated at 60 °C for 6 h.

Preparation of the multi-directional LCE walker. In general, three fully cross-linked LCE films including a LCE796 (7 mm long × 2.5 mm wide), a LCE512 (7 mm long × 2.5 mm wide) with a stretching ratio about 150% of their original lengths and a LCE1002 (7 mm long × 3 mm wide) with a stretching ratio ~140% of its original length, were carefully glued to a Y-shaped three-legged LCE film by using a silicone adhesive (HF-T326, Dongguang Fangguan Industrial Materials Co. Ltd.). Subsequently, the bilayered LCE film was kept at room temperature for 2 h to provide the desired multi-directional LCE walker.

Data availability

The source data underlying Figs. 1c, e–j, 2c, d, 3d, e, f, 5–h, and 6d, Supplementary Figs. 1, 3c, 4, 5, and 7b are provided as a Source Data file. The data underlying all figures in the main text and supplementary information are publicly available at https://doi.org/10.6084/m9.figshare.9860255.v1.

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Additional information

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