Microrobots with Programmable Three-Dimensional Magnetizations and Motions

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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Abstract

Flexible magnetic small-scale robots use patterned magnetization to achieve fast transformation into complex three-dimensional (3D) shapes, and thereby achieve locomotion capabilities and functions. These capabilities address current challenges for microrobots such as drug delivery, object manipulation, and minimally invasive procedures. However, possible design options are limited by the existing capabilities of patterning magnetic particles in flexible materials. Here, we report a method for patterning hard magnetic microparticles in an elastomer matrix. This method, based on UV-lithography, uses controlled reorientation of magnetic particles and selective exposure to UV light to encode magnetic particles in planar materials with arbitrary orientation with a geometrical feature size as small as 100 µm. Multiple planar microrobots with arbitrary sizes, geometries, and magnetization profiles can be fabricated from a single precursor in one process. Moreover, a 3D magnetization profile allows higher-order and multi-axis bending, large-angle bending, and combined bending and torsion in one sheet of polymer, creating previously unachievable shape changes and micro-robotic locomotion mechanisms such as multi-arm power grasping and multi-legged crawling. A physics-based model is also presented as a design tool to predict the shape changes under magnetic actuation.
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Chapter 1
Introduction

In this chapter, we will briefly introduce the background, the objectives, and the contributions of this work.

1 Introduction

1.1 Motivation

Microrobots are indispensable tools for microscale challenges and new scientific discoveries. Over the past decades, remarkable progress has been made in many aspects of microrobots. Lower level studies include mobility, localization, biocompatibility, sensing, and other on-board capabilities. Higher level studies focus on robot-human interface, autonomous control, swarm control, and artificial intelligence for robotics. With increasing levels of technology, microrobots are starting to tackle real demands in medicine, especially applications such as biopsy, drug delivery, and minimally invasive procedures. Microrobots, being smaller and smarter over time, will support the future development of precision medicine.

However, there are gaps between future vision and current reality. Many challenges have arisen as the size gets smaller, and the development of microrobots requires major breakthroughs in many disciplines. New power sources, battery technologies, and energy-harvesting schemes need to be studied for the long-lasting operation of mobile microrobots. New smart materials that enable new functionalities need to be explored to address different types of on-site challenges in a surgical procedure. New fabrication schemes are necessary to embody these functional materials in a scalable and repeatable manner. These grand challenges are among the most important topics and research directions in the microrobotics community and may have a significant impact on the future of medical robotics.

This study undertakes the research objective of expanding functionalities and on-board capabilities of flexible magnetic microrobots. For the first time, we present a method to pattern three-dimensional magnetization in planar polymer composites to achieve programmable morphology and therefore sophisticated motions. Fast response, wireless operation, and
programmable shape changes make these materials ideal tools for untethered robotic applications in confined areas.

1.2 Research Objectives

Functionalities of flexible magnetic materials are exploited from the magnetic torque-induced shape changes, and the magnetic torque is a function of the applied magnetic field and the local magnetization of the material. In this work, we propose a new method for patterning three-dimensional magnetization in planar flexible composites. Heterogeneous magnetization enables spatially variant magnetic torques and thus gives rise to complex shape changes to perform previously unachievable motions and functionalities.

The main objectives of the thesis are

- studying state-of-the-art technology for fabricating flexible microrobots in terms of their strength and limitations;
- developing a new method that overcomes the weakness of conventional patterning approaches and achieves 3D patterning capability;
- building a prototype that implements the new method;
- evaluating the geometrical resolution, precise magnetization resolution, and patterning accuracy of the prototype design;
- exploring the new shape changes enabled using this technique; and
- fabricating new types of microrobots that benefit from the new shape changes and demonstrating their unique robotic capabilities.
1.3 Contributions

The major contribution of this work is the development of a new method for patterning three-dimensional magnetization in planar materials. Three-dimensional magnetization induces programmable three-dimensional deformation and new types of motions, which significantly expands the functionalities of untethered magnetic microrobots and untethered end effectors.

In summary, the major contribution of this work to the microrobotics community are as follows:

- Fabricated flexible materials that can exhibit multi-axis bending, higher-order bending, large-angle bending, and combined bending and torsion upon magnetic actuation;
- Designed and built the first prototype system that can pattern three-dimensional magnetization in UV curable composites;
- Developed a simulation model to predict the shape changes of planar flexible materials that bear a three-dimensional magnetization profile;
- Designed and fabricated the first film-shaped undulatory magnetic microswimmer that bears segmented magnetizations, with which the swimmers present varying swimming speed under the same actuating conditions;
- Designed and fabricated shape-configurable untethered magnetic power grasping microgrippers with reduced time and cost;
- Designed and fabricated multi-legged crawling robot that can locomote in a microchannel, which is a new type of micro-robotic locomotion mechanism on a flat surface;
- Designed and fabricated a submillimeter-scale spring-shaped structure that can be controlled using a magnetic field, which can be used as precision optical components; and
- Analyzed the limitations of the proposed method in terms of size and biocompatibility and discussed the steps that need to be taken for the findings to be applied.
Chapter 2
Background

In section 2.1, we will start with common actuation mechanisms for microrobots and discuss the limitations. In section 2.2, we will focus on the advantages of magnetic actuation and discuss the recent developments of magnetic microrobots in terms of size, degrees of freedom, and fabrication schemes. At the end of section 2.2, we will highlight the gaps and establish the originality of the research aims by demonstrating the need for investigations in the topic area. In section 2.3, we will give a brief introduction to this work.

2 Background

2.1 Actuation Mechanisms for Microrobots

Millimeter- and micrometer-scale robots have exciting potential applications in healthcare, bioengineering, and microfactories [1]–[4]. Because microrobots are subject to microscale physics and dynamics, the actuation mechanism differs from traditional large-scale robots; new materials and fabrication schemes have always been the leading factor of novel types of microrobots. Figure 2-1 shows some typical microrobot actuation mechanisms including piezoelectric actuators [5], [6], stimuli-responsive materials [7]–[9], chemical fuel [10], acoustic radiation force driving [11], [12], and optothermal trapping [13], [14]. These mechanisms have been used to design various types of artificial muscles and self-folding structures, demonstrating their utility for high-precision applications despite the compact designs. However, there is a trade-off among response speed, ease of access and control, and available modes of transformation. For example, piezoelectric actuators have high-precision, high-bandwidth performance, but they need to be powered by wires. Materials that are temperature-responsive or pH-responsive often have a slow response to the input stimuli, and they present an over-reliance on the environment. Chemical fuels provide high energy density in a small structure, but it is difficult to stop the reaction or to operate the robot in a controlled manner. Optically triggered microrobots are hard to be implemented to in vivo applications because of the limited penetration depth into animal skins. Unfortunately, untethered microrobots that have programmable deformation and instantaneous response have not been fully achieved. Once developed, these microrobots can be ideal tools for minimally invasive surgeries, bioengineering, and microobject manipulation in enclosed space.
Figure 2-1 Actuation mechanisms of microrobots. (A) Millimeter-scale delta robot using piezoelectric actuators [5]. (B) Microrockets that use chemical fuel [10]. (C) Opto-thermally controlled microbubbles [14]. (D) Chemically triggered grippers [8]. (E) Acoustically triggered microcannons [11].
2.2 Magnetically Actuated Microrobots

2.2.1 Hard-bodied magnetic microrobots

Unlike most other actuator materials, magnetic materials have a fast response to input signals and can be controlled wirelessly to accomplish tasks in confined spaces. Also, safe robot-human interaction and lower cost make them ideal tools for in vivo disease diagnosis and treatment [15]–[17]. To date, most studies focused on rigid magnetic microrobots. Although these robots have no more than five actuated degrees of freedom under a magnetic field, their geometries help convert simple translation and rotation into functional motions for targeted drug delivery [12], [17]–[19], cell culture [20], and assisted fertilization [21]. For example, Figure 2-2(A) shows a helical swimmer that can swim in the liquid using corkscrew motion. In this design, the magnetic field is used for actuation and UV light is used for releasing the drug. However, because these robots are confined by the simple uniform distribution of magnetic moments in a rigid body, they lack abilities to form internal deformation, which are necessary for sophisticated motions such as grasping and crawling. To overcome these limitations, flexible magnetic materials that have programmable morphologies are studied [22].

Figure 2-2 Rigid magnetic microrobots. (A) (B) Helical microswimmers that have light-triggered drug release capability [17]. (B) Three-dimensional porous structures for cell culture [20]. (C) Capture, transport, and release of a single immotile live sperm cell using a helical swimmer [21].
2.2.2 Soft-bodied magnetic microrobots

Programmable morphologies of flexible magnetic materials are realized by patterning magnetic particles in a polymer matrix. The magnetic particles can either be magnetically soft, not retaining their magnetization when an applied field is removed, or magnetically hard, retaining some magnetization. Soft magnetic particles can be synthesized at nanometer level [23] and can be lithographically patterned in hydrogel sheets [24]. Figure 2-3(C) shows hydrogel sheets with reconfigurable self-folding architectures. In these hydrogel sheets, the aligned soft magnetic nanoparticles function as preferred magnetic axes as well as reinforcing components, which can allow thermally-induced and magnetically-induced deformation, respectively. In comparison, hard magnetic particles can be synthesized only at micrometer or larger size, but the remanent magnetization of pre-magnetized particles enables more sophisticated functionalities such as complex locomotion modes [25]–[27], object manipulation and assembly [28]–[30], and fast 3D transformation [31]. Figure 2-3(A), (B), and (D) exhibit some of the capabilities of hard magnet flexible microrobots.

Figure 2-3 Flexible magnetic microrobots. (A) Fast-transforming soft materials that have 3D printed ferromagnetic domains. Hard magnetic particles are used. (B) A small-scale robot with
multimodal locomotion [27]. Hard magnetic particles are used. (C) Lithographically patterned magnetic hydrogel sheets [24]. Soft magnetic particles are used. (D) Six-degree-of-freedom untethered four-arm magnetic microgripper for microobject manipulation [30]. Hard magnetic particles are used.

2.2.3 Magnet Patterning Techniques and Limitations

In these flexible magnetic microrobot designs, people used different patterning techniques (Table 1) to realize the heterogeneous magnetization and thus the independent addressability to different parts with a global actuating magnetic field. Soft magnetic particles have a lower coercivity and can be demagnetized easily, and they are often electrodeposited uniformly on a lithographically fabricated microstructure to impart magnetic actuation capability. Other studies show the pattern of soft magnetic particles in a hydrogel sheet using particle alignment [24], where the magnetic particles are first aligned using an external magnetic field and cured using UV light.

As opposed to soft magnets, patterning hard magnetic particles has been much more common not only in studies of magnetic microrobots but also in data storage. Magnetic storage of audio on a wire was first publicized in 1888, and the usage of commercial hard disk began in 1957. As for microrobots, two major techniques have been used for patterning hard magnetic particles in a soft polymer matrix: template-aided magnetizing and microassembly of magnetic components. Template-aided magnetizing uses a template made of wood or other materials to bend a piece of a magnetic sheet into a pre-designed shape before magnetizing it [25]–[27]. By designing the shape of the template, people can design the magnetization profile of the robot and thus the deformation. However, only continuum 2D magnetization profile can be patterned using this technique, greatly limiting the possible robot designs. In the method that requires manual assembly, many pre-magnetized magnetic components are put together using glue or adhesives to form a structure that has a non-continuum 3D magnetization profile [29], [30], [32]. Using this method people can fabricate microrobots with much more complex motions such as grasping, but the cost and difficulty rise dramatically in association with size, number of parts, and magnetization complexity. Alternatively, Y. Kim et al. present a new patterning method that can print programmable 2D ferromagnetic domains in a 3D structure [31]. This new method opens up many possibilities for designing 3D magnetically-actuated microrobots, but the ability to pattern arbitrary 3D magnetization is still lacking, which can enable large-angle deflection (greater than 90°) or combined bending and torsion in one piece of polymer. Therefore, we undertake the research of developing a new method to pattern 3D magnetizations in planar materials.
### Table 1 Capabilities of major existing methods to pattern magnetic particles

<table>
<thead>
<tr>
<th>Method</th>
<th>Magnet type</th>
<th>Shape of media</th>
<th>States of magnetization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic particle coating [33][20][21]</td>
<td>Soft</td>
<td>3D</td>
<td>N/A</td>
</tr>
<tr>
<td>Other additive manufacturing methods [34][35]</td>
<td>Soft</td>
<td>3D</td>
<td>N/A</td>
</tr>
<tr>
<td>Lithographic patterning of magnetic nanoparticles [24]</td>
<td>Soft</td>
<td>2D</td>
<td>Discrete, 3D*</td>
</tr>
<tr>
<td>Magnetic recording technology† [36]</td>
<td>Hard</td>
<td>2D</td>
<td>Discrete, 1D‡</td>
</tr>
<tr>
<td>Template-aided magnetizing [25][26][27]</td>
<td>Hard</td>
<td>2D</td>
<td>Continuum, 2D</td>
</tr>
<tr>
<td>Microassembly of magnetic components [29][30][32]</td>
<td>Hard</td>
<td>3D</td>
<td>Discrete, 3D</td>
</tr>
<tr>
<td>3D printing of ferromagnetic domains [31]</td>
<td>Hard</td>
<td>3D</td>
<td>Discrete, 2D</td>
</tr>
<tr>
<td>This work</td>
<td>Hard</td>
<td>2D</td>
<td>Discrete, 3D</td>
</tr>
</tbody>
</table>

* For soft magnets, we use 3D to refer to the direction of magnetic axis patterned instead of the direction of local magnetization.
† Mainly used for hard disk drives, tapes, credit cards.
‡ Most HDDs use longitudinal recording or perpendicular recording, presenting two magnetic states (1D).

### 2.3 Brief Introduction to This Work

Here, we report a UV-lithography-based method to encode 3D magnetization in planar flexible composites. In this method, we precisely reorient pre-magnetized permanent magnetic particles and then selectively cure UV resin to pattern the local magnetization. Multiple microrobots that have different geometries and 3D magnetization profiles can be fabricated from the same precursor in a single process. We achieve the geometrical feature size as small as 100 µm × 100 µm and the precise magnetization feature size as small as 250 µm × 250 µm on a 100 µm thick UV resin layer.

We fabricate millimeter-scale structures that exhibit higher-order and multi-axis deformation, large-angle bending, or combined torsion and bending. We also present new robotic capabilities enabled by this technique and provide models to predict the shape changes.
Chapter 3
Method

In section 3.1, we will show the basic formulas that relate the magnetic forces and torques with respect to the actuating magnetic field and the magnetization of a robot. These formulas show why it is important for magnetic microrobots to have 3D magnetization profiles to achieve a variety of programmable deformations. We will also describe the basic concept of the UV-lithography-based method (hereinafter called the new method). In section 3.2, 3.3, and 3.4, we will discuss the material used in the method, the physical apparatus we designed, and the fabrication procedure. In section 3.5 and 3.6, we will provide some detailed characterizations of the proposed physical apparatus.

3 Method and System Characterization

3.1 Basic Concept

Magnetic microrobots are controlled using magnetic torques and forces. Magnetic torques and magnetic forces can be expressed as a function of the magnetic moment $\vec{m}$ of the body and the magnetic field $\vec{H}$ generated by an electromagnetic coil system or a permanent magnet,

$$\vec{\tau} = \vec{m} \times \vec{H}, \quad (3.1)$$

$$\vec{F} = \nabla(\vec{m} \cdot \vec{H}). \quad (3.2)$$

In general, most rigid magnetic materials have a uniform magnetization, so the whole body is subject to a universal force and torque, resulting in pure translation or rotation. On the other hand, by patterning magnetic particles, flexible materials can develop an inhomogeneous distribution of magnetization. This makes it possible to apply different local torques and forces at different positions and thus independently address different parts of the body. For untethered magnetic microrobots, continuum 2D magnetization profile allows pure bending in one plane, discrete 2D magnetizations allow higher-order bending, and discrete 3D magnetizations allow large-angle bending and combined bending and torsion.

In this new method, we mix pre-magnetized magnetic particles with UV resin. The magnetic slurry is loaded on a custom patterning system we designed. We first apply a magnetic
field to reorient the magnetic particles that are integrated into a UV-curable elastomer matrix and then cure regions of the polymers with UV light. UV light initiates polymerization in the regions exposed, and selectively freezes the orientation of the magnetic particles within it. By optionally repeating the above-mentioned procedure, we can pattern the magnetization profile of the whole material, each of which has a unique local magnetization direction.
3.2 Materials

Permanent magnetic particles that have an average diameter of 5 µm (MQFP-15-7, NdFeB, Magnequench) were pre-magnetized in a 1.1 T uniform magnetic field generated by two N52 one-inch permanent magnets. Acquiring saturation remanence, the magnetic particles were mixed sufficiently with UV resin (DLP/SLA 3D Printer UV Resin, Flexible Type, GC3D-EBE) in a mass ratio of 1:1 to form a homogeneous magnetic slurry. The magnetic slurry is placed in a vacuum degassing chamber for 1 min to remove the bubbles. Then the magnetic slurry is loaded into a negative SU8 mold (6 mm × 6 mm × 0.1 mm) prepared using photolithography. The thickness of the SU8 photoresist layer determines the thickness of the final product. The magnetic slurry is covered by a No.1 microscope coverslip (22 mm × 22 mm × 0.15 mm) and the substrate is mounted to the center of the fabrication stage. Figure 3-1 shows the schematic diagram of materials preparation.

Figure 3-1 Schematic diagram of materials preparation. (A) Mixing pre-magnetized particles with UV resin. (B) Filling the magnetic slurry in the SU8 mold.
3.3 Physical Apparatus

3.3.1 Hardware Design

Figure 3-2 shows the physical apparatus for patterning the magnetic particles in the UV resin. The apparatus consists of a DLP-based (Digital Light Processing) lithography system and a magnetic field generator.

The DLP-based lithography system comprises a UV DLP projector (Texas Instruments DLP Lightcrafter 4500, modified with a 405 nm light engine), a plano-convex lens (N-BK7, Ø50.8 mm, f = 75.0 mm, Thorlabs), two cube-mounted non-polarizing beamsplitters, a Nikon 10x/0.30A microscope objective lens, and a vertical precision stage. A CMOS camera is installed above the beamsplitter, vertically aligned with the objective lens and the fabrication stage for focus adjustment. With a digital micromirror array in the DLP projector serving as a photomask, the binary image from the projector aperture passes through the plano-convex lens and the objective lens, forming a demagnified image in the workspace (approximately 6 mm × 6 mm) on the object plane. The height of the fabrication stage can be adjusted by the vertical precision knob to bring the object image into focus.

The magnetic field generator comprises an N52 one-inch permanent magnet, two stepper motors, and a 3-axis magnetic field sensor (TLV493D-A1B6, DigiKey). The permanent magnet is held by the stepper motors in a way that the azimuthal and polar angles can be controlled independently while the center of the magnet is fixed. The permanent magnet is placed 4.5 cm under the fabrication stage so that it generates an 80 - 160 mT magnetic flux density in the workspace area, depending on the magnet orientation. We assume that the direction and the strength of the magnetic field in this area is nearly uniform. Based on the magnetic dipole model and the feedback data from the 3-axis magnetic field sensor, we can generate a magnetic field to reorient the pre-magnetized particles in the slurry and bring them into alignment with any 3D direction. Alternatively, an electromagnetic coil system can be substituted for the permanent magnet design for better uniformity and controllability, but custom coil designs are necessary because the magnetic field strength required to reorient the particles is beyond the capacity of common electromagnetic coil systems [37].
Figure 3-2 Schematic diagram of the physical apparatus.

Figure 3-3 Image of the physical apparatus.
3.3.2 Signal Flow and Hardware Control

The DLP-based lithography system and the magnetic field generator are integrated and controlled by a computer to enable automated fabrication. Figure 3-4 shows the signal flow and hardware control. First, the computer sends the desired field direction to Raspberry Pi. Based on the distribution of magnetic flux around a permanent magnet, Raspberry Pi converts the field direction angle to the angle values of the two stepper motors. Once the shafts of the two motors are driven to the targeted position, Raspberry Pi reads the field angle value from the magnetic field sensor and compensate for the errors. This is repeated until the error of the field angle measured by the sensor is within the tolerance of 1°. When the field generation is finished, Raspberry Pi sends a command back to the computer to indicate the completion of field generation, and to start curing the polymer with UV light. The program determines the curing region, the intensity of UV light, and the time of exposure to UV light. When the curing is done, the computer sends a new command to Raspberry Pi to indicate the second magnetic field direction. The whole process is optionally repeated until the completion of the whole device.

![Schematic diagram showing the signal flow and the hardware control. Black blocks and lines are controllers and commands, blue blocks and lines are hardware, and red blocks and lines are processes on the sample.](image)
3.4 Fabrication procedure

The substrate is placed at the center of the fabrication stage, vertically aligned with the objective lens and the magnetic field sensor. Patterning of local magnetization involves two steps: reorientation of included magnetic particles and selective curing of UV resin. First, the stepper motors orient the permanent magnet to generate the desired magnetic field, which reorient all the pre-magnetized magnetic particles in the magnetic slurry. After allowing 2 min for particle reorientation, UV light shines on selected regions of the magnetic slurry, initiating polymerization and freezing the magnetic particles within that area. The two steps are repeated optionally until all the regions are patterned and cured properly. For example, Figure 3-5 shows the fabrication procedure of the “accordion” structure presented in Figure 4-2.

Figure 3-5 Sequence diagram of the fabrication procedure of an “accordion”.
3.5 Characterization of the Geometrical Resolution

We used a UV-Spiricon Ophir (BGP-USB-SP928-OSI) camera to determine the geometrical resolution of the focused beam at object plane. We used the 10/90 edge-steepness metric to calculate the geometrical resolution of the laser beam. The geometrical resolution of the beam is defined as the half-power width of the beam when the width of the rising edge is 10% of the half-power beam width. According to the beam profiles of a series of squares in Figure 3-6, the geometrical resolution of the UV-lithography system is approximately 100 μm. The intensity profiles of other irregular shapes are shown in Figure 3-7.

![Figure 3-6 Intensity profile of squares on the object plane measured using a beam profiler. Side length of the squares are (A) 3 mm (B) 1.5 mm (C) 0.75 mm (D) 0.4 mm (E) 0.75 mm (F) 0.1 mm.](image)

![Figure 3-7 Intensity profile of other shapes on the object plane measured using a beam profiler.](image)
3.6 Characterization of Developed Magnetization

Accurate patterning of the magnetization profile determines the performance of a flexible magnetic microrobot. In this patterning method, the developed magnetization is closely related to the magnetic field applied to reorient the particles. The process can be modeled as a black box system that takes the magnitude and the direction of the applied magnetic field when curing as the system input and takes the magnitude and the direction of the developed magnetization as the system output. In section 3.6.1 and 3.6.2, we will run two sets of experiments to find out the transfer characteristics of the black box system.

3.6.1 Magnitude of Developed Magnetization

The preparation of materials is described in section 3.2. The prepared magnetic slurry was filled into a $5 \times 5 \times 0.7$ mm acrylic mold and covered by a microscope coverslip to avoid spilling. To generate different magnetic fields to rotate the particles, two 0.75-inch N40 permanent magnets were placed $d$ mm apart with opposite poles facing each other. We selected $d = 100$ mm, 80 mm, 60 mm, 50 mm, and 45 mm, which generates a magnetic flux density of 13 mT, 22.5 mT, 45 mT, 65 mT, and 80 mT, respectively. Each sample was left at rest between the two magnets for 2 minutes for particle reorientation. Then the samples were exposed to uniform UV light (405 nm, 1.67mW/cm²) for 1 min, which initiated polymerization of the materials and froze the orientation of the particles within it. A magneto-optical sensor (Magview-S, Matesy GmbH) is used to measure the magnetic flux distribution at the surfaces of the cured samples. The data collected were fitted to a theoretical model (Figure 5-1) to estimate the magnitude of magnetization.

Three samples with maximum remanent magnetization were prepared by direct exposure to a 1.1 T magnetic field to obtain saturation remanence (group A). Figure 3-8(A) shows the raw data obtained from one of the samples. The average magnetization value of the three samples is 40.059 kA/m. Five samples were prepared by the orientation of magnetic particles before curing (group B). Figure 3-8(B) shows the normal component of the magnetic flux density of all five samples in group B. It is obvious that a stronger external magnetic field leads to a steeper positive and negative peak at $x = 0$ and $x = 5$ mm, suggesting a stronger development of magnetization. The red solid line is a reference for the average magnetization magnitude of samples in group A. Based on the analysis of the data, it is considered at least 80 mT is required for developing a magnetization strength that is comparable to the saturation remanence.
Figure 3-8 Distribution of magnetic flux at the near surface of the samples. (A) The sample that obtains maximum remanent magnetization. Magnetization direction: normal to the sensor. (B) Samples that developed magnetization under different field strength. Magnetization direction: parallel to the sensor.
3.6.2 Direction of Developed Magnetization

A permanent magnet-based field generating system was built (Figure 3-9(A)). This system is a simplified version of the physical apparatus described in section 3.3, so they share a similar hardware schematic and working routine. This configuration generates a magnetic flux density ranging from 80 mT to 160 mT depending on the magnet orientation.

The preparation of materials is described in 3.2. A sample was made by filling a 60-µm thick SU-8 mold with the magnetic slurry and covering it with a microscope coverslip. Each sample was placed at the center of the fabrication stage, exposed to the field generated by the permanent magnet. Since the near-equilibrium magnetic torque is weak, we applied to the magnet a tiny oscillation with linear amplitude decay to accelerate the rotation of magnetic dipoles in the slurry before curing. In this experiment, we collected 6 samples for each magnetic field angle ($\theta_H = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \text{ and } 90^\circ$) to reduce random error. To measure the direction of magnetization, each sample was extracted from the mold and mounted on the wall of an acrylic raft that can rotate freely on the water surface (Figure 3-9 (B)). The magnetization angle was measured by reading the angle formed by the wall of the raft and the external magnetic field in a top view camera (Figure 3-9 (C)).

**Figure 3-9 Experimental setup.** (A) Schematic of the permanent magnet-based magnetic field generating system. (B) Close-up image of the sample mounted on an acrylic raft. Scale bar is 4 mm. (C) Schematic showing the raft floating on the surface of the water in a petri dish. The magnetization angle equals to the angle between the wall of the raft and the horizontal dashed line.
Figure 3-10 shows the relationship between the measured magnetization angle $\theta_M$ and the direction of the external magnetic field $\theta_H$ in which the samples were cured. Regardless of initial conditions, the direction of induced magnetization shows a good agreement with the field direction when $\theta_H$ is within $0^\circ$ to $15^\circ$. $\theta_M$ starts to fall behind the field angle by $10^\circ$ when $\theta_H$ is $30^\circ$, and the gap becomes even larger by $10^\circ$ to $20^\circ$ when $\theta_H$ is $45^\circ$ to $90^\circ$. For each angle $\theta_H$, the initial conditions also slightly influence the angle of the developed magnetization, but it is reasonable to expect that the difference can be eliminated if longer time was allowed for magnetic particle alignment.

The trend of the data can be explained by the demagnetizing field acting on the magnetic dipoles. When an external magnetic field is applied, magnetic particles try to reach a new equilibrium state by realignment. However, the demagnetizing field of the material cancels the external magnetic field, which slows down the orientation process. Besides, the remanent magnetization of magnetic particles causes the unfavorable formation of magnet chains in the material. This may require extra energy for the particles to break the chains and realign themselves with the externally applied magnetic field.

![Figure 3-10](image)

**Figure 3-10 Relationship between the direction of developed magnetization and the direction of the external magnetic field applied when curing.** Samples were fabricated for two different initial conditions.
Chapter 4
Results

In this chapter, we will present various types of magnetic actuators that we fabricated using the method described in chapter 3. In section 4.1, we will present some basic shape changes that we can achieve using the new patterning technique. Simulations models will be given to help predict the deformation based on the magnetization and the geometry. In section 4.2 through 4.5, we will show some specific designs that have robotic capabilities.

4 Results
4.1 Basic Shape Changes

Planar soft materials that have non-continuum 3D magnetization can transform into pre-designed 3D shapes upon the application of a uniform magnetic field and return to the original shape as soon as the field is removed. Figure 4-1 and Figure 4-2 show the original states, actuating states, and schematic designs of different types of planar structures. Most of them are patterned in a symmetric or centrosymmetric manner so that the net magnetization is in alignment with the external magnetic field during actuation, resulting in internal deformation rather than the rigid body rotation. As a general design rule, bending requires varying magnetizations in the neutral axis plane (Figure 4-2(B), (C)), while torsion requires magnetizations perpendicular to the neutral axis (Figure 4-2(E)). Structures that contain both parallel and normal components to the neutral axis yields a combined bending and torsion (Figure 4-2(F)). Furthermore, advanced torque-induced deformation can be achieved by combing these design rules together. Higher-order bending (undulatory bending) is realized by alternating magnetization segments that generate pairs of counteracting magnetic torques (Figure 4-2(A), (D)). Large-angle (greater than 90°) deflection is realized by the non-continuum transitions of magnetization angles in the plane of bending (Figure 4-2(G)). By having multiple large-angle deflection structures, planar polymers can fold up to form a hollow sphere in the center (Figure 4-2(H)-(J)). In Figure 4-3, we provide simulation models to predict the shape changes. In Figure 4-4, we show the capability to have different morphology for the same tri-arm structure by modifying the patterning angle. The capability to pattern arbitrary 3D magnetization in arbitrary geometries allow highly deformable millimeter-scale structures under a magnetic field of 20 mT, which is readily available in a general electromagnetic coil system.
Figure 4-1 Magnetizations and dimensions of the devices fabricated. Unit in mm. (A) accordion (B) stool (C) ring – 2 bumps (D) ring – 3 bumps (E) twisting (F) swimmer (G) fan (H) six-arm gripper (I) centipede type A (J) centipede type B (K) zigzag spring.
Figure 4-2 Flexible magnetic planar structures that have non-continuum 3D magnetization profiles. Yellow arrows represent the direction of local magnetizations and green arrows represent the direction of the actuating magnetic field. The materials are approximately 100 µm thick. The actuating field is 200 mT for item (A) and less than 20 mT for all the others. All the items present reversible and rapid transformation between the original shape and the folding shape. Scale bars, 2 mm.
Figure 4-3 Models for predicting the shape changes. (A) Side view images showing large-angle deflection under 20 mT. (B) Numerical model of the large-angle deflection. (C) Side view images showing undulatory bending of a ring under 20 mT. (D) Simulation of the ring using the finite element method.

Figure 4-4 Capabilities to tune the patterning angle in the material. (A) Geometry, dimension, and the magnetization profile of the tri-arm structure. Unit, mm. (B) Top view images showing the combined bending and torsion of the tri-arm structures. Actuated under 20 mT.
4.2 Speed-Tunable Segmented Magnetic Swimmer

Magnetic microscale swimmers make use of corkscrew motion [38], beating flagellar motion [39], [40], and traveling wave undulatory motion [25] for propulsion. Magnetic undulatory swimmers benefit from a simple structure, but the shape of the traveling wave in previous work cannot be tuned due to the continuous distribution of magnetization developed by template-aided magnetizing [25], [41]. Using the new patterning technique in this work, we present undulatory swimmers that have the same size and volume magnetization but the arbitrary magnetic pattern, resulting in different shape changes and swimming speeds under a rotating magnetic field. This arbitrary patterning method thus can serve as a versatile fabrication tool for optimized designs with tunable performance.

Figure 4-5(A), Figure 4-5(D), and Table 2 show the designs of three types of swimmers fabricated from the same precursor. The swimming speed of each swimmer design on the water surface (6 samples per design) was measured under different field strength and rotating frequencies (Figure 4-5(C)). The theoretical swimming speed of each design is characterized using Traveling Wave Component (TWC) analysis [41], a method to evaluate the time-integral propulsive forces and the swimming speed of film-shaped undulatory swimmers. A detailed analysis is provided in Fig. S1- Fig. S3. Figure 4-5(B), the blue dots represent the theoretical deflection amplitude of the swimmers at each phase angle, and the size of the equivalent circle serves as an indicator of the amplitude of the traveling wave and thus can serve as a heuristic for propulsive force of the swimmer in one period. The measured data show a similar tendency as the TWC analysis; type 1 design has an equivalent circle radius of 0.222 mm and thus the fastest swimming speed, followed by type 2 and type 3 design. In addition, the swimmers present high controllability in a coil system. Figure 4-5(E) shows a swimmer following an M-shaped path using a closed-loop vision feedback. The swimmer was actuated in a 9 mT rotating field at 20 Hz, presenting an average velocity of 3.38 mm/s (78.6% body length) and the maximum deviation of 0.2 mm (4.65 % body length).

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (mm)</th>
<th>L1: L2: L3</th>
<th>Equivalent circle radius (mm)</th>
<th>Normalized equivalent circle radius R$_{nor}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
<td>0.1125:0.3:0.175</td>
<td>0.2218</td>
<td>0.0493</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>0.15:0.225:0.25</td>
<td>0.1661</td>
<td>0.0369</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>0.1875:0.155:0.325</td>
<td>0.1199</td>
<td>0.0266</td>
</tr>
</tbody>
</table>
Figure 4-5 Millimeter-scale segmented magnetic swimmer. (A) Magnetization profiles of three types of swimmers, denoted by black arrows. (B) TWC analysis of the swimmers. Blue markers represent the deformation at each phase, while the yellow dashed line represents the equivalent deformation circle in one period. (C) Swimming speed of the swimmers under different conditions. Solid triangles denote the average of six samples and error bars denote their deviations. (D) Segmented swimmers fabricated from the same precursor in one process. Scale bar, 1 mm. (E) Path following of a magnetic swimmer. (F) Path following error of a magnetic swimmer.
4.3 Untethered Multi-Arm Magnetic Gripper

Grasping capability is among the most useful motions of microrobots, and the magnetically-actuated grippers have the advantages of being untethered and responsive. However, existing power grasping magnetic grippers can be fabricated only by manual assembly of magnetic components, which poses a great challenge to scaling and batch fabrication. Using the new method presented in this work, we achieve one-process fabrication of magnetic microgrippers that have configurable number of arms to target various cargos types. Figure 4-6(A) shows the design of a magnetically actuated six-degree-of-freedom microgripper. Here, six actuated degrees of freedom refers to translation in three dimensions, pitch, yaw, and grasping motion. The microgripper consists of a base part that provides net magnetization of the device and multiple numbers of arms that form a bore in the center when a magnetic field is applied. Tiny hinges are fabricated between the magnetic blocks so that the arms can bend along them. Once the arms are folded, the gripper can be modeled as a ball that has a net magnetization along the opening, so it can locomote using rolling motion or pulling force generated by magnetic gradients.

Figure 4-6 Design and concept of untethered six-arm magnetic microgripper. (A) Geometry, magnetization profile, and working mechanism of a magnetic microgripper. Black arrows represent the direction of the magnetic moment in each magnetic part, while blue arrows represent the actuating magnetic field. (B) Illustration of the cargo transportation task.

Using controllable motion enabled by the design, multi-arm microgrippers can transport cargos in fluid environments. Here, we present the teleoperation of a microgripper using a joystick controller. Figure 4-7(C) shows the transportation of a green triangular prism-shaped PDMS cargo onto a 15° slope which simulates the terrain height of real cargo transporting tasks. The cargo and the gripper began lying prone on the ground in silicone oil. Then the gripper folded up and rolled toward the cargo under a rotating magnetic field. Because of the surface-to-surface contact
between the cargo and the ground, it was impossible for the gripper to slide its tips under the cargo; instead, the cargo was picked up using the pure pinching force of the tips. Then the cargo was turned upside down and enclosed by the arms for secure grasping. Once the gripper reached the target position, the cargo was released by slowly applying a magnetic field in the opposite direction. Finally, the gripper rolled to the home position for the next pick-and-place task.

Figure 4-7 Top view and side view images of the cargo transportation task. Scale bar, 5 mm.

Compared with past gripper designs that used hybrid materials and requires two different actuation inputs (for example, magnetic actuation plus thermally-triggered grasping motion or pH-induced grasping motion), this untethered magnetic microgripper design has a distinct advantage: instantaneous response and not relying on the working environment. Also, unlike the previous fabrication process in [30], with the new method, we can easily configure the number of arms without considerably increasing the fabrication time (Table 3 and Table 4). It takes less than 15 minutes to fabricate one six-arm magnetic gripper, compared with several hours using the previous method because of the manual assembly process. The UV-lithography-based method also makes it easier to modify the geometry of the device, for example, the shape of the tips and the dimension of the hinges, to target cargos that have different shapes. Figure 4-8 shows three types of microgrippers under different magnetic fields.
Figure 4-8 Untethered grippers with configurable number of arms. Scale bar, 2 mm.

Table 3  Time required to fabricate a four-arm gripper using the conventional method

<table>
<thead>
<tr>
<th>Step</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fabricating a photomask (one time)</td>
<td>2</td>
</tr>
<tr>
<td>preparing SU8 mold using photolithography (one time)</td>
<td>2</td>
</tr>
<tr>
<td>mixing the polymer with particles and waiting for curing</td>
<td>3</td>
</tr>
<tr>
<td>magnetizing each polymer block in the desired direction and placing them in the SU8 mold for microassembly</td>
<td>1</td>
</tr>
<tr>
<td>casting Ecoflex in the SU8 mold and waiting for curing</td>
<td>3</td>
</tr>
<tr>
<td>extracting the final device from the mold with tweezers under a microscope</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>4 + 8n *</td>
</tr>
</tbody>
</table>

* n equals to the number of grippers that needs to be fabricated

Table 4 Time required to fabricate a four-arm gripper using the new method

<table>
<thead>
<tr>
<th>Step</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fabricating a photomask (one time)</td>
<td>2</td>
</tr>
<tr>
<td>preparing SU8 mold using photolithography (one time)</td>
<td>2</td>
</tr>
<tr>
<td>magnetizing ferromagnetic particles and mixing them with UV resins</td>
<td>0.15</td>
</tr>
<tr>
<td>filling the SU8 mold with magnetic slurry and running fabrication program</td>
<td>0.15</td>
</tr>
<tr>
<td>Total</td>
<td>4 + 0.3n *</td>
</tr>
</tbody>
</table>

* n equals to the number of grippers that needs to be fabricated. Actual time can be shortened if multiple microgrippers are fabricated because they can be patterned in parallel.
4.4 Multi-Legged Crawling Robot

For small-scale robots, walking on a 2D surface requires breaking strong surface adhesion using techniques such as periodical vibration [42] or stick-slip-based motion [37]. Here, we propose a new locomotion mechanism realized by the higher-order deformation of the legs of the robot. By alternatingly patterning the magnetizations of the legs, we can program the phase variation and thus the walking gaits.

Figure 4-9 shows the design and the gait graph of an eight-legged crawling robot. Legs G1 or G2 come into contact with the ground in turn, and the static friction during power stroke periods pushes the robot forward or backward depending on the rotating direction of the magnetic field. Figure 4-11(A) shows the mechanism for the robot to change its heading. When we apply a horizontal magnetic field along the primary axis of the robot, it develops a deflection-induced net magnetization; with an oscillating vertical magnetic field breaking the surface adhesive forces, the robot can be steered slowly by sweeping the horizontal magnetic field. Figure 4-10 shows the crawling speed of a 4.5-mm-long robot under a 2 Hz rotating magnetic field. The robot has an average stride length of 0.13 mm, 0.19 mm, 0.28 mm, and 0.42 mm at 3 mT, 4 mT, 5 mT, and 7 mT, respectively. Using this crawling motion, we can achieve controlled locomotion in tiny areas, such as a channel that has a cross section of 4.70 mm × 1.0 mm (Figure 4-11(B) and (C)).

Figure 4-9 Gait diagram and actuation scheme of the multi-legged crawling robot. (A) Magnetization profile of the robot. (B) Gait graph of the robot. (C) Sequence diagram of the gait.
Figure 4-10 Walking speed of a multi-legged gait under different field strength. The multi-legged gait is actuated under a rotating magnetic field at 2 Hz.

Figure 4-11 Turning and controlling in a simulated surgical terrain. (A) Magnetic field applied to change the heading. (B) Illustration of the maze. The cross section of the channel is 4.7 mm × 1.0 mm. (C) Top view images of the maze demo. Scale bar, 4 mm.
4.5 Laser-Steering Magnetic Mirror Mount

UV curing allows direct printing of intricate features or tiny joints on a substrate without assembly process. With these tiny joints and patterned magnetizations, we can fabricate untethered compact devices that have controllable minimal elastic deformations. Here, we show a two-degree-of-freedom magnetic mirror mount that achieves high precision without complex sensing or control.

Figure 4-12(A) and Figure 4-12(C) show the design of an untethered mirror mount in a coil system. The structure comprises a central stage for the mirror and four spring joints connected to the base. The tilting angle of the mirror can be controlled using a horizontal magnetic field, and it turns to the original position when the field is removed. To demonstrate the repeatability and accuracy, we performed a trajectory following experiment with the reflection of a laser beam using an open-loop control (Figure 4-12(B)). The reflected laser fell on a 20 mm × 20 mm region on the laser viewing card, and the position of the reflected laser was controlled using bilinear interpolation of the magnetic field in the region of interest. In Figure 4-13, we generated a time-varying magnetic field to draw a T trajectory and a star trajectory on the laser viewing card at 0.5 Hz and 0.2 Hz, respectively. The RMS accuracy (deviation from the desired trajectory) and the RMS precision (deviation from the mean trajectory) are summarized in Table 5. At frequencies higher than 0.5 Hz, the deviation from the desired trajectory becomes larger because of the momentum of the mirror.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Frequency (Hz)</th>
<th>Path length (mm)</th>
<th>RMS accuracy (mm)</th>
<th>RMS precision (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>0.02</td>
<td>61</td>
<td>1.78 ± 2.46</td>
<td>0.10 ± 0.14</td>
</tr>
<tr>
<td>T</td>
<td>0.5</td>
<td>61</td>
<td>1.76 ± 2.42</td>
<td>0.10 ± 0.13</td>
</tr>
<tr>
<td>Star</td>
<td>0.02</td>
<td>72</td>
<td>1.72 ± 2.60</td>
<td>0.08 ± 0.11</td>
</tr>
<tr>
<td>Star</td>
<td>0.2</td>
<td>72</td>
<td>1.73 ± 2.49</td>
<td>0.62 ± 0.79</td>
</tr>
</tbody>
</table>
Figure 4-12 Magnetically controlled laser steering mirror mount. (A) Close-up image of the mirror mount with a tiny mirror mounted at the center. (B) Schematic representation of the laser steering experimental setup. (C) Coil system used in the experiment [43].

Figure 4-13 Target trajectories (orange) and experimental trajectories (blue) of the laser. The T-shaped and star-shaped trajectories are tracked at 0.5 and 0.2 Hz, respectively.
Chapter 5
Discussions

In chapter 5, we will verify the patterning accuracy of the magnetization angle, outline the limitations of our methods, and discuss the biocompatibility of the devices fabricated.

5 Discussions

5.1 Verification of Patterning Accuracy

The performance of a soft-bodied magnetic actuator depends on the precise patterning of magnetic particles. For example, the microgripper design in this paper requires 90° in the base block, -30° in the arm blocks, and -60° in the tip blocks to function properly. Here, we evaluate the patterning accuracy by viewing the distribution of the magnetic flux at sample surfaces using a magneto-optical sensor (Magview-S, Matesy GmbH). The measured data are compared with a magnetic dipole array-based model, in which we assume that the magnetic moment density in the material is uniform.

5.1.1 Magnetic Dipole Array Model

The external magnetic flux distribution generated by a magnetic dipole moment is given by

\[
\vec{B} = \frac{\mu_0}{4\pi r^3} \left( \frac{3\vec{r}(\vec{m} \cdot \vec{r})}{r^2} - \vec{m} \right),
\]

(5.1)

where \(\mu_0\) is the permeability of free space, \(\vec{r}\) is the vector from the center of the dipole to the point in the space, and \(\vec{m}\) is the magnetic moment of the dipole. When we compute the distribution of magnetic flux at the near surface of a sample, we conceptually divide the sample into many tiny elements, each of which is represented by a magnetic dipole (Figure 5-1). By this means, the magnetic flux density at any point of the measuring surface can be estimated by the sum of the magnetic flux density generated by all the magnetic dipoles

\[
\vec{B}(x, y, z) = \sum_{x_d=x_0}^{x_d} \sum_{y_d=y_0}^{y_d} \sum_{z_d=z_0}^{z_d} \vec{B}(x_d, y_d, z_d),
\]

(5.2)
where i, j, and k are the number of elements in x, y, and z-axis, respectively.

Figure 5-1 Schematic diagram of the magnetic dipole array model. The magnetic flux density at any point in the measurement plane can be calculated by adding up the magnetic flux generated by all the elements, each of which is modeled using a magnetic dipole array model.

5.1.2 Near Surface Distribution of Magnetic Flux

Figure 5-2 shows the normal component of the magnetic flux 60 µm away from the sample surfaces. In Figure 5-2(A)-(C), the measured magnetic flux density curves show good agreements with the model, demonstrating the capability to pattern the angle of magnetizations in planar materials. In Figure 5-2(E) and (F), we magnetically encoded a QR code to a 5 mm × 5 mm region on a piece of polymer. It shows that the magnetization feature size of 250 µm can be achieved using this technique, with clearly defined boundaries and sharp edges. The measured and the calculated magnetic flux distribution are in good agreement with each other, showing that the magnetization angles can be pattern precisely on the scale of as small as 250 µm × 250 µm.
Figure 5-2 Distribution of magnetic flux at the near surface of different samples. Modeled magnetic flux distribution, measured magnetic flux distribution, and the fitting results along the black dashed line of (A) a six-arm magnetic microgripper (front), (B) a six-arm magnetic microgripper (back), (C) an accordion, and (D) a multi-legged crawling robot. The data are collected 60 μm away from the sample surfaces. The magnitude of magnetization in the model is fitted to that in the measured data using least squares fitting. (E) A piece of thin material that carries the QR code encoded “UofT”. Scale bar, 2 mm. (F) Magnetic flux measured at the surface of the QR code sample.
5.2 Limitations on the Feature Size

Typical stereolithography-based printing can achieve a feature size of several micrometers, but the theoretical feature size in the magnetic patterning method presented in this work is limited by the size of the included permanent magnetic particles. The assumption of homogeneous magnetic moment density does not hold if the size of individual magnetization area is on the same scale as the particles; in addition, because the particle size imposes a limit to the thickness of the fabricated product, the microrobots cannot be scaled down arbitrarily small even if the assumption is valid. Therefore, we expect the smallest possible magnetization feature size to be no less than 50 μm, which is one order of magnitude larger than the diameter of permanent magnetic particles.

The layer thickness also has an upper limit because the magnetic slurry used in this method is opaque to UV light. It imposes an upper limit to the thickness of the layer that can be cured in one process, which is estimated to be less than 1 mm in practice. Besides, the thickness should ideally smaller than the feature size, because a high aspect ratio structure is not preferred in stereolithography.

5.3 Biocompatibility

Biocompatibility is also a critical factor for successful application in biomedical use. In this work, the NdFeB permanent magnetic particles are used for magnetic actuation, but permanent magnetic particles are not biocompatible because of the presence of heavy metal. Once the permanent magnetic particles are directly in contact with human body, the harmful heavy metal elements might affect the normal function of the body. Therefore, we propose three ways to reduce the potential harm of the microrobots. First, we use Ecoflex-10, one type of biocompatible flexible polymer, to encase the magnetic particles so that they are not in direct contact with the environment to harm biological tissue. Ecoflex-10 has a very low stiffness, so it does not significantly increase the stiffness of the overall structure. In addition, the patterning technique is transferable to most UV curing polymers, so different encasement materials can be chosen according to the temperature and acidity of the working environment. Second, other permanent magnetic particles can be substituted for NdFeB to reduce heavy metal toxicity. Typical magnetic particles include samarium cobalt and ferrite permanent magnetic particles, which are not as magnetically strong as NdFeB but are considered safer. Lastly, typical use of small-scale robots requires removal from the human body upon completion of their tasks to minimize the harm.
Chapter 6
Conclusions and Future Work

In this chapter, we conclude the results and the contributions of this work. We will also discuss the future steps for the research outcome to be implemented.

6 Conclusions and Future Work

6.1 Conclusions and Contributions

In this thesis, we present a novel method for patterning permanent magnetic particles in a polymer matrix by controlled reorientation of pre-magnetized magnetic particles and selective curing using UV light. Compared with the conventional patterning method using templates or microassembly, this new method can pattern discrete 3D magnetization of the material with reduced time and cost in one single process. We also present that with programmable 3D magnetization, planar flexible sheets exhibit previously unachievable shape changes such as multi-axis and higher-order bending, large-angle deflection, and combined bending and torsion, which greatly expands the possible designs of microrobots. These sophisticated motions help exploit functionalities to target specific robotic tasks such as drug delivery in enclosed areas and locomotion in microchannels.

A prototype physical apparatus is presented to realize the proposed concept of patterning magnetic particles. The physical apparatus comprises of a permanent magnet held by a robotic arm to generate the magnetic field and a custom UV stereolithography system to cure the polymers. A program is developed to establish communication between the hardware and to automate the fabrication process. We also show the patterning accuracy, the geometrical resolution, and the precise magnetization resolution are high enough for sub-millimeter scale microrobot fabrication.

Lastly, we present a number of planar flexible structures that can transform into complex 3D shapes upon magnetic actuation. We demonstrate four microrobot designs that incorporate the complex deformation to achieve robotic capabilities. The microrobots exhibit complex motions (multi-arm power grasping), sophisticated locomotion mechanisms (multi-legged crawling), and compliant structures (micromirror mount with spring-shaped hinges). These advanced functions enabled by the patterning technique have potential to change the way we design flexible magnetic microrobots.
The study of mobile microrobots is motivated by remote constrained tasks such as targeted drug delivery, intravascular surgery, and microobject manipulation. To date, most of the work focused on the mobility of wireless agents, and thus there are gaps between functionalization with on-board capabilities such as grasping and drug release. This work addresses the gap between past studies and the challenges, which advances the capability of microrobots to achieve arbitrary deformations to be used for a variety of applications.

6.2 Future Work

One of the problems of the physical apparatus proposed in this paper is the use of the permanent magnet for particle reorientation. As the magnetic flux distribution around a permanent magnet is not uniform, we do not have control over the magnitude of the field in a specific field direction. In addition, as the magnetic field generated by a permanent magnet cannot be turned on and off, the history of the magnetic field may affect the process of magnetic particle reorientation, degrading the patterning quality. Use of electromagnetic coils instead of a permanent magnet can solve the issue because of its uniformity, precision, and the fact that they can be turned on and off. However, custom coil designs are necessary because the magnetic field strength required to reorient the particles is beyond the capacity of common electromagnetic coil systems [37]. In the future coil system design, we expect that multiple coils with iron cores should be placed at proximity and that there should be a path for the UV light from the top of the sample. By these means, we can reorient the magnetization more precisely to achieve better patterning quality and thus higher robotic performance.

The other future work is the development of simulation models to design the magnetization according to the desired shape changes. To date, most simulation models are forward models. They take the magnetization profile of the materials as input and can predict the magnetic torque-induced shape changes as an output. The inverse models, however, can take the desired shape changes as input and the magnetization profile as output, which are more useful for applications that have specific requirements on the shape changes. Inverse models for planar structures that bear a continuous 2D magnetization profile have been studied [26], but inverse models for discrete 3D magnetization profiles have not been studied because of difficulty in creating a simulation model. As the discrete 3D magnetization enables combined bending and torsion as well as large-angle deflection in the meshes, linear elastic elements cannot predict the shape changes correctly.
Moreover, the shape and size of meshes have a big impact on the simulation results and must be selected smartly for different simulation conditions. Once the inverse model is developed, this patterning method comes as a handy fabrication tool for fabricating flexible structures with arbitrary programmable 3D deformation.
References


Appendix A: TWC Analysis of Segmented Swimmers

TWC analysis is a method to quantitively evaluate the propulsive force of an undulatory swimmer at the air-water interface [41]. In this method, the shape of the swimmer under different magnetic field angle is either measured or simulated. The profile of the swimmer is then decomposed into a Fourier series and only the first-order terms are kept.

\[ w(s) \approx a \cdot \cos\left(\frac{2\pi s}{L}\right) + b \cdot \sin\left(\frac{2\pi s}{L}\right) + c, \]

where \( a \) and \( b \) are coefficients to be determined, \( s \) is the horizontal position along the swimmer body, and \( L \) is the body length of the swimmer. Fig. S1, Fig. S2, and Fig. S3 show the simulation of the swimmer shape under 9 mT at different magnetic field phase angles. The swimmer has a dimension of \( 4.5 \text{ mm} \times 1.5 \text{ mm} \times 0.2 \text{ mm} \) and a magnetization of 45000 A/m. Table S2 shows the coefficients of the first-order terms. Table S1 shows the calculated equivalent circle radius and the normalized radius \( R_{nor} \) with respect to the swimmer body length, which represent the propulsive force of the swimmer.

Fig. S1 TWC analysis of the deformation of type 1 swimmer at different magnetic field angles.
Fig. S2 TWC analysis of the deformation of type 2 swimmer at different magnetic field angles.

Fig. S3 TWC analysis of the deformation of type 3 swimmer at different magnetic field angles.
Appendix B: Young’s Modulus of the Cured Polymer

Following Euler-Bernoulli beam theory, we adopted the cantilever beam with end load model. Young’s modulus of the material can be calculated using the following equations:

\[ E = \frac{FL^3}{3lw_c} = \frac{L^3}{3l} \cdot \frac{F}{w_c} = \frac{L^3}{3l} \cdot \frac{\Delta F}{\Delta w_c}, \]

\[ l = \frac{bh^3}{12}, \]

where \( F \) is the end load applied to the beam, \( l \) is second moment of inertia, \( L \) is the distance from the force point to the fixed point, \( b \) is the width of the sample, \( h \) is the thickness of the sample, and \( w_c \) is the deflection at the force point. Table 6 shows the measured dimensions and other properties of the specimen. \( L \) is measured using the force sensor motorized stage, while \( b \) and \( h \) are measured using a laser profile scanner. Fig. S4 shows the measurement of \( \frac{\Delta F}{\Delta w_c} \) and the curve fitting results. Young’s modulus of the material is approximately

\[ E = \frac{(4.64 \times 10^{-3})^3}{3 \times \frac{4.238 \times 10^{-3} \times (0.37 \times 10^{-3})^3}{12}} \times 0.178 = 331.8\, kPa. \]

Fig. S4 Measurement of the stiffness of the material using microforce sensor. (A) Image showing the measurement process. (B) Curve fitting result.
Table 6. Dimensions of the sample used in Young’s Modulus Measurement.

<table>
<thead>
<tr>
<th>Length L (mm)</th>
<th>Width b (mm)</th>
<th>Thickness h (mm)</th>
<th>UV wavelength (nm)</th>
<th>Illuminance (lx)</th>
<th>Exposure Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.64</td>
<td>4.238</td>
<td>0.37</td>
<td>405</td>
<td>72.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Appendix C: Electromagnetic Coil System Used for Actuation

In this paper, we use a custom Helholtz electromagnetic coil system for actuating the microrobots unless noted otherwise. Fig. S5 shows the image of the coil system. Each coil is powered by an individual amplifier (ADVANCED Motion Controls, 30A8, maximum 15 A continuous current) and controlled by the analog output of a multifunction analog/digital I/O board (Sensoray, Model 826). It can generate a uniform amgnetic field up to 20 mT in any direction, and up to 50 Hz without significant drop in field strength. The measured workspace area is approximately 2.0 cm × 5.5 cm × 4.5 cm.

Fig. S5 Electromagnetic coil system used for actuation. The background is removed for clarity.