3D printed microrobots controlled by light – Towards environmental and biomedical applications

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Abstract

Microrobots are rapidly developing as a valuable solution for performing microscale tasks, among which they seem particularly promising for biomedical and environmental applications. Two-photon polymerization enables the fabrication of microstructures with complex shapes, while focused laser beams allow for precise manipulation of such 3D printed objects. Whereas several challenges have yet to be overcome before microrobots can perform in the real world, many interesting laboratory applications have already been demonstrated, while others are being explored.

1. Introduction

Microrobots are raising enormous interest in the scientific community because of their potential for performing various tasks at the microscale. Among their target fields of use, biomedical and environmental applications are likely the most promising. Recently, we reviewed the literature on the use of microrobots for biomedical applications [1], and would like to highlight that, while the use of microrobots *in vivo* is a noble goal, there are yet numerous related challenges when it comes to e.g. deployment and retrieval strategies, control, or imaging. On the other hand, microrobots could in the near future become valuable tools for laboratory testing, where for example hyperlocalized sensing is particularly interesting for both biomedical and environmental applications.

2. 3D printing by two-photon polymerization

Two-photon polymerization 3D printing is a direct laser writing technique, where the structure is written layer-by-layer and voxel-by-voxel into a suitable negative photoresist using a highly focused femtosecond-pulsed laser beam. We use a Nanoscribe GT+ system for the microfabrication of polyacrylate robots amenable to optical trapping and manipulation. Typically, for producing microstructures with maximum resolution, we use a Plan-APOCHROMAT 63×/1.40 Oil DIC objective and the commercial photoresists IP-L 780 or IP-Dip. With optimal parameters, the resolution of the system is 100-200 nm in the XY plane and, because the laser focal spot is ellipsoidal rather than spherical, around 1.5-3.5 lower on the Z-axis [2,3]. An example of a 3D printed polyacrylate microrobot is shown in Fig. 1.

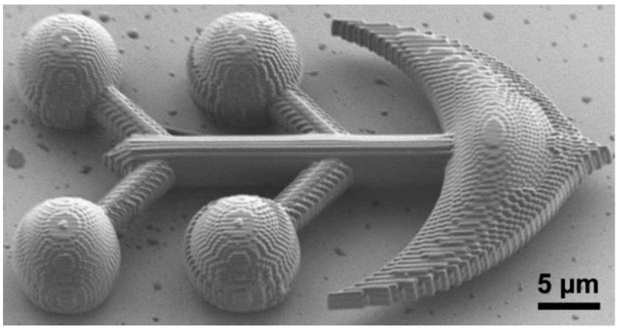

Figure 1: Scanning electron micrograph of a 3D printed microrobot including four spherical handles for optical manipulation and a large disk designed for a certain task.

3. Light-controlled micromanipulation

Among the many different approaches to microrobot propulsion and control, light offers unique opportunities in terms of precision, as highly focused near-infrared laser beams can be employed for simultaneous micromanipulation of multiple microrobotic components [2]. Furthermore, the use of light-responsive materials which deform when exposed to ultraviolet or visible light also offers interesting perspectives for introducing additional functionality (Fig. 2).

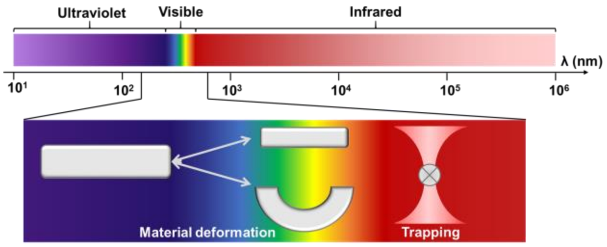

Figure 2: Light spectrum by wavelength. UV light with a wavelength above 200 nm and/or visible light can induce material deformation in photoresponsive materials. The nIR range is typically used for optical trapping, most commonly between 1060 and 1090 nm. Reproduced with permission [2], © 2021 The Authors. Advanced Intelligent Systems published by Wiley-VCH GmbH.

In our group, we employ a custom-made optical trapping setup called the Biophotonics WorkStation (BWS) for precise microrobot manipulation with six degrees of freedom (Fig. 3). The setup allows for visualizing the microrobots in motion both from the top and from the side.

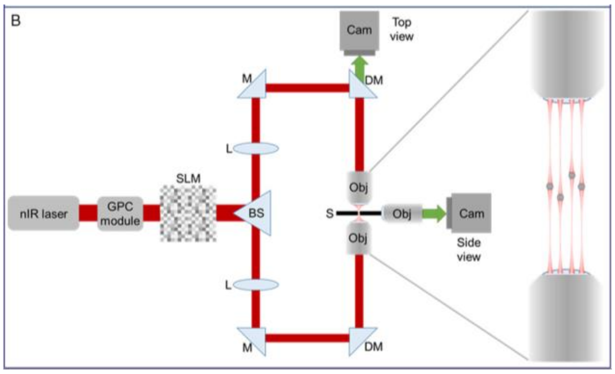

Figure 3: The Biophotonics Workstation (BWS) used for microrobot manipulation. The nIR light path used for trapping is shown in red, whereas the visible light source and light path are omitted to simplify the schematics. M—mirror; DM—dichroic mirror; L—lens; SLM—spatial light modulator; A—aperture; Cam—camera; Obj—objective; Cond—condenser; S—sample; BS—beamsplitter. The Gaussian beam coming from a 1080 nm laser is first shaped using a generalized phase contrast (GPC) module and then the SLM. The shaped beam is then split into two beams of equal intensity using a 50/50 beamsplitter, and relayed onto the sample from opposite directions using two 50× objectives with a NA of 0.55. This leaves space in the system for a 20× side-view objective. The microrobot handles are trapped in between the foci of the top and bottom counter-propagating beams. Reproduced with permission [2], © 2021 The Authors. Advanced Intelligent Systems published by Wiley-VCH GmbH.

4. Environmental and biomedical applications

Light-controlled microrobots are extremely precise and have therefore been employed for e.g. surface probing [4], localized micromixing [5], or indirect cell manipulation [6]. However, trapping in complex media, such as biological fluids or environmental samples, is rather challenging, particularly because of issues raised by the absorption and dispersion of light in such samples [7]. Nevertheless, there are several strategies for overcoming these challenges by e.g. wavefront engineering through wavefront correction algorithms, optical phase conjugation or metasurfaces. Furthermore, tailoring the microrobot surface chemistry can help reduce unwanted interactions between a microrobot and its environment, conferring “stealth” properties [8]. Recently, all-optic actuation of a microrobot in blood was demonstrated [9]. Overall, exploring combined solutions for improving light focusing in turbid media, as well as reducing the hindering interactions, should prove extremely beneficial for the future progress of microrobots in environmental and biomedical applications.

5. Conclusions

Although microrobots have yet to overcome several important challenges before they can become truly useful for real-world applications, current research is paving the way for such progress. Two-photon polymerization 3D printing enables the fabrication of microrobots with arbitrary and complex shapes and submicrometer critical dimensions. On the other hand, the use of focused beams for optical manipulation provides extreme precision for the micromanipulation of such objects. Implementing state-of-the-art solutions to improve light focusing in complex media while simultaneously tailoring the surface chemistry of the microrobots should foster applications in complex media, which is extremely relevant for many envisioned environmental and biomedical applications. Light-controlled microrobots with the ability to sense target analytes, deliver therapeutic agents, or neutralize toxic chemicals should soon become the go-to solution for laboratory experiments where such tasks need to be performed on the microscale with extreme precision. Ultimately, we envision that more complex microrobots will be able to perform microscale tasks in the real world, for example in lakes, rivers, or the human body.

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