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## Three-dimensional closed-loop control of self-propelled microjets

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We demonstrate precise closed-loop control of microjets under the influence of the magnetic fields in three-dimensional (3D) space. For this purpose, we design a magnetic-based control system that directs the field lines towards reference positions. Microjets align along the controlled field lines using the magnetic torque exerted on their magnetic dipole, and move towards the reference positions using their self-propulsion force. We demonstrate the controlled motion of microjets in 3D space, and show that their propulsion force allows them to overcome vertical forces, such as buoyancy forces, interaction forces with oxygen bubbles, and vertical flow. The closed-loop control localizes the microjets within a spherical region of convergence with an average diameter of  $406\pm220 \,\mu\text{m}$ , whereas the self-propulsion force allows them to swim at an average speed of  $222\pm74 \,\mu\text{m/s}$  within the horizontal plane. Furthermore, we observe that the controlled microjets dive downward and swim upward towards reference positions at average speeds of  $232\pm40 \,\mu\text{m/s}$  and  $316\pm81 \,\mu\text{m/s}$ , respectively. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4826141]

There is great interest in developing nano/microscale robots that can be used in diverse future applications such as targeted drug delivery,<sup>1</sup> sensing and diagnostics,<sup>2</sup> and biopsy.<sup>3</sup> Several groups have proposed a variety of magnetically-driven<sup>4,5</sup> and self-driven<sup>6-8</sup> mechanisms to realize these robots at low Reynolds numbers regime.<sup>9,10</sup> The first man-made magnetically driven microrobot was developed by Dreyfus et al.<sup>11</sup> Their microrobot generated a thrust force using a propagating bending wave along a chain of paramagnetic beads by external magnetic field. Bell et al.<sup>12</sup> have developed a helical microrobot that rotates and acts like a corkscrew upon the application of rotating magnetic fields. The previously mentioned magnetically-driven microrobots benefit from the larger projection distance of magnetic field, as opposed to magnetic microrobots that are driven using magnetic field gradients. Self-driven microrobots also benefit from the larger projection distance of magnetic fields. Paxton et al. developed the first man-made self-driven microrobot.<sup>13</sup> This microrobot is driven by bubble generation through the catalytic decomposition of hydrogen peroxide solution. Solovev et al.<sup>10</sup> and Mei et al.<sup>9</sup> have also demonstrated propulsion of microtubular layers of platinum and silver, respectively, by the catalytic decomposition of hydrogen peroxide, formation and release of oxygen bubbles (Fig. 1). Sanchez et al.<sup>14</sup> and Khalil et al.<sup>15</sup> have demonstrated that self-propelled microjets provide enough force to move against flowing streams in microfluidic channels using open- and closed-loop control systems, respectively. Further, it has been shown that microjets can transport spherical microparticles to a desired location, and selectively transport large amounts of particles on chip as well as Murine Cath.a-differentiated cells.<sup>16</sup> To utilize selfdriven microrobots in realizing the mentioned applications, it is essential to precisely control their motion in threedimensional (3D) space. This study shows that the selfpropulsion allows microjets to overcome buoyancy forces, the vertical component of the bubbles-microjets interaction forces, and vertical flow. The self-propulsion force and the magnetic control allow microjets to dive and swim upwards, and hence reach reference positions in 3D space using an electromagnetic system.

The self-propelled microjets we consider consist of layers of platinum, titanium, and iron. These microjets are immersed in hydrogen peroxide solution with concentrations ranging from 5% to 15% to which small amounts of isopropanol and Triton X are added. The length and outer diameter of these microjets are 50  $\mu$ m and 5  $\mu$ m, respectively. Further, the magnetic layers of the microjet have an average magnetic dipole moment of  $1.4 \times 10^{-13}$  A m<sup>2</sup> that allows them to align along external magnetic fields by the magnetic torque <sup>15</sup>. The self-propulsion force developed by the catalytic decomposition of the hydrogen peroxide and the external magnetic torque exerted on the magnetic layers of the microjets allow us to devise a control strategy to achieve point-to-point motion control in 3D space. This control strategy is based on directing the magnetic fields towards a reference position using an electromagnetic system. This system consists of 8 independent iron-core electromagnetic coils and two microscopic vision systems with auto-focusing capability. The electromagnetic coils

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FIG. 1. Electromagnetic system for the wireless control of microjets in three-dimensional space. Insets in the bottom right corner show a microjet moving towards a reference position (crosshair) under the influence of its propulsion force and the controlled magnetic fields. The upper left inset shows the propulsion mechanics of the microjet. The bottom left inset shows a reservoir for the hydrogen peroxide that contains microjets. The electromagnetic system consists of two sets of orthogonal arrays of iron-core ① electromagnetic coils ②. The upper set has  $45^{\circ}$  with respect to *z*-axis and similar configuration to the lower set (upper right inset). Motion of microjets is tracked using two microscopic vision systems (③ and ④) with auto-focusing and adjustable illumination ⑤.

surround a reservoir  $(10 \times 10 \times 10 \text{ mm}^3)$  of hydrogen peroxide solution and provide maximum magnetic fields of 40 mT, 38 mT, and 65 mT along *x*, *y*, and *z*-axis, respectively. The microjets are controlled in a workspace of  $2.4 \times 2.4 \times 2.4 \text{ mm}^3$  within the center of the reservoir. Two sets of electromagnetic coils are used to generate controlled magnetic fields. The lower set consists of 4 orthogonal electromagnets, each has 45° with respect to the horizontal (*xy*) plane. The upper set is similar to the lower set and has 45° with respect to the *z*-axis (upper right inset in Fig. 1). The electromagnetic system exerts a magnetic torque ( $\mathbf{T}(\mathbf{P})$  $\in \mathbb{R}^{3\times 1}$ ) that is related to the applied current ( $\mathbf{I} \in \mathbb{R}^{8\times 1}$ ) at each of the electromagnets using the following mapping:

$$\mathbf{T}(\mathbf{P}) = \mathbf{m} \times \mathbf{B}(\mathbf{P}) = \mathbf{m} \times \mathbf{B}(\mathbf{P})\mathbf{I} = \hat{\mathbf{m}}\mathbf{B}(\mathbf{P})\mathbf{I}, \qquad (1)$$

where  $\mathbf{m} \in \mathbb{R}^{3 \times 1}$  and  $\mathbf{B}(\mathbf{P})$  are the magnetic dipole moment of the microjet and the induced magnetic field at point  $(\mathbf{P} \in \mathbb{R}^{3 \times 1})$ , respectively. Further,  $\tilde{\mathbf{B}}(\mathbf{P}) \in \mathbb{R}^{3 \times 8}$  is a constant matrix that maps the currents onto magnetic fields. Finally,  $\hat{\cdot}$  is the cross-product operator (3 × 3 skewsymmetric matrix)<sup>4</sup>. Based on the orientation of the microjet and the position of the reference position, we use (1) to calculate the current at each of the electromagnets using the pseudoinverse of  $\hat{\mathbf{m}}\tilde{\mathbf{B}}(\mathbf{P})$ . This level of control allows the microjet to be oriented along the field lines, and move towards the reference positions. Figure 2 depicts a

representative motion control result of a microjet in 3D space. The microjet moves towards 4 reference positions. At time, t=0 seconds, the 1<sup>st</sup> reference position (blue circle) is provided to the control system. The microjet dives downward and reaches the reference at an average speed of  $220 \,\mu\text{m/s}$ . Multiple reversals of the magnetic fields within the vicinity of the reference position localize the microjet within a spherical region of convergence of  $320 \,\mu\text{m}$  in diameter. At t = 1.2 s, t = 1.5 s, and t = 2 s, the microjet moves towards the 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> reference positions, respectively. We observe that the microjet dives towards the 1<sup>st</sup> and  $2^{nd}$  reference positions at a speed of  $225 \,\mu$ m/s and swims up towards the 3<sup>rd</sup> reference position at a speed of  $320 \,\mu\text{m/s}$ . The difference between the downward and upward swimming speeds of the microjet is due to the upward flow of the solution. This flow is produced by the oxygen bubbles generated in the reservoir that move upward to the surface of the solution. The bubbles also interact with the microjets and cause instantaneous deviations in their controlled path. However, the controlled magnetic torque exerted on the magnetic dipole of the microjets align them again along the field lines.

Another representative motion control result of a microjet is shown in Fig. 3. Three reference positions are given to the control system. The microjet is positioned within a spherical region of convergence with a maximum diameter of 400  $\mu$ m along the *xy*-axes (1<sup>st</sup> reference position). We repeated this motion control trial 5 times, and observed that our control



FIG. 2. Representative closed-loop motion control result of a self-propelled microjet in three-dimensional space. The red-dashed circle indicates the region of convergence in which the microjet is localized using the controlled magnetic fields. The red arrows and the blue circles indicate the direction of the controlled jet and the reference positions, respectively.

system localizes microjets within a spherical region of convergence with an average diameter of  $406 \pm 220 \,\mu\text{m}$ . The self-propulsion force of these microjets allows them to achieve an average speed of  $222\pm74 \,\mu\text{m/s}$  along the *x*- and *y*-axes. Further, microjets dive downward and swim upward at average speeds of  $232\pm40 \,\mu\text{m/s}$  and  $316\pm81 \,\mu\text{m/s}$ , respectively. The swimming speed of the microjets in 3D space varies based on the swimming direction. Maximum speed is observed when microjets swim up due to the upward flow in the reservoir.

In conclusion, we have demonstrated point-to-point closed-loop motion control of self-propelled microjets in 3D

space. Not only do we find that our electromagnetic system and the self-propulsion due the catalytic decomposition of hydrogen peroxide are capable of localizing microjets within the vicinity of reference positions, but we also observe that the propulsion mechanism of microjets allows them to dive against the flow of hydrogen peroxide, the interaction forces with the oxygen bubbles, and the buoyancy forces. Further, their propulsion allows them to swim upward and overcome forces due to gravity. Our closed-loop motion control results suggest that microjets have the potential to be used in diverse future applications that require precise positioning such as actuation and microassembly.



FIG. 3. Trajectory of a controlled microjet towards three reference positions (blue circles). The insets show representative snapshots of the controlled microjet. The red arrows indicate the direction of motion of the microjet. Scale bar: 250  $\mu$ m.

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