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Light robotics: a new field of research

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ABSTRACT

After years of working on light-driven trapping and manipulation, we can see that a confluence of developments is now ripe for the emergence of a new area that can contribute to nanobiophotonics - Light Robotics - which combines advances in microfabrication and optical micromanipulation together with intelligent control ideas from robotics, wavefront engineering and information optics. In the Summer 2017 we are publishing a 482 pages edited Elsevier book volume covering the fundamental aspects needed for Light Robotics including optical trapping systems, microfabrication and microassembly as well as underlying theoretical principles and experimental illustrations for optimizing optical forces and torques for Light Robotics.

Keywords: light-driven micro-robotics, micro-fabrication, optical tracking, holography, Generalized Phase Contrast

1. INTRODUCTION

Light robotics brings together advances in optics and photonics and combines it with control system ideas to provide access to microscopic and even nanoscopic processes [1]. Recent developments are harnessed in the areas of light-based fabrication and manipulation to create and control small structures that can mimic real-life tools except that they are being utilized in a microscopic environment. Exploiting various light-induced physical phenomena in a microfluidic system, light robotics is becoming a key tool for remote inspection of minute features and courier to locations that are difficult to access with conventional tools. Light-driven micro-robots can be actuated and manipulated precisely in a manner that can be beneficial in biological experiments, medical investigations and drug delivery, among other applications. Disruptive innovations in the

areas of microfabrication and optical micromanipulation paved the way for different applications in diverse fields; a survey of which can be found in the recently published *Light Robotics: Structure-mediated Nanobiophotonics* [1].

One of the key developments in light-based microfabrication is two-photon polymerization (TPP). Photopolymerization is assisted when a focused near-infrared (NIR) light source induces a nonlinear 2 photon absorption within the volume of a resin [2]. TPP in bio-compatible resins can be used to fabricate small-scale medical devices (i.e. microneedles, sensors, pumps) that can be very significant for rapid medical prototyping [3, 4]. With some kind of physical or chemical treatment like metal deposition, a fabricated microstructure can be functionalized to elicit information or properties of its environment. Such complexity in terms of the functions provided by these tools directly benefits simulating biological processes in a microfluidic system, material delivery and even in tissue engineering. Fig. 1 shows a micro-tool fabricated using Nanoscribe Photonics Professional that implements TPP on IP-L780 photoresist.

Fig. 1 Micro-tools fabricated using two-photon polymerization, and imaged under a bright field microscope. Each tool is $30 \times 10 \times 5 \mu\text{m}^3$.

Having fabricated micro-tools, the next challenge is to actuate these structures and move them to sites where they are to perform their tasks. While actuation can be achieved with other different techniques, optical manipulation provides remote capability where light mediates between the user and the structure. The structure's trapping handles are locked in high intensity areas, hence the structure itself is trapped to a specific location. Optical manipulation employs only a beam-shaping setup that does not intervene with the actual setup itself. With beam-shaping techniques, a number of trap beams are generated and can be independently and dynamically controlled [5, 6]. Recent developments in the field have led in optical forces achieved by optimizing light illumination

and implementing conceptually simple yet experimentally tedious solutions such as anti-reflection coating of particles and minimizing aberrations in the setup. Our optical trapping system uses a GPC-based counter-propagating beam (CP) configuration that offers wider working distance compared to a single-objective optical tweezer [7]. Moreover, the CP configuration also affords the insertion of another camera for a side-view perspective of the optical trapping.

Light robotics combines all these developments to achieve an all-optical toolbox in probing micro and nano-environments, opening up new avenues of applications of structure-mediated control of objects. Optical trapping can be used for on-site assembly or disassembly of larger structures into component parts, as well as their actuation to pre-determined sites. Fig. 2 shows the micro-tool trapped and controlled inside a cuvette. Since the CP configuration is employed in our setup, the micro-tool can be viewed in both top and side perspectives. Given the wide working distance, it can as well be manipulated along the beam axis. Employing a high NA objective for the top-view would result in fast defocusing when the micro-tool goes out of the focal plane (Fig. 2 Rows 2 and 3). The side-view camera then provides a convenient way to locate the micro-tool in any spatial location. This ability could be very advantageous in several applications such as in material deposition over a layer in a lab-on-a-chip setup.

Optically trapped and controlled fabricated structures can be used to carry loads that can as well be functionalized to perform some specific tasks. Structure-mediated transport provides convenience over direct particle trapping without compromising how precise the particle can be moved. In cell trapping or transport, for example, damage due to direct irradiation is minimized by loading the cell into some kind of fabricated platform that is illuminated and moved around instead. Not only does this lessen the negative impact of high-intense radiation, but also adds the benefit of having 6DOF-control on the structure, hence on the specimen itself.

Fig 2: Optical manipulation of disk-tip tool inside a micro-chamber.

Light robotics goes even beyond the interplay between fabrication and manipulation by exploiting light-induced phenomena to add various and unique functionalities to the fabricated structures. For example, selective illumination in the micro-regime was achieved with a fabricated optical waveguide that is controlled using four trapping arms [10]. Light from a low NA objective is collected through one end and an even more confined beam is produced at the tip of the mobile waveguide. Using such device, light is focused and delivered in micrometer precision to target locations that are otherwise difficult to access with ordinary illumination resulting in localized excitation for fluorescence microscopy. The fabricated structure can be easily maneuvered to

anywhere else and was also shown to serve as an endoscope to detect signal in tiny areas of a specimen. Different sensing capabilities of micro-robots have already been demonstrated by other groups with the use of optically trapped spheres and designed micro-structures for Raman sensing [11] and surface imaging [12], among many others, that have resolutions comparable to present techniques.

Figure 3. Image from G. Vizsnyiczai et al in Complex polymer micro-tools for on-demand contact-free applications, Light Robotics Chapter 6 [9].

Currently, we are working towards the fabrication of structures that look very similar with the free-standing waveguide, but with a metal-coated tip to possibly enhance Raman signal for particle characterization. This tool would likely be also useful for transfection studies with the heated metal tip being used to perforate through host cells. This is just one of the wide variety of possible light robotics applications when merged with some physical treatment to achieve tedious processes.

Our group recently reported a TPP-fabricated micro-tool that was subsequently deposited with thin layers of titanium and gold to achieve draw-and-eject action [13]. A thermocapillary phenomenon, known as Marangoni convection, is induced by heating the metal layer with a laser that draws the particles into the tool. The micro-syringe, which is first of its kind [14], was then maneuvered using counter-propagating traps to locations where the particles are to be expelled.

Ejection occurs as an effect of heating the surrounding areas of the metal layers, although the mechanism of which is not fully understood at the moment. This mode of material delivery is foreseen to be useful in drug delivery investigations in epithelial models in the future. With the use of high-speed cameras, it can also shed light to some of the less understood phenomena such as the mechanisms of thermocapillarity.

2. Conclusion and Outlook

With the different applications mentioned above, Light Robotics provides new and exciting possible applications of optically-fabricated and manipulated micro-tools. Present applications of this all-optics toolbox are discussed in our newly-published Light Robotics book. While many applications have taken off already, further advancements in the field of microfabrication and manipulation as well as in control systems will be significant to realize a fully remote and autonomous light-based micro-robots [15].

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