Light-Driven Soft Robot Mimics Caterpillar Locomotion in Natural Scale

Light driven soft robot mimics caterpillar locomotion in natural scale

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Abstract: Caterpillars use travelling deformation waves to propell their soft bodies in stepping motion. Several demonstrations of soft robot to date failed to realize this behavior in natural scale, mainly due to the limits in the miniaturization and control of individual actuators. Here, we report a natural scale caterpillar robot using opto-mechanical actuation in liquid crystalline elastomer structure. The robot body is made of light sensitive elastomer film with patterned molecular alignment that enables to introduce travelling deformation by sequential, non-reciprocal illumination. The robot demonstrates different gaits and is capable of performing various tasks in complex environments. The light-driven, miniature elastomer robot concept opens up new possibilities in adaptive locomotion with soft matter.

Introduction

Soft animals such as earthworms, snails and larval insects can deform their bodies to navigate in complex three dimensional topographies and to adapt to the environmental confinements. This approach to locomotion has inspired scientists and engineers to seek for similar strategies for bio-inspired soft robots [1, 2]. Unlike conventional hard-body machines with rigid joints and links, constructions based on soft matter have extra degrees of freedom that allow for self-shaping during the robotic motion in an adaptive way. In particular, continuous, rather than discrete deformation allows for adaptation to many situations the robot may encounter. Recently developed soft robots are able to perform various tasks in confined spaces [3], grip arbitrary-shaped objects [4, 5] or jump, mimicking biological behaviors [6, 7].

Caterpillar terrestrial locomotion had been thoroughly studied [8, 9] and their kinematics, notably the traveling deformation wave locomotion, has been an inspiration for soft robots [10-12]. Realizing a natural size caterpillar robot faces two challenges. First, the size of available actuators, either based on shape-memory alloys [13], dielectric elastomers [14] or pneumatic/fluidic artificial muscles [15, 3] prevents miniaturization. Not only are the smallest robots to date tens of centimeters in size, but they also require external power supply via wires or tubing. Second, travelling wave motion requires that many discrete actuators within the robot body are controlled in synchrony [10].

These two factors indicate that approaching natural scale in caterpillar-inspired or similar robots calls for both novel materials for structural miniaturization and new approaches to the motion control.

Liquid Crystalline Elastomers (LCEs) are smart materials that can exhibit large shape change under light stimuli [16]. With the recently developed laser lithography and molecular alignment engineering [17, 18] it is now possible to pattern these soft materials in arbitrary three dimensional forms with a pre-defined actuation performance. The light-induced deformation can vary with illumination conditions, allowing one LCE structure to perform different actions, while a conventional robot would need numerous discrete actuators, each of them individually controlled. In one of the recent works, with the illuminating light field modulated with a travelling wave pattern and projected onto an LCE micro-filament, the latter deforms into a shape following the light wave pattern and thus propels itself in a liquid [19].

Here we report a soft robot that mimics caterpillar locomotion in natural scale, powered and controlled remotely with light. The robot is made of a stripe of LCE film with a patterned molecular alignment that enables curling deformation under light illumination. Travelling deformation pattern is implemented by scanning a laser beam along the robot body. By controlling the travelling deformation pattern the robot exhibits different gaits while walking on horizontal surfaces. It can also perform in difficult environments that is demonstrated by walking up a slope, squeezing through a narrow slit and execute various tasks, e.g. moving (pushing) an object around.

Mimicking caterpillar locomotion in a soft robot

Caterpillars have soft cylindrical bodies, with three pairs of thoracic legs in the front, two to five pairs of soft legs on the abdomen and terminal legs on the back, as shown in Figure 1a. In each cycle of crawling, terminal legs are first released from the ground and move forward to re-contact with the substrate. Sequentially, each leg on the abdomen is lifted and takes one step forward, forming a wave-like pattern travelling from tail to head. The displacement of each leg in one crawling circle is approximately one step length.

Rather than constructing the caterpillar robot with individual actuators (active legs), our approach is to implement a single light-sensitive LCE film stripe, and to use spatially modulated light field to trigger synchronized, time-dependent deformations within different parts of the robot body, as shown in Figure 1b. A laser beam is firstly projected on the tail (the trailing end of the stripe) and it deforms into a curly shape upon absorbing the light, at the same time lifting from the ground and shortening. By scanning the laser beam towards the robot head (the leading end), a travelling deformation is created, like in crawling caterpillars. After the light beam completes the scan, the robot returns to the original flat state, thus completing one step forward in the stepping cycle.

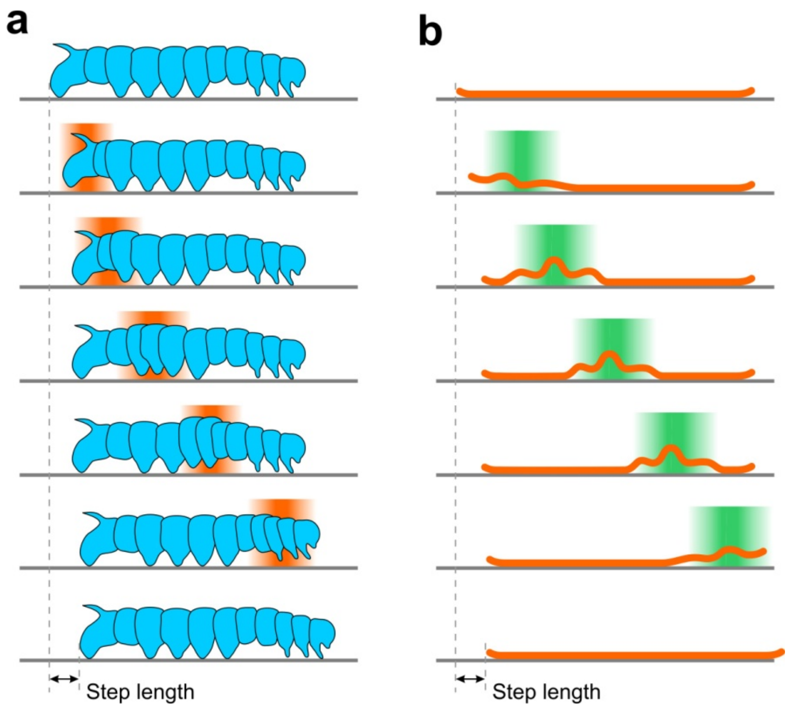

Figure 1 Traveling deformation enables walking locomotion in caterpillars and soft robots. a, Caterpillars propel themselves by contracting a part of their bodies and at the same time detaching the respective legs from the ground. The deformation wave travels from the tail to the head. Orange shading indicates the region of the contracted and lifted segments. **b**, A soft robot mimics the caterpillar gait by local contraction associated with curly bending. Green shading indicates the area illuminated with laser beam that induces the robot curling deformation. **a** adopted from [20].

Material and fabrication

The caterpillar robot is made of liquid crystalline elastomer film with alternately patterned alignment. In the liquid crystalline monomer mixture, the LC molecules are responsible for molecular orientation and the acrylate bonding, activated by photoinitiator, for forming the elastomeric network [16]. After polymerization in the nematic state, the resulting elastomer exhibits around 18% contraction in the direction parallel to the molecular orientation (director) and at the same time around 10% expansion in the perpendicular direction due to destruction of the molecular order [17] (compare Figure 2a). The monomer mixture is melted and infiltrated into a 50 µm glass cell with polyimide orienting coating on both inner surfaces (for details see Methods). The top and bottom glass plates are mechanically rubbed with a pattern of 1 mm wide stripes and aligned in such a way that the rubbed areas on one glass face the non-rubbed areas on the other, as shown in Figure 2 (b). In this cell, the LC monomers are oriented with a spatially modulated alignment pattern as shown in the cross section in Figure 2c - in the regions close to the rubbed areas the molecules are preferentially aligned along the rubbing direction due to surface anchoring, while near the non-rubbed areas they are randomly oriented. After curing with UV light, the alignment pattern is preserved within the LCE film. When heated above the phase transition temperature T_{pt} the rearrangement of the molecules leads to expansion of the film areas in the well-oriented segments (regions indicated by arrows in Figure 2c) resulting in the macroscopic shape change - the flat film becomes curly.

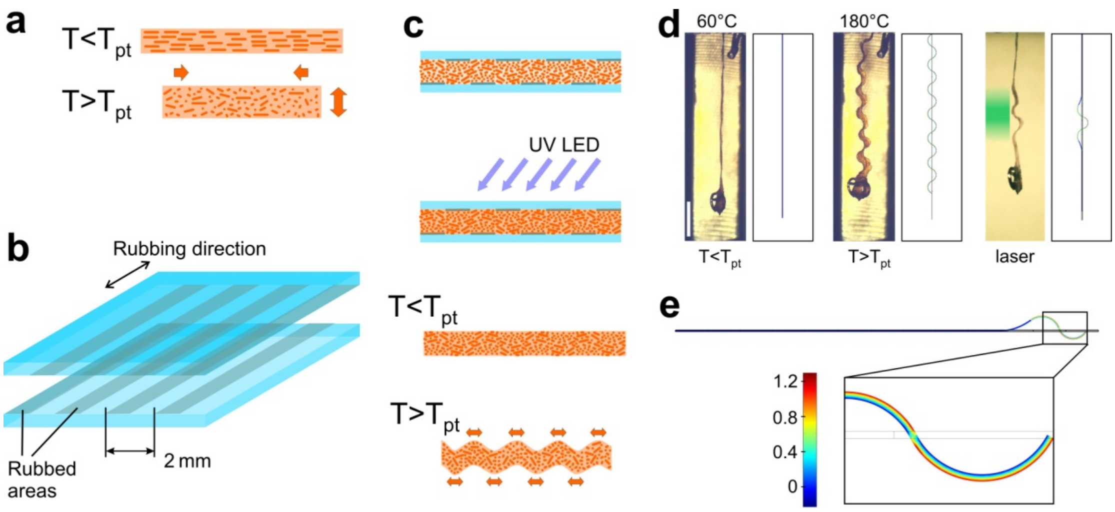

Figure 2 LCE film with patterned molecular orientation for light driven LCE soft robot. a, Liquid crystalline elastomer film with nematic molecular order changes shape upon phase transition at the temperature T_{pt} - it contracts along the director and expands in the perpendicular directions. **b**, Two glass plates with a pattern of alternating linearly rubbed and non-rubbed areas in the form of 1 mm wide parallel stripes. **c**, After arranging the rubbed plates to form a 50 µm thick cell, it is filled with molten LC composition. The molecules (both monomer and dye) are oriented along the rubbing direction in the vicinity of the rubbed surfaces and the orientation is lost as the distance from the latter increases. The mixture is cured with UV light and the film released from the cell. Upon heating above the phase transition temperature T_{pt} the nematic order is destroyed and the resulting molecule rearrangement leads to film deformation (expansion in the regions indicated by the arrows). **d**, Stationary state photographs of an LCE film stripe, cut perpendicular to the rubbing direction, hanging vertically in a thermostatic chamber, below and above the phase transition temperature and upon 480 mW laser beam illumination (beam position and size shown schematically in green). Scale bar, 3 mm. Also shown are the results of the finite-element numerical simulations. **e**, Numerical simulation result of local deformation of the soft robot body. Inset shows the calculated strain gradient across the stripe thickness.

We fabricate a soft robot, cutting a stripe (14.8 mm long, 3.8 mm wide) from the 50 µm thick LCE film in the direction perpendicular to the patterned rubbing. This soft robot can perform reversible shape change under external heat stimuli, as shown in Figure 2d. The phase transition can also be induced by light being absorbed in the dye that absorbs green light effectively and triggers the heat induced actuation (Fig. 2d, see Methods). We use the finite-element model to numerically simulate the light induced response (shape change) in patterned LCE stripes (Figure 2d , see also Methods). The results show that light absorption and subsequent heat generation triggers local decrease of the liquid crystalline order within the illuminated volume and thus induces an inner stress, responsible for the stripe deformation. Taking into account the alignment distribution, the strain gradient across the stripe thickness has the maximum value of 0.119 (see inset in Fig. 2e) on the rubbed surface (corresponding to approximately 10% expansion of the deformed LCE film).

Light driven locomotion of the caterpillar-mimicking soft robot

The optical set up for powering and remote control of the robot is schematically shown in Figure 3a - a CW green laser beam is reflected by a mirror installed on a galvo scanner driven by an asymmetric sawtooth signal. The laser beam is scanned slowly along the robot body during the stepping phase, and then rapidly scanned backwards to its original position. When scanning the laser beam (from left to right), a travelling deformation of the soft robot is observed and it starts walking in the direction of the slow laser beam scan. Figure 3b shows a series of photographs of the robot walking its body length on a flat surface covered with 2000 grit sandpaper. The light beam is scanned at 0.4 Hz (i.e. each full stepping cycle takes 2.5 s) and with a CW power of 2.5 W. In 59 s the robot walks through a distance of 14.2 mm, with an average speed of 0.24 mm/s (Movie 1). Walking in the opposite direction, this time with the speed of 0.18 mm/s, is achieved with switching the laser scanning direction (slow scan from right to left), as shown in Figure 3c. Figure 3d presents the step length distribution of 37 steps taken during the walk from Figure 3b. As expected, a normal distribution is observed, as the process results mainly from random distribution of the local friction conditions during each step.

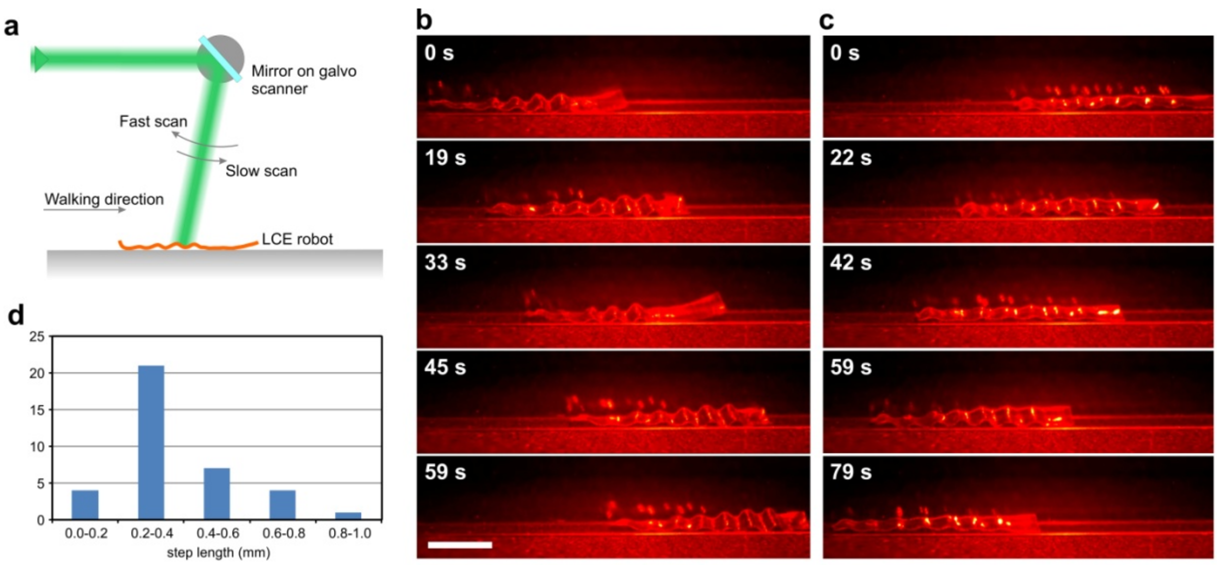

Figure 3 Light driven locomotion of the LCE soft robot. a, Schematic of the experiment. The laser beam is scanned along the robot body with an asymmetric sawtooth signal driving a galvo scanner. Series of photographs for the light driven locomotion in the forward (**b**) and backward (**c**) directions, scale bar for all photographs, 5 mm. **d**, Histogram of the step lengths for 37 steps taken during the walk in **b.** Orange filter is used to cut off scattered green light.

One stepping cycle is shown in more details in Figure 4a. As the laser beam is scanned from the back of the robot, it starts inducing the curling deformation at around t=0.5 s. With the laser beam travelling forward, the deformation follows, while the previously actuated parts (tail) returns to the original flat state (t=1.17 s). Around t=1.67 s the deformation wave reaches the robot head and from this time on, the entire body relaxes to the original shape, finishing one stepping cycle.

There are several parameters that govern the stepping dynamics. First, the two time constants of the LCE film deformation - curling with absorption of the light energy and release to the original state after switching off the light. Second, the laser scanning speed and average power determine the amount of energy absorbed by the dyes embedded in the LCE film. Third, the heat diffusion in the polymer and its characteristic time scale. And finally, the laser spot size in the film that affects the activated body area. For a given laser power, different bean scanning frequencies result in different heat distribution in the film, and different parts of the robot body can be actuated at the same time, leading to different gaits. We observe a travelling deformation in the form of a "short wave" (Figure 4b) or a "long wave" that spans the entire body length (Figure 4 c). For higher laser power the global bending of the robot body results, most likely due to residual stress in the film from the difference between the upper and lower surfaces during UV curing and/or from the film mechanical removal from the cell. This curling and bending combined result in the third robot gait - "bending", as shown in Figure 4 d, very similar to the inching walking strategy, observed in live caterpillars [8]. Figure 4e summarizes the three robot gaits and the respective average speeds for various laser powers and stepping frequencies.

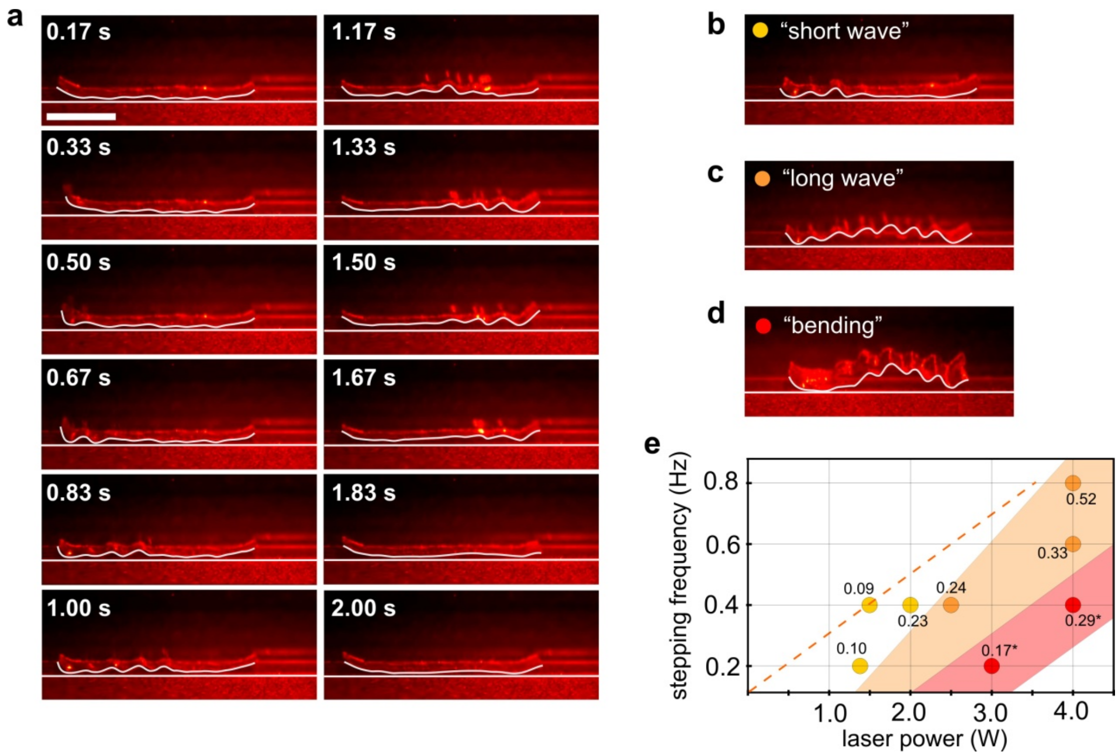

Figure 4 Walking modes of the LCE soft robot. a, Series of photographs showing the deformation wave travelling along the robot body during one stepping cycle. White lines are traced on the photographs along the walking surface and the edge of the robot body for guiding the eye. Scale bar (for all photographs): 5 mm. **b**, **c**, **d**, Different gaits of the soft robot: "short wave", "long wave" and "bending" modes. **e**, LCE robot modes of locomotion as observed for different laser powers and stepping frequencies. Colored circles correspond to different gaits and the numbers next to each circle are measured average speeds in mm/s. Asterisks mark the conditions where accelerated film damage occurs. Dashed orange line corresponds to a constant laser power per unit area per unit time i.e. laser light intensity/frequency=constant.

Locomotion in various conditions and task execution

To test the robot performance in different environments, we set it on a slope with 11 degree incline. Light induced travelling deformation enables the robot to climb the slope with a speed of 0.068 mm/s, as shown in Figure 5a (Movie 2). One of the great features of soft animals (and soft robots alike) is the capability to operate in confined spaces. We set up a 0.9 mm high slit on the robot walking path. Figure 5 b and Movie 3, show that the travelling deformation walking allows the robot to adjust to the environmental conditions (topology) and after 5 minute long effort the caterpillar robot has squeezed under the narrow slit. In Figure 5c and Movie 4 we demonstrate a 1 mm diameter, 19.1 mg (more than 6 times the robot mass) metal cylinder being pushed by the robot without much decrease of the walking speed.

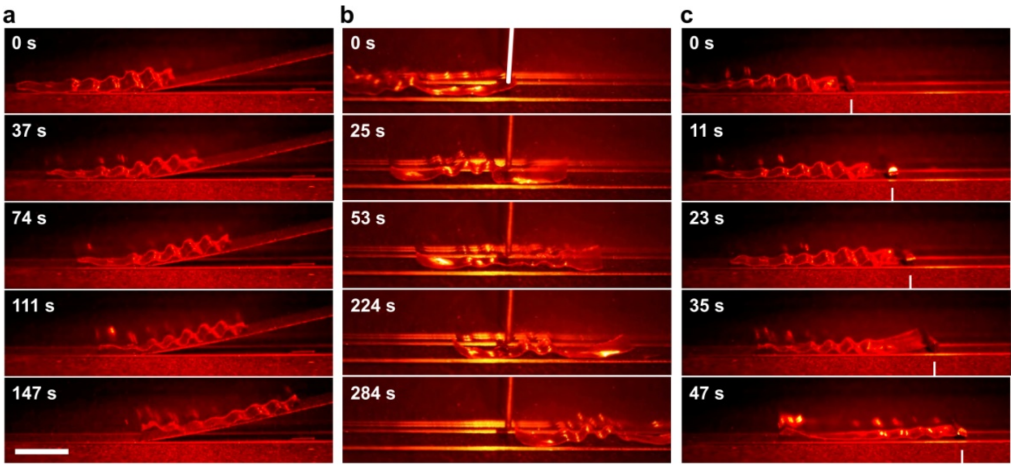

Figure 5 LCE soft robot in various tasks. a, Climbing an 11 degree slope. **b**, Squeezing through a 0.9 mm high slit. White line is traced in the first photograph along the slit upper wall. **c**, Moving a metal cylinder with 0.2 mm/s average speed. White tick marks indicate the cylinder center position. Scale bar for all photographs, 5 mm.

Discussion and conclusions

With an alternately patterned alignment and thus engineered light-induced deformation, the liquid crystalline elastomer based robot closely mimics the mechanics of the walking caterpillar. A comparison of the kinematic parameters between our soft robot and some caterpillar species [20] is shown in Table 1.

	Body Length (mm)	Motion frequency (Hz)	Step length (mm)	Speed (mm/s)
Robot	14.5	0.2-0.8	0.2 – 0.8	0.1-0.5
C. verbasci	12	2	3.1	6.2
P. ruralis	24	1.7	6	10.2
T. jacobaea	26	1.8	4.2	7.5

Table 1 Kinematic parameters of selected caterpillar species and the caterpillar robot.

While the robot in this study has a similar body size and stepping frequency as his natural relatives, its step length is significantly shorter, resulting in lower walking speeds. Living caterpillars use various gripping mechanism on their legs and thus manage the contact with the ground. Our robot lacks this mechanism and relies solely on friction at the body-ground interface. The caterpillar robot performs a complex slipping motion in both forward and backward directions during each stepping cycle, resulting in the net forward movement along the travelling deformation direction. This reduces the step length in every actuation cycle and thus limits the walking velocity. Exploring efficient actuators with gripping control remains a challenge for soft robotics in the quest for matching the efficiency of natural species. The maximum walking speed is also limited by the LCE film damage threshold and for the highest powers used in our experiments, the film (dye) bleaching and subsequent damage (burning along the laser beam center) was observed.

We fabricated a natural scale light driven walking robot capable of mimicking caterpillar travelling deformation wave mode of locomotion. We demonstrated different robot gaits by choosing the light excitation conditions. Several tasks like climbing a slope, squeezing through a slit and pushing a micro-object were realized. These results prove that light can be a useful energy source for micro-robot actuation and control, driving complex movements in soft matter structures. The technology of patterned orientation and light actuation of LCE structures and the design of the caterpillar robot itself open up new horizons in micro actuation and complex, remotely powered and controlled soft-robotics in millimeter and micrometer scales.

Methods

Materials: The monomer mixture contains 77 wt % of the LC monomer (Synthon), 20 wt % of the LC crosslinker (Synthon), 2 wt % of the photoinitiator (Irgacure 369, Sigma Aldrich) as reported in **Ref. 17**, and 1 wt % of green light absorbing dye (Disperse Orange 3, Sigma Aldrich).

Glass slides preparation: Two microscope cover slides are spin-coated with SE 130 polyimide resin (Nissan Chemicals) and dried on a hot plate. Mechanical rubbing with a cloth is done after applying masks with cut-out 1 mm wide slits. Two slides are put together with rubbed surfaces facing each other, shifted so that the rubbed areas on one plate face the unrubbed areas on the other. 50 μm diameter glass spheres are used as spacers.

Caterpillar robot fabrication: molten LC monomer mixture is infiltrated into the cell on a hot plate at 80 °C and then the temperature is decreased to 40 °C. A 375 nm peak wavelength UV LED is used to cure the sample for 20 min. The cell is opened with a blade, and a stripe of film is cut along the direction perpendicular to the rubbing direction and then detached from the substrate.

Optical set up for light actuation: A CW green 532 nm laser (Lighthouse Photonics, Sprout, maximum power 5.5 W, beam size expanded to 3 mm FWHM, as measured in the robot position) is used to power and control the soft robot. The beam is steered with flat mirror on a galvo scanner, driven with a sawtooth signal: the slow motion (94% of the cycle duration) drives the robot and the fast backwards scan reverses the beam to the initial position. No visible actuation is observed during the fast backward scan. The robot walks in a "corridor" formed by two vertical glass slides held 5 mm apart.

Finite element numerical simulation: The numerical simulation is performed in COMSOL Multiphysics using the Solid Mechanics model. The LCE is modeled as incompressible elastic material with Poisson's ratio of 0.5 and the elastic modulus of 1 MPa. The original distribution of the liquid crystalline order parameter P_o in the patterned orientation stripe is the following: the maximum in the vicinity of the rubbed surfaces with a value of P_m=0.21 (corresponding to the 18% contraction along the nematic director - 0.18=$1-(1+2P_m/1-P_m)^{-1/3}$ [21]), and linearly decreasing (across the thickness) to zero on the opposite (unrubbed) surface. Under external stimulus with the absorbed light, the local order parameter decreases from P_o to zero and the elastomer deforms (bends).

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Author contributions: P. W conceived the project and carried out experiments; M. R. prepared the LCE films and carried out experiments; H. Z. prepared the manuscript with help from P. W; C. X. and J. B. performed simulations; All authors discussed and developed the concept.

Competing financial interests:
The authors declare no competing financial interests.

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