Motion Control and Shape Optimization of Artificial Bacterial Flagella

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Abstract—**Artificial bacterial flagella (ABFs) are swimming microrobots that mimic the swimming motion of E. coli bacteria. The helical swimmer consists of an InGaAs/GaAs/Cr helical nanobelt tail fabricated by a self-scrolling technique with dimensions similar to a natural flagellum, and a thin soft-magnetic metal "head" consisting of a Cr/Ni/Au multi-layer. Experimental investigation shows that an ABF can be propelled and steered in 3D with micrometer precision by a low-strength, rotating magnetic field. Moreover, the swimming properties are tunable by changing the input magnetic field frequency and the shape of the ABF. Swarm-like behavior of multiple ABFs as a single entity is also demonstrated under the control of the magnetic field, and two approaches can be applied to decouple an individual ABF from the swarm, i.e. using the step-out frequency in a high frequency range or the wobbling effect at low frequencies. The influence of the magnetic head and the helical tail on the swimming behavior will be discussed. These miniaturized devices made of helical nanobelts could be used as magnetically driven wireless manipulators for medical and biological applications in fluid environments, such as cell manipulation and removal of tissue. Due to its large surface to volume ratio, surface functionalized ABFs have the potential to sense and transmit inter- or intracellular information, and to perform targeted drug delivery.**

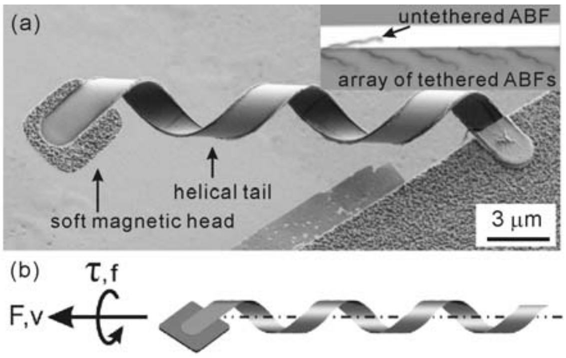

Fig. 1. FESEM micrograph of an as-fabricated ABF with a diameter of 2.8 μm. The ABF has an InGaAs/GaAs/Cr helical tail and a thin square shaped head. Inset: Optical microscope image of a batch of tethered ABFs and an untethered ABF immersed in water. (e) CAD Model of the ABF showing the propulsion of the ABF based on the corkscrew motion. By applying a torque (τ) the ABF is rotated along its helical axis and self-propelled with a velocity (*v*) by the helical tail.

I. INTRODUCTION

THE controlled locomotion of artificial swimmer in micro- and nanoscale is of interest for both fundamental research and biomedical applications. However, at such a small scale, powering and actuation are still big challenges, traditional onboard power supply, e.g. batteries, cannot be scaled down to such a tiny dimension. Mainly two approaches are proposed to address this issue: i.e., (a) using the external field, or (b) harvesting energy from the environment. Previously, diverse artificial micro- and nanoswimmers have been demonstrated based on either of the approaches, which are capable to swim in the low-Re number regime [1]. The chemical-driven swimmers, similar to microorganisms, are able to harvest energy from the specified chemical fuels in the environment; and the motion of entity in an ensemble is independent [2-5]. However, the motion of the chemical-driven swimmers is limited by the inflexible operation environment, which is similar to biomolecular motors [6].

Alternatively, artificial swimmers driven by external field has low requirement to the environment. Among them, bio-inspired microswimmers, actuated by a magnetic field, have been developed recently. In 2005, Dreyfus et al., showed a breakthrough of artificial microswimmer by mimicking the motion of spermatozoa [7], in which a thin paramagnetic filament with an assembled blood cell was actuated in an oscillating magnetic field. Due to the continuous deformation of the filament, the cell was propelled with the filament. Afterwards, helical microswimmers, named artificial bacterial flagella (ABFs), were demonstrated, which have comparable geometries and dimensions to E. coli [8] and can swim in a controllable fashion using weak applied magnetic fields [9-10]. ABFs represent the first demonstration of artificial swimmers in microscale which mimic the propulsion method of E. coli, and are approximately three orders of magnitude smaller than untethered artificial helical swimmers developed by Honda et al., in 1996 [11]. Self-propelled devices such as ABFs can provide a 6-DOF micro- and nanomanipulation tool for manipulating cellular or sub-cellular objects, for sensing and transmitting inter- or intracellular information, and for targeted drug delivery.

In this presentation, we will summarize the recent development of such kind of miniaturized helical swimmers, and discuss the challenges and opportunities for future development. It is apparent that, to apply the ABFs for diverse potential applications, several issues have to be figure

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This work is partially supported by the Swiss National Science Foundation (SNSF)

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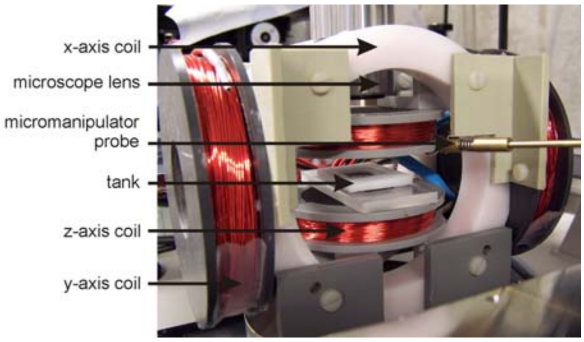

Fig. 2: Experimental setup. The ABF swims inside the white tank which is placed in the middle of three orthogonal coil pairs. A camera mounted on the optical microscope is used for recording the motion of the ABF.

out such as the precise control of motion and force, optimization and functionalization. Particularly, the following questions will be addressed: (1) How to decouple individual ABF from the ensemble with some straightforward approaches? (2) What is the optimized shape of an ABF for swimming? (3) What kinds of manipulation tasks are applicable by ABFs?

II. METHODS

A. *Fabrication*

An ABF consists of two parts: a helical nanobelt tail resembling a natural flagellum in both size and shape and a soft-magnetic head in the shape of a thin square plate. Fig. 1a shows an SEM micrograph of an as-fabricated ABF. The fabrication of ABFs is based on a self-scrolling technique [12-13], which combines “top-down” lithographic patterning and a “self-organization” step to generate 3-D structures from planar thin films. The details of the fabrication are given in ref. [9]. One main advantage of the self-scrolling technique is that it can scale-up or scale-down the dimension of the 3-D structures from sub-millimeter to nanometer scale in a controllable fashion. Moreover, the geometrical parameters of the helix, such as diameter, chirality, helicity angle and pitch, can be precisely controlled [14-15]. In addition, different materials, such as metals, dielectrics, polymers and hybrid structures [16-17], could be integrated into the structures based on thin film growth and lithographic patterning techniques.

B. *Experimental setup*

To actuate the ABF, a magnetic torque is applied on the soft- magnetic head to rotate it along the helical axis (see Fig. 1b), due to the helical shaped tail, the swimmer is self-propelled. In the experiments, three pairs of home-made orthogonal electromagnetic coils were constructed to generate a uniform rotating magnetic field to actuate and control the swimming of the ABFs. They were placed surrounding the microscope lens as shown in Fig. 2. Maximum 2 mT magnetic field strength was used in the experiments.

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