Nature provides a valuable source of inspiration for many fields of research. From optical effects to engineering problems, organisms have often adapted elaborate solutions and strategies, being the result of many years of natural selection.\cite{1,2}

Within this context, there is a lot of interest in creating artificial structures (robots) that can walk,\cite{3} swim,\cite{4} and perform various tasks.\cite{5} Micrometer scale robots, in particular, have been proposed for applications, including drug delivery,\cite{6} biosensing,\cite{7} and microsurgery.\cite{8} Based on the development of artificial muscles, a variety of soft robots that mimic natural creatures have been designed.\cite{9–12} Such artificial muscles rely on power delivered from outside, while the entire mechanical actuation is due to the inner stress of the muscle. Differently from external field driven devices,\cite{6,7} they approach naturally occurring living systems and are considered of broad scientific interest and technological value. Terrestrial soft robots have been realized with walking,\cite{9,10} gripping,\cite{11} and camouflage\cite{12} functionalities, but still remain in the centimeter scale. Working in the microscopic scale, strong adhesion arising from the surface related forces (e.g., van der Waals and the capillary forces) is the limit of systems, such obtained artificial creatures are capable of different autonomous movements influenced by the interaction with their environment—similar to existing walking creatures in nature subject to the same van der Waals forces.

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Muscles (soft sections of the creatures) have always been well isolated from the environment, while hard crust and hairy-like surfaces often assist to reduce the surface contact zone and hence minimize the biological adhesion. Liquid crystalline elastomers (LCEs), that combine elastomeric properties with liquid crystalline orientational order, can reversibly deform in response to external stimuli with dramatic contraction (up to 400%) and with a stress compatible to natural muscles.\cite{21} Therefore, LCEs have been considered as artificial muscles with great potential for creating biomimetic soft robot.\cite{22} Recently developed technologies enable to control molecular order in the microscopic and macroscopic scale\cite{23,24} (instinct related to actuation) and fabricate patterned actuator with micrometer-sized complex shapes.\cite{25} However, such soft materials with typical elastic moduli $E$ in the MPa range,\cite{26} behave extremely sticky. All approaches to these artificial muscles in the microscopic scale have failed, as the natural adhesion poses a huge hurdle for robot’s locomotion. To isolate the LCE muscle from the environment, and then solve the natural adhesion problem, we chose acrylic resin (IP-Dip) for fabrication of walker’s limbs with a relative high $E$ ($\approx$ 4 GPa). The LCE composition shown in Figure 1a is chosen,\cite{25} and interestingly the light sensitive element (azo-dye) is designed to open a transparency window for 780 nm fs laser and two-photon absorption polymerization at 390 nm in the direct laser writing (DLW) system, and to be activated by green light. DLW is used to pattern the complex 3D hybrid robot structures. This technique allows to arbitrary design 3D robot structures with nanometer scale resolution by a well control of sample position and laser exposure condition. Moreover, it consents a single polymerization/crosslinking step for the LC monomer mixture. Light energy is used to power the walker, with no external force applied. Approaching biological systems, such obtained artificial creatures are capable of different autonomous movements influenced by the interaction with their environment—similar to existing walking creatures in nature subject to the same van der Waals forces.

In the first stage, we prepared a LCE structure in order to characterize the optomechanical response of our materials, as reported in Figure 1. The mechanical response to light is fully reversible and consists in a contraction of around 20% along...
axis, while heated above 100 °C by a focused laser beam. d) Response of the actuator along the long natural muscles (10–200 kPa, and up to 1 kHz). These results are reported in Supporting Information). Maximum light induced stress is measured to be 260 ± 19 MPa (inset in Figure 2e). Taking the maximum van der Waals attractive force $F_{vdW} = A/6\pi D_0^3$ per unit area (Hamaker constant $A$ is typically between $0.5 \times 10^{-19}$ and $1 \times 10^{-19}$ J) and assuming that the gap between the leg and the glass is $D_0 = 0.3 \text{ nm}$,[27] the friction coefficient $\mu$ being in the range from 0.2 to 1.0,[28] the maximum friction force $F = \mu F_{vdW}$ is between 7.9 and 78.5 µN. With the driving elastomeric force larger than the friction, the walker starts to slip. Local fluctuations of the adhesion on the nonuniform PI coating result in a random walking behavior—the instantaneous movement direction is determined by the friction differences from one leg to the other. An example of random walking trajectory is shown in Figure 3c (see Movie S2, Supporting Information). The friction strength on PI coating is relative high that the asymmetric tilted leg geometry does not provide any directional walking tendency. The walking velocity has an average value of some µm/s, while the maximum speed is observed to be around 22 µm/s.[29] In this mode, once a leg gets stuck to the surface, the walking terminates, and continuous rotation in one direction begins (Figure 3d–f, Movie S4, Supporting Information). The maximum rotation speed is measured in 1.5 rad s$^{-1}$.

In order to obtain directional walking on these length scales one has to overcome the local fluctuations in the adhesion forces. An example of this is reported in Figure 3g–i. The walker is positioned on a clean glass substrate and moves with a preferred direction defined by the leg tilt due to the shear off anisotropy, as previously demonstrated in biomimetic artificial adhesive structures.[29] No leg sticking is present; instead the continuous actuation of the walker body results in the net walking movement in the leg tilt direction. Local adhesion fluctuation may also induce rotation of the body, followed however by automatic reorientation (Figure 3i, Movie S4, Supporting Information). The walking direction is very sensitive to the friction fluctuation due to the small mass and to the high adhesion strength. Therefore, a straight walking direction is difficult to maintain. The average walking velocity in this case is measured to be around 37 µm s$^{-1}$.
In the above case the walking direction is decided by the walker itself. It is also possible, on the other hand, to create an environment in which the direction is determined externally using patterned surfaces. On a blazed diffraction grating with 1300 lines per mm, the walker prefers to move in a certain direction, due to the interaction between different tilted nanoslope. A steady walking direction is maintained, independent from the leg tilt (Figure 3 j–l)—the walker can actually rotate the full 360° while maintaining the net movement direction (Movie S5, Supporting Information). On such grating surface, a 10 times larger walking velocity (380 µm s⁻¹) comparing to the previous cases has been observed.

Yet another behavior—up to ≈1 cm (100 body lengths) long jumps—was obtained on a Teflon surface. Conical legs provide advantage for walking, however, they can easily get stuck into the micro-gully on the Teflon surface. For this reason, we have also designed the walker with a 100 × 50 × 10 µm³ body size and three sets of lamellar legs (see Figure S2, Supporting Information). By increasing the laser power, such robot approached to the maximum deformation and stored the light energy inside the LCE body as elastic potential. At some point the walker overcome the adhesion on one side, and the elastic body converted the elastic energy into kinetic energy. Thus, a sudden jump occurred as shown in Movie S6 in the Supporting Information. Inspired by fleas, jumping could be a more efficient way of transport for robots at the micrometer scale, where the influence of gravity and inertia are significantly reduced and the air drag dominates the kinetic energy loss (see the Experimental Section).

In conclusion, we demonstrated the preparation of a microscopic walker entirely powered by light and based on LCE artificial muscles. The locomotion of such artificial creatures is influenced by their design and how they interact with the environment—random or directional walking, rotation or jumping is possible and demonstrated above. With an average muscle stress of 200 kPa, assuming 1 µm² of the foot-surface contact area and taking adhesive forces per unit area of 1 MPa into account, a minimum muscle cross section of 5 µm² is needed to overcome adhesion for every single step. This results in the lower estimate of moving terrestrial creatures of the order of tens of micrometers, already saturated by our walker. Note that, although a laser source was used for convenience in all the experiments, such laser is defocused and illuminates large areas and the LCE muscles can, in principle, use energy from any light source. Importantly, there is also no need to target specific individual parts of the robots with a light beam. The walkers simply absorb the light from their overall environment. Optimization of the body geometry, actuator shape, and action and the leg tilt angle may still result in improved locomotion performance. The method presented allows to create, in principle, large amounts of elastomer-based robots in a relatively easy manner and with a versatile approach. Variety of LCE-based autonomous robot can be expected, e.g., microswimmers, microjumpers, origami photonic devices, and so on.
Light-Induced Stress Measurement: For measuring the light induced stress, a 5 × 2.5 × 0.05 mm² LCE sample was hung vertically attached to a force sensor and a 532 nm laser illumination (5 W cm⁻²) was applied to induce contraction. A maximum stress of 260 ± 2 kPa was measured.

Glass Treatment: The surface of the glass substrates was cleaned by rinsing in a 1:300 diluted HF water solution for 10 min.

Jumping Dynamics Estimation: Assuming 50% of the elastic energy turned into kinetic energy the launch speed was ≈4.7 m s⁻¹ (LCE Young’s modulus E = 1.3 MPa, density ρ_{LCE} = 1.16 g cm⁻³, and strain of 20%). The Reynolds number Re was calculated to be no more than 12 (Re = νD/ρ = 4.7 m s⁻¹, approximate object diameter D = 40 µm, air dynamic viscosity υ = 18.6 µPa s) for the entire flight. In a low Reynolds number environment, the drag contributed to the majority of the energy lost.

Supporting Information

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

Acknowledgments

The research leading to these results has received funding from the IIT SEED project Microswim and the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007–2013)/ ERC Grant Agreement No. 291349 on photonic microrobotics. H.Z. was supported by the ICTP Ph.D. Program. The authors gratefully thank the entire Optics of Complex Systems group at LENS for feedback and discussions.

Received: March 26, 2015
Revised: April 26, 2015
Published online: May 28, 2015

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Figure 3. Surface dependent locomotion behaviors. Under the same chopped laser excitation (532 nm, 50 Hz, 10 W mm⁻²), the 60 µm size microscopic walker: a–c) randomly walks on the PI coated glass surface; d–f) rotates with one leg stuck onto the PI coated surface; g–i) walks with self-reorientation on the clean glass surface; j–l) walks in the direction determined by the grating groove pattern (vertical). Insets of (a), (d), (g), (j) show the schematics of the surface. Inset in (b) shows the orientation of the arrow with respect to the walker.

Experimental Section

Materials: The monomer mixture contains 78 mol% of the LC monomer 1, 20 mol% of the LC crosslinker 2, 1 mol% of the azo dye 3, and 1 mol% of the photoinhibitor (Irgacure 369) as reported by Zeng et al.[25]

Direct Laser Writing Fabrication: Fabrication of the walker was performed in a Dip-in Laser Lithography system (Nanoscribe GmbH). Sample preparation and development followed the procedure presented in ref. [25].

Characterization: For testing the LCE light response, a 60 × 30 × 10 µm³ LCE actuator was held on a glass tip. Two laser beams: 300 mW continuous 532 nm solid state laser and 2 mW He-Ne laser were focused on the center and edge of the structure, respectively, by a 20x (NA 0.4) objective. The 532 nm laser was chopped to induce the modulated deformation, while the transmitted He-Ne laser beam was detected by a photodiode as a signal related to the LCE deformation.

Two glass tips (1 and 5 µm in diameter) were used to transfer the microwalker onto different substrates with the help of 3D manual translation stages. A chopped 532 nm laser was defocused by a 10x objective (NA = 0.2) to a spot of around 200 µm diameter and ≈10 W mm⁻² intensity for the walker actuation. As the walker body temperature exceeded 100 °C under laser illumination the environment could be assumed to be dry, and thus ignored capillary interactions. A scanning electron microscope (PHENOM-World) was used to observe the structures after sputter-coating them with a 10 nm gold layer.
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