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

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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 sought 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 microrobots that, by combining concepts from microrobotics 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, recent progress in soft microrobotics is highlighted based on light-responsive liquid-crystal elastomers and polymer networks, focusing on photomobile devices such as walkers, swimmers, and mechanical oscillators, which may ultimately lead to flying microrobots. Finally, self-regulated actuation is proposed as a new pathway toward 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 preprogramming to perform even simple tasks, lacking flexibility, and adaptability. Two grand challenges in conventional robotics relate to adaptivity in motion and difficulties in scaling 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 Section 1.1 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 toward 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 is very difficult, if not impossible, on 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 that rely on computer algorithms to control body movements, externally powered microrobots call for a new paradigm of actuation based on material design.

Recently, various stimuli-responsive materials have been implemented in microrobotics 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, and polarization) can be optimized for the specific needs 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 micromirrors, 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 Section 1.1 for our definition) is
to develop light-responsive systems incorporating sensors, actuators, and controllers, all in one element. Liquid-crystal polymers (LCPs; see Section 1.1),\textsuperscript{[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,\textsuperscript{[16,17]} or photothermal heating.\textsuperscript{[18]} Light-induced deformations can respond to changing light intensity,\textsuperscript{[19]} wavelength,\textsuperscript{[20,21]} or polarization.\textsuperscript{[17,22]} Compared to other stimuli-responsive materials such as electroactive polymers,\textsuperscript{[23]} compound polymers,\textsuperscript{[24]} or shape-memory polymers/alloys,\textsuperscript{[25]} liquid-crystal polymers can exhibit various modes of actuation and sensing through molecular-alignment control.\textsuperscript{[15,26]} This has led to development of miniature robots composed of multiple light-controlled actuators, thus bridging the gap between microrobotics 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.\textsuperscript{[27–36]} However, a limited number of examples of light-powered, miniature mobile devices exist.\textsuperscript{[18,31–36]} Herein, we summarize the latest results in LCP-based photomobile (see Section 1.1 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.\textsuperscript{[37–39]} Also energy conversion based on photovoltaic technologies is omitted.\textsuperscript{[40]}

1.1. Terminology and Vocabulary

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

Microrobot: For roboticists, “micro” means “small”, i.e., a “microrobot” 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 nanorobots.

Soft Robot: A robotic system that is primarily composed of materials with elastic moduli in the range similar to soft biological materials ($10^4$–$10^6$ Pa).\textsuperscript{[2]}

Liquid-Crystal Polymer: Herein, we use liquid-crystal polymer (LCP) 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: 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 LCP synthesis, characterization, and actuation performance comprises numerous studies on molecular design, alignment control, and actuation mechanisms/modes, as highlighted in several recent reviews.\textsuperscript{[19,26,41–43]} Here, we wish to provide a concise introduction to the field.

Liquid crystals\textsuperscript{[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 maintain the ordered molecular alignment of the 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 solid, polymeric materials, using light as an energy source. Due to the tight packing of molecules (most often rod-like in shape) that have been confined in ordered polymer networks, 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,\textsuperscript{[45,46]} in order to yield the desired actuation mode when fueled at some specific wavelength 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.\textsuperscript{[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).\textsuperscript{[51,52]} By patterning the orientation onto a 2D surface, one can obtain a further degree of control over the deformation (Figure 1d). As an example, a radially aligned molecular distribution leads to a local buckling of the initially flat polymer film.\textsuperscript{[53]} Such defect-like alignment can be further engineered into more complex forms (azimuthal/radial defects),\textsuperscript{[29,55–57]} which result in cone/anticone shapes.\textsuperscript{[58,59]} A matrix composed of several such defects exhibits periodic buckling, leading to complex 3D surface deformation upon irradiation (Figure 1e).\textsuperscript{[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.\textsuperscript{[61]} A technique that can arbitrarily pattern the director distribution and thus the deformation in three dimensions is highly demanded, and laser lithography\textsuperscript{[62]} and 3D printing\textsuperscript{[63]} have been developed to fabricate 3D polymeric structures with sophisticated control over the deformation. In particular, two-photon-absorption-based laser writing has been exploited to produce 3D LCP microstructures (Figure 1g), in which global deformations can be activated with a single, focused laser beam.\textsuperscript{[64]} Moving beyond light-driven actuators, the key question is how to harness the shape changes to build light robots that move in a predesigned manner.
3. From Light-Driven Actuators to Photomobile Robots

Several mobile robots powered by external stimuli exist. Microdevices dragged in liquid by a magnetic-field gradient or propelled by a torque originating from a rotating magnetic field, and an optical-tweezer robot activated by gradient and scattering forces, 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, and the inner force(s) allow the robot to overcome environmental resistance. These dynamics are similar to that 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 an alternately patterned, splay-aligned, monolithic liquid-crystal-polymer strip (Figure 2a) was demonstrated. The body responsible for the caterpillar-like inching locomotion could be fabricated within a few simple steps, and was easily 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 micrometers by using laser lithography, with rigid, conical legs reducing the walking friction. In Figure 2b, a 60 µm long walker, sitting on a human hair, is presented. Directional walking at small scales faces specific hurdles. First, 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 arises from the reduced number of degrees of freedom. One can overcome the environmental resistance if a sufficient number of degrees of freedom are available. Humans implement static friction on the foot-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 microwalker with limited degrees of freedom, this phase of “switching on/off” friction between the robot body and the surface is more difficult.

A directional moving tendency can be created in photoactuators by introducing a friction bias into the walker feet through...
Figure 2. Photomobile robots. a) An inching walker on a human hand. The inset shows the actuation: light on, the robot body extends; light off, the body bends.\[67\] b) Scanning electron microscopy image of a microscopic walker sitting on human hair. The insets show the method 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.\[84\] f) Peristaltic crawling motion of a liquid-crystal-polymer tube inside a capillary.\[71\] g) Different mechanisms for fluidic propulsion, and the corresponding geometries in the polymer films: spiral,\[46\] bending,\[95\] and wave-like.\[34\] h) The design of a miniature swimming robot.\[35\] i) A dynamic light field from a digital micro-mirror device is projected onto the liquid-crystal-polymer robot (left), which propels itself in a liquid by a traveling-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 centimeter-sized incher shown in (a) and a 100 µm sized incher, similar to that in (b). l) Wingbeat frequency versus body mass for flying species.\[94\] a) Reproduced with permission.\[67\] Copyright 2017, Wiley-VCH. b) Reproduced with permission.\[32\] Copyright 2015, Wiley-VCH. c) Reproduced with permission.\[33\] Copyright 2016, Wiley-VCH. e) Reproduced with permission.\[36\] Copyright 2016, Nature Publishing Group. f) Reproduced with permission.\[71\] Copyright 2016, Royal Society of Chemistry. g) Reproduced with permission.\[46\] Copyright 2014, Nature Publishing Group. Center: Reproduced with permission.\[95\] Copyright 2009, Nature Publishing Group. Bottom and i): Reproduced with permission.\[34\] Copyright 2016, Nature Publishing Group. h) Reproduced with permission.\[35\] Copyright 2015, Nature Publishing Group. j) Reproduced with permission.\[34\] Copyright 2008, Royal Society of Chemistry. l) Adapted with permission.\[87\] Copyright 2005, The Company of Biologists.
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 microcrawler 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, \(f'_{\text{back}} > f'_{\text{front}}\) and \(f''_{\text{back}} > f''_{\text{front}}\), where \(f'_{\text{front}}\) and \(f''_{\text{front}}\) 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., \(f'_{\text{back}} < f'_{\text{front}}\) or \(f''_{\text{back}} < f''_{\text{front}}\). In such a case, the walker is stuck on either the front legs or back legs, as shown in Figure 2d, center. Another interesting phenomenon is the microrobot jumping. As shown at the bottom of Figure 2d, all the legs are initially stuck on a rough surface (e.g., paper or a 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 the crawling locomotion of a caterpillar with a traveling-wave deformation. The locomotion is induced by scanning a laser beam along the robot body, which triggers a 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 a capillary-type actuator also provides access to light-based micromanipulation of droplets.\(^{[72]}\) A liquid-crystal-polymer spiral ribbon rolling over large distance under spatially and temporally stationary illumination was demonstrated earlier this year (Figure 2e).\(^{[36]}\) In this system, the upper part of the polymer tends to exhibit a larger twist compared to the shadowed bottom part. The asymmetric illumination brings about photoinduced strains, thus continuously impulsing the spiral geometry and giving rise to a net twisting moment. A similar rolling motion was very recently also reported in a bilayer 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 microworld. The uppermost 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 nonreciprocal motion—a prerequisite to obtain swimming in low-Reynolds-number liquids.\(^{[75]}\) Interestingly, helical deformations have been reported in liquid-crystal polymers by many groups,\(^{[76-78]}\) yet, so far, there has been no experimental demonstration of helical LCP swimmers, 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 LCP 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 (Figure 2h). More sophisticated motions have been found in organisms using collective, synchronized motion of cilia, to create a traveling-wave liquid flow (Figure 2g, 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 Figure 2c) can trigger local shape change in an LCP. This has been demonstrated using a 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 Kelvin up to \(\approx 100\) 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 are based on electrically powered propeller(s) or piezoactuators driving the wings.\(^{[85,86]}\) When scaled down to few centimeters or below, an on-board battery becomes impractical because of the increase in the weight-to-power ratio, whereas liquid-crystal polymers might provide alternative routes toward 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, an oscillation frequency as high as 271 Hz was reached.\(^{[89]}\) More recently, similar self-oscillation, based on photothermal actuation in a 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 bilayer oscillator capable of transferring light energy into electricity was 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
nafocused sunlight has been reported, however, with relatively low oscillation amplitude and frequency.\textsuperscript{[20]}

To obtain fast, high-amplitude oscillation, 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\textsuperscript{[32]} to below 1 s\textsuperscript{[35]} (as shown, for example, in the fish robot in Figure 2h). The fast response observed in high-frequency oscillators is mostly related to photothermal heating, which has also been confirmed by infrared imaging.\textsuperscript{[93]} This photothermal actuation, often neglected or considered somewhat 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 an 8 mm long inching robot (the same as in Figure 2a) deforms its body on the time scale of a few seconds,\textsuperscript{[67]} whereas a walker with a size of 100 \( \mu \)m (similar to that in Figure 2b) can undergo complete deformation (20% contraction in length) within 30 ms. As a downside, the illumination light intensity level has to be elevated from 1 mW mm\textsuperscript{-2} (former) to 1.4 W mm\textsuperscript{-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.\textsuperscript{[94]} The blue region indicates the feasible frequency range in contemporary liquid-crystal polymers. While an 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\textsuperscript{[95]} or modifying the crosslinking density within a monolithic liquid-crystal-polymer structure\textsuperscript{[96]} are the ways to yield nonreciprocal actuation—an efficient way to create thrust during material–air interaction.

We expect that future research efforts will concentrate on the maximization of the actuation frequency as well as measurements of the thrust forces under nonreciprocal movements, together with design of stable structures capable of balancing gravity, and the inertial and thrust forces during the movement. Reaching these milestones will be important steps toward 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

![Figure 3](adv.mat.2018.30.1703554.fig3.sm.png)
(e.g., position, image, and temperature) are processed, and decisions are sent to actuators, which execute a 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-sized flytrap-like gripping device that can distinguish different objects based on optical feedback and perform an automatic gripping action only when certain conditions are met. It is based on a polymeric actuator attached onto the tip of a multimode 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, does the polymer bend and grip the object (Figure 3c).

This device relies on light power (energy coupled into the fiber) in the range 50–250 mW, corresponding to irradiation intensity of ≈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 programmed by, for example, 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, which has the proper reflectance, while it remains open for targets that do not meet its “taste” and do not provide sufficient optical feedback. This behavior is similar to the self-regulating action of the flytrap plant that allows it to distinguish between, for example, dust particles and insects by different mechanical stimuli, and self-close only in response to the latter.

While many researchers focus their efforts on applying sophisticated, structured light fields to control liquid-crystal-polymer actuation, the opposite direction may also turn out to be fruitful: instead of controlling the 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. 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 devices mimic the self-regulating behavior of the human iris, which can adjust to changes in environmental conditions (light intensity). The specific actuator design allows the interplay between the light field and material response, and may guide roboticists toward 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 microscale, 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 toward the future) of LCP-based light robots, showing a decreasing trend in complexity of the required control strategy in the light field and, at the same time, increasing the functionality and degree of automation. Some robots may cross different generations, depending on their specific method 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\(^{[33]}\) (Figure 2c) and light swimmer\(^{[34]}\) (Figure 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\(^{[35]}\) (Figure 2a,b,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\(^{[87]}\) (Figure 2j) is very promising here, one example being a recently demonstrated self-propelled walker using an oscillating wave-like motion.\(^{[99]}\) The fourth generation includes control via, for example, light color or polarization. Examples falling into this category may be, for instance, using the light wavelength to control the robot direction, or using the light polarization to steer the movement. Ultimately, light robots of the last, fifth generation will be able to interact with the environment, for example, 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 is work under way, and we expect to witness spectacular results in the field of light robotics in the near future.

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Conflict of Interest

The authors declare no conflict of interest.

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