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Micro Manipulation Using Magnetic Microrobots

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Abstract

When developing microscale robotic systems it is desired that they are capable of performing microscale tasks such as small scale manipulation and transport. In this paper, we demonstrate the transport of microscale objects using single or multiple microrobots in low Reynolds number fluidic environment. The microrobot is composed of a ‘U’ shaped SU-8 body, coated on one side with nickel. Once the nickel coating is magnetized, the motion of the microrobots can be driven by external magnetic fields. To invoke different responses from two microrobots under a global magnetic field, two batches of microrobots were fabricated with different thicknesses of nickel coating as a way to promote heterogeneity within the microrobot population. The heterogeneity in magnetic content induces different spatial and temporal responses under the same control input, resulting in differences in movement speed. The nickel coated microstructure is manually controlled through a user interface developed using C++. This paper presents a control strategy to navigate the microrobots by controlling the direction and strength of externally applied magnetic field, as well as orientation of the microrobots based on their polarity. In addition, multiple microrobots are used to perform transport tasks.

Keywords: microrobot, magnetic control, microtransport, magnetic polarity, micromanipulation

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1 Introduction

As nano/micro scale manufacturing technology has matured, the realm of small scale robotics is beginning to become a reality as many researchers have turned their attention towards developing microrobots for medical applications. As a result, various microrobots have been proposed in terms of material, motion design, and control method. These advanced microrobots have the potential to perform tasks such as drug delivery, cell manipulation, and medical imaging[1–3]. While these operations are currently achieved using various means, for example cell manipulation is routinely carried out using pipette based micromanipulators and optical tweezers[4,5], microrobots have the potential to automate and scale up these tasks. Recently, magnetic control of microrobots and microgrippers has demonstrated micromanipulation capabilities[6–8].

For *in vitro* and *in vivo* applications, microrobots must be designed to navigate in small scale aqueous environments[9–12]. In response to the physics of fluids at small scale, it is necessary to develop a propulsion mechanism suitable for low Reynolds number locomotion, where viscous effects are dominant over inertial effects[9], and miniaturization of macroscale actuators are ineffective or infeasible[13–17].

There are different approaches to propel swimming microrobots. One of the ways is to develop artificially engineered microstructures[8,18–28]. The other way is to control engineered microorganisms[29–31]. In terms of artificial microstructure fabrication, so far the majority of microrobots have been produced using techniques such as 3D printing, micro-molding, or with the aid of laser machining systems[6,32,33]. Another fabrication method uses standard photolithography to pattern robots using photoresist with embed magnetic particles (*e.g.* SU8 with Fe_2O_3)[7]. To propel these untethered microrobots, wireless control systems are necessary. Towards this end, magnetic fields are commonly employed as the external forces used to drive microrobots.

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This paper presents the fabrication and control of nickel coated magnetic microrobots for micromanipulation. The metal deposition subsequence results in more reliable microrobots comparing to previous robots that used iron oxide doped SU8[7]. This method can generate a uniform layer of magnetic material and helps to translate the microrobots more uniformly. A set of control strategies is proposed and is demonstrated by several experiments in terms of polarity and motility. The ability of microrobots to perform manipulation tasks are examined in micro particle transport experiments. It is difficult to control multiple microrobots in a global coordinate frame control systems with only one control input since all microrobots receive identical control inputs[34]. In this paper, even though we cannot generate selective control input, we carry out experiment for transport of micro object using multiple microrobots by differentiating the magnetic responsiveness of the microrobots, so that they can be actuated with varied velocities. These results enhance the ability of a microrobotic system for micro manipulation using a single global input.

2 Methods

2.1 Fabrication of magnetic microrobots

There were two main steps to fabricate U-shaped (gripper) microrobots with the dimensions of 35 × 30 × 3 μm^3, as depicted in Fig. 1. The first step was to use standard photolithography to make the SU-8 body of the micro robots, shown in Fig. 1a. First, a sacrificial layer of 5% (w/v) 60 kDa – 90 kDa dextran (Avantor, PA, USA) was spin coated onto a clean glass slide followed by baking at 120 °C for 5 minutes.

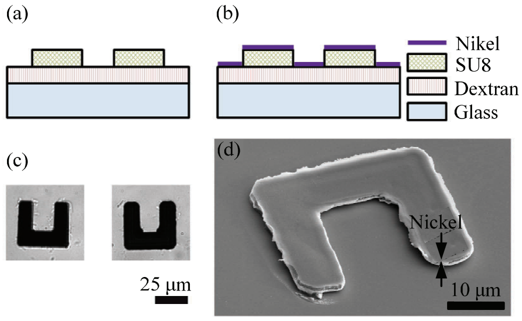

Fig. 1 Manufacturing processes of magnetic microrobots. (a) Microfabrication of the bodies of microrobots; (b) thermal vapor deposition of nickel; (c) released magnetic microrobots with different amounts of nickel (the coating thickness is 300 nm and 600 nm, on the left and right, respectively); (d) SEM image for a nickel coated microrobot.

Next, a 2 μm layer of SU-8 2002 was spun-coated on top of the dextran layer followed by 2 minutes of soft baking at 95 °C. A dark field chrome mask was then used during UV exposure followed by hard baking at 95 °C for 1 minute, after which patterns were developed in propylene glycol monomethyl ether acetate. The substrate was then placed in a thermal evaporator (Thermionics VE-90 thermal evaporator; Port Townsend, WA, USA) where a film of nickel film was deposited as described in Fig. 1b. Nickel pellets (99.995%, Kurt J. Lesker, PA, USA) were evaporated at a rate of 0.1 Å·s^{-1} – 0.5 Å·s^{-1} with a chamber background pressure of 10^{-7} torr. These sequences result in the pattern of microstructures that have nickel metal on the top surface as shown in Fig. 1c. The nickel coating was observed using a field emission scanning electron microscope (FE-SEM, Zeiss Supra 50VP) operated at 1 kV (Fig. 1d).

Magnetization of the nickel film was then performed by placing the substrate overnight underneath a permanent neodymium-iron-boron magnet (K&J Magnetics, Pipersville, PA), with a surface field strength of 160.1 mT. Finally, The magnetized nickel coated magnetic microrobots were then released from the sacrificial dextran layer by gentle agitation in a petri dish channel that was filled motility buffer (0.01 M potassium phosphate, 0.067 M sodium chloride, 10^{-4} M Ethylendediaminetetraacetic Acid (EDTA), 0.01M glucose, pH 7.4) as shown in Fig. 1d. Before magnetized microrobots were used in experiments, those structures were released into a petri dish first. Then, the undamaged magnetic microrobots were transferred, *via* micro pipetting, from the petri dish to a PDMS chamber where experiments were performed.

2.2 Control strategy using externally generated magnetic fields

To control the magnetic microrobot, we designed a 2D magnetic field control system consisting of four electromagnetic coils located on the four sides of the test chamber. The four coils are designated as *x*-*R*, *x*-*L*, *y*-*U*, and *y*-*D*; they are responsible for attracting the microrobots in the $+x$, $-x$, $+y$, and $-y$ directions on the xy plane, respectively. The diagonal directional fields, *i.e.* 45°, 135°, 225°, 315°, were obtained from the resultant magnetic field generated when two individual electromagnetic coils, on x-axis and y-axis, were turned on. The resultant magnetic field can be expressed as: