BATCH-FABRICATION OF DIAMAGNETICALLY LEVITATED MICROROBOTS

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ABSTRACT

This paper reports the batch fabrication of magnetically patterned bases for millimeter-scale, diamagnetically levitated microrobots. A selective-magnetization process is used to imprint checkerboard magnetic pole patterns in a single NdFeB substrate. Further machining of the substrate produces nine microrobots per batch (limited by the surface area of the magnetic substrate). This process represents a leap forward compared to the current fabrication approach, which relies on hand-assembly and gluing arrays of discrete magnets. The diamagnetic repelling forces of bases with two thickness (400 μm and 280 μm) are directly measured (227 μN and 64 μN), showing that the thicker base produced higher force. Furthermore, the microrobots are capable of assisted levitation (external magnetic field bias) and operation in sliding mode (lateral movement) using microfactory drive platform.

INTRODUCTION

Robotics is a driving force for a new industrial revolution, comprising a \$26 B [1] worldwide market with the goal for the next 15 years to develop the manufacturing industry (12% of U.S. GDP) by combining advances in micro/nano scale [2]. While there are enumerable macroscale robot systems, there is a huge technology gap for robotic systems that can manipulate/control micron-sized ($\sim 10^{-6}$ m) objects with nanometer resolution. Since the first mention of small scale machines (called today microrobots) in 1959 by Richard Feynman [3], [4], numerous fields of applications for micro/milli robotic systems have emerged such as minimal invasive medicine [5], bioengineering [6], and microassembly [7]–[9]. Inspired by Feynman, some visionaries such as A.M. Flynn [10] and W. Trimmer [11], foresaw creating complex machines with sizes and abilities of insects. Most of researchers working in the field of microrobotics recognize their inspiration in the founding works of R.S. Fearing [12], F. Arai and T. Fukuda [13], that in the International conference on Intelligent robots and systems (ICIRS) on 1995, set the fundamentals of micromanipulation and adhesive forces at microscale.

To address the challenge of microassembly in non-aqueous environments, SRI International has developed a microfactory platform for computer-controlled magnetic manipulation of swarms of microrobots [14] [15]. A typical microrobot comprises a magnet base made of a 3x3 array of poled permanent magnets in a checkerboard pattern and a stick-like end-effector. The microrobots are distributed over a diamagnetic material (pyrolytic graphite) and levitate above this surface via repulsive forces between the magnetic base and the diamagnetic material, as shown in Figure 1. The robots are driven across the substrate using a grid of current-carrying wires positioned beneath the diamagnetic layer, providing lateral positioning capability in the xy-plane, as well as some control of the levitation height in the z-direction.

Heretofore, these millimeter-scale microrobots are assembled and glued together by hand. The contribution of this paper is the first published report of a scalable fabrication technique for mass-manufacturing the magnetic microrobot bases to be operated on the microfactory platform built by SRI. The process yields a mechanically monolithic magnetic base that is magnetically poled

into the desired magnetic pattern, as opposed to assembling discrete magnets. In addition to improving fabrication throughput, the process could also be used to fabricate even smaller magnetic microrobots, which are not currently possible with hand assembly.

Figure 1: Schematic of diamagnetic levitated robot over a microfactory platform. Colors on robot indicate vertical magnetization polarity to form “checkerboard” pattern. Adapted from [14].

EXPERIMENTAL METHODS

The proposed batch fabrication of levitated microrobotic bases begins with an NdFeB grade N42 substrate (10,000 μm x 10,000 μm x 400 μm) sourced from BJA magnetics. The fabrication could be summarized in three main steps: 1) Polishing the NdFeB substrate, 2) batch-magnetizing the substrate to imprint a complex magnetic pole pattern using a technique called selective-magnetization, and finally, 3) singulating the substrate to create individual magnetic bases. The detailed process steps are:

- Lapping one side of a commercial 10 mm x 10 mm x 0.4 mm NdFeB magnetic substrate, to obtain a designated thickness.
- Polishing the lapped side to obtain mirror finish.
- Fully magnetizing the substrate to create north poles (7 T).
- Selectively reversing areas of the substrate using a magnetization mask to create south poles (1 T).
- Dicing the substrate into 9 microrobot bases using dicing saw.
- Manually cleaning, separating, and packaging the bases.

A total of nine magnetic bases (3 mm x 3 mm) can be fabricated in the selected substrate. Robot distribution over a substrate is presented in Figure 2. Two batches of magnetic bases were fully produced. A ~ 280 μm and a ~ 400 μm thick batches, with nine bases each.

Figure 2: Magnetic base fabrication for microrobots using selective magnetization. (a) Designed and (b) fabricated (singulated and polished) microrobots with two thickness.

Microrobot machining

The first important step to guaranty good levitation of the micro-robots is the polishing of the magnetic layer before magnetization. Polishing is mainly necessary on the side facing the diamagnetic board. Because the levitation is of only tens of microns, any particle or surface roughness will be critical and will reduce the motion of the robots. A manual polishing process using progressively smaller grid polish pads was implemented. Sand papers and different lubricants used were used in a sequence: P220/dry, P500/dry, P100/water, P1200/oil, P1200/water. With this process, the magnetic layer with original thickness of 400 μm was lapped to 280 μm . After lapping, a polishing pad of 3 μm grid and water was used, followed by a polishing pad with 0.06 μm of silica slurry. A mirror finish was obtained.

For singulated the robots a hubbed resin-bond diamond dicing blade was used. 2.250" X .750" X .007" Thick, 325 mesh with 40-60 μm grit size (reference CA-007-325-030-H from Dicing Technologies). The parameters used to set up the dicing were: blade thickness of 178 μm , blade exposure of 762 μm , rotation speed of 15 -18 kRPM, feed rate of 0.1 mm/s. Magnetic substrates were successfully diced in 9 squares of 3 mm x 3 mm each. The use of a dicing saw proved to generate repetitive and reliable dimensions with very tight tolerances (dicing lines $\sim$ 214 μm wide kerf and 422 μm deep).

Low aspect ratio magnetization mask

The most important aspect of the levitated microrobot fabrication is imprinting the magnetic pattern using selective-magnetization [16][17]. Because of the importance of the magnetization mask, this should be accomplished after defining geometry parameters, magnetization mask material and reversal field to be applied during the selective magnetization process (it varies with the mask and substrate material). The mask fabrication is a critical step towards obtaining multiple magnetic bases from a single magnetic substrate (batch-fabrication). Two different masks constructions were evaluated: Low and high aspect ratio.

The aspect ratio of the mask is designated as the thickness divided by the feature length. A square pattern mask was selected to comply with the specifications of the microfactory base. All resulting robots should have the same magnetic pattern. Resulting magnetic square poles at individual bases should have 1 mm side.

To guaranty full magnetization through the substrate thickness, it was important to design and fabricate a double side magnetization mask. The complete mask was designed as sandwich of two identical patterned masks, made of carbon steel (AISI 1018 mild/low carbon steel - ASTM A108). All mask features are 1 mm depth (feature in the mask will have an aspect ratio of 1). In the middle, a zinc spacer was designed to align the magnetic substrate. Figure 3a shows and explosion schematic of the mask. The three parts of the mask and the magnetic layer will hold together using three wood alignment pins. The mask pieces were machined using a Sherline 2000 CNC and 1/64"-two flutes end mills. Figure 3b shows the final machined mask disassembled.

Figure 3: Low aspect ratio magnetization masks. (a) Schematic and (b) disassembled representation of the magnetization mask.

High aspect ratio magnetization mask

A set of finite element simulations modeled the selective-magnetization process using 2D/3D quasi-static magnetic fields in COMSOL multiphysics. Simulation results yielded that the higher the aspect ratio of the mask the better magnetic field quality will be generated during the reversal magnetization. An example of the simulations conducted could be seen in Figure 4.

Figure 4: High aspect ratio magnetization mask. Fabrication progress from individual layers.

With this premise of higher aspect ratios in mind, it is necessary to fabricate different magnetization masks, but this raises a fabrication problem. The high complexity of machine carbon steel with high aspect ratios using dimensions smaller than 1 mm. Commercial end-mills smaller than 1/64" are limited to 1 mm length. Therefore, a laminated design was proposed to obtain high aspect ratios: By using a CNC or laser cut to machine individual layers out of 1 mm thick carbon steel sheets (two different designs of layers, one with 6 x 1 mm³ poles and other with 3 x 1 mm³ poles to create the checkerboard). This process will generate perfect square shape angles in the features and the most important, controllable aspect ratios higher than 10. After three layers are machined, they will be glued together in rows (6/3/6 pole layer) and three rows will be glued with a 300 μm spacer between them, as shown in Figure 5. This fabrication concept was originally tested using laser cut over stainless steel (easier to machine) and then implemented in carbon steel using CNC.

Figure 5: High aspect ratio magnetization mask. Fabrication progress from individual layers.

MICROROBOTS CHARACTERIZATION

Using fabrication methods described above and selective magnetization process to create magnetic bases (at 1 T reversal field), the following results are presented: Figure 6 shows resulting microrobots and the magnetization of the BJA magnetic layer using the low aspect ratio machined double mask. Magnetization images were obtained using magneto optical (MO) sensor of 38 mT saturation field in the “Minimo” magnetic camera (Matesy). These pictures show the entire substrate (10 mm x 10 mm x 0.4 mm) before and after being singulated.

Figure 6: Magnetic base fabrication for microrobots using selective magnetization. (a) Magneto optic image of the 10 mm x 10 mm magnetic base. (b) Singulation of 9 robots (3 mm x 3 mm) per substrate. MOI superposition in the bottom right robot.

Magnetic characterization

A first attempt to quantify the stray magnetic field and confirm magnetic images, was made using an in-house scanning hall probe. This is a rastering technique that displaces the scanning hall sensor over the magnet area. Scanning hall probe confirms that selective magnetization of 280 μm thick substrates generates patterns with only $\sim 39\%$ of the magnetic field strength of the manually assembled patterns.

Figure 7 depicts the results of the images obtained using magneto optical imaging/field-measurement system [18], comparing manually assembled and selectively magnetized micro-robots. The advantage of this technique is that the intensity of the magnetic field can be quantified and data acquisition is faster than scanning hall probe. By quantifying the stray magnetic field from the magneto optical image, a comparison between three different masks (low and high aspect ratio stainless and low carbon steel) is presented in Figure 8. These measurements show the B field peaks, obtained from the selectively magnetized samples (~ 50 mT maximum) are about 50% weaker than the manually assembled robot (~ 100 mT maximum).

Figure 7: Magneto optical measurements. Assembled and selectively-magnetized levitated micro-robot's comparison. Measurements at 600 μm above the surface.

Figure 8: Magneto optical image of a selectively magnetized samples using each of the machined masks. Measured at 500 μm from magnet surface.

Magnetic forces

The final goal of the micro-robots is the diamagnetic levitation of their own masses plus a payload. In this order of ideas, we studied the diamagnetic force generated for three samples: a manually assembled robot, a selectively magnetized 400 μm thick robot and a 280 μm thick robot.

We used a combination of a microbalance (Explorer 2, Ohaus) and a polished pyrolytic graphite as a sensing mechanism, as a variation of experiment conducted by [19]. Each sample was attached to a glass and plastic sample holder facing the graphite and connected the holder using a stiff brass beam with a 3D micro positioner (built in-house with Newport DC servo controllers). By cautiously lowering the magnet on top of the graphite, the repelling diamagnetic levitation force will push the graphite away and this force is measured by the balance. Figure 9 illustrates the experiment and results.

Figure 9: Diamagnetic force measurement using a microbalance. (a) General assembly, (b) close-up of sample holder, and (c) force analytical solution, simulation and measurement results.

Figure 9c compares measurements of the magnetic force with COMSOL simulations and charge model calculations [20]. A factor of 0.35 and 2.8 (simulation and analytic model) are used arbitrarily to compensate variations on material properties for the specific samples. Differences in the slope of the manually assembled base compared with models are attributed to instrumentation error.

It is clear from Figure 9c that the force produced by the manually assembled base is higher than its own weight (red curve). On the other hand, the force produced by 400 μm thick selectively magnetized bases is slightly smaller than their own weights, and

therefore it won't levitate. Similar behavior occurs with the 280 μm thick bases, but the produced force is considerably lower. Enhancing the magnetic field produced by the selective magnetization will increase the diamagnetic force and overcome the weight of the magnet making the micro-robot levitate.

Levitation and sliding

Although the selectively magnetized fields and the diamagnetic forces are weaker than the manually assembled counterparts, experiments conducted using SRI microfactory (Figure 10) verify that this technique can in fact fabricate microrobots to perform assisted levitation (diamagnetic levitation biased by an additional external magnetic field) and assisted magnetic sliding (using the microfactory platform to displace bases, achieved by controlled electric currents and diamagnetic layer).

Figure 10: Characterization of batch fabricated robots at SRI. Left: assisted sliding and right: assisted levitation.

CONCLUSIONS

A batch fabrication of monolithic magnetic bases for microrobots was successfully obtained. Selective magnetization was used to imprint alternated magnetic pole patterns in a machinable NdFeB substrate, producing 9 microrobots per batch. Two types of magnetization mask were explored (low and high magnetization) showing similar results among them. The diamagnetic repelling force of bases with two thickness (400 μm and 280 μm) was measured, showing that the thicker base produced higher force. Even though the fabricated bases don't self-levitate, they were capable of assisted levitation (external magnetic field bias) and operation in sliding mode (lateral movement using microfactory platform).

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