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Light-driven micro-robotics with holographic 3D tracking

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ABSTRACT

We recently pioneered the concept of light-driven micro-robotics including the new and disruptive 3D-printed micro-tools coined Wave-guided Optical Waveguides that can be real-time optically trapped and “remote-controlled” in a volume with six-degrees-of-freedom. To be exploring the full potential of this new drone-like 3D light robotics approach in challenging microscopic geometries requires a versatile and real-time reconfigurable light coupling that can dynamically track a plurality of “light robots” in 3D to ensure continuous optimal light coupling on the fly. Our latest developments in this new and exciting area will be reviewed in this invited paper.

Keywords: 3D micro-fabrication, optical trapping, optical tracking, diffractive optics, Generalized Phase Contrast

1. INTRODUCTION

At the smallest biological scales scientific endeavors become almost similar to former days mining expeditions where the quality of what could be excavated depended crucially on the quality of the available tools. Highly advanced nanoscale light-based microscopy - now by many coined ‘optical nanoscopy’ in celebration of the 2014 Nobel Prize in Chemistry - can already today surpass the classical far-field diffraction limit and provide optical resolutions down to a few nanometers.

Strongly linked to the recent achievements in optical nanoscopy is the rapidly emerging field of light-based 3D-printing using powerful approaches offered by nonlinear photo-polymerization processes. Using light from an ultra-fast pulsed laser makes it today possible to 3D-print nanoscopic polymer structures with a voxel resolution down to approximately 20-30 nanometers laterally. The process that makes this amazing capability possible is known as multi-photon or two-photon based

micro-fabrication and is basically rooted in an ingenious combination of techniques from the aforementioned optical nanoscopy and non-linear optical effects obtained in light-sensitive polymer materials.

Fig. 1: Drone-like interaction within the context of light-driven micro-robotics

By adding one additional scientific accomplishment - namely the fascinating ability of focused coherent light to capture, trap and 3D-manipulate microscopic objects - we can gradually approach the functionalities required for true light-driven micro-robotics. As Arthur Ashkin et al. showed in pioneering experiments at Bell Labs in the early 70es [1] and culminating with real optical tweezing demonstrations in the mid 80es, focused laser light is able to exchange momentum with small refractive particles and make them seek toward the laser-beam foci and thereafter stay stable with strongly reduced Brownian motions. In biological experiments, this takes best place in aqueous solutions in which living cells and other micro-organisms can be sustained and thrive in a relatively

natural environment. Moreover, the liquid environment provides inherent cooling of the laser trapped particles and additional damping of Brownian fluctuations. As we all know, Ashkin's student Steven Chu continued this research work and refined it to the level where even atoms under special circumstances could be trapped and laser-manipulated i.e. the Nobel Prize in Physics in 1997.

By cleverly combining and integrating all these amazing optics and photonics breakthroughs we can create the conditions for most of the functionalities required to develop functional light-driven micro-robotics [2-10]. An example of light-driven micro-robotics in action is graphically illustrated in figure 1 above and figure 2 below.

Fig. 2: Real-time 3D tracking of a plurality of 3D-printed light robots. Adapted from ref. [9].

2. TOWARDS NANOPROBING ‘LIGHT ROBOTICS’

By exploring the aforementioned two-photon polymerization micro-fabrication, it is possible to equip 3D-printed optical micro-robotic structures with multi-functional biophotonic nanoproboscopes or nanotips fabricated with nanoscopic resolution. The uniqueness of such an approach is that even if a

micro-biologist aims at exploring e.g. cell biology at nanoscopic scales, the main structure of each 3D-printed micro-robotic structure has a size and shape that allows convenient optical micro-manipulation in full 3D – even using relatively modest numerical aperture optics. Our earlier experimental examples are illustrated below – with simultaneous top and side-view imaging.

Fig. 3: (1)-(4) Show light robotic probing of a live T-cell imaged from top and side. (5)-(10) show an opto-mechanical probe-interaction with a tiny surface-positioned object. Adapted from refs. [3,4].

As can be seen in Figure 3 above each optical micro-robot is typically equipped with four 3D-printed "track-balls" that allow for real-time 3D light manipulation with six-degrees-of-freedom. This creates a drone-like functionality where each light-driven micro-robot can be e.g. joystick-controlled and provide the user a feeling of stretching his/her hands directly into and interacting with the biologic micro-environment. Light-guiding micro-robotic tools can be 3D-fabricated so that targeted and real-time coupled light [12-16] can be used as near-field irradiating and receiving nano-torches i.e. Figure 4 below.

Fig. 4: Light robotic tool equipped with an integrated waveguide structure to act as an optical near-field probe for e.g. tip-enhanced Raman signal acquisition. Adapted from Ref. [8].

The light-guided micro-robots can thus act as free-floating probes to monitor micro-biologic processes and provide spatially targeted mechanical, chemical or even optical stimuli that would otherwise be very difficult to achieve in a full 3D biologic environment. A single light robotic tool can e.g. be envisioned to perform measurement operations of receptors on a cell membrane and potentially even use the cell signaling network to initiate biochemical processes within the cell itself.

Moreover, light-programmed mechanical stimuli from the tools can be used to explore molecular effects that e.g. can convert mechanical signals picked up by cell membranes and converted to biochemical responses deeper within cells.

Fig. 5: *Our vision of fabricating a light robotic tool acting like an artificial virus.*

Figure 5 illustrates one of our future aims of fabricating and demonstrating the world's first artificial optical virus to perform a variety of light-actuated robotic functionalities on e.g. a living cell. Preliminary test 3D-prints of such embodiments are SEM-imaged in Figure 6 below.

Fig. 6: *Our first-generation hollow micro-body structures for cargo-delivering 'optical vira'.*

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