Photonic Microhand with Autonomous Action

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Abstract

Grabbing and holding objects at the microscale is a complex function, even for microscopic living animals. Inspired by the hominid-type hand, we engineered a microscopic equivalent able to catch micro elements. This micro hand is light sensitive and can be either remotely controlled by optical illumination or can act autonomously and grab small particles on the basis of their optical properties. Since the energy is delivered optically, without the need for wires or batteries, the artificial hand could be shrunk down to the micrometer scale. Soft material is used, in particular a custom made liquid crystal network that is patterned by a photolithographic technique. The elastic reshaping properties of this material allow for the finger movement, using environmental light as the only energy source. The hand can be either controlled externally (via the light field), or one can

create the conditions in which it autonomously grabs a particle in its vicinity. This micro robot has the unique feature that it can distinguish between particles of different color and grey level. The realization of this autonomous hand constitutes a crucial element in the development of microscopic creatures that can perform tasks without human intervention and self-organized automation at the micrometer scale.

The ability to grab and manipulate objects is one of the basic functions of hominid hands whereas object handling becomes rarer in microscopic living creatures. Nature has provided different strategies for object grabbing, not only by the use of fingers, but also by different limbs (e.g. spiraling tentacles). Mimicking such functionality is a fundamental task in robotics, and it represents a great challenge especially at the micrometer scale.[1] Very appealing would be the implementation of either remote-controlled or autonomous micro actuators to enhance the functionalities of lab-on-chip microfluidic devices, and even for non-invasive surgery and diagnostics.[2] While hard-body robots, made of rigid elements and joints, are prepared by traditional assembly and powered by electrical motors, batteries, hydraulic or pneumatic systems, the miniaturization of a robotic system requires alternative fabrication techniques and power sources.[3] A promising strategy is provided by smart polymers, able to respond to external stimuli like light, temperature, electric and magnetic fields.[4] The combination of such materials with photopolymerization strategies can be used to obtain different polymers with modulated mechanical properties,[5] and fabricate objects with nanometric resolution.[6,7] The soft nature of polymeric robots would offer to manipulate fragile objects with different morphologies (e.g. biological samples), thanks to the material flexibility and adaptive shaping under actuation. In this respect, Liquid Crystalline Networks (LCNs) are smart materials that combine the anisotropic properties of liquid crystals with the mechanical behavior of polymeric networks.[8,9] These materials exhibit a shape change that depends on the local alignment of the liquid crystal director field inside the network. This means that by programming the alignment of the molecules, one can achieve different deformations such as contraction or torsion when an appropriate stimulus is applied.[10] Recent preliminary results in this field include prototype microswimmers,[11,12] and basic micro walkers, able to move on different substrates in a dry environment.[13]

Reproduction of hominid hand ability is more difficult to achieve on the microscale. Actuators have been realized so far only with sub-millimeter dimensions or bigger, using hydrogels or other polymers.[14-18] The easiest design for a micro gripper is that of two different fingers able to bend towards the same point allowing to catch an object between them.[18] To achieve a more stable grip of the object, independently of its shape, an efficient structure is that of multiple opposites[19] (see **Figure 1a**). To obtain a bending element, several strategies were adopted in the past, like the use of bilayer structures,[15] such as hydrogels with different elastic modulus able to asymmetric swell.[16]

The micro hand we propose is made by LCNs. In particular, choosing splayed alignment results in the bending of the realized polymeric four orthogonal fingers, chosen for our micro hand design, when actuated (Figure 1b).[20]

Another very challenging issue is that of obtaining autonomous robotic action, that is, to create micro robots able to perform tasks in which they recognize and manipulate objects, and can take 'decisions' without human intervention, taking into account their local environment.

We report on the realization of a truly microscopic light-fueled micro hand, able to capture microscopic objects. The novelty is not only the extremely small size of the device, but also its capacity of being either controlled externally or performing autonomous operation in response to the presence of particles of specific optical properties. We show that the hand can grab particles based on their absorption spectrum; in particular, it grabs a black particle and not a white one. This response is autonomous and not human controlled. The system can also be made color specific and the illumination conditions can be chosen such that the micro hand only responds when a target material of the right absorption properties is present. Since LCNs are compatible with the standard polymer platform used for creating photonic components, the micro hand can be incorporated into a photonic circuit.[21] Moreover, several hands and other actuators can be combined with photonic components and even integrated with microscopic soft robots. Recent results have confirmed that these materials are also biocompatible,[22,23] which means also biomedical applications can be foreseen.

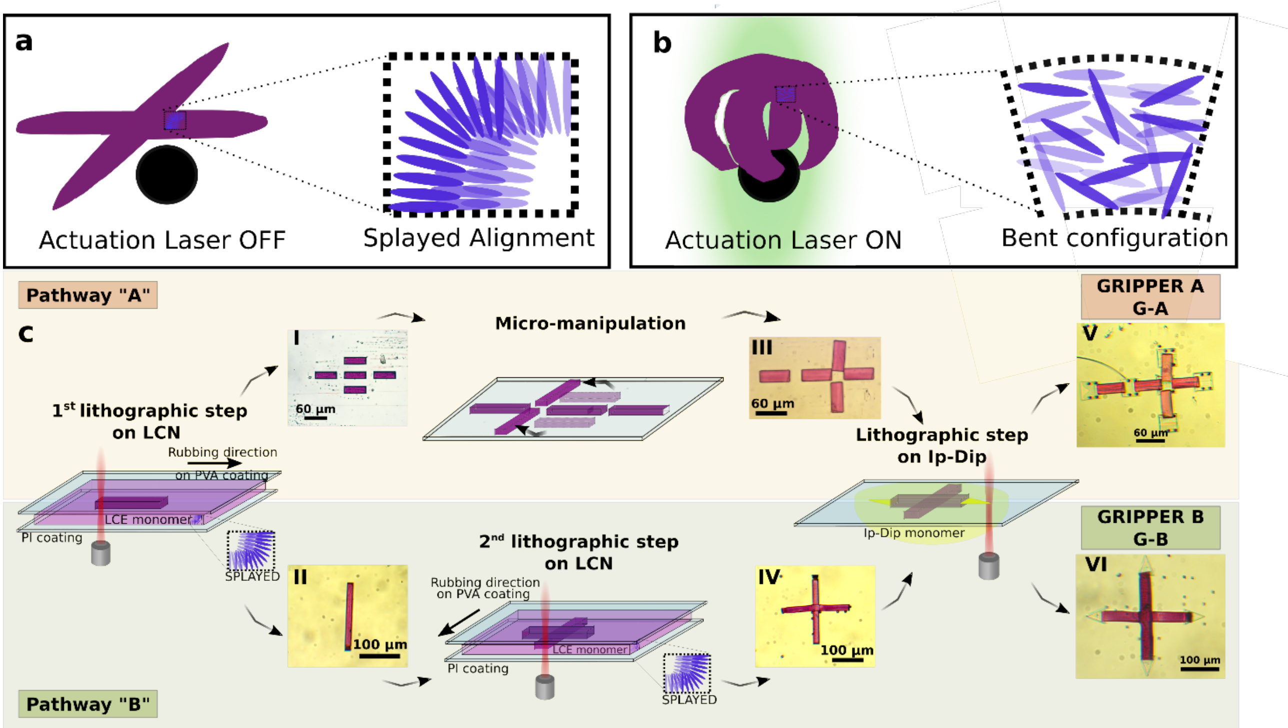

Figure 1. Micro hand design and fabrication. a) Illustration of a micro hand and related mesogen alignment. b) Illustration of the closed micro fingers in response to an optical stimulus and the related change in molecular alignment. c) Illustration of the two alternative fabrication routes. The upper part, Pathway A, describes the fabrication of Gripper A, while the bottom part, Pathway B, illustrates the fabrication of Gripper B. Two lithographic steps are common to both strategies. Optical images (I-VI) of the developed structures are shown for each step.

To fabricate the reported micro hands, a liquid crystalline mixture was prepared (reported in **Figure S1**), suitable to be polymerized and cross-linked by the photolithographic technique called Direct Laser Writing (DLW).[24-26] Typically, an azo-dye molecule[24] is embedded in the molecular structure to assure photoresponsivity,[27,28] through an intermediate heating step.[5] Two different procedure were developed for the micro hand fabrication and for both Direct Laser Writing was employed. In the first, we used rigid elements (Ip-Dip, commercial polymer from Nanoscribe) to connect LCN blocks as phalanges in between knuckles (Figure 1c, Pathway A). Later on, we simplified the fabrication procedure by the introduction of fingers composed only by monolithic LCN stripes (Figure 1c, Pathway B). In all cases, the splayed molecular orientation was obtained by the use of standard coated glass cells. The structure “Gripper A (G-A)” was prepared by two lithographic steps. Simultaneous fabrication of all the LCN structures was performed, followed by block positioning, which was achieved by mechanical reorientation of two blocks on the glass substrate. This micro-manipulation step allowed to achieve the desired position of the light-responsive parts of the hand. In the last lithographic step, Ip-Dip squares were fabricated both in the central region (as rigid connectors) and at the ends of the LCN parts. These terminal rigid elements function like extended nails and limit the adhesive forces when the fingers get in contact with objects or with each other, thus assuring for a correct recovery of the initial position.

However, picking up the blocks from the glass substrate and exactly positioning them in the right configuration is not trivial and often results in deterioration of the micro hands. We therefore developed the second fabrication strategy, resulting in “Gripper B (G-B)” (Figure 1c, Pathway B) through three lithographic steps. First, a stripe (20 x 200 x 20 μm^3) of LCN was written in a splayed cell. The subsequent writing step employed a splayed cell in which the planar homogenous side was perpendicular with respect to the previous one, allowing to obtain one polymeric structure with two different alignments. Thus, in the final cross shape G-B, the four orthogonal fingers bend towards the same point. Ultimately, with a third writing step, triangular Ip-Dip structures (30 base x 40 x 2 μm^3) were added at the finger ends (extended nails).

Multiple grippers can be fabricated during the same process allowing to obtain many structures at the end of each fabrication pathway. Even though one more lithographic step is required, pathway B allows for a more rapid preparation since one can avoid the intermediate mechanical manipulation of the LCN blocks. Moreover, the presence of fewer components resulted in an easier manipulation of the final structures, which can be quickly detached from the substrate without damage. However, pathway A, thanks to the possibility of mechanically moving single blocks, presents a great potential for the development of more complex structures. We therefore considered both structures interesting and a complete dynamic characterization of the two micro hands was performed.

Irradiation of the micro hands with a green laser causes the reversible folding of the structures into a closed shape, thanks to the different director alignments in each finger (**Figure 2a-b** and **movie S1** and **S2**). The LCN blocks present progressive bending as the laser power increases and it can be controlled in order to manage partial or complete closure of the micro hands. As mentioned above, the shape change of these materials takes mainly place via a heating step that occurs when the laser is absorbed. The movement of the fingers is then generated by different thermal expansion coefficients in the direction parallel and perpendicular to the alignment, and thus by the different response of the two sides of the splayed LCN.[20]

The stimulus intensity is not the only parameter that allows to control the micro finger movement. In fact, also the dimensions of the LCN blocks (thickness and length) influence the material deformation. The proposed structures were characterized over a range of different optical intensities. From the collected data, represented in Figure 2c**,** the contraction and relaxation times are determined as a function of the excitation power. As the power increases, the bending angle of each finger increases while also the contraction process rapidly speeds up.[5] These two effects contribute to the actuation time (Figure 2c) that is required by the structure to reach a bigger bending angle. On the contrary, the relaxation time is independent on the power and it is influenced only by the initial position of the contracted block. The actuation threshold for G-B (21 mW) results about a factor of two smaller than that for G-A (37 mW), and the same behavior is found for the complete closure of the micro hand (51 mW for G-B, compared to 90 mW for G-A). This trend is probably due to the bigger dimension of G-A and the structural strain that is introduced by the rigid polymeric phalanges of this design. The faster dynamics (20 ms for complete closure) is obtained for G-A probably due to the smaller sizes of its LCN blocks, with respect to the fingers of G-B, leading to faster heat diffusion and dissipation. In any case, the dynamics of these micro hands remains always in the millisecond range, which is very appealing for robotic, and other actuator-type applications. Considering the more complex fabrication and manipulation of G-A, and the comparable behavior of the two designs, we decided to pursue the rest of the experiments on micro hand G-B.

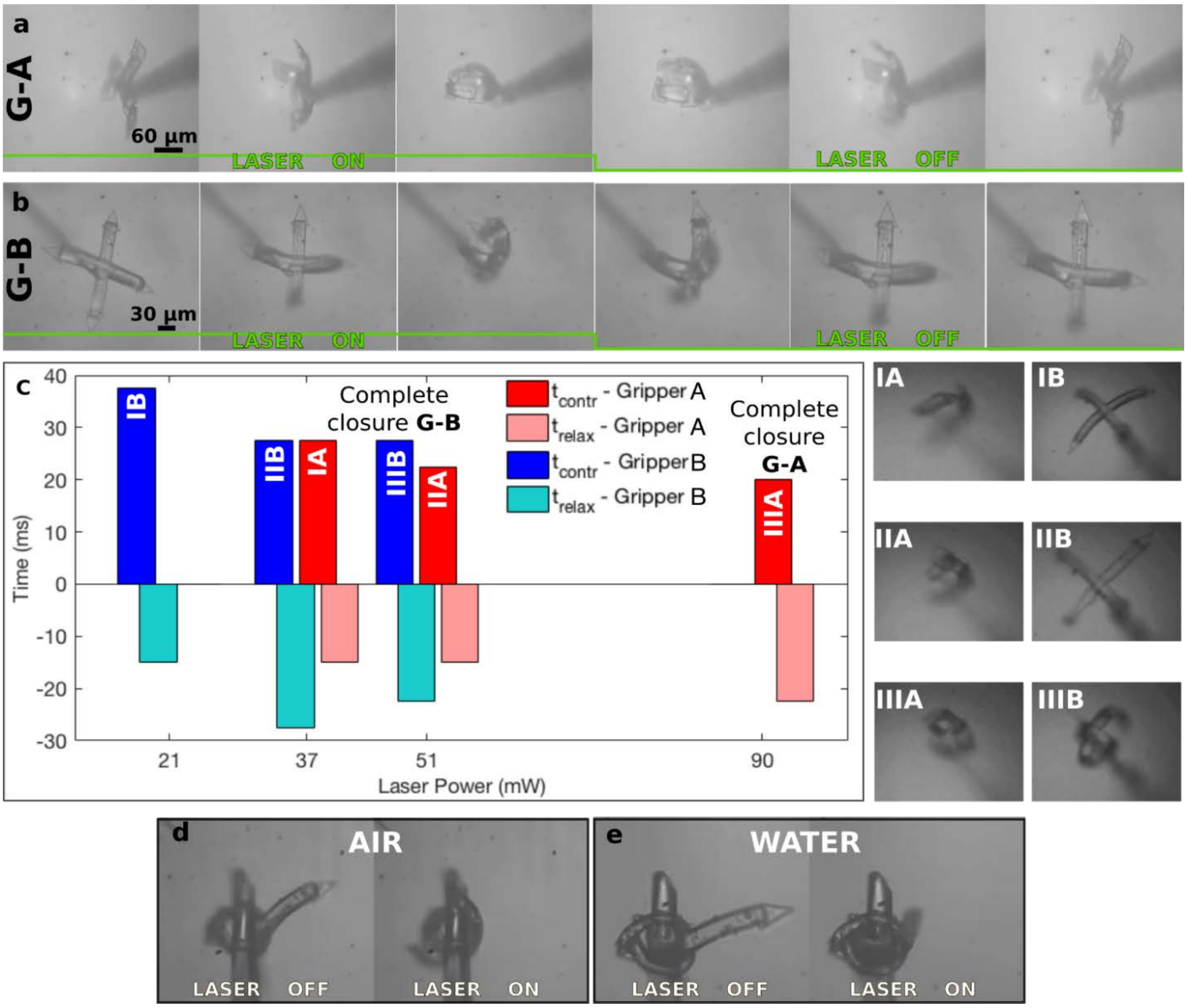

Figure 2. Shape-change of the two micro hands under laser irradiation. a) Movement sequence of G-A and b) of G-B once the laser is incident on the structures. The hands start to bend their fingers up to the complete closure. Turning off the excitation, both hands relaxed towards the starting (rest) position, leading to a perfectly reversible action. c) Times of contraction (t_{contr}) and relaxation (t_{relax}) of the two micro hands, under excitation power values of 21 mW, 37 mW, 51 mW and 90 mW. The contraction and relaxation times have been measured with an ultra-fast camera and the relative images are reported (IA-IIIA and IB-IIIB). The micro hand (G-B) action was demonstrated in two diverse environments: d) air and e) water.

The shape-change behavior is an intrinsic property of the material and does not require a specific environment, which means that liquid crystalline network actuators can be applied, for instance, in air or immersed in a liquid, like water. As a proof of concept, we tightly fixed G-B to a fiber using two of its four fingers and we evaluated the bending action of the other two arms in air and in water (Figure 2d-e). In both cases, G-B showed an efficient structural response with actuation dynamics in the millisecond range, although the activation power for bending is five times higher than in air. This is consistent with the much higher thermal conductivity of water, meaning that the cooling will be more efficient when the hand is immersed in water.

The optical sensitivity of the material makes it very straightforward to control the micro hands externally. To demonstrate this modus of operation, we attached the micro hand to the tip of a glass fiber mounted on a highly stable positioner. We show that one can grab various types of microscopic objects (positioned on another tip of glass fiber) and detach them from their support, using optical control to modulate the hand from the open state (laser off) to the closed state (laser on). In **Figure 3**, some examples are shown. The considered targets include different polymeric micro blocks realized by DLW (as reported in **Figure S2**). In particular, we find that the micro hand was able to grab and subsequently detach such blocks (40 x 40 x 20 μm^3 and 20 x 60 x 20 μm^3) from a glass tip (Figure 4a-b**)**. The micro hand was brought in the proximity of the target, and an entire area of hundreds of square micrometer was illuminated homogeneously to actuate it. Full closure of the hand was reached at a laser power of 50 mW. The target cubes were subsequently detached from the fiber and kept tight by the micro hand (see **Movie S3** for an example**)**.

In addition to the externally controlled operation above described, LCNs should also allow for autonomous operation. In particular, the micro hands can be configured in such a way that they autonomously grab objects that satisfy certain optical characteristics. One could expect that objects with an absorption spectrum peak that matches the illumination wavelength, create a local heating effect that triggers the micro hand to close.

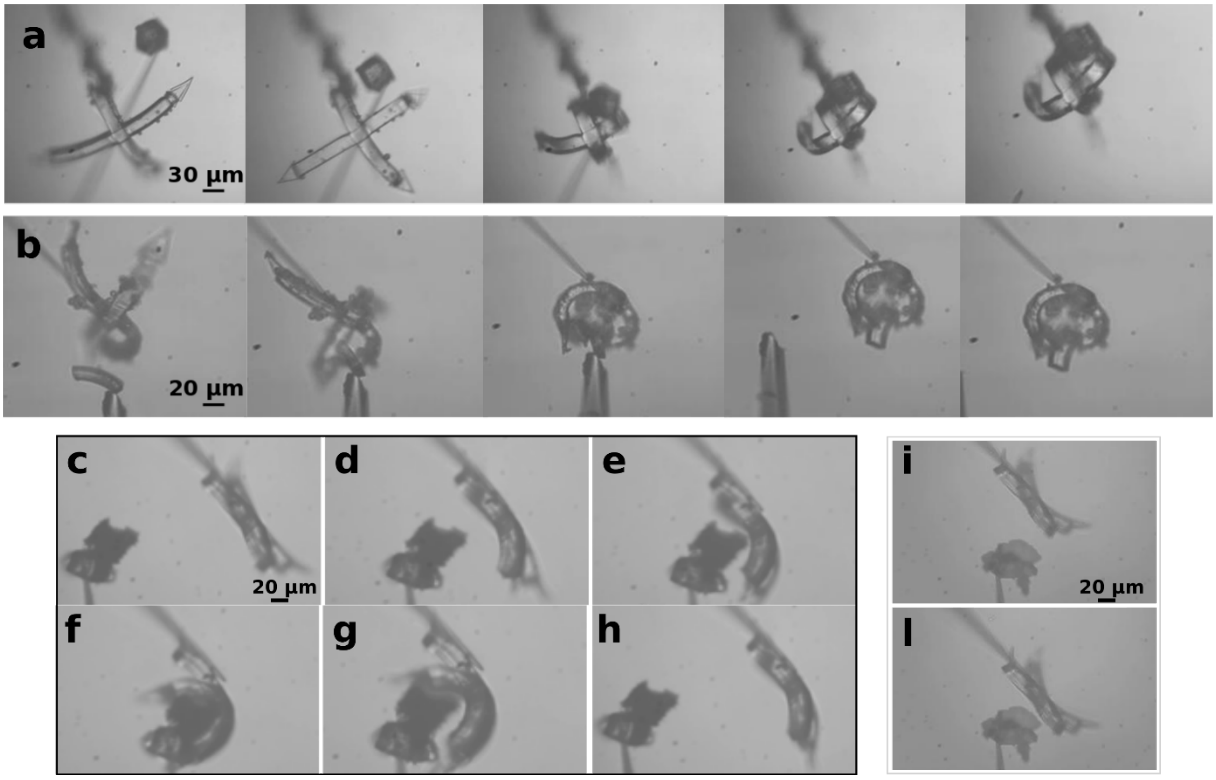

Figure 3. Different operation modes of the micro hand. a) - b) Grabbing of polymeric micro block by laser activation: in sequence a) the hand is positioned close to a polymeric micro cube (40 x 40 x 20 µm^3) and, activated with a green laser, it catches the micro cube detaching it from a fiber tip. The laser power required for closure of the micro hand was 51 mW. b) The same effect is demonstrated for a block of LCN (20 x 60 x 20 µm^3). c-l) Demonstration of the autonomous operation of the micro hand. c-h) Sequence of images during the approach of carbon nano powder: c) initial stage with the black cluster attached to a glass fiber. The cluster has a radius of about 50 µm. The green laser was used at 25 mW constant power and the object was progressively put closer to the micro hand (d-e) until the micro hand fully closed (f). By forcing the micro-object back, the micro hand also returned to its original shape (g-h). i-l) Sequence of images during the approach of white titanium dioxide cluster. i) Initial stage with the titanium dioxide cluster attached to a glass fiber. The particle cluster has a radius of about 60 µm. The same green laser was used at 25 mW and the white titanium dioxide cluster was progressively brought close to the micro hand (l), which in this case does not respond.

In a first series of tests, we studied the behavior of the micro hand when approached with two different types of objects: clusters of carbon nanopowder (Figure 3c-h) – a black material able to absorb a broad wavelength range, and clusters of titanium dioxide particles (Figure 3i-l) – a well-known scattering material that is white and nearly not absorbing at visible wavelengths. First, we verified that no interaction between the objects and the micro hand occurred when light irradiation was absent. During the approach of the two kinds of objects indeed the micro hand remained in its resting configuration, indicating the absence of interaction forces (e.g. electrostatic interaction) between the objects and the micro hand (**Figure S3**). Then the laser was switched on at 25 mW and kept at constant power during the following tests. Under these illumination conditions, the micro hand is close to actuation but the hand does not fold yet. When a black object, in the form of a cluster of carbon nano particles, is approached (Figure 3c-h), the micro hand closes and grabs the object (Figure 3f). The effect can be explained by the increased absorption of light when the black micro object is present.

In the other case, approaching the micro hand with a white cluster of titanium dioxide particles results in nearly no response (Figure 3i-l). The white object functions as a strong scattering element so it will change the local light intensity to a certain extent. This is apparently not enough, however, to provoke a mechanical response of the micro hand. The complete video sequences is reported in **Video S4**. From the difference between the two cases, we can conclude that the micro hand responds differently to the presence of an absorbing object compared to a non-absorbing one, and the overall system (light+micro hand) can therefore distinguish autonomously between black and white objects.

To further demonstrate the potential of such discriminating ability, we demonstrated the autonomous action of a single finger upon the approach of micro objects with different colors (**Figure 4**). In particular, we prepared two blocks (purple and yellow) with different, non-overlapping, absorption spectra (Figure 4b-c). The experiments were performed with a single LCN finger and with a green laser at constant power (30 mW). This introduced a tiny pre-bending, but the finger remained basically outstretched (second line of panels in Figure 4). Subsequently the finger was approached by micro blocks of different color and, for comparison, also again with a black and a white cluster of particles (bottom line of panels in Figure 4 and **Movie S5**). The finger bends towards the black carbon nanoparticle cluster and the purple block while no response is observed when a yellow or white object is approached. The bending at the presence of the purple block is slightly less evident than that for the black one, able to activate the finger also using a lower laser power (25 mW, see **Figure S4**), probably due to a difference in overall absorption coefficient. On the basis of these findings, proper modification of the molecular composition of the micro hand could further expand its recognition ability, making it sensitive to different colors.

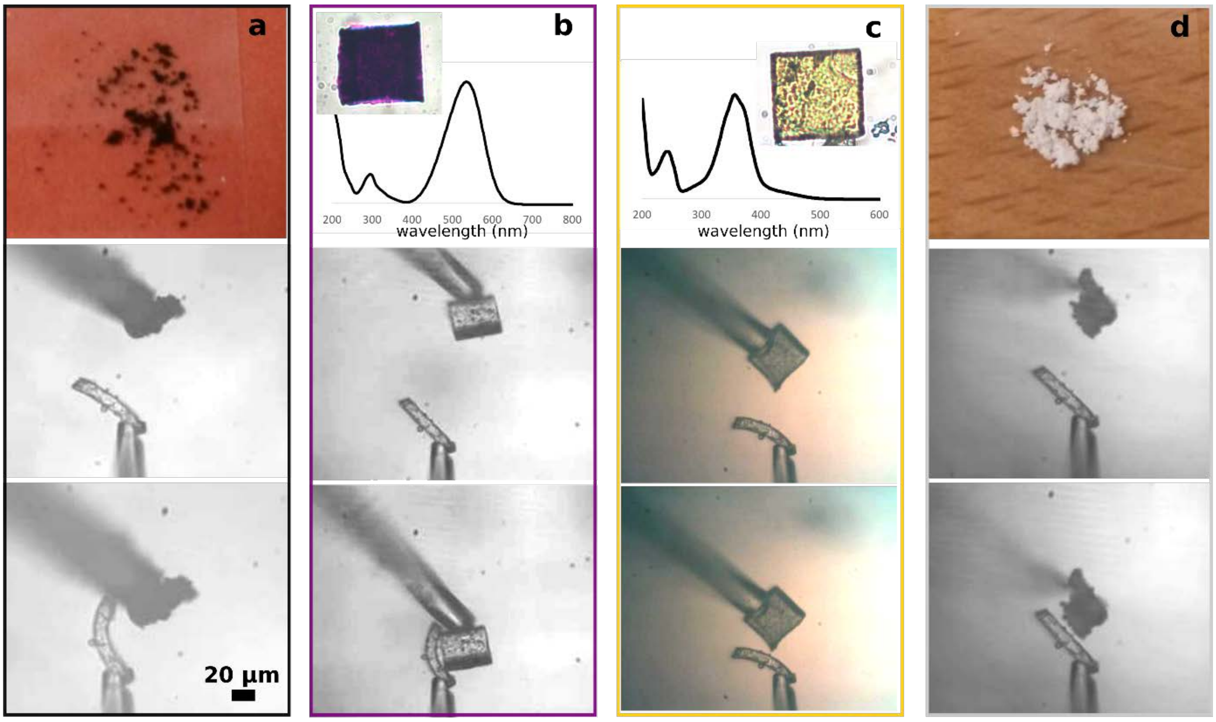

Figure 4. Autonomous response of a micro finger when approached by different types of micro objects**.** Top panels represent the different objects tested: a) carbon nanoparticles, b) purple polymeric block (40 x 40 x 20 µm^3), c) yellow polymeric block (40 x 40 x 20 µm^3) and d) white TiO_2 nanoparticles. Below, frames of video recorded during the approach of different particles under a flat illumination by the green laser (30 mW) are shown. Images of the finger, with the objects at a certain distance (middle line) and, close to them (bottom line) are reported. Only when carbon nanoparticles or the purple block are approached the self-actuation of the LCN finger is observed (column a and b).

In summary, a light-powered microscopic hand was fabricated that can grab microscopic objects, either by external control through a light beam or by autonomous operation. We showed that the micro hand can respond on the basis of the optical properties of the target object and grab only particles that exhibit the right absorption properties. We demonstrated this for black, white, and two colored micro objects. The concept can be easily extended to recognition of objects based on their very specific absorption spectra by targeting the resonant laser lines of the material of interest.

Thanks to the material responsivity both in dry and liquid environment, this type of micro hand can be easily combined, for instance, with a photonic waveguide or resonator, and could also be embedded in a microfluidic/photonic lab-on-chip device. Furthermore, the technology is relatively cheap and this micro hand, together with other types of photonic/mechanical components, can be produced in large quantities. We have recently examined the compatibility of the used materials with a biological environment,[23] and find that, for instance, human heart muscle cells survive on a substrate of this polymer and maintain their functionality. This means one could, in principle, also foresee future applications that are compatible with the human body.

Experimental Section

Materials: Composition of the monomeric mixtures and preparation of the liquid crystalline cells are described in Supporting Information.

Direct Laser Writing (DLW): Two-photon absorption polymerization was performed by the commercial DLW workstation (Photonic Professional, Nanoscribe GmbH) according to previously reported methods.[24] Complete fabrication steps are described in Supporting Information.

*Light-induced movements and characterization***:** The micro robot actuation was tested in a home-made micromanipulator setup. First, the structures were detached with the help of two glass tips. Light-induced deformations were observed during irradiation with a continuous or a chopped (10 Hz) DPSS 532 nm laser through a 10X, 0.25 NA (Plan Achromat, Olympus) objective placed above the sample. The irradiated area had a radius of around 300 µm. The light intensity was varied using a neutral density wheel-filter and measured by a power meter after the objective. The dynamics was studied by an ultra-high speed fast camera (Photron FASTCAM SA4) with a recording frame rate of 500 fps. The other movies were recorder by a CCD camera.

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

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The paper describes a micro hand made by liquid crystalline networks able to grab different objects. It can be controlled from remote by optical illumination or can act autonomously and grab small particles on the basis of their optical properties. The micro hand can distinguish between particles of different color and grey level.

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