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3D PRINTED MINIATURIZED SOFT MICROSWIMMER FOR MULTIMODAL 3D AIR-LIQUID NAVIGATION AND MANIPULATION

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ABSTRACT

Major challenges of microscale swimmers for biomedical applications could be listed as the 3D motion for air-liquid navigation, selective motion control of multiple swimmers, visual servo automation control and micromanipulation functionality. Here we report a miniaturized soft microswimmer for serving as a wireless microrobotic manipulator in air-liquid environments. We fabricated these micrometric soft swimmers by two-photon 3D nanoprinting of Polydimethylsiloxane (PDMS) and metallization of ferromagnetic nickel layer for magnetic propulsion. We demonstrated for the first time 3D air-liquid navigation and selective motion control of multiple soft swimmers thanks to the multimodal propulsion with magnetic and buoyancy force. We further reduced stick-slip phenomenon by applying high frequency vibration by piezo disc actuator. This allowed real-time visual tracking of the soft microswimmers and also the micromanipulation of microfibers. We believe that this 3D printed and miniaturized mobile agents should enlarge the application areas from *in-vitro* microfluidics to bio/chemical assay.

KEYWORDS

3D printing, Two-photon nanolithography, Soft microswimmer, Magnetic Actuation, Microfluidics

INTRODUCTION

Microfluidics is an essential platform for lab-on-a-chip based point-of-care diagnostics or organ-on-a-chip [1]. There is huge need for micromanipulation of biological or chemical samples in confined microfluidic environment [2]. In the recent decade, wirelessly propelled mobile microrobotic swimmers have drawn much interest due to the small footprint with a high accessibility to confined

microfluidic environments [3,4]. More recently soft artificial swimmers have shown their great promise due to their excellent compatibility to biological environments which have more complex mechanics and dynamics [5]. Although they are promising, we now face more complex manufacturing challenges than ever before. Manufacturing of such soft 3D microstructures often requires other fabrication methods such as soft lithography based on mold-casting process than the standard cleanroom microfabrication processes. This adds more fabrication steps to the cleanroom microelectromechanical system (MEMS) process.

Recently 3D printing has been widely used for mostly the rapid-prototyping. In this context, 3D printing by direct laser writing could be a promising solution for printing 3D micro/nanostructures. 3D printing of microscale mechanical transducers could accelerate and facilitate the manufacturing process. Although 3D printing was attempted for microscale actuators [6], they are still very limited in the manufacturable scale, material and morphology. Alternatively, the cleanroom micro/nanofabrication technologies have been used to fabricate microscale soft actuators [7]. This is a promising alternative but the fabricated microstructures based on this method can swim in only liquid environment which limits their potential applications. Millimeter scale soft robots have been developed by on-demand magnetization assisted printing [8] and this has further been extended to be a better fit for liquid/air operation [9]. This work is to further miniaturize the millimeter scale soft swimmers [9] in microscale and also to extend the propulsion in 3D for air-liquid navigation by multimodal propulsion combining the magnetic and buoyancy force due to gravity compensation by bubble trap. In addition, this can separate the motions of

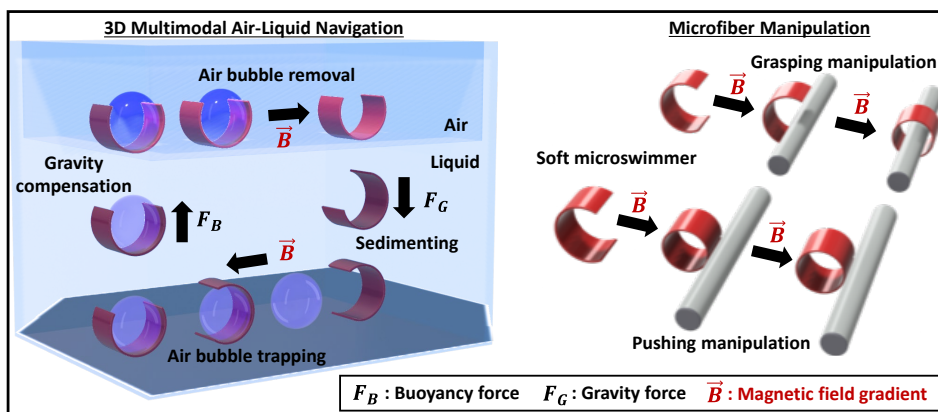


Figure 1: Schematic concept of multimodal soft microswimmer: (left) 3D motion by bubble trap (right) 2D manipulation of microfibers.

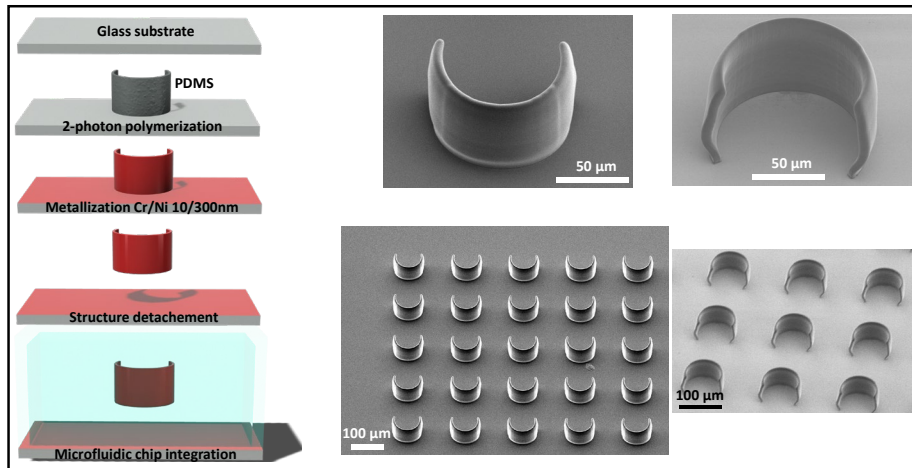


Figure 2: Fabrication process (left): 1) 3D printing PDMS by two-photon polymerization. 2) Metallization of ferromagnetic nickel layer by sputtering. 3) Structure detachment by micromanipulation. 4) Microfluidic chip integration. (right) SEM photograph of the fabricated soft microswimmers.

multiple soft microswimmers thus selective motion control is possible (Figure 1). The proposed 3D multimodal air-liquid navigation is achieved by combining the propulsion by magnetic field gradient and the gravity compensation from air bubble trapping as shown in the Figure 1. The soft and deformable mechanics should also facilitate robust 2D manipulation of microfiber structures by pushing or pulling.

FABRICATION

Microfabrication of 3D soft microswimmers

We chose 3D printing method to fabricate the proposed soft microswimmers. Figure 1 shows the design and fabrication of the proposed soft microswimmer. In this work, we miniaturized the millimeter scale soft swimmers [9] to microscale by two-photon 3D nanoprinting (GT+, Nanoscribe GmbH) of PDMS and magnetic layer metallizations (Cr/Ni 10/300 nm). Photosensitive PDMS (IP-PDMS, Nanoscribe) deposited on top of a glass substrate coated with indium-tin-oxide (ITO) layer. After developing the lithography, the sample was rinsed with isopropyl alcohol and carefully dried. Then additional metal layers (Cr/Ni 10/300 nm) were sputtered. Finally, each soft microswimmer was detached by micromanipulation with a nanoprobe. The detached soft microswimmer was placed onto a glass substrate then a PDMS fluidic chamber is bounded by oxygen plasmas treatment on both the glass and the PDMS chamber. This allows to fill liquid and make the swimmer experiments.

Magnetic propulsion system

A microscale soft swimmer was developed to be able to move by external magnetic field gradient so to trap a micro air bubble in liquid by the curved morphology (Figure 1). For the magnetic propulsion, single electromagnetic coil mounted upward direction on the robotic arm manipulator for generating and controlling magnetic field gradient pulling the soft microswimmers downward direction. Magnetic field can switch on/off and/or the intensity of magnetic field is controlled either by the applied current to the coils and also by the distance between the soft microswimmer and the coil. The magnetic

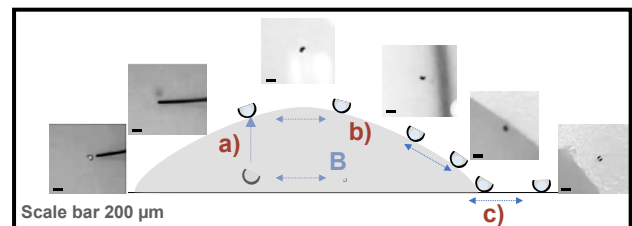


Figure 3: Air-liquid 3D motion of soft microswimmer by bubble trap gravity compensation and droplet surface motion.

field trapped soft microswimmers can move horizontally by moving the coil by the robotic arm. A similar configuration of this magnetic field generator is described in more detail elsewhere [4].

RESULT

Major results obtained by the proposed soft microswimmers are the multimodal 3D air-liquid navigation and the selective motion control of multiple soft microswimmers. These are important characteristics for them to be applied for micromanipulation in wet or dry environments.

Multimodal 3D navigation

First for the 3D motions, instead of adding upward pulling electromagnetic coil, we used air bubble trap for gravity compensation. This allows to secure an optical path and objective lens for upright microscope and also the microfluidic circuit tube connections. In addition, this avoids additional consumption of energy and also heat dissipation. Instead, we propose to use buoyancy force of the soft microswimmer by trapping an air bubble. Air bubbles are injected by pushing air via a syringe and a tube to fluidic chamber. Thanks to the increased buoyancy force by trapped air bubble, the soft microswimmer is able to compensate the gravity without magnetic field gradient pulling upward so it can come out of the liquid surface. Then the trapped air bubble is removed at the air-liquid interface thus the buoyancy force of soft microswimmer decreases. Soft microswimmer should then sediment by also applying a downward direction magnetic field

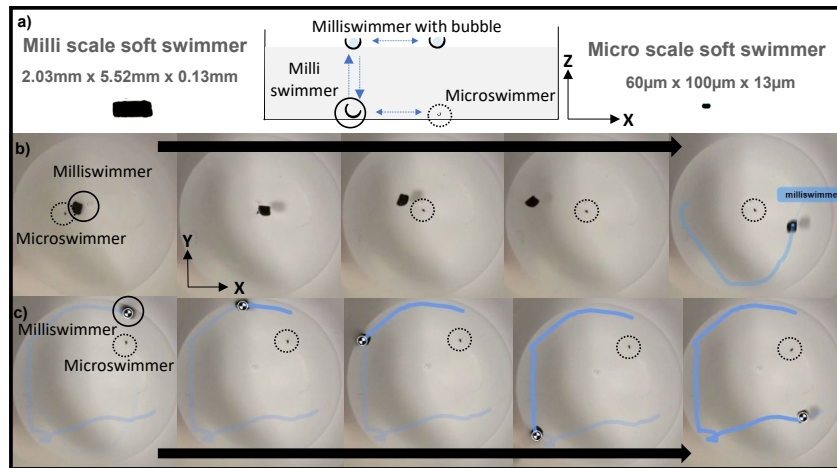


Figure 4: Multiswimmer motion control selectivity. The floating milliswimmer with bubble trap and the sinking microswimmer are selectively controlled by external magnetic field gradient.

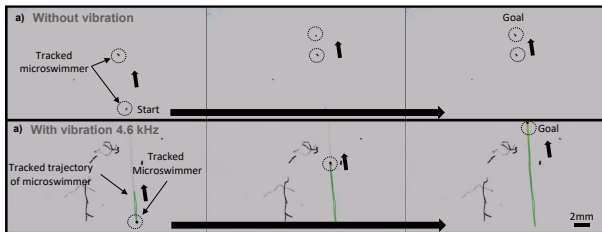


Figure 5: (a) Stick-slip motion without vibration, (b) Enhancement of motion control and visual tracking by adding high frequency vibration (4.6 kHz).

gradient. This multimodal 3D motion by buoyancy and magnetic force is an energy efficient 3D motion control strategy for microscopic soft swimmers. Figure 3 shows the air-liquid 3D navigation by the trapped air bubble of soft microswimmer propelled by magnetic field gradient. Thanks to the compensated gravity by the trapped air bubble and the soft deformable morphology, they can navigate in 3D and they can also move in/out of a droplet. This is one of the most requiring features for microswimmers to be able to navigate in between air-liquid environments. This seamless air-liquid navigation must be an important asset towards their real-life biological or environmental applications which require seamless handlings of liquid or solid samples.

Selective motion control of multiple swimmers

Second for the selective motion control of multiple swimmers, the selectivity of each swimmer is essential. Typically, the selectivity can be attained by differentiating the magnetization of each swimmer [10]. Compared to the horizontally placed electromagnetic coils, the electromagnetic field gradient generated by the upward direction coil placed on the bottom of the fluidic chamber in this work could counterbalance the surface tension at the water surface. In this way, multiple soft microswimmers can be separately controlled by global magnetic field gradient. A better selectivity can be achieved by differentiating the size of the soft microswimmers. Applying two swimmers (mm scale and micro scale) could separate the motions of the two swimmers (one floating and the other sinking) (Figure 4). Therefore, manufacturing scalability is highly demanding. In this work, we miniaturized the conventional millimetric soft swimmers

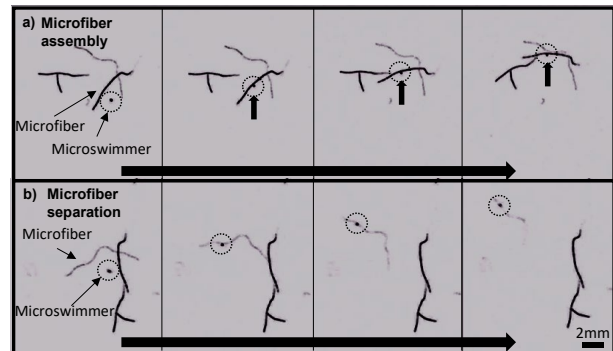


Figure 6: Manipulation of microfiber by soft microswimmer (a) assembly and (b) separation.

[9] to micro scale soft swimmers by nanoscale 3D printing and consecutive ferromagnetic metal layer deposition by sputtering. As shown in the Figure 4, we fabricated a milli scale soft swimmer and a micro scale soft swimmer. The size of the micro scale soft swimmer is miniaturized by 55 times of the milli scale one. Both swimmers are sedimented inside a fluidic chamber filled with water and the milliswimmer traps a bubble so to float to water/air surface. Adjusting the magnetic field intensity of bottom coil and its distance to the fluidic chamber, only the floating milliswimmer can move by moving the coil but the microswimmer can stay static on the bottom substrate. This is due to the weak magnetization of the small volume microswimmer compared to the milliswimmer and also due to the substrate friction. Thanks to the proposed concept of the multimodal swimmers, we were able to demonstrate the selective motion control of multiple swimmers with using a single electromagnetic coil.

Micromanipulation

In addition to the 3D navigation, the soft microswimmers are also able to manipulate microstructures. In this work, we aim to further demonstrate their micromanipulation capabilities. However, the bottom pulling magnetic force has a disadvantage of increasing surface stiction. While this was useful for the selective motion control of multiple swimmers in the prior section, the motion of soft microswimmer becomes to be the stick-slip phenomenon. This is problematic for both the stable micromanipulation and also the stable visual tracking which are essential to

Table 1. Comparison table of soft swimmers.

	[6]	[7]	[8]	[9]	This work
Size	~ 100 μm	~ 5 mm	~ 5 mm	~ 5 mm	~ 100 μm
Environment	Liquid	Liquid	Liquid or Air	Liquid & Air	Liquid & Air
Motion	3D	2D	2D	2D	3D
Propulsion	Single (Magnetic)	Single (Magnetic)	Single (Magnetic)	Single (Magnetic)	Multi (Magnetic+Buoyancy)
Selective motion	N	N	N	N	Y

their applications and automation control. To avoid the stick-slip phenomenon, we applied high frequency vibrations to the fluidic chamber containing the soft microswimmers by a piezoelectric disc actuator placed on the bottom of the fluidic chamber. The soft microswimmers under piezoelectric disc vibrations in 4.6 kHz allowed to reduce the typical stick-slip phenomenon of the soft microswimmers propelled by magnetic field gradient pulling. This stabilizes the motion control and enables the real-time visual tracking of soft microswimmers. We demonstrated the closed-loop motion control as shown in the Figure 5.

For the micromanipulation, we used microfibers as the target to manipulate. To manipulate microstructures on the substrate, soft microswimmers need to be sufficiently stiff in their mechanics and also the surface friction needs to be sufficiently high to be able to generate enough manipulation force while pushing. The magnetic force applied to the bottom direction allows the soft swimmer to deform to make itself stiffer. Moreover, this increases the friction between the swimmer and the surface which is necessary for the manipulation of very large footprint (millimeter-long) microfibers or other microstructures. Finally, this vibration-induced motion control and the soft deformable microswimmer by magnetic field gradient allowed successful manipulation of mm-long microfibers (Figure 6).

CONCLUSIONS

In this work, we proposed a magnetically actuated micrometric soft swimmers fabricated by nanoscale 3D printing. We achieved the manufacturing scalability of the soft microswimmers and their multimodal 3D air-liquid navigations by combining magnetic and buoyancy force. Thanks to these features, we demonstrated the selective motion control of multiple swimmers and this is one most challenging but highly demanding. Furthermore, the proposed soft microswimmers showed their possible visual tracking of motion by avoiding stick-slip phenomenon. This shows a great promise for the closed-loop automation control. Finally, we demonstrated micromanipulation of microfiber structures. The achieved results of the miniaturization in sub-millimeter scale, the motion compatibility in air-liquid environments, the multimodal 3D navigation, the selective motion control of multiple swimmers and the micromanipulation capability. These are indispensable features for soft microswimmers to get a step closer to their biological or environmental applications.

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