Structured light enables biomimetic swimming and versatile locomotion of photoresponsive soft microrobots

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Abstract

Microorganisms move in challenging environments by periodic changes in body shape. By contrast, current artificial microrobots cannot actively deform, exhibiting at best passive bending under external fields. Here, by taking advantage of the wireless, scalable and spatiotemporally selective capabilities that light allows, we show that soft microrobots consisting of photoactive liquid-crystal elastomers can be driven by structured monochromatic light to perform sophisticated biomimetic motions. We realized continuum yet selectively addressable artificial microswimmers that generate travelling-wave motions to self-propel without external forces or torques, as well as microrobots capable of versatile locomotion behaviours on demand. Both theoretical predictions and experimental results confirm that multiple gaits, mimicking either symplectic or antiplectic metachrony of ciliate protozoa, can be achieved with single microrobots. The principle of using structured light can be extended to other applications that require microscale actuation with sophisticated spatiotemporal coordination for advanced microrobotic technologies.

Mobile micro-scale robots are envisioned to navigate within the human body to perform minimally invasive diagnostic or therapeutic tasks[1,2]. Biological microorganisms represent the natural inspiration for this vision. For instance, microorganisms successfully swim and move through a variety of fluids and tissues. Locomotion in this regime, where viscous forces dominate over inertia (low Reynolds number), is only possible through non-reciprocal motions demanding spatiotemporal coordination of multiple actuators[3]. A variety of biological propulsion mechanisms at different scales, from the peristalsis of annelids (Fig. 1a) to the metachrony of ciliates (Fig. 1b), are based on the common principle of travelling waves (Fig. 1c). These emerge from the distributed and self-coordinated action of many independent molecular motors[4,5].

Implementing travelling wave propulsion in an artificial device would require many discrete actuators, each individually addressed and powered in a coordinated fashion (Fig. 1d). The integration of actuators into microrobots that are mobile poses additional hurdles, since power and control need to be distributed without affecting the microrobots' mobility. Existing microscale actuators generally rely on applying external magnetic[6-10], electric[11], or optical[12,13] fields globally over the entire workspace. However, these approaches do not permit the spatial selectivity required to independently address individual actuators within a micro-device. Nevertheless, complex non-reciprocal motion patterns have been achieved by carefully engineering the response of different regions in a device to a spatially uniform external field[13,14]. The drawback is that this complicates the fabrication process, inhibits down-scaling and constrains the device to a single predefined behaviour. These challenges mean that most artificial microrobots actually have no actuators. Rather, they are in most cases rigid monolithic structures, either pushed by chemical reactions[15] or directly

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manipulated by torques or forces applied by external magnetic fields[16-20].

Alternatively, they consist of flexible materials embedding, at best, a small number of passive degrees of freedom (DOFs)[21,22].

In macroscale robots, one approach to increase the number of DOFs has been to adopt soft bodies, capable of biomimetic actuation[23-28] . However, these approaches have resisted miniaturization. Soft active materials such as hydrogels[29] and liquid crystal elastomers (LCEs), which exhibit stimuli-responsive behaviours, represent a potential route towards advanced biomimetic microrobots. At the microscale, soft active materials have enriched microrobots with additional functionalities, *e.g.* on-demand drug release[30,31], and LCEs have recently actuated a walking microrobot[32]. Nevertheless, despite their soft bodies these microrobots have each a unique function, predefined by its form, and few DOFs.

Here we present the use of structured light to power and control intra-body shape changes in microrobots. The technique enables fully-artificial, self-propelled microswimmers. Indeed, they are true swimmers, since they move by deforming their soft body in a periodic way[4], and they do so with no forces or torques applied by external fields and no embedded biological cells. The versatility of the actuation mechanism allows a single device to execute a variety of gaits including propulsive motions that mimic the symplectic and antiplectic metachrony of ciliate protozoa. We describe the system as a new type of continuum actuator having a function-agnostic structure within which the light field can address a virtually unlimited number of DOFs (Fig. 1e). This versatility permits sophisticated and adaptable locomotion behaviours in sub-millimetre devices.

System concept

LCE materials exhibit a reversible shape change triggered by either heat or light[33,34]. Since they can be fabricated at small length scales[35,36] and powered remotely, they are ideally suited for building mobile active robots with body sizes on the scale of hundreds of microns[32]. Instead of uniformly illuminating a complex, carefully-engineered device[13] or focusing the light onto a single spot[37-39], our approach is to use structured dynamic light fields to excite sophisticated intra-body deformations within LCE microrobots with very simple and agnostic designs. In this scheme the microrobot is regarded as a continuously addressable body that acts as an extended array of many infinitesimally small actuators, each of which can be independently triggered by the local light field. This makes the remote power, synchronization and control easily solved macro-scale problems. It also has the benefit of transferring the burden of function from the microrobot's form into the light field, thereby simplifying its design and fabrication. So, rather than defining the microrobot's action once at the fabrication stage, it can be dynamically reconfigured in real-time through software, with virtually limitless flexibility.

Selective deformation of soft continuous micro-scale bodies

We fabricate LCE microrobots in the form of long cylinders (about 1 mm in length and 200-300 μm in diameter), and flat disks (50 μm thick and either 200 or 400 μm in diameter) using the procedures reported in the Methods section. At room temperature, the functional liquid crystalline units (mesogens) possess orientational order, whose local direction and strength are described by the nematic director $\mathbf{n}$ and the order parameter Q[33]. The photoresponse arises when the covalently bound azo-benzene dye in the LCE absorbs the light, driving the elastomer through the nematic-to-isotropic phase transition. The mechanism consists of two different, but likely concurrent effects: the dye's *trans-cis* photoisomerization, and a light-induced

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thermal effect[32,33,37]. The axial nematic alignment of our cylinders leads, under

homogeneous illumination, to axial contraction and simultaneous radial expansion

(Fig. 2a). By small-angle X-ray scattering we estimate a value for Q of 0.38 and axial

contractions of about 30% (see Supplementary Information S4), corresponding to

radial expansions of more than 18%. The elastomer formulations that we use

possess two key characteristics: first, they do not require a second wavelength of

light to excite relaxation after excitation; and they possess the fastest responses

among LCEs[32], a prerequisite for the propulsion that we demonstrate[13,40].

Structured light fields are generated by an optical system based on a Digital

Micromirror Device (DMD) with 1024x768 mirrors. The DMD spatially and temporally

modulates the intensity of the laser light field that is projected into the microrobot

workspace through a microscope objective (Fig. 2b – see Methods). Only those

sections of the body that are illuminated are expected to deform, while the remainder

will remain relaxed. Inspired by the locomotion of microorganisms, we implement

travelling-wave body deformations with selectable wave parameters. We simulate the

response of the cylindrical microrobots to periodic patterns of light and dark stripes

using a finite element model (Figs. 2c and 2f – see Methods). The numerical

simulations show that a localized decrease in the order parameter within the LCE

material indeed results in a selective shape change. However, because of the

material continuity conditions, binary illumination results in smooth transitions

between the relaxed and deformed regions (Figs. 2c – simulation – and 2d –

experiment). The continuous actuator mimics, at microscopic scales, the action of the

hydrostatic skeleton of worms during peristaltic motion, coupling radial and

longitudinal deformation at constant volume.

Figure 2d shows a close up side-view of the experimental deformation of a cylindrical

microrobot. A binary periodic light pattern, with a spatial wavelength of 260 μm, is

projected onto the microrobot (radius of about 100 μm), leading to localized shape changes in the illuminated regions (see Methods and Supplementary Movie 1). Importantly, neither relaxation nor spreading of the deformation due to heat transfer is observed, rather the shape changes are localized and stable. The light absorption profile through the material results in stronger illumination and heating of the surface that faces the light source compared with the opposite surface. However, so long as the temperature and illumination are sufficient to drive the response above the critical point and into saturation (see Supplementary Fig. S4), there is no strong differential deformation between the upper and lower surfaces.

The dynamic behaviour of a microrobot (length of 1.3 mm and radius of 170 μm) is shown by the sequence of frames in Fig. 2e, imaged from the top. A binary periodic light field (shown as the green overlay), travelling from left to right at a frequency of 1 Hz, is projected onto the microrobot, which is anchored to the lower surface. The portions of the device that are illuminated expand transversely, and follow the projected pattern as it travels along the body (see Supplementary Movie 1). For comparison, Fig. 2f shows the results from the corresponding numerical simulation. Hence, it is possible to generate, locally address, and power an extended continuous actuator system using light, and thus obtain complex coordinated motion behaviours such as biomimetic travelling-wave deformations. Waves not only mimic the behaviours that many small organisms use for propulsion, but have the benefit of abstracting a theoretically infinite number of intrinsic DOFs down to a handful of easily recognized parameters.

Self-propulsion by biomimetic travelling-wave body deformations

We exploit these travelling-wave shape changes to achieve fully-artificial self-propelled microswimmers. Like biological microswimmers, these microrobots propel

themselves through periodic body deformations[4], which are generated neither by externally applied forces or torques, nor by embedded biological cells.

Figure 3a shows how a fiducial point on the top surface of a microrobot moves in the body-frame in response to a light-induced travelling wave that moves from right to left. Over one cycle, the point describes a counter clockwise loop, deforming radially by ±5 μm at the peak and trough of the passing illumination. It also moves longitudinally due to the contraction of its neighbouring regions. The trajectory calculated based on the measured order parameter and assuming sinusoidal wave deformation (yellow, see Supplementary Information S9) is in substantial agreement with the experimental one. The important characteristic for swimming is that, because of the material properties of the soft actuator, any point on the surface of the body describes an open orbit, meaning that its trajectory is non-reciprocal.

Figure 3c illustrates the movement of a microrobot (length of 1230 μm, radius of 120 μm) freely suspended in a fluid and undergoing travelling wave deformations. The microrobot is suspended within a viscous glycerol–water solution far from any solid boundary (see Methods), while a periodic binary light pattern (pattern wavelength $\lambda =$ 387 μm, frequency $f = 2$ Hz, shown as a green overlay) is projected onto it to drive wave deformations along its length. The body undergoes a net displacement of 110 μm at a speed of 2.1 μm/s in the direction opposite to that of the wave. Switching the direction of the moving light pattern reverses the swimming direction. Moving backwards, the microrobot displaces about 120 μm at a speed of 2.8 μm/s (see Supplementary Movie 2). The current propulsion performance can be enhanced by improving the active response of the soft materials. For instance, a lower transition temperature leads to a faster response in the fluid. Moreover, an improved order parameter enables larger deformation amplitudes.

Distinct from the case of manipulation by magnetic fields, the external light field only provides power and permits control of the microrobots. The driving actions are generated by the light-triggered molecular re-orientation within the soft active material, so that the microrobots' propulsion is fully remotely controllable.

The self-propulsion of the cylindrical microrobot by travelling wave motions closely mimics the propulsion of microscopic biological swimmers[4], in particular ciliates (*e.g. Paramecium*) which self-propel using metachronal waves. Here, the directed motion of periodic light patterns drives deformation waves along the cylinder, thereby dragging the surrounding fluid. Propulsion, generally in the direction opposite to the waves, arises because the net hydrodynamic force on the cylinder must be zero. An analysis similar to that first developed in Refs. [41,42] can be applied to the current geometry, with details shown in the Supplementary Information S9. Considering an infinitely long cylinder of radius a undergoing sinusoidal radial deformation of amplitude $b \ll a$, wavelength λ and frequency f, and assuming the cylinder to be incompressible, we predict the body's propulsion velocity V to be

$$V = \frac{(2\pi b)^2 f}{\lambda} G\left(\frac{2\pi a}{\lambda}\right),$$

(1)

where the function G is given by

$$G(x) = \frac{1}{2}\left[\frac{(1 + (2/x)^2)K_1^2(x) - K_0^2(x)}{K_0^2(x) - K_1^2(x) + (2/x)K_0(x)K_1(x)} - \left(\frac{2}{x}\right)^2\right],$$

(2)

with K_i being the modified Bessel function of the second kind ($i = 0,1$). The predicted fluid velocity field near the swimmer is shown in Fig. 3b, as observed in the body frame.

According to the numerical simulations and experimental results reported in Fig. 2c-d, the deformation profile is smoother than the applied illumination profile, because of the finite elasticity of the LCE. For this reason, the amplitude of the wave deformation

b exhibits a wavelength dependence, which we describe by the following empirical relationship

$$b = b_0 \left(1 - e^{-\frac{\lambda}{\lambda_c}} \right),$$ (3)

where b_0 is the maximum amplitude of deformation, which occurs at long wavelengths, and λ_c is the critical wavelength below which the deformation amplitude is attenuated (see Supplementary Information S7 and S8). In particular, a lower value of λ_c implies a lower smoothing effect and an improved ability of the microswimmer to execute deformations with narrow spatial features. Moreover, the linear dependence of the swimming speed on the frequency of actuation reported in (1) is valid only for relatively low frequencies, limited by the characteristic time of the material response (see Supplementary Information S10). Nonetheless, for the swimming experiment reported above, the model predicts a swimming speed of 2.6 μm/s, in very good agreement with the measured speed of 2.1-2.8 μm/s.

Equation (1) predicts a dependence of the swimming velocity on the deformation wavelength. We investigated this dependence by driving another microrobot (length of 680 μm, radius of 75 μm) with patterns of various wavelengths (shown as green overlays in Fig. 3d) and compared its speed with the model's predictions (Fig. 3e – see Methods). Notably, this analysis is only possible because in our scheme deformation parameters such as the wavelength are not pre-programmed in the swimmer's structure, but can be arbitrarily controlled by the applied light field. The most striking feature is the counterintuitive retrograde swimming that occurs without wave reversal at long wavelengths. This arises because the amplitude of the longitudinal deformation increases with wavelength, thus changing its importance relative to the radial expansion. The microswimmer therefore exhibits two different swimming modes, one 'positive' and one 'negative', dominated by the radial and

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longitudinal deformations, respectively. We observe the transition between the two modes at somewhat shorter wavelengths (>425 μm) than predicted by the model (>600 μm). This is likely because the theory models an infinitely long swimmer. For our finite-length swimmer the effects of truncation become more pronounced at long wavelengths as λ approaches the length of the swimmer.

The positive swimming mode observed at short wavelengths closely mimics the symplectic metachrony executed by many ciliate protozoa[43]. In this mode the metachronal wave travels in the same direction as the cilia's power stroke, opposite to the swimming direction. Other ciliates use antiplectic metachrony in which the wave and the swimming directions are the same. Since the sense of the orbit described by a surface point (cf. Fig. 3a) does not reverse with respect to the travelling wave, our negative mode mimics antiplectic metachrony by changing the relative amplitude of the longitudinal vs. axial deformation, rather than by reversal of the relative phase (see Supplementary Information S9)[44]. This pseudo-antiplectic behaviour is an unusual mode, predicted by classical models but so far not seen in nature. True antiplectic metachrony could be achieved by constructing the swimmer's body from an auxetic (negative Poisson's ratio) material. Passive, micro-scale auxetic metamaterials have been fabricated using technology that can be applied to LCEs[45,46]. Nevertheless, our microswimmers are capable of broader functionality than is found in nature, where any given species of ciliate exhibits only one mode of metachrony.

Equation (1) suggests that the swimming speed will scale favourably as the swimmers are made smaller. The frequency is limited by the material response time; since this is a thermally driven process it is expected to scale inversely with system size, with smaller structures heating more rapidly. Similarly, the finite element results

in Supplementary Information S8 indicate that the critical wavelength λ_c scales

linearly with swimmer radius, so smaller structures are capable of deforming with

smaller wavelengths. On the other hand, since it is essentially a strain, the maximum

radial deformation scales linearly with radius, and shrinks with the size of the

structure. The net result is that V is expected to remain unchanged with body size.

Versatile microrobots exhibit different behaviours on demand

We also fabricated microrobots by photolithographically patterning disks (400 μm in

diameter and 50 μm thick) where the nematic director **n** is oriented perpendicular to

the disk's surface. These simple structures undergo thickness compression

accompanied by radial expansion (Fig. 4a). The nematic LCE used for these disks

exhibits typical contractions of about 20%[32]. Crucially, their axial symmetry means

that, within the disk's plane, there is no preferential direction of movement. Thus, the

disk's course can be controlled in 2D by the direction of the induced wave

deformations (Fig. 4b).

The disk microrobots are immersed in silicone oil, close to the bottom of the

container, and oriented so that the light patterns are projected onto their face (see

Methods). We direct the locomotion of a disk microrobot along a two-dimensional 500

μm square path (Fig. 4c and Supplementary Movie 3). The microrobot's position is

automatically tracked by closed-loop control software and directed to the next

waypoint (red squares) by the proper travelling wave pattern. The direction of motion

(white arrows) is opposite to the travelling wave direction (green arrows). The

average speed of the microrobot along the path is about 40 μm/s, which corresponds

to about 0.1 bodylengths/s. Supplementary Movie 3 also shows the microrobot being

guided along a different, diamond-shaped path. The microrobot does not rotate at the

vertices, but only changes its course according to the applied light pattern.

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The high symmetry of the disks means that these microrobots offer the possibility of new deformation behaviours in addition to linear waves. This can be used to generate alternative gaits. As an example, we project rotating fan-shaped light fields as azimuthal travelling waves ($\lambda = 2\pi/3$ rad, $f = 3$ Hz) centred on the very same microrobot (Fig. 4d-e). This generates controlled rotation without translation (see Supplementary Movie 3) with a rotation speed of about 0.5°/s.

The high spatial selectively of light fields can also enable the independent control of multiple microrobots at once[47]. Here we simultaneously control two smaller disk-shaped microrobots (diameter: 200 μm; thickness: 50 μm) executing a rotation stroke (Supplementary Movie 4 and Fig. 4f). Fan-shaped rotating light patterns ($\lambda = \pi$ rad, $f = 3$ Hz, shown as green overlays) are projected onto each of the two microrobots. First, the two light patterns are both rotated clockwise, so that both of the disks rotate counter-clockwise (white arrows in Fig. 4f left). Then, the left microrobot's sense of rotation is reversed (cyan arrow in Fig. 4f right), while the right one continues to rotate counter-clockwise (white arrow in Fig. 4f right). The average absolute rotation speed is about 1°/sec. Independent control over the rotation of the two microrobots is thus achieved.

The disk microrobots demonstrate that a single microrobot can be directed to execute internal wave-like deformations with a variety of frequencies, wavelengths and symmetries, which in turn drive a number of different whole-body gaits. For the motions shown here, we estimate that traditional schemes would require approximately 100 actuators to be embedded, individually controlled and macroscopically coordinated within a 400 μm-diameter untethered device to obtain the same spatial resolution of actuation achieved in the current implementation.

Outlook

In summary, structured light fields allow us to exercise low-level control over the local actuation dynamics within the body of microrobots made of soft active materials. This in turn enables the high-level control over the microrobots' macroscopic behaviour, such as locomotion, with a level of versatility that is unmatched in micro-scale robotics. Even though a light-based approach requires optical access, which may limit the range of applications, such access is a natural prerequisite in any scheme that requires visualisation. Moreover, although here we focus on bioinspired travelling waves, our approach is not limited to wave-like motions. In fact, more complex behaviours can easily be achieved by simply conceiving the proper structured light fields. Although our subject here was generating sophisticated functions from simple robots by structured light fields, even more powerful and exotic behaviours can be expected when complicated fields are combined with intrinsically functional microrobot designs[48]. While we have focused on metachronal waves used by ciliates, it should be noted that nematodes, whose size is comparable to our swimmers, swim by another propulsion mechanism: undulation[49]. The implementation of undulation is in principle possible with the system we describe, but would require a modified fabrication procedure for the swimmers. The level of control that we demonstrate represents an essential step towards sophisticated microrobotic technologies and advanced microrobotic applications.

Acknowledgements

Author Contributions

SP, AGM and PF proposed the experiment; SP, AGM, KM built the structured light setup; HZ, CP, DM, and DSW synthesized the LCE and formed the cylindrical samples; SP performed the experiments and numerical simulations; SP and TQ fabricated the disk by photolithography; SP, AGM, ASC, NK, and FG characterized the LCE material by SAXS; SYR and EL developed the analytical theory model; SP, AGM, and PF wrote the manuscript with contributions from all authors.

Competing Financial Interests

The authors declare no competing financial interests.

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Methods

Fabrication of the microrobots.

The microrobots consist of nematic LCEs based on either the side-on mesogen M1 (cylindrical microrobots) or the end-on mesogen M2 (disk microrobots), both containing a custom azobenzene-dye (mesogens and dye synthesized following previously reported procedures, see Supplementary Information S3).

For the cylinders, a mixture is prepared with 85 mol% of mesogen M1, 13 mol% of cross-linker CL1, 1 mol% initiator and 1 mol% azo-dye. A drop of the mixture is placed on a glass slide and heated to the isotropic phase (T > 80 ºC). It is then allowed to cool until it becomes viscous enough to pull a continuous fibre using a fine tip. The fibre is cured with a UV lamp during pulling, then cut with a scalpel into 1 mm long cylinders.

For the disks, a mixture is prepared with 77 mol% of mesogen M2, 20 mol% of cross-linker CL2, 2 mol% initiator and 1 mol% azo-dye. The mixture is infiltrated into a glass cell at 80 ºC, and then slowly cooled to room temperature. The cell consists of two glass slides, cleaned by Ar-plasma, separated by 50 μm spacers. The mixture is then UV-cured through a photo-mask by a mask-aligner (MJB4, SUSS MicroTec, Germany) to obtain disks with diameters of either 200 or 400 μm. Once the cell is opened, the disks are manually detached from the substrate with a razor blade.

Generation of dynamic light fields.

A Digital Micromirror Device (DMD) module (V-7000, ViaLUX, Germany) is addressed by custom software to dynamically modulate the intensity of a 532 nm laser beam (Verdi G10, Coherent, USA). The beam is expanded upstream of the DMD, to fully cover the DMD surface. The modulated beam is then projected through a 4X microscope objective (Nikon, Japan) onto the working area containing the

microrobots. The light power onto the microrobots is of the order of few hundreds of mW. A CMOS camera (resolution 1280x1024 – Thorlabs, USA) images the workspace through the same objective. Details of the setup are reported in Supplementary Information S2.

Finite-element models.

The numerical simulations are performed in COMSOL Multiphysics (COMSOL, Sweden). For the cylinders a 2D-axisymmetric stationary analysis is performed, while a 3D stationary analysis is done for the disks. The models simulate the solid mechanics of the microstructures and do not take into account the absorption of light, the conduction of heat through the material, or the hydrodynamic response of the surroundings. Strains arise in proportion to a locally imposed reduction of the order parameter Q. For additional details refer to the Supplementary Information S5.

Deformation experiments.

For the top-view experiments an LCE cylinder is positioned on a glass covered with PTFE tape. The sample is excited with a linear periodic binary light pattern (rectangular wave: frequency $f = 1$ Hz, effective pattern wavelength $\lambda = 950$ μm, and duty cycle $dc = 1/3$ – see Supplementary Information S6).

For the side-view experiments an LCE cylinder is positioned on a glass covered with a thin layer of silicone oil to avoid adhesion. An additional camera (Dragonfly 2 HIBW, Point Grey Research, Canada) is placed to the side of the workspace where it images the cylinder through a 10X microscope objective (Nikon, Japan). A linear periodic binary light pattern (rectangular wave: $f = 1$ Hz, $\lambda = 260$ μm, $dc = 1/3$) is projected onto the sample.

Swimming experiments.

In the first swimming experiment a cylindrical LCE sample is suspended far from any solid surface in a solution of glycerol and water, in which a density gradient is established. A linear periodic binary light pattern (rectangular wave: $f = 2$ Hz, $\lambda = 390$ μm, $dc = 1/3$) is projected onto the sample. First, the light pattern travels from left to right for about 50 s, then the LCE is let relax for about 10 s, and then a light pattern travelling from right to left is projected for another 50 s.

In the wavelength-dependence analysis, linear periodic binary light pattern with varying wavelengths ($f = 3$ Hz, $dc = 0.3$) are projected onto the sample for 10 s each. After each projection the sample is allowed to relax for 5 s. The swimming speeds are evaluated from the displacements estimated by automatic thresholding and particle analysis (ImageJ, USA).

2D-locomotion and rotation experiments.

A disk is immersed in silicone oil close to the bottom of a petri dish covered with a thin layer of polydimethylsiloxane (PDMS). For the 2D locomotion tests, a closed-loop control algorithm tracks the microrobot's position and projects a bounded linear periodic light pattern onto it (square wave: $f = 3$ Hz, $\lambda = 650$ μm). The travelling direction of the wave pattern is automatically calculated to drive the disk towards the next target position in the route. The rotations are driven by azimuthal square waves ($f = 3$ Hz, $\lambda = 2\pi/3$ rad, see Supplementary Information S6) centred on the disk. The light pattern is rotated clockwise for 60 s, and then counter-clockwise for another 60 s. The rotation of the disk is estimated by measuring the position of a small defect on its edge, used as fiducial mark, with respect to its centre.

Multiple microrobots experiments.

The two small disks are immersed in silicone oil, close to the bottom of the PDMS coated petri dish, and close enough to each other to fit within the workspace.

Independent periodic binary light patterns are projected onto the two disks (azimuthal square waves: $f = 3$ Hz, $\lambda = \pi$ rad). In the first 60 s both light patterns are rotated in a counter-clockwise direction; for the next 60 s the pattern on the left disk is reversed.

Code availability

The custom code for DMD control is available on request by contacting the corresponding author.

Figure Legends

Figure 1. Locomotion based on travelling wave features: from nature to technology. a, peristaltic locomotion of a worm by travelling waves of radial expansion and longitudinal elongation. **b**, propulsion of a ciliate by metachronal waves emerging from the coordination of the cilia. **c**, abstraction of the concept of travelling waves as a general locomotion principle. **d**, the artificial implementation of a travelling wave propulsion would normally require the use of a large number of actuators that can be controlled in a precisely synchronized manner; this is unfeasible at the micro-scale. **e**, concept of a selectively-triggered continuous microrobot consisting of a soft active material.

Figure 2. Deformation of microrobots made of soft active materials wirelessly controlled by dynamic light fields. a, Finite element simulation of a cylindrical microrobot (length = 1 mm, diameter = 200 μm) at rest (left) and after full deformation (right, emphasized by a 2X factor). The blue and yellow arrows represent the axial contraction and radial expansion, respectively. **b**, Concept and main elements of the system, namely the Digital Micromirror Device (DMD), which modulates the incoming light beam in both space and time, and the microscope objective that projects the dynamic light field upon the soft microrobot, which in turns deforms in a selective fashion. **c**, Deformation profile obtained from finite element simulation: rest configuration (black), light field (green) and deformed profile (blue). Because of incompressibility of the material, the discontinuous pattern of illumination results in a continuous, smooth profile of deformation, and longitudinal displacement of the surface elements (grey lines). **d**, High resolution experimental side-view image of the selective deformation of a microrobot confined to the area of illumination. Scale bar: 100 μm. **e**, Experimental top-view images showing the deformation of an anchored cylindrical microrobot under a periodic light pattern travelling from left to right (illuminated area represented by the green overlay; first frame and yellow dotted line: rest configuration; red dashed line: deformed profile). Scale bar: 200 μm. **f**, Corresponding simulations of the behaviour of the microrobot.

Figure 3. Force- and torque-free swimming of a cylindrical microrobot driven by light-controlled travelling wave deformations. a, Trajectory of a fiducial point on the surface of a 100 μm diameter cylindrical microrobot exposed to a periodic travelling light pattern ($f = 1$ Hz, $dc = 1/3$). Over one cycle the point displaces radially and longitudinally in response to the passing light field. The time within the cycle is indicated by the colour of the points. The yellow line represents a calculated trajectory based on the measured order parameter for the same microrobot radius and deformation wavelength, assuming a sinusoidal wave. **b**, Instantaneous fluid velocity field induced by the deformation of a cylindrical microrobot in the body frame of the cylinder from the analytical theory. The colour map shows the magnitudes of the fluid velocity v scaled by the wave velocity U, *i.e. v/U*. The white arrows indicate the direction of the fluid flow. The wave travels from the right to the left. **c**, Back and forth swimming of a cylindrical microrobot propelled by travelling wave deformations (red dashed line: deformed profile). The green overlays and arrows represent the periodic light pattern and its travelling direction, respectively. **d**, Displacements of a microrobot (yellow dashed line: reference position) when travelling light patterns having different wavelengths (green overlays, direction according to green arrows) are applied. The swimming direction (white arrows) is opposite to the patterns' travelling direction for short wavelengths, but is the same for longer ones. **e**, Velocity (red circles and dash-dot line; average over 8 independent measurements – error bars: standard deviation), along with the analytical model (blue solid line; light blue area: 95% confidence interval – wave amplitude b and wavelength constant λ_c estimated by fitting over experimental data). The three encircled measures refer to the three images in **d**. Scale bars: 200 μm.

Figure 4. In-plane controlled locomotion of disk-shaped microrobots. The symmetry of the disk means that several different deformation behaviours can be implemented by the appropriate light fields. **a**, FE simulation of uniform deformation: thickness contraction (blue arrow) and radial expansion (yellow arrows). Initial diameter: 400 μm; initial thickness: 50 μm. **b-c**, Translational locomotion by plane travelling waves. **b**, Simulated deformation of a disk under a plane wave light field (wavelength 400 μm); green arrow: travelling wave direction; black arrow: expected translation. The disk's symmetry permits motion in every in-plane direction. **c**, 2D translational locomotion along a square path by plane-wave light patterns travelling in different directions (green arrows). The microrobot does not rotate at the vertices, but only changes its course. **d-e**, In-place rotation by azimuthal travelling waves. **d**, Simulated deformation of a disk under an azimuthal wave light field; green arrow: travelling wave direction; black arrow: expected microrobot rotation . **e**, In-place rotation of the same microrobot driven by azimuthal-wave light patterns (green overlays) rotating in different directions (green arrows) relative to a reference orientation (dashed line). **f-g**, Parallel independent control of multiple microrobots by local light patterns. **f**, First, two azimuthal-wave light patterns (green overlays) rotating in the same direction are applied, driving the concordant rotation of the microrobots (white arrows). Then the rotation direction of the left microrobot is changed (cyan arrow) by reversing the direction of the driving local light field. **g**, Resulting angle of the two microrobots. Scale bars: 200 μm.

a

1 cm

b

50 μm

c

d

Actuators' Control

e