Magnetically-Actuated Micro-Scale Bristle-Bots

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***Abstract*— This work presents micro-scale bristle robots, with the size of 233 μm $\times$ 113 μm $\times$ 75 μm, having five bristles on the top and bottom sides of the robot body. The bristles are tilted 60° from the horizontal surface. The presented micro bristle-bots are fabricated using two-photon lithography direct laser write, followed by nickel (Ni) deposition as the magnetic material. A single electromagnet lying underneath the substrate is used to actuate the robots. The magnetic field applies a torque on the nickel layer of the robot body and, combined with the ON/OFF switching of the magnetic field, induces a rocking motion. This, in turn, modulates the friction forces at the bristle tips via stick-slip cycle, resulting in a net horizontal displacement. This work marks the smallest reported bristle-bot to date.**

I. INTRODUCTION

In this paper, we demonstrate a magnetically-actuated micro-scale bristle robot (bristle-bot) with no dimension exceeding 250 μm (Figure 1) which is significantly smaller than previously-reported bristle-bots [1], [2], summarized in Table I. The robot is fabricated using a combination of two-photon polymerization (TPP) for 3D printing of the body/bristles and electron-beam (e-beam) deposition of nickle (Ni) as the magnetic material. The 600 nm-thick Ni film covers the upper side of the bristle-bots and responds to the changing external magnetic field caused by the ON/OFF switching of a single electromagnet with a square-wave current input. This alternating magnetic force induces torque on the robot body, causing the bristle tips to slide back and forth on the substrate. The asymmetry of the friction forces results in a net displacement in each cycle of oscillation, also known as a stick-slip cycle. Under a square-wave magnetic field, with a frequency of 8 Hz and a magnetic field amplitude of 4.359 mT, the robot moves at a speed of 5.14 $\mu m/s$. The bristle-bots are further equipped with two add-on arms (i.e. micro-wedges) to be used as manipulation tools in future developments. The demonstrated locomotion of bristle robot in micro-scale with a single-coil magnetic actuator can be used for numerous micro-scale applications such as in-vitro cell manipulation.

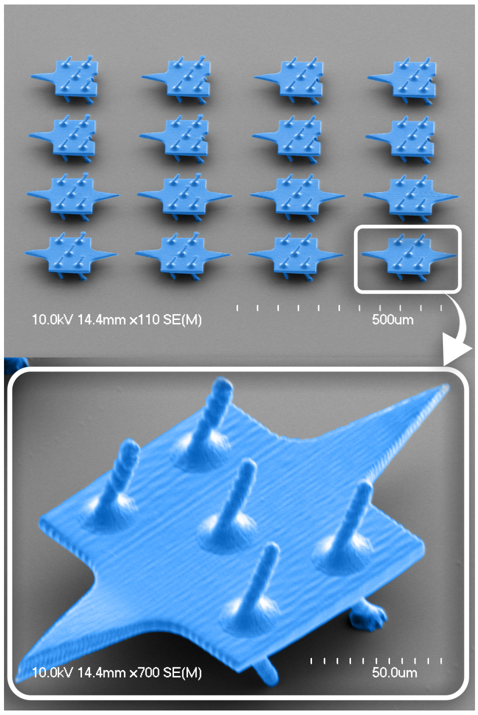
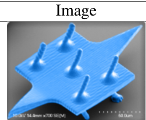
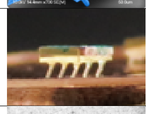
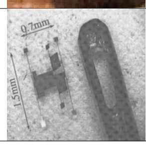


Fig. 1: False-colored scanning electron microscope (SEM) images of the fabricated micro-scale bristle-bots of two proposed designs.

TABLE I: Comparison of size of various bristle robots.

Description	Image	Actuation Mechanism	Critical feature Size
Magnetic Micro Bristle-Bot* *[This work]		Electromagnet	233um
Micro Bristle-Bot with on-board PZT [1]		Piezoelectric Shaker	2mm
Vibration Microrobot [2]		Vibration Table	1.5mm

Bristle-bots use oscillations to drive their in-plane movement due to the stick-slip cycle of bristles. Macro-scale (with dimensions in the centimeter scale) bristle-bots can utilize vibrations from on-board actuators, such as mass-motor [3]–[6] and piezoelectric actuators [7], [8]. It is shown that external actuation sources placed underneath the bris-

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tle robots (e.g. electrodynamic shakers [9] or piezoelectric shakers [1]) can cause locomotion similar to those with on-board actuators. This is crucial for robots too small to have integrated on-board actuators and electronics. A magnetic robot by *Sitti et al.* [10], [11] utilizes magnetic actuation to achieve locomotion via stick-slip cycle and is comparable in size to the presented robot in this work. The presented wireless magnetic actuation mechanism using ON/OFF switching of a single magnet provides an elegant solution to the aforementioned challenges, as the magnetic robot body can be excited without moving the ground surface. The main difference between this work and *Sitti et al's* work [10], [11] is their robot needs multiple electromagnetic coils to achieve locomotion, whereas the presented micro bristle-bot uses only a single electromagnet underneath the walking substrate. This is possible because of the micro bristle-bot's design with tilted bristles.

Magnetic fields are widely used for micro-scale robotic actuation. In particular, magnetically-actuated micro-robots can be categorized as follows: 1) direct application of driving magnetic forces on the robot to guide its motion [12]–[17] and 2) periodic deformation of the robot structure to achieve inchworm-like motion [18]–[20]. In both cases, a multi-coil electromagnet system (e.g. Helmholtz coil) is required to precisely generate the magnetic field for full control of the motion [13]–[17], [19], [20].

Our fabricated micro bristle-bots, on the other hand, can utilize the resonance behavior of the bristles and thus do not rely on the orientation of the external field vector for achieving directional motion. In other words, the direction of the robot locomotion and its dependency on the actuation frequency is encoded in the bristle design (e.g. bristle diameter, length, and tilt angle) [7]. In [7], we showed that steering can be achieved in bristle-bots by using an asymmetric bristle design. The steering was achieved by selective excitation of a set of bristles at its particular resonance frequency. Although only forward motion with symmetric bristle design has been implemented in this work, future iterations of these robots can achieve steering capability by modulation of the actuation frequency, similar to [7], with asymmetric bristle design and without further complicating the system.

II. Theory

The mechanics of bristle-bots' motion has been studied previously, both theoretically [1], [21]–[26] and experimentally [8], [9], [27]. The bristle-bots utilize asymmetrical friction forces at the bristle/leg tips during different phases of stick-slip cycle to achieve locomotion [21], [28]. Previous works on external actuation of bristle-bots relied on the physical shaking of the ground surface/substrate via a piezoelectric transducer [1], [9]. The presented robot utilizes a magnetic force instead of the aforementioned approach and applies a torque on the robot body due to magnetization of the nickel layer (Figure 2).

The magnetization simulation in Figure 2b indicates that a horizontal magnetization field develops despite the vertical magnetic field applied, which may be explained by the shape

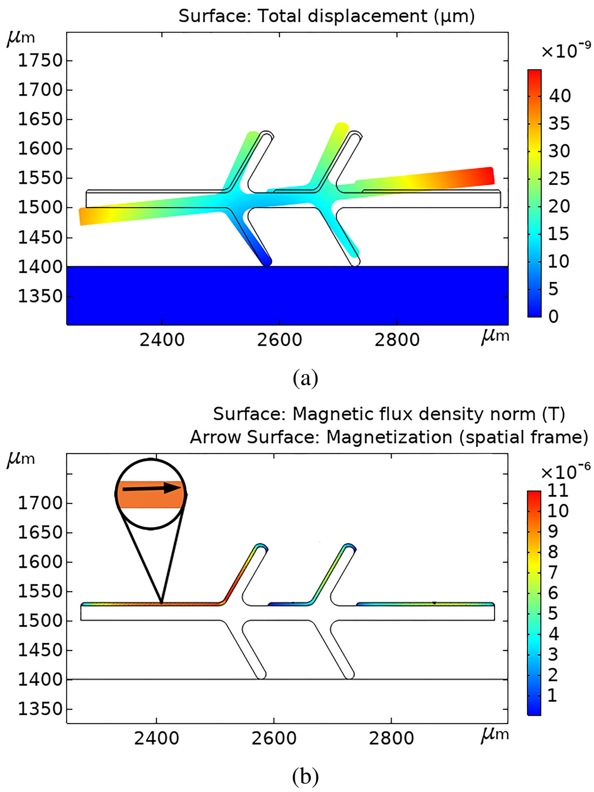


Fig. 2: COMSOL simulation results of the thin-film Ni coated magnetic bristle-bot for (a) the displacement caused by the magnetic field. (b) Magnetization profile with close-ups on the horizontal Ni layer.

anisotropy of the nickel deposited layer. When one dimension of a soft magnet is considerably larger than the others, the easy magnetization axis will be mostly aligned to its direction [29], [30]. As a result, the horizontally aligned portion of the nickel layer will experience magnetization, and this proves implicitly that the susceptibility tensor is not diagonal [31], unlike simpler shapes such as ellipsoids, whose demagnetization factors have already been derived [32].

The misalignment between the magnetic and magnetization vector fields induces a torque on the robot body, which becomes more significant than the magnetic force at the micro-scale [33]. As a result, the front of the robot's body will dip down during its stick phase (Figure 2) and return to its neutral position during its slip phase, leading to net displacement.

III. Materials and Methods

A. Fabrication

The micro-scale bristle-bots are designed in 3D CAD software from the STL (stereolithography) file. The dimensions of the presented bristle-bots are detailed in Figure 3.

Five tilted bristles were designed on the top and bottom sides of the robot body to accommodate motion when flipped. The design of the bristles on both sides can also

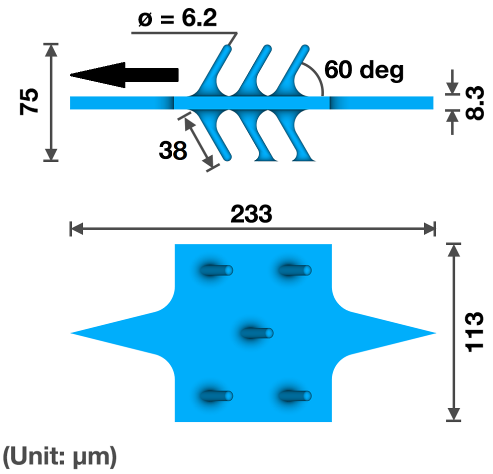


Fig. 3: 3D CAD model of micro bristle-bot. The arrow indicates the forward direction.

assist with locomotion in confined environments, such as narrow crevices, where both sets are engaged and can generate forces for locomotion. The use of upper bristle for locomotion is not presented in this work and is the subject of our future work. The tilted bristle designs also provide more directionality, compared to the un-tilted (i.e. 90° angle from the surface) bristle design [1]. The two micro-wedges on the front and back of the robots are designed for future manipulation applications. The generated STL file is used for direct laser writing of the body/bristles of the micro bristle-bots using Nanoscribe Photonic Professional GT, a two-photon-lithography tool [34], on ITO (indium tin oxide) layered glass slide using similar methods as discussed in [1]. The photoresist used for direct laser write is Ip-S, provided by Nanoscribe GmbH [35]. The material properties are shown in Table II. The sample is then developed in SU-8 developer, washed with isopropyl alcohol, and dried using a stream of nitrogen gas. Next, a 600 nm-thick Ni film is deposited on top of the micro bristle-bot via electron beam deposition. Finally, the micro bristle-bots are released from the ITO substrate using a probe manipulator under a microscope. The sequential steps of the fabrication process are shown in Figure 4.

B. Test Setup

Once the fabrication of the array of micro-scale bristle-bots is completed and the bots are released from the substrate, a layer of oil is placed on the ITO slide. This reduces the stiction and adhesion forces, which are dominant in the micro-scale regime [36], [37], by coating the surface with a hydrophobic layer and preventing the Ip-S bristle tips from sticking to the substrate. Additionally, buoyant forces in the fluid reduce the resting gravitational torque required for actuation by $\frac{\rho_f}{\rho_r}$, where ρ_f is the density of the fluid and ρ_r is the density of the robot material [38]. As a result, mobility of the robot is enhanced in oil and may even be applied towards biological fluids such as blood and cerebrospinal

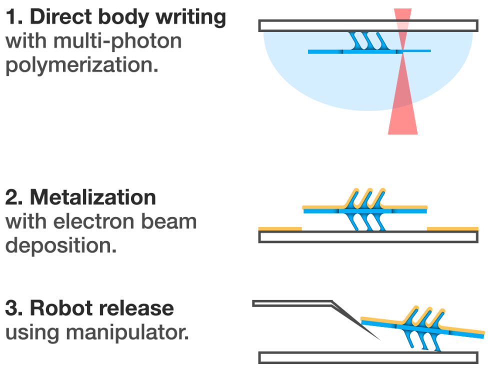


Fig. 4: Process flow of micro bristle-bot fabrication.

fluid. However, the presence of a meniscus around micro bristle-bots must be avoided as the meniscus forces can be large and prevent the robot from moving [36].

Next, a DC electromagnet is placed underneath the ITO substrate and is connected to Agilent 33220A function generator, which connects to a Krohn-Hite 7602M voltage amplifier. A top-down view microscope is connected to a Moticam 1080 camera to record the video of the robot trajectories, as shown in the supplementary video. Probe manipulators are used for micro bristle-bot manipulation. The experiment setup is shown in full detail in Figure 5. The function generator produces a square-wave current input signal with a frequency of 8 Hz and duty cycle of 50%. This generates an ON/OFF switchable magnetic field with a magnetic flux density amplitude of 4.359 mT with the same frequency and duty cycle (shown in Figure 6).

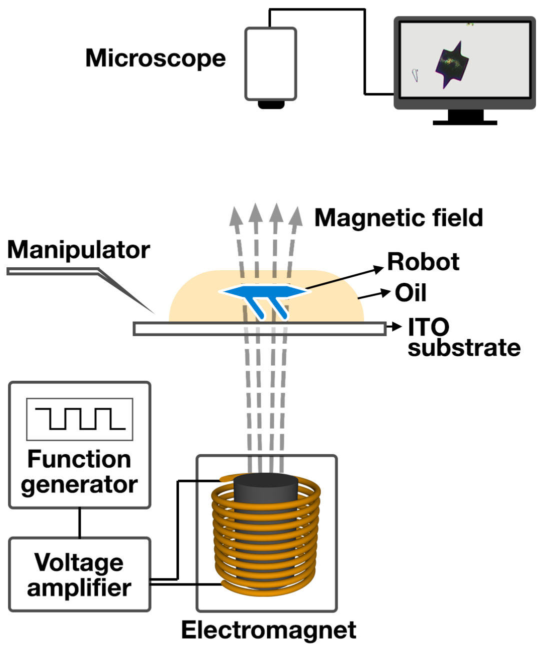


Fig. 5: Test setup used to actuate and record the micro bristle-bot trajectory.

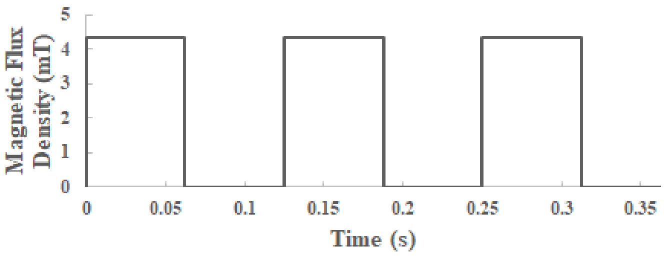


Fig. 6: Magnetic flux density ON/OFF square-wave generated by the electromagnet.

TABLE II: Material properties of Ip-S polymer from Nanoscribe GmbH [35].

Property	Value
Young's Modulus	4.6 GPa
Hardness	160MPa
Storage Modulus	5 GPa
Loss Modulus	150-350MPa
Shrinkage After Polymerization	2-12%
Density (liquid)	1.111 g/cm^3

After the video is captured, a DLTdv digitizing tool from [39] is used for tracking the micro bristle-bot motion. The average speed is extracted from the data.

IV. Results and Discussion

The trajectory, orientation, and speed of a sample micro bristle-bot, along with the frame shots of the trajectory video provided in the supplementary material, are shown in Figure 7. The robot moves with an average speed of 5.14μm/s over a time length of 150 seconds. This speed is comparable to the crawling speed of Amoeba proteus [40], which moves with an average speed of 0.5 to 5μm/s, and the presented robot has a comparable size with the smallest specimens (size ranges from 220 to 760μm) [41] (See Figure 8)

The locomotion of the tested micro bristle-bot over 150 seconds yields 700μm of forward movement with 200μm of lateral drift. Possible reasons for lateral drift include: (1) fabrication nonidealities, such as nonuniform deposition of Ni thin film that results in nonuniform deformation from the magnetic pull, (2) slight lateral deformation of bristle from the release step using the probe manipulator, and (3) the front wedge hitting the ground from periodic tilting of the robot and in axis of rotation between front leg tip and tip of wedge.

COMSOL multi-physics simulations have been used to find the vibration modes of the micro bristle-bots. The material properties of the bristle-bots used in the simulation are summarized in Table II. The ideal slipping of the bristle tips on the surface (corresponding to the friction-free case) can be represented as a roller constraint. In practice, the presence of directional friction forces will remove the eigenvalue degeneracy and result in the bifurcation of the resonance frequencies [8]. Another implicit assumption in this theoretical treatment is that the bristle tips will keep their contact with the substrate at all times. Submergence in the oil will also introduce drag forces and thus, increase the damping and energy dissipation compared to air medium. A possible simulated displacement mode shape, corresponding to the forward motion of the micro bristle-bot (as observed in the supplementary video), is shown in Figure 9.

Furthermore, previous work has shown that magnetically-

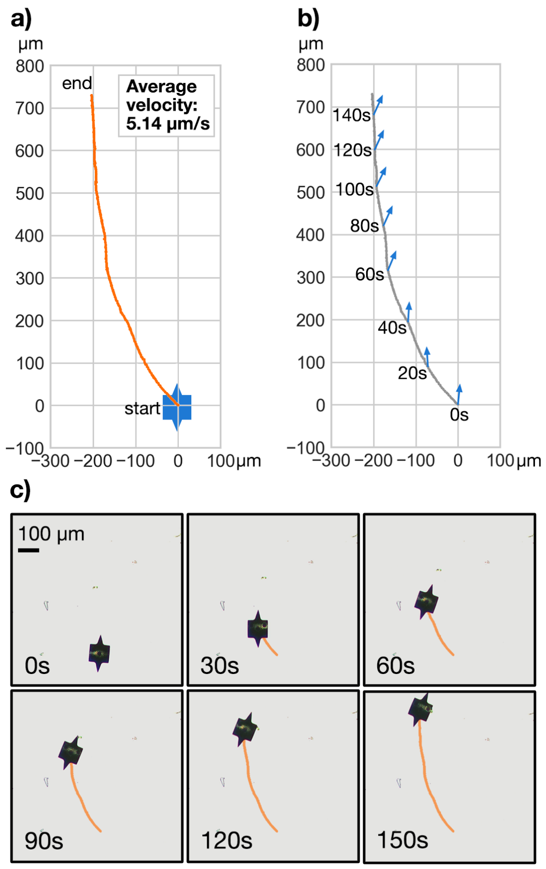


Fig. 7: a) Trajectory of the robot. b) Orientation of the robot sampled every 20 seconds. c) Screenshots of the recorded testing video with trajectory overlaid.

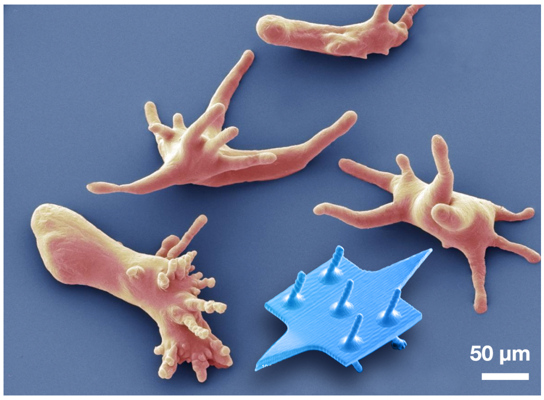
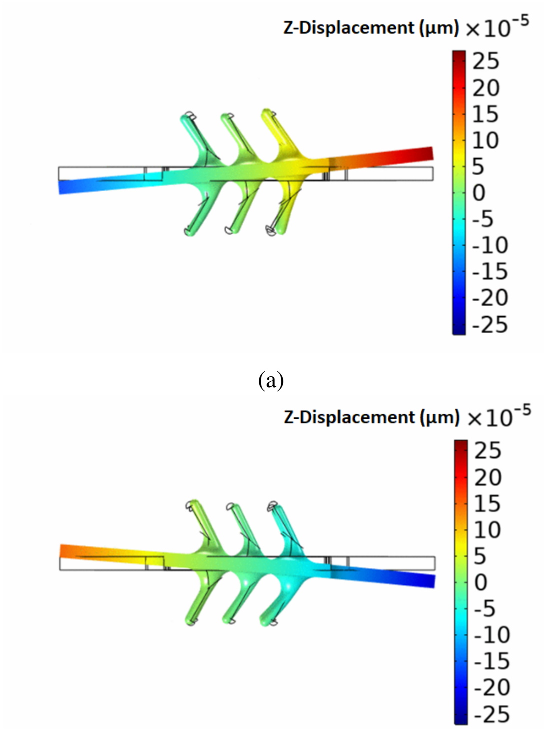


Fig. 8: Fabricated micro-scale bristle-bot vs. *Amoeba proteus* (Amoebas photo courtesy of [42].)



(a)

(b)

Fig. 9: Vertical displacement of micro bristle-bot mode shape when (a) counter clockwise and (b) clockwise moment is applied on nickel layer of the robot body.

actuated micro-robots no longer synchronize with the applied magnetic field beyond their step-out frequency [43]–[47]. This frequency usually lies under 100 Hz and scales with magnetic volume and applied field strength. By adjusting these parameters to be unique for different robots, *Mahoney et al.* [43] and *Ishiyama et al.* [44] demonstrated selective locomotion based on the applied field frequency. For the robot in this work, the step-out frequency is 8 Hz.

Such flexibility in design signifies that, along with selective locomotion of multiple robots, directionality and steering may be encoded in a single robot by depositing different thicknesses on various parts for local step-out frequencies. For example, the left side of the bristle-bot can be coated twice as much as the right side in nickel, leading to a frequency range where the left side is active and the right side is inactive. As a result, these robots can possibly not only move forward but also turn left and right.

V. Conclusion

This paper presents the smallest reported bristle-bot to date, comparable in size to many uni-cellular organisms. The presented micro-scale bristle-bots are actuated using a periodic square-wave magnetic field generated by an ON/OFF switching current running through an electromagnet. The induced changing magnetic field applies periodic torque on the Ni-coated robot body, causing locomotion via stick-slip cycle with a travel speed of 5.14 μm/s. The geometry and orientation of the robot bristles dictate the locomotion direction. Therefore, the direction of the motion of the robots, encoded in the bristle design, is independent of the particularities of the magnet, significantly simplifying the setup. Future work includes improving the speed of micro bristle-bot as well as utilizing bristle sets with different geometries to add steering capability via actuation frequency change to the micro-scale bristle-bots. By superimposing various actuation frequencies that target step-out frequencies of the nickel layer to excite particular bristle sets, it would be possible to fully steer the micro bristle-bots and gain full control of the motion.

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