Light Robots: Bridging the Gap between Microrobotics and Photomechanics in Soft Materials

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Title: Light robots: bridging the gap between micro-robotics and photomechanics in soft materials

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Abstract. For decades, roboticists have focused their efforts on rigid systems that enable programmable, automated action and sophisticated control with maximal movement precision and speed. Meanwhile, material scientists have seeked for compounds and fabrication strategies to devise polymeric actuators that are small, soft, adaptive and stimuli-responsive. Merging these two fields has given birth to a new class of devices – soft micro-robots that, by combining concepts from micro-robotics and stimuli-responsive materials research, provide several advantages in a miniature form: external, remotely controllable power supply, adaptive motion, and human-friendly interaction, with device design and action often inspired by biological systems. Herein, we highlight recent progress in soft micro-robotics based on light-responsive liquid-crystal polymers. We focus on photomobile devices such as walkers, swimmers, and mechanical oscillators that may ultimately lead to flying micro-robots. Finally, self-regulated actuation is proposed as a new pathway towards fully autonomous, intelligent light robots of the future.

1. Introduction

The term "Robot" was first coined in 1920 by Czech writer Karel Čapek in a science-fiction play "R.U.R.".[1] Although many people envisioned robots to become the technology of the future, robots did not stand up to the expectations in the following decades. Up to date, the majority of robots are electronically driven rigid machines that require pre-programming to perform even simple tasks, lacking flexibility and adaptability. Two grand challenges in conventional robotics relate to adaptivity in motion and difficulties to scale down in size. To face the first challenge, soft-robotic systems, where soft actuators are used to replace rigid links and joints, have been developed (see Table 1 for terminology).[2,3] Soft materials provide additional degrees of freedom for continuous actuation and shape-change, allowing soft robots to adapt to unpredictable obstacles.[4] Although currently the control accuracy in soft actuators remains inferior to that of electronics-based rigid machines, soft-robotic devices pave their way towards practical applications. For example, a soft, multiple-gait walker can squeeze into confined spaces,[5] and a soft robotic arm can pick up fragile objects or act in a "human-friendly" manner,[6] which would be beyond the capabilities of rigid robots. As for the second challenge – miniaturization – the straightforward rescaling of the actuators, sensors, control circuitry, and power sources is possible down to centimeters but very difficult, if not impossible, in the millimeter scale and below.[7,8] An alternative approach is to fuel the system from outside and use a stimuli-responsive actuator,[9] to initiate the robotic motion and task execution. In this case, the control circuitry and the power source (battery) can be removed from the robot body, which is beneficial for miniaturization, while the stimuli-responsiveness of the material can be directly adopted to build up the actuators and sensors in the systems. Unlike conventional robots relying on computer algorithms to control body movements, externally powered micro-robots call for a new paradigm of actuation based on material design.

Recently, various stimuli-responsive materials have been implemented in micro-robotics using power supplies based on magnetic fields,[10] acoustic waves,[11] light fields[12] and chemical reactions.[13] Among these, light is a particularly versatile energy source, as it is ubiquitous, and its properties (wavelength, intensity, polarization) can be optimized for the specific need with high spatial and temporal resolution. A sophisticated control over light distribution can be achieved not only using laboratory-level devices such as mirror scanners and digital micro-mirrors, but also commercially developed devices like computer projectors, which often provide high output powers with multiple wavelengths, and are capable of changing the displayed light pattern at high frequencies (> 30 Hz). The key challenge in realizing light

robots (see Table 1 for our definition) is to develop light-responsive systems incorporating sensors, actuators, and controllers, all in one element. Liquid-crystal polymers (see Table 1),[14,15] used as artificial muscles, have already proven to withstand this challenge. Properly designed liquid-crystal polymers can undergo large, reversible shape-changes upon light irradiation, triggered by photochemical reactions[16,17] or photothermal heating.[18] The light-induced deformations can respond to changing light intensity,[19] wavelength,[20,21] or polarization.[17,22] Compared to other stimuli-responsive materials such as electroactive polymers,[23] compound polymers,[24] or shape-memory polymers/alloys,[25] liquid-crystal polymers can exhibit various modes of actuation and sensing through molecular-alignment control.[15,26] This has led to development of miniature robots composed of multiple light-controlled actuators, thus bridging the gap between micro-robotics and light-driven artificial muscles.

In the past decade, a significant number of spectacular results have been obtained in light-responsive liquid-crystal polymer technology and its applications, mainly regarding chemical synthesis and novel fabrication techniques.[27-30] However, limited number of examples of light-powered, miniature mobile devices exist.[18,31-36] Herein, we summarize the latest results in LCP-based photomobile (see Table 1 for terminology) robots that can walk, swim, and one day perhaps even fly in response to light stimulus. We discuss the potential of self-regulation in robotic actuation as a tool for next-generation autonomous light robots. We exclude chemical approaches to photoactuation and deformation control as they have been reviewed elsewhere.[37-39] Also energy conversion based on photovoltaic technologies is omitted. [40]

Table 1. Vocabulary.

Light robot: A robotic system that is (i) driven by *light*, and (ii) *light* in weight (i.e. small in size).

Micro-robot: For roboticists, "micro" means "small", *i.e.*, a "micro-robot" is a system smaller than conventional human-sized machines. For material scientists, "micro" refers to "microscopic", say less than a millimeter in size. Herein, we focus on device scales ranging from few centimeters down to micrometer-scale, while we exclude molecular motors, which have been popularized as *nano-robots*.

Soft robot: A robotic system that is primarily composed of materials with elastic moduli in the range similar to soft biological materials (10^4-10^9 Pa).[2]

Liquid-crystal polymer: We use liquid-crystal polymer as a general term to describe liquid-crystal elastomers, liquid-crystal gels, and glassy liquid-crystal polymer networks, which are distinguished by their mechanical properties, crosslinking density, and chemical composition.

Photomobility: Refers herein to the ability to continuously translate the center of mass under illumination (excluding direct momentum transfer from photons).

2. It all starts from the material

The literature on chemical approaches to liquid-crystal polymer synthesis, characterization and actuation performance comprises numerous studies on molecular design, alignment control, and actuation mechanisms/modes, as highlighted in several recent reviews.[19,26,41-43] Here we wish to provide a concise introduction to the field ~~from a birds-eye perspective~~.

Liquid crystals[44] are organic liquids that under certain conditions exhibit positional and/or rotational ordering in the arrangement of their constituent components. Liquid-crystal polymers are solid, polymeric systems with well-defined shape, yet maintaining the ordered molecular alignment of liquid-crystal phase. Upon heating, liquid crystals undergo a transition from the anisotropic liquid-crystal phase into isotropic phase, turning the system from ordered into disordered. In light-responsive liquid-crystal polymers, the order-disorder transition can be induced in the solid, polymeric material, using light as an energy source. Due to tight packing of molecules (most often rod-like in shape) that have been confined in ordered polymer chains, the order-disorder transition reduces the average spacing between molecules along the alignment direction (the director) and increases the spacing in the perpendicular directions. As a result, the material undergoes shape-change (contraction and expansion), where the specific deformation geometry is determined by the director distribution within the material volume (Figure 1a). From the synthesis point of view, the ultimate goal is to design and fabricate actuators that are as efficient as possible in terms of sensitivity and response time,[45,46] in order to yield the desired actuation mode when fuelled at some specific wavelength(s) of light. At the same time, different physical approaches have been taken in order to pattern the material structure and molecular alignment, and to obtain diverse, often complex, deformation and actuation modes.[47-50]

Most actuators can be modeled with analogies to simple paper cutting and folding. As shown in Figure 1b, when molecular orientation varies across the film thickness, resulting in expansion on one side and contraction on the other**,** an initially flat film bends into a tube. If a stripe is cut along the director, it bends; if it is cut at an angle with respect to the director, it will twist into a helix (Figure 1c).[51,52] By patterning the orientation onto a two-dimensional surface, one can obtain further degree of control over the deformation (Figure 1d).[53] As an example, radially-aligned molecular distribution leads to local buckling of the initially flat polymer film.[54] Such defect-like alignment can be further engineered into more complex forms (azimuthal/radial defects),[29,55-57] which result in cone/anti-cone shapes.[58,59] A matrix composed of several such defects exhibits periodic buckling, leading to complex 3D surface deformation upon irradiation (Figure 1e).[53,60] Bending of a liquid-crystal polymer film can also be used in analogy to folding paper in origami. Figure 1f shows an example, where the deformation at the hinges has been optimized, thereby leading to a polymeric film folding into a box.[61] Up to date, a technique that can arbitrarily pattern the director distribution and thus the deformation in three dimensions is still missing. However, laser lithography[62] and 3D printing[63] have enabled fabrication of 3D polymeric structures with engineered deformations.

In particular, two-photon-absorption-based laser writing has been exploited to produce 3D liquid-crystal polymer microstructures (Figure 1g), in which global deformations can be activated with a single focused laser beam.[64] Moving beyond light-driven actuators, the key question is how to harness the shape-changes to build light robots that move in a pre-designed manner.

3. From light-driven actuators to photomobile robots

Several mobile robots powered by external stimuli exist. Micro-devices dragged in liquid by a magnetic field gradient or propelled by a torque originating from a rotating magnetic field,[65] and an optical tweezer robot activated by gradient and scattering forces,[66] serve as prominent examples. Photomobile liquid-crystal-polymer robots use light only as an energy source, without any external force applied to the system. In other words, there is only energy transfer from the light source into the robot, but no momentum exchange. The light response generates elastic stresses inside the material,[19] and the inner force(s) allow the robot to overcome environmental resistance. This dynamics is similar to the one found in biological species, where motion is controlled by the body deformation interacting with the surrounding medium. Whereas their natural counterparts have been optimized by millions of years of natural evolution, the optimization of liquid-crystal-polymer robots is limited so far to a few years of laboratory experiments. Biological systems can in that sense serve as a valuable source of inspiration for the design and optimization of (micro) robots.

3.1. The first lesson for a robot larva: walking

Earlier this year, a millimeter-sized inching walker based on alternately patterned, splay-aligned, monolithic liquid-crystal polymer strip (Figure 2a) has been demonstrated.[67] The body responsible for the caterpillar-like inching locomotion can be fabricated within a few simple steps, and is easyly powered by a temporally modulated light-emitting diode. However, due to reciprocal actuation and absence of any friction bias, such walkers rely on substrate characteristics to determine the walking direction, resulting in limited control over the movement. Liquid-crystal polymer walkers can be fabricated into an overall size down to microns by using laser lithography, with rigid, conical legs inducing the walking friction.[32] In Figure 2b, a 60 μm long walker, sitting on a human hair, is presented. Directional walking at small scales faces specific hurdles. Firstly, bending deformation, beneficial in the walker design due to significant modification of the body length, becomes challenging in microstructures. The

deflection angle of a bending strip is proportional to the ratio between the sample length L and its thickness d. Hence, the commonly observed large bending in macroscopic samples (large L/d, Figure 2a) becomes much less pronounced in microscopic structures (small L/d). Another issue araises from the reduced number of degrees of freedom. One can overcome the environmental resistance if sufficient number of degrees of freedom are available. Humans implement static friction on the feet-ground interface for body acceleration, and then lift up a leg to reduce the load on the ground to bring the friction down. For a micro-walker with limited degrees of freedom, this phase of "switching on/off" friction between the robot body and the surface is more difficult.[68]

Directional moving tendency can be created in photoactuators by introducing a friction bias into the walker feet through asymmetric segments.[31,18] This approach, however, becomes problematic at sufficiently small size scales. As illustrated in Figure 2d, to obtain displacement after one actuation cycle (contraction-expansion), the micro-walker needs to have tilted legs and satisfy the following conditions: the light-induced elastic force F_e, must be larger than the leg-ground friction force f, $F_e > f$. At the same time, $f'_{back} > f_{front}$ and $f'_{front} > f_{back}$, where f_{front}/f'_{front} and f_{back}/f'_{back} are the maximum static friction forces experienced by the front and back legs, respectively, in the forward/backward direction. Under such conditions, the walker is capable of sticking the front and back legs alternatively, and transferring the body deformation into a forward step. These conditions are very strict, and strongly affected by any fabrication defects or fluctuations in local friction, rendering, *e.g.*, $f'_{back} < f_{front}$ *or* $f'_{front} < f_{back}$. In such case, the walker is stuck on either the front legs or back legs, as shown in Figure 2d, center. Another interesting phenomenon is the micro-robot jumping. As shown at the bottom of Figure 2d, all the legs are initially stuck on a rough surface (e.g. paper or Teflon surface, where $F_e < f$). Once the elastic energy is released due to some random fluctuations in environmental conditions, the light robot can jump over long distances.[32]

There are also other alternatives for obtaining directional movement.[69,70] Figure 2c presents an inch-long monolithic robot that can mimic caterpillar crawling locomotion with a travelling-wave deformation. The locomotion is induced by scanning a laser beam along the robot body, which triggers local curling-type shape change in the material, thus propelling the robot to move forward in the scanning direction, and even adaptively squeezing through a narrow slit (inset of Figure 2c).[33] It has also been demonstrated that a liquid-crystal polymer tube can crawl inside a glass capillary, with a peristaltic motion mimicking an earthworm (Figure 2f).[71] Such capillary-type actuator also provides access to light-based micro-manipulation of droplets.[72] A liquid-crystal polymer spiral ribbon rolling over large distance

under spatially and temporally stationary illumination has been demonstrated earlier this year (Figure 2e).[36] In this system, the upper part of the polymer tends to exhbit larger twist compared to the shadowed bottom part. The asymmetric illumination brings about photoinduced strains, thus continously impulsing the spiral geometry and giving rise to a net twisting moment. Similar rolling motion has very recently been also reported in a bi-layer liquid-crystal polymer wheel and spring-like motor. [73]

3.2. An advanced lesson for grown-up robots: swimming

Nature provides countless inspirations for devising swimming robots at all scales. The schematic drawings in Figure 2g represent some of the examples from the micro-world. The upmost example shows screw-like motion, where a bacterium propels itself with the help of a helical-type rotating flagellum.[74] This mechanism has been considered as the most efficient mechanism to generate non-reciprocal motion – a pre-requisite to obtain swimming in low-Reynolds-number liquids.[75] Interestingly, helical deformations have been reported in liquid-crystal polymers by many groups,[46,76-78] yet, so far there has been no experimental demonstration of helical liquid-crystal polymeric swimmer, only theoretical studies.[79] Very recently, however, the shape change in a microscopic hydrogel helix was controlled by light-induced plasmonic heating, yielding propulsion via cyclic deformations.[80,81] This result may catalyze further research on swimming liquid-crystal polymer robots.

The second mechanism shown in Figure 2g (center) is based on a continuously beating flexible tail to provide propulsion, like in fish or spermatozoa.[74] Since bending is the most conventional deformation in liquid-crystal polymers, this may be the easiest mechanism to explore and indeed, a miniature swimming robot has been created by connecting a liquid-crystal polymer actuator to a flexible flagellum.[35] Driven by cyclic light irradiation, the robot is able to propel itself and transfer an object with a light-switchable clamp at its head (Fig. 2h). More sophisticated motions have been found in organisms using collective, synchronized motion of cilia, to create a travelling-wave liquid flow (Fig. 2d, bottom).[82] Also this can be a feasible approach for artificial cilia[83] and light swimmers in which a moving light pattern or a scanned laser beam (see the inset of Fig. 2c) can trigger local shape-change in LCP. This has been demonstrated using an liquid-crystal polymer cylinder about 1 mm long and structured light field to obtain versatile robot locomotion in liquid environment, as shown in Figure 2i.[34]

Due to strong light absorption, the temperature in the actuator usually increases upon irradiation, from a few K[72] up to approximately 100 K.[36] The heat transfer is very different in air and in water, where the thermal conductivity is 20 times higher. The swimmer shown in

Figure 2i utilizes light-induced heating to trigger a shape change in a mixture of glycerol and water. In some cases, photothermal heating may melt the surrounding medium, assisting the soft robot in penetrating into a viscous liquid.[84]

3.3. The final frontier: flying

The majority of miniature flying robots is based on electrically powered propeller(s) or piezo actuators driving wings.[85,86] When scaled down to few centimeters or below, on-board battery becomes impractical because of the increase in weight-to-power ratio, whereas liquid-crystal polymers might provide alternative ways towards small-scale flying devices. It has been demonstrated that liquid-crystal polymer actuators can self-oscillate under excitation with a continuous light beam (Figure 2j).[87,88] The oscillation is based on a laser beam hitting the two surfaces of the actuator strip alternately, inducing bending actuation that deflects the strip inside and outside of the confined irradiation area. In one example, the oscillation frequency matched the cantilever resonance, and after optimization of the strip size, thickness, and excitation power, oscillation frequency as high as 271 Hz was reached.[89] More recently, similar self-oscillation, based on photothermal actuation in splay-aligned bending strip, was demonstrated.[90] The latter utilized self-shadowing to obtain oscillation, relaxing the limits in choosing the monomers and dyes. Finally, a bi-layer oscillator capable of transferring light energy into electricity has been reported.[91] All these self-oscillating devices, however, need to be fixed at a well-defined position and angle with respect to the incident beam in order to initiate and stabilize the oscillations. As an alternative approach, a chaotic oscillator fueled by non-focused sunlight has been reported, however, with relatively low oscillation amplitude and frequency.[20]

To obtain fast, high-amplitude ocillation, one may alternatively use temporally modulated illumination, which would relax the requirement for precise alignment of the light source(s) with respect to the robot position. With this approach, the challenge will be the maximum oscillation frequency. Light-induced deformations based on photochemical actuation have characteristic time scales ranging from minutes[92] to below one second[35] (as shown e.g. in the fish robot in Fig. 2h). The fast response observed in high-frequency oscillators is mostly related to photothermal heating, which has also been confirmed by infrared imaging.[93] This photothermal actuation, often neglected or considered somehow inferior, can be used to significantly enhance the actuation speed, particularly for small-size devices. Since the heat capacity scales down with L_c^3, where L_c is the characteristic length of the structure, the heat capacity of a polymeric actuator dramatically decreases with decreasing size. This, in turn, decreases the time of the heat transfer (heating, light on; cooling, light off) and boosts the

actuation speed. A comparison is shown in Figure 2k, where a 8 mm long inching robot (same as in Fig. 2a) deforms its body in the time scale of few seconds,[67] while a walker with a size of 100 μm (similar as in Fig. 2b) can undergo complete deformation (20% contraction in length) within 30 ms. As a down-side, the illumination light intensity level has to be elevated from 1 mW mm^{-2} (former) to 1.4 W mm^{-2} (latter) to compensate for the higher heat losses due to the larger temperature gradients.

Figure 2l compiles the wing-beating frequencies and body mass data for several flying species.[94] The blue region indicates the feasible frequency range in contemporary liquid-crystal polymers. While LCP-based flight robot may beat at a high enough frequency, there is a strong demand to optimize the actuation performance to generate sufficient thrust to support flying. Utilizing different dyes in a liquid-crystal polymer and using variable-wavelength illumination,[95] as well as modifying the crosslinking density within a monolithic liquid-crystal polymer structure[96], are the ways to yield non-reciprocal actuation – an efficient way to create thrust during material-air interaction. We expect that future research efforts will concentrate on maximization of the actuation frequency as well as measurements of the thrust forces under non-reciprocal movements, together with design of stable structures capable of balancing the gravity, inertial and thrust forces during the movement. Reaching these milestones would be important steps towards flying light robots.

4. Self-regulation for robot automation

Conventionally, robots are equipped with sensors, actuators and data processing devices operating in synchrony, as illustrated in Figure 3a. Information gathered by sensors (e.g. position, image, temperature) are processed and decisions are sent to actuators, which execute specific action. Can all these functions be integrated into a piece of plastic only a few millimeters in size? Two recent examples of self-regulating liquid-crystal polymer actuators are early realizations of this concept. Figure 3b shows a millimeter-size flytrap-like gripping device that can distinguish different objects based on optical feedback and perform automatic gripping action only when certain conditions are met.[97] It is based on a polymeric actuator attached onto the tip of a multi-mode optical fiber, which emits the probing light to the space in front. Only when an object enters the field of view of the device and enough light is reflected back to the actuator surface, the polymer bends and grips the object (Fig. 3c). This device relies on light power (energy coupled into the fiber) in the range 50 to 250 mW, corresponding to irradiation intensity of *ca*. 20-100 mW cm^{-2} at the probing area (fiber-coupling efficiency > 80 %;

propagation losses 10 dB km^{-1}). It exemplifies a case where the liquid-crystal polymer acts as both the sensor and the actuator, while the robot performance can be in principle programmed, by, *e.g.*, changing the absorbing dye, tweaking the device dimensions and/or the excitation wavelength. As shown in Figure 3d, the gripper closes on its favorite prey that has the proper reflectance, while it remains open for targets that do not meet its "taste" and not provide sufficient optical feedback. This behavior is similar to the self-regulating action of the flytap plant that allows it to distinguish between e.g. dust particles and insects by different mechanical stimuli, and self-close only in response to the latter.

While many researches focus their efforts on applying sophisticated, structured light fields to control liquid-crystal polymer actuation, also the opposite direction may turn out to be fruitful: instead of controlling light properties, why not let the robot sense the illumination conditions and act accordingly? Along these lines, the second example of self-regulation demonstrates an artificial iris shown in Figure 3e. Radial photoalignment patterning was used in the 14 mm diameter structure with 12 independent segments.[98] When the illumination intensity reaches a certain level, the segments close and block the beam. The light transmission drops from 70% in the open state to 30% when the iris closes (Figure 3f). Such device mimics the self-regulating behavior of the human iris, which can adjust to changes in environmental conditions (light intensity). The specific actuator design allows for the interplay between the light field and material response, and may guide roboticists towards autonomous robotic action, fueled remotely with light.

5. Outlook

After highlighting the most important recent examples in liquid-crystal polymer based photomobile robots and exploring how light-induced shape-changes can be harnessed to achieve mobility and automation at the micro-scale, we would like to propose a classification of the recent and future light robots into five generations. These generations reveal the evolution trends (in the past and also extended towards the future) of liquid-crystal-polymer-based light robots, showing a decreasing trend in complexity of the required control strategy in the light field and, at the same time, increasing functionality and degree of automation. Some of the robots may cross different generations, depending on their specific way of actuation. Common to robots of all the five generations, it is also imperative to drive the motion with ever-decreasing light power, ultimately with unfocused sunlight. In the first generation, the robots require spatial light modulation, *e.g.*, scanned or structured laser beam(s) – the crawling caterpillar[33] (Fig. 2 c) and light swimmer[34] (Fig. 2i) belonging to this category. In the second

generation, the light fields are spatially uniform and temporal modulation is used to induce locomotion. The inching walker[67] and the miniature swimmer[35] (Fig. 2 a, b and h) are early demonstrations of this robot class. The third generation will be powered by stationary light fields (without spatial or temporal modulation), capable of self-propelling locomotion, as demonstrated by the rolling spiral ribbon in Figure 2e.[36] Integration of miniature robots with self-oscillating motors[87] (Fig. 2j) is very promising here, one example being a recently demonstrated self-propelled walker using oscillating wave-like motion.[99] The fourth generation includes control via, *e.g.*, light color or polarization. Examples falling into this category may be, for instance, using light wavelength to control the robot direction, or using light polarization to steer the movement. Ultimately, the light robots of the last, fifth generation will be able to interact with the environment, *e.g.*, exhibiting phototropism and/or social behavior, joining efforts to autonomously execute complex tasks. While we are not aware of any demonstrations in the last two generations to date, we know there are works under way and we expect to witness spectacular results in the field of light robotics in the near future.

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The table of contents entry

Light-controlled soft micro-robotics is a nascent field that explores technologies bridging the gap between micro-robotics and polymeric artificial muscles. This Research News article highlights recent progress in photomobile devices based on liquid-crystal polymers, such as walkers, swimmers and oscillators that may ultimately lead to flying micro-robots. Self-regulating mechanisms are introduced as a potential route towards intelligent, light-driven micro-robotics.

Keyword: liquid crystal, micro-robot, soft robot, photomobile, actuator

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Title: Light robots: bridging the gap between micro-robotics and photomechanics in soft materials

ToC figure

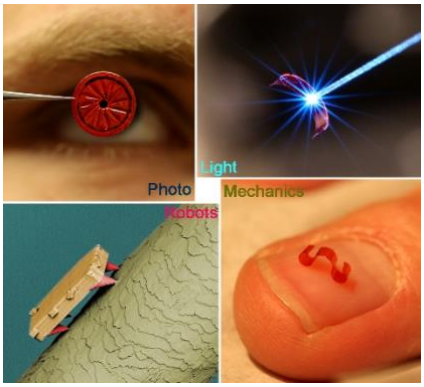

Table 1. Vocabulary.

Light robot: A robotic system that is (i) driven by *light*, and (ii) *light* in weight (i.e. small in size).

Micro-robot: For roboticists, "micro" means "small", *i.e.*, a "micro-robot" is a system smaller than conventional human-sized machines. For material scientists, "micro" refers to "microscopic", say less than a millimeter in size. Herein, we focus on device scales ranging from few centimeters down to micrometer-scale, while we exclude molecular motors, which have been popularized as *nano-robots*.

Soft robot: A robotic system that is primarily composed of materials with elastic moduli in the range similar to soft biological materials (10^4-10^9 Pa).[2]

Liquid-crystal polymer: We use liquid-crystal polymer as a general term to describe liquid-crystal elastomers, liquid-crystal gels, and glassy liquid-crystal polymer networks, which are distinguished by their mechanical properties, crosslinking density, and chemical composition.

Photomobility: Refers herein to the ability to continuously translate the center of mass under illumination (excluding direct momentum transfer from photons).

Figure 1. The many faces of liquid-crystal polymer actuation; examples from 1D, 2D, and 3D worlds. a, Schematic of the light-induced shape-change of a liquid-crystal polymer, resulting from order-disorder transition. **b**, **c**, Principle of actuation in a bending polymer film, as illustrated through analogy to paper cutting. **d**, Light-triggered deformation in a liquid-crystal polymer film containing +1 (top) and -1 (bottom) radial defects.[53] **e**, The deformation of a liquid-crystal polymer film with 3×3 +1 azimuthal defects.[53] **f**, Self-folding of a polymer into a box upon heat stimulus.[61] **g**, 3D liquid-crystal polymer microstructures produced by laser writing.[64] Reproduced with permission.[61] Copyright 2015, The Royal Society of Chemistry.

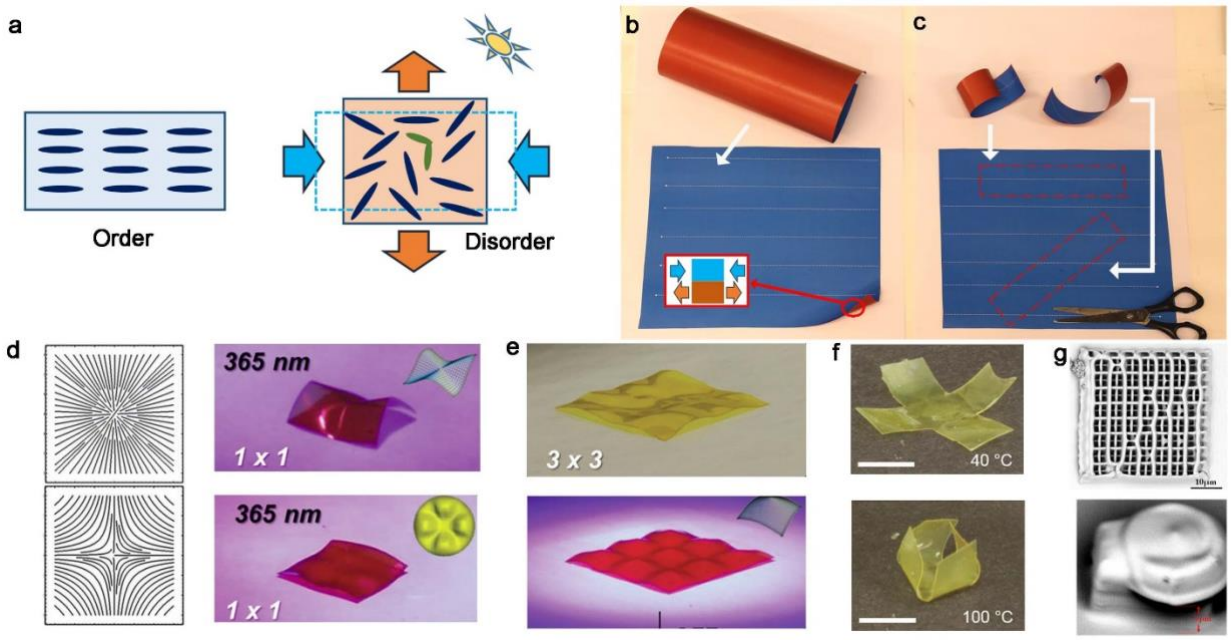

Figure 2. Photomobile robots. a, An inching walker on human hand. The inset shows the actuation: light on, the robot body extends; light off, the body bends.[67] **b**, Scanning electron microscope image of a microscopic walker sitting on human hair. Insets show the way of actuation: light on, body contracts; light off, body extends.[32] **c**, Caterpillar-inspired walking robot. Left inset: laser scanning induces local deformation of the robot body; Right inset: adaptive motion demonstrated by squeezing through a 0.9 mm high slit.[33] **d**, Kinetics in different modes of locomotion: directional walking (top), being stuck (center), and jumping (bottom). **e**, Translation of a spiral liquid-crystal polymer ribbon under continuous light illumination.[36] **f**, Peristaltic crawling motion of a liquid-crystal polymer tube inside a capillary.[71] **g**, Different mechanisms for fluidic propulsion, and corresponding geometries in the polymer films.[34,46,95] **h**, The design of a miniature swimming robot.[35] **i**, A dynamic light field from a digital micromirror device is projected onto the liquid-crystal polymer robot (left), which propels itself in a liquid by a travelling-wave deformation (right).[34] **j**, Principle of light-induced oscillation in a polymer strip (above), and snapshots of the oscillators for different power levels: 1.08 W cm^{-2} (1) and 1.2 W cm^{-2} (2).[87] **k**, Comparison of the light actuation speed between the cm-sized incher shown in **a** and a 100 micron-sized incher, similar as in **b**. **l**, Wingbeat frequency vs. body mass for flying species.[94] Reproduced with permission. **e**,[36] Copyright 2016, **g**, **i**,[34] Copyright 2016, **g**,[95] Copyright 2009, **h**,[35] Copyright 2015, Nature Publishing Group; **f**,[71] Copyright 2016, **j**,[87] Copyright 2008, The Royal Society of Chemistry. Adapted with permission. **l**,[94] Copyright 2005,The Company of Biologists.

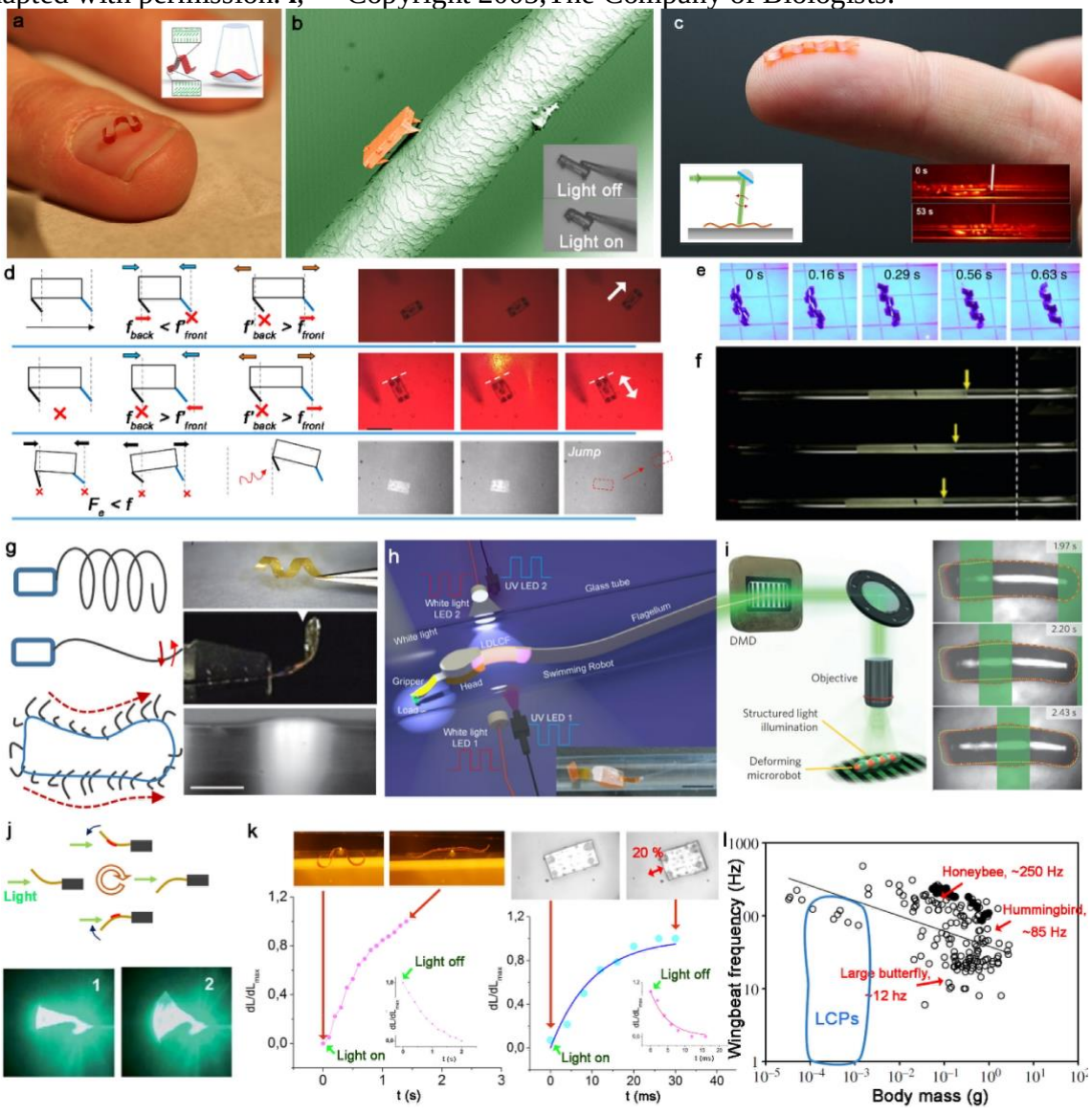

Figure 3. Self-regulation for autonomous soft robotics. a, Schematic of the working principle of electronics-based robot automation. **b**, The design of an automatic gripper, or a light-driven artificial flytrap: light emitted from optical fiber defines the field of view of the device, which closes when an object enters the field of view and causes light reflection to the polymer actuator.[97] **c**, Flytrap-mimicking motion demonstrated by capturing a small scattering object falling on the gripper (fiber output power equals 200 mW). **d**, Under constant light power (70 mW output), gripper self-closes on the highly reflecting target, and remains open when absorbing or transparent targets approach. **e**, Artificial iris autonomously opens/closes upon weak/strong light irradiation.[98] **f**, Measured light transmission (black dots) and transmitted power (red dots) at different input powers on the iris device. The dashed line corresponds to 100% transmission. Reproduced under the terms of the CC-BY-X license.[97] Copyright 2017, Nature Publishing Group.