ENGINEERING MICROSCALE MAGNETIC DEVICES FOR NEXT-GENERATION MICROROBOTICS

By

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To my parents, the real reason all this is possible
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<td>micro electro discharge machining</td>
</tr>
<tr>
<td>CAGR</td>
<td>compound annual rate</td>
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<td>DCD</td>
<td>DC demagnetization</td>
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<td>EPM</td>
<td>electro permanent magnet</td>
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<td>FEM</td>
<td>finite element models</td>
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<td>MEMS</td>
<td>micro electro mechanic systems</td>
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<td>MOI</td>
<td>magneto optical image</td>
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<td>SBS</td>
<td>styrene-butadiene-styrene</td>
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<td>SHPM</td>
<td>scanning Hall probe microscope</td>
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<td>VSM</td>
<td>vibrating sample magnetometer</td>
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TERMS AND SYMBOLS

\( \vec{B} \)  magnetic flux density field

\( \vec{B}_{\text{ext}} \)  external magnetic flux density field

\( \vec{B}_{\text{0}} \)  additional (bias) external magnetic flux density field

\( d \)  differential

\( F \)  magnetic force

\( \varphi_m \)  magnetic scalar potential.

\( \vec{H} \)  magnetic field

\( \vec{H}_{\text{appl}} \)  applied external magnetic field in VSM measurements

\( H_{\text{ci}} \)  intrinsic coercivity

\( H_r \)  remanent coercivity

\( \vec{m} \)  dipole magnetic moment

\( \vec{M} \)  magnetization field

\( M_r \)  remanent magnetization

\( M_s \)  saturation magnetization (or remanent magnetization in some cases)

\( \hat{n}_B \)  \( \vec{B}_{\text{ext}} \) unitary vector (direction of scalar external magnetic flux density)

\( \hat{n}_M \)  \( \vec{M} \) unitary vector (direction of scalar saturation magnetization)

\( N \)  Symmetrical tensor containing the demagnetization coefficients

\( N_{xx} \)  demagnetization coefficients in x coordinate (analogous for yy and zz)

\( \Phi \)  magnetic flux

\( \sigma \)  electrical conductivity
\( \mathbf{T} \)  torque

\( \mu_0 \)  permeability of free space

\( \mu_r \)  relative permeability

\( \mu \)  material permeability \( (\mu = \mu_0 \cdot \mu_r) \)

\( V \)  volume

\( \chi_m \)  material susceptibility
This dissertation focuses on engineering advancements to solve technological challenges in the field of microrobotics. Like colonies of ants or bees, it is conceivable for coordinated “swarms” of small-scale robots to together solve complex tasks, such as micro/nanomanufacturing, biomedical treatments (e.g., direct cell manipulation, minimal invasive medicine, theranostics, etc.), monitor and maintenance of structures, or surveillance and information security. In the last few years, researchers have demonstrated significant advancements along this theme, including locomotion (magnetic, flaying, swimming), multiple robot manipulation, chemical actuation, and human in-vivo experimentation. This sci-fi idea has even been promoted in the general public by films like Fantastic Voyage (20th Century Fox - 1966) and the recent Big Hero 6 (Walt Disney – 2014). However, to fully realize this futuristic vision, the microrobot units must be made smaller, smarter, cheaper, and more capable than anything seen before.

To address some of these challenges, this research focuses on (1) the development of batch-fabrication strategies for scalable manufacturing of magnetic
microrobots and (2) development of magnetic mechanisms to enhance the functionality of microscale robots. These efforts are unified by the micro-engineering of magnetic fields, structures, and devices at sub-millimeter dimensional scales.

In a first thrust, a batch-fabrication process denoted “selective magnetization” is developed to produce complex magnetic field patterns by “imprinting” permanent magnetic films/substrates with alternated microscale poles. Two examples illustrate the utility of the process for microrobotics: 1) a bottom-up approach, using magnetically driven assembly of magnetic nanoparticles for potential roll-to-roll manufacturing of free-floating microscale magnetic microrobots; and 2) a top-down approach, for mass production of diamagnetically levitated millimeter-scale robots to be used in high speed microfactories.

In a second thrust, two magnetic strategies are explored in an effort to enhance the functionality of microrobots (magnetic or non-magnetic robots): 1) magnetically attached end effectors, which are used to demonstrate nanoscale precision manipulation of micron size objects; and 2) sub-millimeter electropermanent magnets, which are magnet assemblies that can be used as electronically switchable magnetic actuators.

Ultimately, this research contributions are: a design a methodology, that can help future researcher in academia to continue building the field of magnetic microrobotics; a selective magnetization technology, that can be potentially used by industry to fabricate better and more functional magnetic devices at nano and micro scale; a novel magnetic force sensing technique at microscale, that can be used by researchers looking to enhance characterization capabilities in the microsystems field; a fabrication process for
free floating magnetically responsive microstructures, that can potentially be used by
researchers in biomedical applications; a fabrication technique for batch production of
levitated microrobots with detachable end effectors, that can be used in new
manufacturing and micropositioning technologies; and a proof of concept of the
microfabrication of electropermanent magnets, that can be used to enhance functionally
in the next generation of microrobots.
CHAPTER 1
INTRODUCTION

Robotics is nowadays a driving force for a new industrial revolution. It is recognized itself as an industry that is in the early stage of fundamental changes for humanity. In a 2016 report from BCC research [1], robotics was a $26 B worldwide industry with a 4% compound annual growth rate (CAGR) projected to 2021 (global distribution of robotics industry in Figure 1-1). Robotics have direct impact in other industries such industrial manufacturing, military, healthcare, domestic services, professional services, security and even entertainment.

![Figure 1-1: Global robotics industry.](image)

In the Roadmap for US Robotics [2], Presented to the congress in November 7 2016 (inspired in the report presented in 2009 under the Obama administration to launch the National Robotics Initiative in 2011, which allocated $70 M and the National Robotics Initiative 2.0 that will allocated $30M-$45M in 2017 to advancing robotics research), it was clearly stated that restructuring U.S. manufacturing (a sector that represents 12% of U.S. GDP) is essential to the future of economic growth of the
country. It also was emphasizing that Robotics is a key transformative technology that can revolutionize this manufacturing. Within manufacturing, robotics represents a $8 B-industry in the U.S. that is growing steadily at 9% per year and that in the last 5-6 years have introduced ~600,000 jobs.

The roadmap also established that for the next 15 years the advances in micro and nano-scale sciences will be able to develop safe, provably-correct designs for any product line to contribute to this manufacturing industry. It also confirmed the necessity for integration of MEMS, low-power VLSI, and nano-technology to enable sub-mm (micro-nano robotics) self-powered robots. Two main technology drivers were defined for sub-mm robotics:

1) Healthcare/Biomedical: Where there is a need for creating, new or improving existing medical procedures and devices for micro-scale interventions, where micro/nano-manufacturing for micro/nano-robots for drug delivery, therapeutics and diagnostics is required. As an example, robotic surgery equipment Manufactory is today a $2.8 B industry in USA, with 12.1% annual growth, projected growth of 14.1% to 2021, catalogued as a quality growth industry and generating ~$394 M in profits. This industry is comprised by 30% neurosurgical robots, 23% orthopedic surgery robots, 12% steerable robotic catheters and 35% to other robots [3]. This shows the potential fertile soil of microrobotics in this in healthcare and biomedical.

2) Manufacturing: Where the next generation of high-value products relaying on embedded computers, advanced sensors and microelectronics requires micro/nano-scale assembly, for which labor-intensive manufacturing with human workers is no longer a viable option. Research and development of new mechanisms and actuators
for new manufacturing techniques to make it possible to fabricate truly microscale robotic elements and incorporate techniques such as massively parallel assembly via self-assembly.

These two technology drivers (healthcare/biomedical and manufacturing) where micro-nano robotics could find niche, do not only have local impact in United States markets, they have created global markets in Europe and Asia Pacific. Based on reports by BCC research [1], [4], [5] the healthcare/biomedical technology driver could find a potential market in minimally invasive medical devices as well as in medical robotics and computer assisted surgery. In 2016, the former one was a $4 B worldwide market of 11.8% CAGR for 2021. By the other hand, looking manufacturing technology driver, the potential market is in the industrial robotics that in 2016 was a $15 B worldwide market with a 2.7% CAGR for 2021. Micro-nano robotics is shyly appearing in any of those reports and that is the big opportunity for this emerging field. Figure 1-2 represents the global potential markets that microrobotics could pursue in the near future.

![Figure 1-2: Potential global markets for microrobotics: A) Surgical robotics and B) industrial robotics.](image-url)
This promising perspective of the global markets are one of the many justifications to push the boundaries of micro-nano robotics field. It is a reality that penetrating the market with microrobotics is ambitious and still distant in the future, but it is an emerging field that requires interdisciplinary research. As an encouraging example of research efforts in the field of microrobotics, it is presented a record of awarded grands in USA by the national science foundation (NSF) in Figure 1-3 [6]. A total of $14.4 M since 1998 has been invested in projects related with microrobotics. Note: data for year 2017 is only available up to June.

![NSF total awarded to microrobotics: $14.4 M](image)

Figure 1-3: NSF awarded grants for microrobotics.

1.1 Purpose & Objectives

1.1.1 Research Purpose

The purpose of this doctoral dissertation is to advance the field of micro-nano robotics and deepen the understanding of relevant physical phenomenon at small scales. This document will mainly focus on robots with micrometer scale feature sizes (therefore only microrobotics appears in the title) and their interactions with magnetic fields.
Researchers in the Interdisciplinary Microsystems Group (IMG) at the University of Florida, led by Professor David Arnold, have identified that methods to fabricate magnetic structures with complex magnetic field patterns at the micro scale are of fundamental importance for the advancement of magnetic microrobots. One of the core technologies under research presented in this document, is a technique of batch-patterning complex magnetic pole shapes (with alternating orientation) on magnetic materials. At least one of the dimensions for the magnetic materials (also called substrates) is in the microscale range. Substrates could be magnetic tapes with thickness below 10 µm (for the magnetic part of the tape) or thin, bulk magnets with 400 µm thickness. The intended pattern sizes range from millimeter to micrometers, depending on the application. These magnetic patterns will be fundamental parts of more complex microsystems.

The technique being explored in this research is called selective magnetization. Figure 1-4 depicts the technique concept. The main idea of selective magnetization is to use a magnetization mask, with the desired patterns, to concentrate external magnetic field and flip the magnetization of the magnetic material underneath the patterns in the mask (like a magnetic stamp process). This method is important to the magnetic, MEMS (micro electro mechanical systems), and microrobotic communities because it expands the usage of permanent magnetic materials in microsystems by creating complex magnetic field patterns.
1.1.2 Research Objectives

The general objective of this dissertation is to study the creation of complex magnetic field patterns at microscale, and the usage of such patterns in the fabrication and functionality of microrobots. The modeling describing the magnetic behavior and fabrication of the magnetic structures must fulfill the geometric necessities of microsystem fabrication.

There are two specific objectives, grouping designated tasks governing the research conducted in this dissertation:

First, to provide strategies and demonstrate processes for batch fabrication of magnetic microrobots, using selective magnetization as a fundamental technology. Designated tasks are: to demonstrate feasibility of patterning complex magnetic field patterns, to model and validate the selective magnetization process, to propose and execute fabrication techniques for multiple magnetic structures in a batch process, propose a technique for particle capturing at the boundary of magnetic poles, and generate diamagnetically levitating micro-robot bases.
Second, to suggest mechanisms to enhance functionality of microrobots, in terms of interaction with the objects to be manipulated. These mechanisms could be implemented over existing microrobotic platforms. Designated tasks are: to prove feasibility of a magnetically detachable end effector, to establish a batch fabrication procedure of end effectors for microrobotics, and to propose alternatives for microfabrication of electropermanent magnets.

1.1.3 Research Methodology

A diagram in Figure 1-5 is presented as a general methodology for this research. The proposed path to elaborate a simulated model is to start from understanding the theory behind some specific natural phenomena or physical behavior. Next, elaborate a theoretical model that describes a simple configuration of this phenomena. Then, use this theoretical model to start the designing process, i.e. selection of components or identifying general constraints in the problem. After, it is possible to elaborate a simulation model that combines the theoretical model and designed variables. The objective of a simulation tool is to improve the design, therefore, better design constraints and an iteration process will lead to a more accurate simulation. It is important to have in mind that simulation is not the ultimate goal. With the design and the simulation results, then it is possible to fabricate a prototype. Testing or measuring this prototype will generate important information to validate or feedback the simulation model. This work believes that multiple iterations on this loop will generate more accurate results each time and will reduce time in future designs.
1.2 Dissertation Overview

Chapter 1 of the dissertation (Introduction) presents an overview of the potential that microrobotics have in the global industry of robotics, as a justification for the importance of the work presented in this document. It also explains the objectives research contributions of the conducted research.

A detail analysis of the state of the art of microrobotics and magnetostatics at small scale is presented in Chapter 2 (Background). Magnetostatics is fundamental to develop validated models (analytical and numeric) that can predict the stray magnetic fields of complex patterns.

It is fundamental to elaborate the theoretical bases of magnetic forces at microscales. Magnetic forces will be the physics governing the mobility mechanism for the selected microrobots (diamagnetic levitated) and governing the fabrication principle for the bottom-up approach (magnetic nanoparticle collection). Chapter 3 (Magnetic
forces at small scale) will explain the concepts and present an alternative solution to the problem of measuring magnetic forces at small scales.

And overview of magnetic field patterning at microscale and a description of the selective magnetization process is presented in Chapter 4 (Selective magnetization). The chapter will also include description of a simulation model for the selective magnetization process, fundamental to interpret the changes in variables involved in this process and predict the stray magnetic fields of the fabricated complex patterns.

The micro-nanorobotics community (as a subset of the microsystems and nanotechnology communities) considered two fabrication approaches: 1) the bottom-up and 2) top-down [7]. Both approaches will be exemplified in this dissertation for fabricating microrobots using magnetic field patterns. 1) A bottom-up approach, centered in the idea of magnetically assemble nanoparticles onto the interface boundary of magnetic patterns, then crosslinking the particles for later release them as magnetic microrobots. This project will be presented in Chapter 5 (Microrobot fabrication: bottom-up approach). 2) A top-down approach of microrobot fabrication will be addressed in Chapter 6 (Microrobot fabrication: top-down approach) by demonstrating a batch fabrication technique for diamagnetic levitated robots. The selective magnetization technique will be used in this approach.

Once the microrobots are fabricated, it is time to give them additional functionality. A first approach will be providing exchangeable/replaceable end effectors with different “tools” to perform variety of tasks. The mechanism to attach every end effector with the microrobot will be by using magnetic patterns. The fabrication procedures will be presented in Chapter 7 (Adding functionality to microrobots: end
effectors). A second approach will be designing a complex magnetic pattern that can turn on/off the external magnetic field. Such magnetic pattern is called electropermanent magnet and will be explained and demonstrated in Chapter 8 (Adding functionality to microrobots: electropermanent magnet).

Figure 1-6 presents a summary of the content of this document and how each chapter is related with the specific objective for this research. This figure compress the main spirit of this work. Remarks of the work conducted in this document and a summary of the accomplishment will be presented in Chapter 9 (conclusions).

![Figure 1-6: Research and document description.](image-url)
CHAPTER 2
BACKGROUND

This chapter is design for future students and researchers exploring the field of microrobotics for the first time. The goal of this chapter is to lead the reader through the brief history of microrobotics and point in the direction of the leaders of the field (in the humble opinion of the writer). This literature review will cover the most important books wrote about microrobotics and the review papers that summarize the work of many research groups in the last 30 years across the world. This review is by any means comprehensive, and many other authors should be included in the future, but it is a starting point for the reader to discover the “big players” in this field that is still in its infant stage.

This chapter also aims to illustrate some theoretical concepts of magnetostatics and the modeling of magnetic materials at the microscale. Magnetostatic problems area commonly simulated nowadays using finite element modeling. These modeling/simulation approaches are common topics in most of the modern magnetic theory textbooks, but there are some important details that need to be considered when modeling structures in the microscale domain, such as material magnetic characterization (and corresponding demagnetization corrections). This chapter will cover a simplified analytical model to evaluate the magnetic B field generated by permanent magnets, as well as soft magnetic materials in the presence of external magnetic fields. The model will be validated, demonstrating the accuracy and

possibilities of this research. A description of the importance of pole boundaries will be also presented and described through simulations.

The magnetostatics section is divided in in seven sub-sections: 1) Classification of the magnetic materials by interpretation of their material properties. 2) Introduction to modeling magnetostatics. 3) Demagnetization correction for ferromagnetic materials, 4) DC demagnetization will be mentioned. 5) Techniques used at University of Florida for measuring stray magnetic fields and visualization of magnetic micropatterning will be presented. 6) Simulation methods and validations used as fundamental block for modeling magneto static problems with finite element approach (single magnet). 7) Simulation of magnetic pole boundaries. 8) Simulation of alternated magnetic pole patterns in the form of a checkerboard.

2.1 Microrobotics

Since the first mention of small scale machines (called today microrobots) in 1959 by Richard Feynman [10], [11], numerous fields of applications for micro/milli robotic systems have emerged such as minimal invasive medicine [12], bioengineering [13], and microassembly [14]–[16]. Inspired by Feynman some visionaries such as A.M. Flynn [17] and W. Trimmer [18], envisioning creating complex machines with sizes and abilities of insects. Advances to achieve those goals were only possible by the progress in the field of microsystems (MEMS), in microfabrication technologies [19] and specially by using silicon as mechanical material [20].

Most of researchers working in the field of microrobotics, recognize their inspiration in the founding works of R.S. Fearing [21], F. Arai and T. Fukuda [22], that in the International conference on Intelligent robots and systems (ICIRS) on 1995, set the fundamentals of micromanipulation and adhesive forces at microscale. Another
important founder in the 90’s was S. Fatikow who author or coauthor some of the first books in the field.

A generation of researchers in the decade of 00’s brought exiting applications and could be easily be named “parents” of the current research groups. During this decade researchers in Europe leans towards biological applications and magnetic actuation mechanisms (B. Nelson, M. Sitti, and O. Schmidt), meanwhile American researchers lean towards enhance mobility in air and ground and industrial applications (R. Pelrine, K. Pister, R. Wood, and D. Rus).

The decade of 10’s is still in its peak and many new groups have sprout, bringing new challenges and facing interesting new problems. Each researcher in this generation is working to develop new technologies and open new frontiers, therefore they could be called the Progeny generation. Figure 2-1 depicts a genealogy tree with the most important contributors in the field of microrobotics. This three is by any means extensive (is a subjective representation based on visibility) and represents a starting point for networking and research in the field. This tree will continue growing to become strong and deliver impactful research.
Figure 2-1: Genealogy tree for microrobotics, containing the most cited researchers in the field.

Searching publications by “microrobotics” in google scholar (up to June 19th 2017) will result in 7.672 references, including patents and citations. A historical representation of this references in Figure 2-2, will show an increasing trend demonstrating the potential growth of the field. The field of microrobotics is in an infancy stage and it can be proven by comparing number of references published in 2016 in better established areas such as nanotechnology (74.100), MEMS (28.800), and Robotics (~52.600). The field of nanorobotics have comparative numbers than microrobotics, with a total of 5.790 references.

Figure 2-2: History of publications related with microrobotics (academic papers, references, citations). Source: Google Scholar.

2.1.1 Books About Microrobotics

If the reader is new to the field of microrobotics, two suggestions are offered: The first (and most important) suggestion is to start familiarizing with the field by reading [23][24]. These references are two parts of the tutorial about robotics in the small (Part I:
Microrobotics and Part II: Nanorobotics) published in IEEE Robotics & Automation Magazine, prepared by Bradley Nelson’s research group. This is a very useful, clear and introductory tutorial that summarizes the most important topics to be considered when studying the field, such as scaling effects, forces, microfabrication, micromanipulation, nature inspiration, power constraints, imaging and assembly.

The second suggestion is Chapter 18 in the Springer Handbook of robotics [25], it is a guide into the micro and nano robotics world describing scaling, actuation mechanisms (electrostatics, electromagnetics, piezoelectric), sensing techniques (optical, electron and scanning probe microscopy), basic techniques in micro/nano fabrication and microassembly. A classification of the microrobots based on their functionality is presented and specific emphasis in bio-microrobotics is made. A general description of nanorobotics with special emphasis on manipulation techniques is made.

After following these two introductory suggestions, the reader is ready to go in depth into the field. Beneath, a list of books directly related to microrobotics (published in English) and a brief comment on the content of each books. As mentioned before, the microrobotics is a field that is in its infancy and probably many books will be written in the future. Four groups of books will be presented: 1) Academic oriented books, 2) books collecting papers about selected topic, and 3) conference proceeding books.

**Academic oriented books**

Researchers in Europe (specially France), have been leading efforts to structure the field of microrobotics along books suitable for the academic environment. The following three books could be perfectly used as text books in courses dedicated to microrobotics. Each book presents a diverse perspective (mechanical, manipulation or
assembly). The constant in these books is the careful and meticulous explanation of every angle of the topic.

*Microrobotics: Methods and applications* [26] (one of the favorite books of the author of this dissertation), is a very complete book from the mechanical engineering perspective of microrobotics. It is constantly supported by mathematical analysis and is divided in three parts: Part I - Prerequisites. It explains the fundamental concepts of linear elasticity and kinetics. Part II - Core technology. It makes descriptions of the applied physics (scaling effect, adhesion forces, material structure and properties), the flexures, actuators and sensors. Part III - Implementation, applications and prospects. It describes state of the art microfabrication techniques and applications (and technologies) that are driving the microrobotic field to the future.

*Microrobotics for Micromanipulation* [27] is a pedagogical book that covers the principles of micromanipulation, from the perspective of the physics of the microworld and the strategies of micro handling. It also includes the fundamentals of the actuation mechanisms for the microrobotics (piezoelectric, electrostatic, thermal and magnetic) and the overall architecture of a micromanipulation system. Class exercises and projects on different topics, are an important inclusion of this book.

Even though, *Robotic microassembly* [28] is a compilation of documents from different authors, it is carefully edited to present microassembly in the form of a coherent book. It starts from modeling of microworld by describing the impact of vacuum, liquids and roughness in the overall force analysis at microscale. A second section dedicated to handling strategies at small scales, describes micro handling, self-assembly and micromanipulation (in dry and wet environments). And a third section
called robotic and microassembly, is dedicated to industrial MEMS structures. It evaluates strategies for 3D microassembly, high-yield automated procedures and microsolder applications.

*Micro-nanorobotic manipulation systems and their applications* [7] offers a clear explanation about the boundaries between the micro and nano world and describes fabrication techniques using the top-down and bottom-up approaches. It describes the physics at small scale by always pointing differences in both worlds. It dedicates a section to the technologies and materials that enable research in both worlds and explains in detail manipulation under optical and electron microscope. It evaluates the complexity of manipulation and motility of three systems at small scale: bacteria flagella, cells, and carbon nanotubes.

*Intracorporeal Robotics* [29] uses a simple classification to present this topic: the scale size. It starts by describing principles, scientific issues and applications for intracorporal millirobots, followed by paradigms, methods and devices used in microrobotics. It has a special chapter dedicate by devices manipulating objects bridging the micro and nano world (such as cells) and finalizes by defining the scientific challenges for biomedical nanorobotics.

A special mention should be made to *Microsystem Technology and Microrobotics* [30], to be the first book (to our acknowledge) dedicated to microrobotics. Its introduction presented a worldwide analysis of the present and future of microsystems (called microsystems technology –MST- in the book) and, even though, many of the techniques available at the 90’s had evolved, it is still a reference point for studying
microrobotics. The book described the actuation principles and sensing mechanisms, containing numerous examples.

**Selected topics**

*Selected topics in micro/nano-robotics for biomedical applications* [31], is an effort to document research results in the biomedical field using micro/nano robotics. The introduction of this book presents a clear description of the challenges presented to the field of microrobotics in the future. In a systemic approach, four examples were presented: biomedical image analysis, a programing a capsule robot to navigate in the gastro-intestinal tract, optical tweezers for cell manipulation and catheter surgery assisted by robots. In a device approach, the book presented alternatives to solve the power problem in microrobots (towards autonomous systems) by the integration of fuel cells and energy harvesting mechanism. The inclusion of a piezoelectric sensor was also commented. Two examples were presented of applications using nanorobot, a cooperative scheme for drug delivery and cancer target therapy.

*Micro- and Nanomanipulation Tools* [32], specially focus on manipulation of biological elements such as cells (mechanic, magnetic, and optic manipulation), bacteria, DNA, and organic molecules. It presents examples of manipulation for plant pathology and untethered tools for surgery. It also presents non-biological examples of manipulation techniques in optical induced electro-kinetics, nanomaterial manipulation, scanning probe microscopes, atomic force microscopy, Industrial tools for micromanipulation, scanning electron microscope, and magnetic helical structures.

*Automated Nanohandling by Microrobots* [33] is based on the assumption that the primordial function of microrobots is the manipulation of object at nanoscale. It evaluates diverse topics such as the trends, automation and problems of nanohandling,
the problem of controlling microrobots, tracking and imaging objects inside scanning electron microscopes, characterization and handling of cells and nanotubes and nanomaterials’ testing and modification.

Not all chapters in *Advanced Mechatronics and MEMS Devices* [34] are dedicated to microrobotics, but it contains certain topics of interest to the microrobotics community such as: microscale sensors (force-torque and elasticity), piezoelectric end-effectors, miniaturization of micromanipulation tools, digital microrobotics, micro gripping and bioinspired (biomimetic) microrobots.

**Conference proceedings**

*Microrobotics: Components and Applications* [35], is a proceedings book for one of the first official conferences in the field of microrobotics. It is important because the design and control methodology for microrobots was not well established. Important contributors such as S. Fatikow, T. Fukuda, and F. Arai presented some of their first work at this conference.

*Small-Scale Robotics* [36], is the proceeding of the first international workshop on microrobotics at the International Conference on Robotics and Automation (ICRA). An introduction on small scale presented examples of robots bridging the gap between millimeter a micrometer fabrication. The main topic of this workshop was the mobility of the microrobots and magnetically actuated was the predominate mechanism described by the presenters. Six device examples were presented by different groups.

Two additional book chapters dedicated to microrobotic applications are of interest: An applications in medicine (locomotion of legged microrobot in gastrointestinal tract) could be found in section V of [37] and the simultaneous control of multiple microrobots [38].
2.1.2 Review Papers in Microrobotics

If the reader is new to the field, it will be very useful to know in which direction to start looking for information. After considering books in the topic, the next logical step is to search for review papers. At least 18 review papers have been written about topics related to microrobotics. A brief description of the most important review papers is presented below, by grouping the papers in three groups: 1) Actuation principles, 2) biological applications, and 3) problematics in the field.

1) A first group of papers is trying to describe research efforts in the field of microrobotics by presenting the trends and technologies [15] and describing the actuation principles [39]. Two main principles are mainly discussed: Swimming and Flying.

For swimming microrobots, magnetic actuation is one of the most important mechanisms of locomotion, as mentioned before. This statement is demonstrated by [40]. A subset of microrobots with magnetic locomotion technique but using rotating fields and helical shapes is presented by [41].

For flying, a very comprehensive review of aerial robots (drones) is presented in [42]. Three specific classification of flying microdrones is presented: micro unmanned air vehicles (µUAV), micro air vehicles (MAV), nano air vehicles (NAV) and pico air vehicles (PAV). It is important to highlight, that names in this classification are highly influenced by marketing strategies and do not represent real dimensions.

2) A second group of review papers is entirely dedicated to biological/biomedical applications. The environment of microrobots dedicated to these applications is mainly liquid and it has its own special characteristics. Evidently, the mobility of the microrobots in these environments requires special attention [43]. And untethered mobile
alternatives are desired [13]. New bio-inspired swimming microrobots arise [44], as well as hybrids combining microfabricated structures with living bacteria [45]. Despite these advances, most of the microrobots in biological applications remain to be manipulated using magnetic fields [46]. Two specific goals are in mind in microrobots for biomedical applications: the minimal invasive medicine [12] and theranostics (the fusion of diagnostics and therapy) [47], that leans towards the usage of nanorobots instead of microrobots.

In a side note and going in the direction of nanorobots, it is important to highlight a review paper about the usage of carbon nanotubes in the field of nanorobotics [48].

3) The third group of papers is dedicated to describe solutions for two of the most pressing problems for microrobotics: power and functionality. The problem of power sources at small scales (with special orientation to remote sensors) is presented in [49] and electrochemistry is presented as one of the alternative for solution [50]. The problem of functionality is partially addressed by researchers in the neighbor field of soft robotics. There is a recent interest in soft robotics because of the versatility and low power consumption of these robots [51] [52]. This interest transcends into the microrobotics field [53] making soft robotics an enabling technology for future applications.

2.2 Understanding Magnetostatics

2.2.1 Classification of Magnetic Materials

The minimum magnetic unit in nature is defined as the magnetic dipole (can be interpreted as a pair of charges or and equivalent small current loop). Not all elements in nature respond the same way to an external magnetic field because each element has an associated dipole magnetic moment ($\vec{m}$ in units of A·m$^2$). This is the
fundamental unit to evaluate magnetic properties in materials. In the analysis of elements more complex than dipoles, it is possible to consider the magnetization $\vec{M}$ as the measurement of the net magnetic dipole moments per unit of volume ($\Delta V$) as in [54]:

$$\vec{M} = \lim_{\Delta V \to 0} \frac{\sum m_i}{\Delta V}$$  \hspace{1cm} (2-1)

For most of the applications involving homogeneous and isotropic materials (it will be clear later that those materials are called diamagnetic and paramagnetic), their magnetization will have a linear behavior in the presence of an external magnetic field $\vec{H}$. This relationship is expressed as $\vec{M} = \chi_m \vec{H}$, were $\chi_m$ is defined as the material magnetic susceptibility. $\vec{H}$ and $\vec{M}$ are expressed in units of A/m.

It is possible to make a rough classification of every element (or materials) based on their susceptibility ($\chi_m$). If $\chi_m < 0$ then the material is considered diamagnetic, meaning that their internal magnetic dipoles will orient in antiparallel direction of any external magnetic field. If $\chi_m > 0$ the material is considered paramagnetic, meaning that their internal dipoles will align in parallel direction with the external magnetic field.

Another important property for materials is the relative permeability $\mu_r$ defined as $1 + \chi_m$ (some authors instead use $\mu$, the material permeability as $\mu = \mu_0 \cdot \mu_r$). This property is mainly used to characterize materials with non-linear behavior in presence of external magnetic field. Those non-linear materials that have a net magnetic moment at the atomic level and a strong coupling between neighboring moments are called ferromagnetic. If the coupled neighboring moments are equal but aligned antiparallel to
each other (no net magnetic moment, therefore magnetization is zero), the material is considered antiferromagnetic. Figure 2-3 shows the periodic table of elements with this magnetic classification. It is important to notice that at room temperature (273 K) there are only four ferromagnetic elements (iron, cobalt, nickel and gadolinium) and one antiferromagnetic (Chromium).

![Magnetism at temperature = 273K](image)

Figure 2-3: Periodic table of elements illustrating their magnetic behavior at 273K. Adapted from © DoITPoMS, University of Cambridge, https://doitpoms.admin.cam.ac.uk/tlplib/ferromagnetic/printall.php.

Ferromagnetic materials are of special interest for this document. Their magnetization curve ($\mathbf{\vec{M}}$ vs $\mathbf{\vec{H}}$) sometimes present two values at each $\mathbf{\vec{H}}$ and its interpretation depends on its prior state of magnetization. This behavior is called hysteresis. The magnetization hysteresis curve will highlight two important properties: remanence and intrinsic coercivity. The first property is evaluated without the presence
of external magnetic field ($\vec{H} = 0$) where the ferromagnetic material will present a remanent magnetization ($M_r$) that is called remanence. The sign of the remanence can be either positive or negative depending on the previous magnetization direction, but the positive and negative remanences generally have equal magnitude. The second property is evaluated when the applied external magnetic field is in opposite direction of the material's magnetization. The internal magnetization of the material will change direction if the external field is high enough ($\vec{M}$ will switch from positive to negative or vice versa). The value of the external magnetic field to switch magnetization is called intrinsic coercivity ($H_c$).

Based on the intrinsic relative permeability, coercivity and remanence, ferromagnetic materials can be classified in two groups: hard and soft ferromagnetic materials. Hard ferromagnetic materials (also called permanent magnets) are characterized for high intrinsic coercivity, high remanence and low relative permeability. They retain the magnetic field and are very difficult to demagnetize (only by high temperatures, large demagnetizing magnetic fields, mechanical stress, or chemical damage). Soft ferromagnetic materials have lower intrinsic coercivity and remanence, but they generally present very high permeability. This means that they will magnetize very easily in the presence of an external magnetic field, achieving a maximum magnetization value called saturation magnetization $M_s$.

A special magnetic classification called superparamagnetic occurs for particles with nanometer diameter. Because of their reduced volume, these particles can spontaneously reverse their own magnetization due to thermal fluctuations even in the absence of external magnetic field. Therefore, in a time-average sense,
Superparamagnetic particles have zero intrinsic coercivity and zero remanence, but act as ferromagnets in the presence of external magnetic fields. The external magnetic field provides enough energy to overcome the thermal fluctuations in order to align the magnetic moments with the field direction.

A comparison of magnetization curve of materials with different magnetic classification is made by measuring their magnetic moments at different external fields using vibrating sample magnetometer (VSM) (ADE Technologies EV9). The measured moments are divided by the volume of each sample to obtain the magnetization. Figure 2-4 compares measurements made for following materials: diamagnetic (pyrolytic graphite), paramagnetic (aluminum), hard-ferromagnetic (nickel coated NdFeB magnet, grade N42 and reference B111 from K&J magnetics Inc.), and soft-ferromagnetic (AISI 1018 mild/low carbon steel). Superparamagnetic particles are also compared (iron oxide nanoparticles embedded in a polystyrene matrix from Corpuscular Inc.), although they were measured using superconducting quantum interference device (SQUID) magnetometer (Quantum Design).
Figure 2-4: Measured magnetization curves of different types of magnetic materials. A) Full scale and B) Zoom-in into \( \mu_0M \) to compare diamagnetic, superparamagnetic and paramagnetic materials.

Because of the nature of the research reported in this document, it is of special interest the magnetic properties of soft ferromagnetic materials. Using information of commercial soft magnetic materials available in COMSOL library, Table 2-1 is created.

For uniformity, the table reports the relative permeability when the external field is 1 µT (called \( \mu_r \)). This field was chosen (~0 T) to guarantee data points in all materials. It also reports the saturation magnetization (\( \mu_0^*M_s \) in units of Tesla) when the external field is 3 T (~\( \infty \)). It also presents the electrical conductivity of the materials (\( \sigma \), in units of MS/m), although this property will not be used during this document.

Table 2-1. Magnetic properties of some commercial soft ferromagnetic materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu_r ) [-]</th>
<th>( \mu_0^*M_s ) [T]</th>
<th>( \sigma ) [MS/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel 1006</td>
<td>3882</td>
<td>2.1</td>
<td>8.4</td>
</tr>
<tr>
<td>Low carbon steel 1008</td>
<td>1221</td>
<td>2.1</td>
<td>8.4</td>
</tr>
<tr>
<td>Low carbon steel 1010</td>
<td>2119</td>
<td>2.1</td>
<td>8.4</td>
</tr>
<tr>
<td>Low carbon steel 1018</td>
<td>835</td>
<td>2.0</td>
<td>8.4</td>
</tr>
<tr>
<td>Metglas Nano Finemet 50 Hz</td>
<td>87031</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Nickel Steel Molypermalloy (Alloy 79)</td>
<td>65709</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Nickel Steel Permalloy Oriented</td>
<td>41882</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Nickel Steel Mumetal 80% Ni</td>
<td>79518</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Alloy Powder Core Ferrite</td>
<td>1229</td>
<td>0.4</td>
<td>1 ( \mu S/m )</td>
</tr>
<tr>
<td>Nickel Steel Supermalloy</td>
<td>445540</td>
<td>0.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Figure 2-5 is a graphic representation of the magnetic properties of commercial available soft ferromagnets (data obtained from COMSOL library). Each element is allocated corresponding to its material properties, where the x axis represents the saturation magnetization in units of Teslas, they y axis represents the relative permeability, and the diameter of the marker represents the electrical conductivity. Figure 2-5B represents a zoom-in view of the material properties for selected low-carbon steels.

![Material properties comparison for some soft ferromagnets in COMSOL library. A) Full list of materials and B) zoom in to low carbon steels.](image)

2.2.2 Magnetic Model of Ferromagnetic Materials

Numerous applications related with magnetic phenomena require the usage of hard ferromagnetic materials. Having a theoretical model that can predict the magnetic field produced by a hard magnet with any geometry will be ideal. Although, because of the nature of the physics in magnetism, the resulting equations (individual solutions of the Maxwell’s equations) will be extremely complicated. The most common approach to recreate the stray magnetic field of any shape is by using finite element models (FEM).
A fundamental step, whenever using numerical methods is to validate the simulations. To this goal, it is always recommended to solve a very simple problem (with the most basic geometries) and to compare the analytical solution with the simulation results. This step will give the researcher the confidence to explore further complicated geometries, assuming accurate results. To the purpose of this dissertation, the validation will be done by calculating the stray magnetic field produced by a sphere of hard ferromagnetic material and compare the results with a COMSOL simulation. Simulation and analytical model will be both compared with measurements of the magnetic flux density to obtain a full validation of our models.

This problem requires the solution of Maxwell’s equations where there is no time variation. This leads to cancel (neglect) the time-dependent terms in the equations. It will also be of interest to consider a current-free problem where only the magnetic component of the equations remains, narrowing the set of equations to a theory called magnetostatics \( \nabla \times \vec{H} = 0 \) and \( \nabla \cdot \vec{B} = 0 \). This theory also includes the constitutive equation (from the Sommerfeld convention):

\[
\vec{B} = \mu_o (\vec{H} + \vec{M})
\]

where \( \vec{B} \) is the magnetic flux density in Tesla, \( \vec{H} \) is the magnetic field strength in A/m, \( \vec{M} \) is the magnetization in A/m and \( \mu_o = 4\pi \times 10^{-7} [T \cdot m / A] \) is a constant representing the permeability of free space. Further results will be derived based on theory from [54]–[56].

The problems that will be solved ahead will be using the charge model as a method to analyzing the magnetic field. Therefore, by using one of the propositions for calculus, where the irrotational vector filed can be written as the gradient of a scalar-
valued function, another important term arises: the scalar potential \( \varphi_m \). This final term will be useful to describe the magnetic field as:

\[
\nabla \times \vec{H} = 0 \implies \vec{H} = -\nabla \varphi_m
\]

By substituting Equation 2-2 and 2-3 into \( \nabla \cdot \vec{B} = 0 \) (from Maxwell’s equations) the magnetostatic Poisson equation can be obtained:

\[
\nabla^2 \varphi_m = \nabla \cdot \vec{M}
\]

The Poisson equation is the fundamental part of the charge model and it is used to find the magnetization field of a ferromagnetic material in any point of the space. The problem with this differential equation is the enormous complexity of its solution for complex geometries. As mentioned before, this is the main reason why it is necessary to use finite element models (simulations) to predict magnetic fields of complicated structures. A schematic of the sphere to be analyzed is presented in Figure 2-6. Figure also depicts the selected coordinated system and conventions to calculate the magnetic flux density in the point P.

Figure 2-6: Coordinate system for the calculation of the magnetic field in a point P near a spherical permanent magnet.
The assumptions are: the sphere of radius $a$, uniformly magnetized with saturation magnetization $M_s$ (could also be interpreted as remanent magnetization) in the direction $\hat{z}$, the sphere is made of isotropic permanent magnet material and it is suspended in free space. For a better solution of the problem it is necessary to represent the Laplace equation (specific case of Poisson equation when $\nabla^2 \varphi_m = 0$) in spherical coordinates. This solution can be found in [54]. The solution of the magnetic flux density can be calculated for two values of radius ($r \leq a$ and $r \geq a$). Those two values represent the field inside the sphere and the field outside the sphere respectively in Equation 2-5.

$$
\vec{B} = \begin{cases} 
\frac{2}{3} \mu_0 M_s \hat{z} & r \leq a \\
\frac{1}{3} \mu_0 M_s \left( \frac{a^3}{r^3} \right) \left[ 2 \cos(\theta) \hat{r} + \sin(\theta) \hat{\theta} \right] & r \geq a 
\end{cases} 
$$

Equation 2-5

An experimental setup is installed to measure the magnetic flux density of a permanent magnet sphere and compare the results with preliminary COMSOL simulations and the theoretical model presented before. A NdFeB sphere with 2" diameter, grade N42 from K&J magnetics was measured using a gaussmeter (F.W. Bell, series 9950) and a micro positioner. The material magnetization of the sphere is estimated to be $M_s = 926$ kA/m, based on vendor specifications and by measuring the maximum B field in the surface of the sphere, that should be $(2/3) \cdot \mu_0 M_s (\sim 776$ mT).

Comparative results are presented in Figure 2-7 and show very good agreement. The positioning error of the hall probe is calculated to be $\sim 200$ µm (probably the error in the position of the sensor inside the probe).
Figure 2-7: Experiment to validate the simulation model of a spherical magnet. A) Sphere and gaussmeter setup. B) Magnetic flux density of in $\mathbf{z}$ direction for theoretical model, simulation and experiment.

Another approach that can be considered for modeling permanent magnets is using the current model, described by [57]. This model is faster to use when the sample has Cartesian coordinates or when calculating periodical arrays of magnets.

### 2.2.3 Demagnetization Corrections for Ferromagnetic Materials

A phenomenon called shape anisotropy is presented in ferromagnetic materials. Even if a material does not possess any magnetic crystalline anisotropy, the shape of the magnet will naturally influence the magnetic behavior, creating preferable magnetization directions (it means the shape will create an artificial anisotropy) [58].

This effect is especially problematic when working with thin films of magnetic materials (like most of the applications on magnetic microsystems). This effect is created because the shape of the magnetic material will induce an internal magnetic field inside the sample. This induced magnetic field will oppose (and subtract) from the external magnetic field expected from the magnet.
A way to understand this phenomenon is by representing the hard ferromagnet using the charge model. It is easy to observe that north and south magnetic poles are represented as a collection of positive and negative charges, respectively. Using this convention, the stray magnetic field $\vec{H}$ will create flux lines outside of the magnet starting from positive charges and ending in negative ones. It is only logical that inside the magnet the magnetic field will create the same lines from positive charges to negative ones. The resulting $\vec{H}$ lines inside the magnet are called demagnetization field and are in opposite direction of the magnetization of the material.

It is very important to account for this demagnetization field (correcting the measurement) whenever a material (with a shape different than a sphere) is being characterized. Otherwise the resulting values will not represent the real properties of the material and will lead to design or simulation errors. It is important to remember that one of the goals is to use the correct measurement of magnetic properties as an input for simulation models.

To have a correct demagnetization correction, the first step is measuring the magnetization curve of the material using a magnetometer. The magnetization curves of all the ferromagnetic materials described below were measured using a vibrating sample magnetometer (VSM) (ADE technologies) with maximum applied fields of 2.26 T. This technique reveals the average distribution of the magnetization of the bulk sample. To calculate the total internal magnetic field of a sample ($\vec{H}$) including the demagnetization, it is necessary to use the formula [59]: 
\[ \vec{H} = \vec{H}_{\text{appl}} - \vec{N} \cdot \vec{M} \]

where \( \vec{H}_{\text{appl}} \) represents applied magnetic field by the VSM and \( \vec{M} \) is the magnetization measured by the instrument. According to this notation, \( \vec{N} \) is a symmetrical tensor [58] [59] that contains the demagnetization factors: \( N_{xx}, N_{yy} \) and \( N_{zz} \). All other non-diagonal factors are =0. These demagnetization factors will be related to the geometry of the sample; every factor will be related with the corresponding coordinate axis (x y and z) and \( N_{xx} + N_{yy} + N_{zz} = 1 \). Calculating each demagnetization factor is not an easy task, each sample geometry will have different set of equations for its calculation. This dissertation focus on magnets with a prism geometry and their demagnetization factors can be found in [60].

Consider a cuboidal magnet (rectangular prisms) as shown in Figure 2-8, with edge dimensions in the x, y, and z directions of \( 2a, 2b \) and \( 2c \). The magnet is subjected to a magnetic field in the z direction. For thin samples with square area, i.e. \( a = b \), a term \( p = c/l/a \) is created for simplification. According to [61] the calculation of \( N_{zz} \) leads to:
\[ N_{zz} = \left( p - \frac{1}{p} \right) \cdot \ln \left( \frac{\sqrt{p^2 + 2} + 1}{\sqrt{(p^2 + 2) - 1}} \right) + \left( \frac{2}{p} \right) \cdot \ln \left( \sqrt{2} + 1 \right) + p \cdot \ln \left( \frac{\sqrt{p^2 + 2} - 1}{\sqrt{(p^2 + 2) + 1}} \right) + \\
2 \arctan \left( \frac{1}{p \sqrt{p^2 + 2}} \right) + \left( \frac{2(1 - p^2)}{3p} \right) \sqrt{(p^2 + 2)} + \left( \frac{2(1 - p^3)}{3p} \right) - \left( \frac{2^{3/2}}{3p} \right) + \\
\frac{2}{3} \sqrt{(p^2 + 1)} \left( 2p - \frac{1}{p} \right) \]

2.7

Figure 2-8: Coordinate system representation used to calculate the demagnetization coefficients. Reprinted from A. Aharoni, "Demagnetizing factors for rectangular ferromagnetic prisms," J. Appl. Phys., vol. 83, no. 6, p. 3432, 1998., with the permission of AIP Publishing [60].

Based on this geometry (square shape in xy plane), the other two demagnetization factors \( N_{xx} \) and \( N_{yy} \) are equal and can be calculated by

\[ N_{xx} = N_{yy} = (1 - N_{zz})/2 \]  (because all factors should sum 1). The use of these theoretical factors has been compared with observations of the saturation process in prisms by [62].

An example of the demagnetization correction process, for an isotropic ferromagnetic material of Pt/Co alloy (platibalt after 700ºC annealing for 40min) is presented in Figure 2-9. It is important to notice how the out and in plane measurements before correction present the shape anisotropy (they look very different),
but once the correction is made both planes look exactly the same (proof that the material has a magnetic crystalline isotropy).

**Figure 2-9:** Example of demagnetization correction using isotropic ferromagnetic material.

### 2.2.4 DC Demagnetization (DCD)

Another important property from ferromagnetic materials that can be measured using the VSM is the DC demagnetization (DCD) [63]. This DCD curve will provide the exact external magnetic field required to cancel all magnetization inside (demagnetize) a material.

For this measurement, the magnetometer will start magnetizing the sample with full negative field (-3 T). Then, a low positive magnet field will be applied (the “demagnetization” field under analysis). The field will be removed and the remanent magnetic moment of the sample will be measured (these are called recoils, because the magnetic material does not retain all the applied magnetic field). The measurement of each recoil point will be part of the DCD curve. All these steps will be repeated, but each time the “demagnetization” field will be slightly incremented (positive value).

A schematic diagram of the DCD measurement process is depicted in Figure 2-10. Each data point requires three steps applying different magnetic fields: a reversal of -3 T, the magnetizing field (variable), and measurement of the remanent magnetization...
at 0 T. In the example, 3 different data points were marked (for external fields equal to 0.2 T, 0.32 T and 0.4 T).

![Diagram of Magnetization curve and DCD curve]

**Demagnetization field** = 0.2 T
**Demagnetization field** = 0.32 T
**Demagnetization field** = 0.4 T

Steps in each data point:

1) \( \mu_0 \cdot H_{\text{external}} = -3 \) T (Reversal)
2) \( \mu_0 \cdot H_{\text{external}} = 0.32 \) T (demagnetization)
3) \( \mu_0 \cdot H_{\text{external}} = 0 \) T (recoil)

Figure 2-10: Schematic of the DC demagnetization measurement procedure.

Figure 2-11 illustrate an example of DCD curve for a hard ferromagnet (Pt/Co platibalt) in plane and out of plane. As mentioned in the previews section, it is important to correct the demagnetization of the material in any magnetization curve (including DCD), to account for the geometry of the sample.

The DCD curve is important because it enables the determination of the remanent coercivity \( H_r \) which represents the required applied field at which the measured remanent magnetization changes sign. One of the hypothesis of this work is that the remanent coercivity is tightly related with the optimal external magnetic needed to obtain a successful selective magnetization. Later in this document, the DCD curve will be an input in the simulations to calculate the optimal external magnetic field to
generate the selectively magnetization and the resulting stray magnetic fields produced by the successfully magnetized samples.

Figure 2-11: DCD in plane and out of plane of an example material. Before and after demagnetization correction.

2.2.5 Stray Magnetic Field Characterization

As mentioned by Patterson [64], the measurement of stray magnetic fields produced by ferromagnetic materials is especially challenging at the microscale and represents a technology gap that must be addressed by the MEMS community. Professor David Arnold’s group at University of Florida have developed two instrumentation systems with two different principles have been developed to enable the visualization and quantification of the stray magnetic field at micro scale: The magneto optical image (MOI) system and the scanning Hall probe microscope (SHPM).

Figure 2-12 illustrate the state of the art of the submillimeter magnetic field measurement techniques (adapted from [64]), comparing each technique by its spatial resolution in meters (x axis), the magnetic field sensitivity in Teslas (y axis) and the frame scan time in seconds (color code). An ideal technique for magnetic fields in
microrobotics will have a spatial resolution between $10^{-7}$ to $10^{-3}$ and minimizing the field sensitivity and the frame scan time.

Figure 2-12: State of the art of submillimeter magnetic field measurement techniques. Adapted from information on [64].

MOI is a technique that uses a magneto-optical indicator film as a lens for reflective polarizing light microscope to image and quantify variations on the intensity in a stray magnetic field. The magneto-optical indicator film leverages the Faraday effect of a light wave crossing through special materials in the presence external magnetic fields. The Faraday effect is a rotation of the plane of polarization, which is (to first order) proportional to the field intensity and the film’s thickness, with the proportionality constant known as the Verdet constant [65]. The fabricated MOI equipment, presents field resolution between ±50 µT to ± 1 mT, field range between ±5 mT to ±230 mT, spatial resolution of 4 µm, and average frame scan time in the order of few seconds. Figure 2-13 illustrate the technique and presents an example image.
Figure 2-13: Magneto optical imaging (MOI) measurement technique. Reprinted from W. C. Patterson, N. Garraud, E. E. Shorman, and D. P. Arnold, “A magneto-optical microscope for quantitative measurement of magnetic microstructures,” Rev. Sci. Instrum., vol. 86, no. 9, p. 94704, 2015, with the permission of AIP Publishing [65].

On the other hand, the SHPM uses a Hall sensor/probe as a gaussmeter mounted on 3D micropositioning stage for raster scanning magnetic fields in space and reconstruct the image computationally. The main advantages of the technique are the accuracy (electrical characterization), the high magnetic field range (>2 T) and high spatial resolution. Unfortunately, because the rastering nature of the technique, the drawback is the long scan time. The system built with this technique provides a range of operation and resolution that can be adjusted by changing the currents in the hall probe. The system also has a spatial resolution of 1.6 µm, raster scan resolution of 0.3 µm, and average scan speed of 0.7 points per second. Figure 2-14 depicts the SHPM technique and provides an example image [64].

Figure 2-14: Scanning hall probe measurement technique.
2.2.6 Single Magnet Simulation

Every simulation should start with the properties of the material to use. A single NdFeB magnet (Figure 2-15A) with dimensions 0.99 x 1.01 x 0.40 mm is characterized to validate finite element model simulations (using material properties described above). Characterizations and simulation results are compared with theoretical calculations using charge model. The magnetic properties are measured using a vibrating sample magnetometer (VSM). Results in Figure 2-15B confirms that the sample has a magnetization anisotropy, with a preference magnetization on the thickness axis (out of plane). The measured maximum energy product (21 MGOe) presented in Figure 2-15C was inferior to the values suggested by the vendor for Grade N52 and N42 magnets (52 to 40 MGOe). Differences could be attributed to vendor characterizations based on magnetic powder before sintered, bulk characterization for thicker samples (not for 400 µm magnets) and/or possible deterioration of the magnetic properties via oxidation of the magnets over time. The most important magnetic parameters for the single magnet are summarized at Figure 2-15D.

Figure 2-15: NdFeB magnet characterization. A) Single NdFeB magnet dimensions, B) magnetization curves (VSM), C) energy product comparison with vendor datasheets and D) table summarizing properties in plane and out of plane.
Knowing the magnetic properties of the permanent magnet, it is possible to predict the stray magnetic field produced in the surroundings. This task is just the implementation of the theory available in textbooks using the charge model. Derivations from Furlani 2001 [54] theory were implemented to obtain the expression for the z component of the B field outside of a cuboidal magnet. A MATLAB code was created to solve the book example for a magnet with dimensions: a=10 mm, b=20 mm and c=10mm and \( M_s = 8.0 \times 10^5 \) A/m. The \( B_z \) field was evaluate at \( z = 0.5 \) mm and \( z = 2 \) mm and the results can be observed in Figure 2-16.

Figure 2-16: Analytical solution of the \( B_z \) field produced by a bar magnet and comparison with literature result. Reprinted from Permanent Magnet and Electromechanical Devices: Materials, Analysis, and Applications, First Edition, E. P. Furlani, Chapter 4 Permanent Magnet Applications, p. 217, Copyright 2001, with permission from Elsevier (Academic Press) [54].
Using a magneto optical image technique, developed by our group and presented in [65], it was possible to evaluate and quantify the $B_z$ field produced by this single NdFeB magnet at different heights from above the surface (Figure 2-17). Evaluated fields are compared with two models: 1) finite-element simulations (COMSOL Multiphysics) using independent measured magnetization curves of the NdFeB material and 2) an analytical solution assuming ideal magnetization [57] using the current model. Figure 2-18 shows the comparison between measured, simulated, and theoretically predicted $B_z$ field, along the centerline of the magnet at increasing $z$ heights. The tight agreement of all three techniques confirms accuracy of the measurements.

![Figure 2-17: Magneto optical images of a single NdFeB magnet at different heights.](image-url)
An additional reconstruction of the full vector B-field from a series of single axis measurement images was made. First, $B_z$ is measured in multiple planes above the sample surface using the magneto optic measuring system. Then, because the vector field is incompressible, the $B_x$ and $B_y$ components are reconstructed by calculating the gradient of $B_z$ with respect to $x$ and $y$, and integrating the new $dB_z$ values in the $z$ direction. The continuous functions for $B_x$ and $B_y$ are converted into a discrete numerical form to make them part of the measurement system’s post processing options and finally are compared with the finite element model. The right side of Figure 2-19 depicts the reconstructed $B_x$ and $B_y$ components of the field and the directly measured $B_z$. Representations are calculated at a slice in the x-y plane 200 µm above the surface of the magnet. Simulations show good agreement with the reconstruction of each field component.
2.2.7 Magnetic Pole Boundary Simulation

After modeling a single pole magnet (previous section), the next logical step is to model the boundary between two magnets: the first one magnetized up (\( z \) direction) and the second one in parallel but with opposite direction (\(-z\)). Such case is presented, for example, in perpendicular media recording; were specific areas of a thin magnetic layer (e.g. films, substrates, tapes) are magnetized out of plane, in opposite direction of the original magnetization of the layer. The interest of this configuration lies in the high magnetic field and high magnetic gradient produced at this pole boundary. As it will be explained later in Chapter 3, higher magnetic gradients correspond to high magnetic forces.
To understand this behavior, a 2D magneto static finite-element simulation was used to estimate the stray magnetic field at a magnetic pole boundary in a magnetic substrate [66]. The simulation was made with COMSOL Multiphysics version 5.1, using “Magnetic Fields, No Currents (mfnc) as the physics [67], [68]. A 2D cross section was recreated with an air domain (17.5 µm height and 15 µm length) surrounding the magnetic substrate (Hi8MP video cassette tape). The substrate domain was designed with thickness and length of 1.75 µm / 15 µm and divided in two even ferromagnetic segments with opposite magnetizations (as representation of two ideal magnetic poles magnetized with opposite directions). As shown in Figure 2-20, the magnetization of the substrate material was defined using demag-corrected magnetization curves measured using VSM. Figure 2-21 presents the resulting B, M and H fields near the boundary. Simulation of the field along the measurement line depicted in Figure 2-A was used to generate Figure 2-21B and Figure 2-21C.

![Graph](image-url)

**Figure 2-20:** Magnetic properties of the substrate measured using VSM (second quadrant of hysteresis loop) and used as input for finite element model simulations. Dashed line represents the $\mu_0M$ field and solid line represents the B field.
Figure 2-21: Finite element simulation of the magnetic field generated by the tape in the pole boundary using COMSOL. A) Simulation of the stray magnetic flux density (B field) near the tape surface and the magnetization field (M field in the y component) in the magnetic substrate. Streamlines represent the magnetic flux density, black arrows the magnetic field direction (H) and white arrows the magnetization field (M) direction. B) Magnetic field norm (H norm) and C) magnetic flux density field norm (B norm) across the measurement line.

### 2.2.8 Checkerboard Pattern Simulation

A 3 x 3 permanent magnet array (1 mm x 1 mm x 0.4 mm each) was built using NdFeB grade N42 (from BJA magnetics) magnets, characterized before. The analyzed array is made by alternated out of plane magnetization direction (alternating poles in checkerboard pattern) magnets. This array of magnets will later become the magnetic bases for diamagnetically levitated microrobots. The MATLAB code with the implementation of the charge model (verified before) was used to calculate the
analytical solution of the stray magnetic field in the surroundings. The concept of superposition of magnetic fields was necessary to generate a solution for the array. An example solution is presented in Figure 2-22.

Figure 2-22: Analytical solution of the B_z produced by a checkerboard pattern of 1mm × 1 mm × 0.4 mm magnets with \( M_s = 1,051 \text{ kA/m} \) and calculations at \( z = 100 \mu\text{m} \) from magnets surface.

Additionally, a 3D COMSOL simulation was made using measured magnetic properties of the materials. The result yielded a solution in good agreement with the theoretical (charge) model, as can be observed in Figure 2-23. The results are calculated at 50 \( \mu\text{m} \) from the surface of the magnet array.

Figure 2-23: Comparison between COMSOL simulation (using magnetization curve) and analytical model (charge model using saturation magnetization) for the magnetic field of the checkerboard pattern with 1 mm x 1 mm x 0.4 mm magnets.
2.3 Summary

This chapter presented a background of microrobotics. The most important researchers in the field were introduced, the main books written to the date of this dissertation were discussed and a list of the review papers was suggested as introductory material to explore this field. A demonstration about the infancy of the field was made, by comparing number of publications in 2016 with related fields.

An introduction to magnetostatics was made, providing tools for solving problems in this field and to design magnetic microsystems that uses magnetic materials. The used methodology is based on the acknowledge of the theoretical model, the magnetic properties of the materials involve (characterization), the construction of a simulation model, the fabrication and testing of a device and a final validation of the proposed models. This process is always iterative. Because of this methodology, an accurate simulation model was created and validated with the theoretical models and experiments.
CHAPTER 3
MAGNETIC FORCES AT SMALL SCALE*

This chapter aims to discuss the relevant forces at small scale, that ultimate will govern the locomotion of microrobots and the interaction with surrounding objects and environment. This chapter is divided in five sections. The first section is a description of all the forces presented at small by dividing them by the type of interaction with the environment. The second section is the theoretical analysis of the magnetic force. The third section presents an analytical solution for the forces exerted by two permanent magnets. Section forth is dedicated to diamagnetic levitation. Finally, section five will describe a novel implementation of a direct magnetic force measurement technique, proposed for this research.

3.1 Relevant Forces for Microrobotics

Even though the laws governing physical behavior at the microscale are the same as the macroscopic world, the relative importance of various physical laws can dramatically change at small scales. For microrobotics, the interest relays on the forces acting on a structure and they depend on the surrounding environment. However, the importance of the forces in microrobotics is not entirely related to dimensions (size scale) but also by the context of application (environment and application). Four scenarios will be described to present the forces for microrobotics: 1) Forces interacting at long range, 2) Surface and contact forces, 3) Hydrodynamic forces, and 4) Actuation forces.

* This section contains extracts from reference [69]. Special thanks to Nicolas Garraud for their contribution on this chapter.
Presenting a proper explanation and a mathematical derivation of each of the possible forces at microscale is beyond the scope of this document. The intention is to introduce the reader to each force, present some relevant references that discuss more carefully each force and in some cases use the scaling theory proposed by Trimmer in [18] to compare the magnitude of forces to understand their importance. The following analysis is limited for scale sizes between 10 nm and 1 mm. For analysis of forces around the nanometer scale it is recommended to follow the work of nanorobots presented by [24] and the study of forces in scanning probe microscopy by [70]. Only the magnetic forces will be discussed in detail in the next section, for the relevance of this force for the research projects described in this document.

3.1.1 Forces Interacting at Long Ranges

In this document, the expression “long range” means forces that start interacting at the surfaces of the object and disappear several size-scale of the object under analysis (interactions far from the object are the interest). The three forces that interact in the long range are the gravitational force, the electrical (electrostatic) force and the magnetic force. It is common to find the electric and magnetic forces named electrophoresis and magnetophoresis, respectively (per the etymology, phoresis - φόρησις - in ancient Greek that means “the act of bearing”).

A descriptive comparison of these three forces is presented in [23] and summarized in Figure 3-1, where the force over the weight (assuming Earth’s gravity) of an element is plotted at different sizes. The thought experiment considers how to lift (against gravity) a sphere of conductive material of radius \( r \) (this will be the main variable for scaling) and density \( \rho = 6.72 \times 10^3 \, \text{kg/m}^3 \) (as a fictional example). One way is by using electrostatic (capacitive) force produce by an infinite plate, made of the same
material of the sphere, and potential difference $U = 100$ V. Another way is by using magnetic force with a cylindrical permanent magnet of radius $4r$ and height $8r$. Both, the sphere and the cylinder are permanent magnets with magnetization $M = 1.1 \times 10^6$ A/m in the same direction (aligned). The distance between the sphere and the actuation mechanism is $\alpha r$, with dimensionless value of 1 or 0.1 (to evaluate the importance of the sphere’s proximity to the actuation mechanism).

The gravitational force is one of the most important forces in the macroworld, but often becomes minimized in the microworld. It is observed in the figure that the magnetic force quickly surpasses gravity when $r$ is below 1 m. The electrostatic force surpasses gravity below $\sim 100$ µm. The electrostatic force surpasses the magnetic force when $r$ is below $\sim 1$ µm. This is a very important result because it presents the magnetic forces as the strongest forces in the most common scales of operation of the microrobots (1 µm to 100 mm). This analysis motivates specific focus on magnetic forces.
3.1.2 Surface and Contact Forces

The former section described forces when the elements were apart, although at microscale most of the strongest interactions occur when the elements are “touching” each other. The interaction between surfaces of two objects (or contact forces), at microscale will originate adhesion forces between them, capable of surpassing gravity. One of the first authors to discuss the forces that generate adhesions at small scales was Ronald Fearing [21]. He summarized the most important adhesion forces as the electrostatic, the van der Waal’s and surface tension (when the humidity of the environment is enough to create a liquid film surrounding the elements). The scaling
analysis of the surface forces is presented in Figure 3-2A. Even though the figure is extracted from [71], it is an adaptation of the original analysis made by Fearing.


Once again it is observed that the gravity diminishes with the reduction of the scale. The surface tension is higher than the van der Waal’s forces, but scales at the same rate (it is more difficult to separate wet surfaces than dry surfaces). Meanwhile the electrostatic is weaker than the van der Waal’s below 1 mm but reduces faster. These ratify the importance of the surfaces forces and how dominant they are in the microscale. Of special interest in microscale are the van der Waal’s forces [72]. They describe intermolecular forces and the importance increases when the objects have dimensions below $10^{-7}$ m (as demonstrated in Figure 3-2). These forces became so
strong that manipulations objects at small scale became very challenging \cite{73} (e.g. when manipulate sub-micron size objects, releasing the object is very complicated).

A later analysis of the surface forces (with a more mechanical engineering perspective) was made in Chapter 4 of \textit{Microrobotics Methods and Applications} \cite{26}. Additional experimental analysis of the physical phenomena made by Gauthier et al. \cite{74}, separated these types of forces in two separated groups: 1) The surface forces (non-contact), including the van de Waals, the electrostatic and capillary forces (as a special form of the surface tension). 2) The contact forces, which includes the pull-off force, as the force necessary to break the contact surface between two objects.

It is necessary to mention that from the perspective of the damage these surface forces inflicted in objects, a different field of engineering emerged called microtribology \cite{75}. The force per unit of area is more relevant in this cases, as shown in Figure 3-2B. In this example the analysis is made for two atomically-smooth SiO₂ surfaces in close proximity (surface sizes consider infinite compared with proximity). Instead of scaling the size of the object it was scaled the distance between surfaces. This plot confirms the importance of the capillary forces and how difficult result to overcome them. It also illustrates how close the three forces became when reducing the scale (keeping the charge constant). For this document purposes (and microrobotics in general) it becomes more important to control and mitigate the effects generated by those forces.

\subsection*{3.1.3 Hydrodynamic Forces}

Because many of the applications of microrobotics are in liquids, it is very important to mention the forces experimented by objects in fluids at microscale. One of the most complete descriptions of these types of forces is presented in \cite{76}. It is evident that the form and shape of the object affect the forces but for a dimensional analysis it is
possible to simplify the object as a sphere. In the field of microfluidics these spheres are described as particles or even as “cells,” and the scaling analysis is made by changing the particle diameter.

The main forces discussed in microfluidics are the buoyancy (capability to float an object against the gravity), the Brownian (a random movement produced by random collision of molecules of the fluid with the suspended particles), the Stokes’ drag (a force that oppose the particle movement), and the lift (results in a velocity perpendicular to the streamlines and is divided in two types: shear gradient-induced lift and boundary layer lift).

Figure 3-3 presents a comparison of the hydrodynamic forces adapted from [76], were a particle is moved by a magnetic force. As described by [77] the magnetic actuation on particles is very common in these field, which is why it is included in the figure. The selected velocity is 1 mm s\(^{-1}\) and channel width and depth of 100 μm. As mentioned before, the gravitational force is once again present in the analysis, but in fluidics, it is converted into the buoyancy force. It is important to mention that the buoyancy and the magnetic force scales at the same rate, but magnetic force is stronger. And is also important to show how the magnetic force became smaller than the drag force for particles smaller than 1 μm. Finally, it is interesting how Brownian forces are not problematic in the microscale but gain influence in the nanoscale.
3.1.4 Actuation Forces

Another perspective to analyze the forces at microscale is regarding the actuation mechanisms (actuators) for object positioning. It generally involves nanometer positioning or displacement techniques. An analysis of these actuation forces was made in Chapter 18 of the *Springer Handbook of Robotics* [25]. In this analysis, the three main actuation forces are electrostatic, magnetic (electromagnetic) and piezoelectric. It also mentioned that additional forces used in the field are thermomechanical, phase change, shape memory, magnetostrictive, electrorheological, electrohydrodynamic and
diamagnetism. Table 3-1 summarizes the actuation mechanisms that generate forces at micro-nano scale and comments on the efficiency, the speed of actuation (on/off commuting) and the power density required to actuate each mechanism. Each characteristic is represented in the table with arrows denoting if is very high, high, medium or low (e.g. Electromagnetic has high efficiency speed and power density compared with others). The table shows electrostatic, electromagnetic and piezoelectric are preferable actuation forces because their high efficiencies at high speeds.

<table>
<thead>
<tr>
<th>Method</th>
<th>Efficiency</th>
<th>Speed</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic</td>
<td>↑↑↑</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>↑↑↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>↑↑↑</td>
<td>↔</td>
<td>↔</td>
</tr>
<tr>
<td>Phase change</td>
<td>↑↑↑</td>
<td>↔</td>
<td>↑</td>
</tr>
<tr>
<td>Shape memory</td>
<td>↓</td>
<td>↔</td>
<td>↑↑↑</td>
</tr>
<tr>
<td>Magnetostrictive</td>
<td>↔</td>
<td>↑</td>
<td>↑↑↑</td>
</tr>
<tr>
<td>Electrorheological</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
</tr>
<tr>
<td>Electrohydrodynamic</td>
<td>↔</td>
<td>↔</td>
<td>↓</td>
</tr>
<tr>
<td>Diamagnetism</td>
<td>↑↑↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

↑↑↑ Very high        ↑ High/Fast        ↔ Medium        ↓ Low

3.2 Theoretical Analysis of the Magnetic Forces

As mentioned before, the magnetic forces have great importance in the microworld because their strength and the ability to use them for remote actuation. This section will present magnetic forces using a differential analysis, due to the convenience to use them on application were finite element model simulations are required. For simplicity, no theoretical analysis of the stray magnetic field will be presented in this section. This section was conceived thanks to the fundamental collaboration of Nicolas Garraud.
3.2.1 General Expression for the Magnetic Force

Magnetism theory textbooks often start to analyze magnetic forces using the magnetic dipole pair. Before 1988, there was a discrepancy among physicists about the equation that models the magnetic force generated by this magnetic dipole pair. The differences originated in the model for the dipole itself. The electric current loop model leads to the force \( \vec{F} = \nabla (\vec{m} \cdot \vec{B}) \), where \( \vec{F} \) is the magnetic force, \( \vec{m} \) is the dipole magnetic moment and \( \vec{B} \) is the magnetic flux density. If instead, the charge model is selected as the magnetic model for the dipole then the resulting force will be \( \vec{F} = (\vec{m} \cdot \nabla) \vec{B} \). Timothy Boyer [78] contributed to clarify the discrepancy in 1988, which is explained below.

Boyer highlights that differences between one or the other equation should be considered depending on the specific application. But as a general analysis, he proposed to expand the term \( \nabla (\vec{m} \cdot \vec{B}) \) using the vector identity to obtain:

\[
\nabla (\vec{m} \cdot \vec{B}) = (\vec{m} \cdot \nabla) \vec{B} + \vec{m} \times (\nabla \times \vec{B}) + \vec{B} \times (\nabla \times \vec{m}) + (\vec{B} \cdot \nabla) \vec{m} \tag{3-1}
\]

Boyer explained that from Equation 3-1 the terms: \( \vec{B} \times (\nabla \times \vec{m}) + (\vec{B} \cdot \nabla) \vec{m} \) will be negligible in most of the applications, because a dipole should not have any space dependence for \( \vec{m} \) (assumption that \( \vec{m} \) is independent of the spatial derivative because the dipole definition). Later on in 1990 Vaidman [79] reinforce this concept and explained that in term \( \vec{m} \times (\nabla \times \vec{B}) \) of Equation 3-1, a replacement could be made following Ampere’s law as \( \vec{J} = (\nabla \times \vec{B}) \), with \( \vec{J} \) as a current density. Therefore, if a specific problem does not involve electric current, this term could be reduced as well. This leads us to consider that for general purposes the dipole magnetic force where no external currents are considered can be expressed in both ways \( \nabla (\vec{m} \cdot \vec{B}) = (\vec{m} \cdot \nabla) \vec{B} \).
In the doctoral dissertation [80], the author presents analytical models, experiments and simulations to analyze both equations in the problem of calculating the diamagnetic levitation force and the levitation height for a diamagnetic material suspended over an array of magnets. In her conclusions, the most accurate model was $F = \nabla(\vec{m} \cdot \vec{B})$ obtained from the current model.

No additional literature presenting substantial information related to the comparison between these two models was found. Therefore, in this document the magnetic force (in the magnetic particle assembly and in the diamagnetic levitation problem) will be described using the current model in the form:

$$F = \nabla(\vec{m} \cdot \vec{B})$$

3-2

In a broader analysis of the force for elements more complex than dipoles, it is possible to consider the magnetization $\vec{M}$ as the measurement of the net magnetic dipole moments per unit of volume ($\Delta V$) as in [54]:

$$\vec{M} = \lim_{\Delta V \to 0} \frac{\sum m_i}{\Delta V}$$

3-3

In a differential analysis, the magnetization of a material with multiple magnetic moments ($\vec{m}$) of the same magnitude and direction, in a differential of volume ($dV$) could be defined as $\vec{m} = \vec{M}dV$. Therefore, a differential of force ($dF$) can be interpreted from Equation 3-2 as $dF = \nabla(\vec{M}dV \cdot \vec{B})$ and because of the scalar nature of $dV$ we obtain:
\[ d\vec{F} = \nabla (\vec{M} \cdot \vec{B}) dV \]

It is very important to make the following analysis, based on Equation 3-4: If we imagine that the magnetization vector \( \vec{M} \) is in the same direction of \( \vec{B} \), then the force will be applied in the direction of the magnetic field gradient, \( \nabla |\vec{B}| \).

Another important concept to consider is the magnetic torque [81]. A derivation of the torque experienced by a magnetic material in an external magnetic field can be found in Chapter 3.4 of [54]. Because the torque will not be used for any of the specific applications covered in this dissertation, the author refrains to present the full derivation on this chapter. It is important to mention that the general formula for the torque is obtained from the current model and it is always calculated in uniform external magnetic fields (where \( \nabla |\vec{B}| = 0 \), to simplify the analysis. In its differential form, the torque \( d\vec{T} \) in units of Nm) is presented as:

\[ d\vec{T} = (\vec{M} \times \vec{B}) dV \]

Equation 3-4 and 3-5 are fundamental to understand the role of magnetism at small scales (i.e. microrobotics). In an interpretation of them, the behavior of magnetic objects at microscale can be summarized in the following two sentences (Figure 3-4): 1) The object that experience an external magnetic field gradient, will feel an attraction and will tend to be displaced towards the direction of the gradient (force). 2) The object in the presence of a constant magnetic field will tend to rotate and align its magnetic moment with the direction of the field (torque).
Figure 3-4: Interpretation of the magnetic force and magnetic torque at microscale.

3.2.2 Specific Cases for the Magnetic Force

Returning to the analysis of the magnetic force. Using Equation 3-4 as a general expression for the force it is possible to obtain equivalent simplified equations for several groups of problems, if the magnetization is interpreted based on its behavior (non-linear, linear and constant) and its direction (aligned or not aligned with the external field). These simplified equations are very useful in finite element model simulations like COMSOL. Therefore, the following cases are presented:

**Linear and not aligned**

For most of the applications involving homogeneous and isotropic diamagnetic or paramagnetic materials, their magnetization will have a linear behavior and can be expressed as \( \vec{M} = \chi_m \vec{H} \), were \( \chi_m \) is the material magnetic susceptibility and \( \vec{H} \) is the field strength inside the material. This magnetic field is a vector and has its own direction. If \( \vec{B} \) represents the magnetic flux density in the direction of the magnetic source, then the force will be expressed as:
Linear and aligned

If the magnetization of the material is aligned with the applied magnetic field (assumption in most of the cases), then the Sommerfeld convention can be used and the field strength can be expressed in terms of the flux density using the permeability of free space $\mu_0 = 4\pi \times 10^{-7}[Tm/A]$ by the expression $\vec{M} = \frac{\chi_m \vec{B}}{\mu_0}$ and obtaining:

$$d\vec{F} = \frac{\chi_m}{\mu_0} \nabla(\vec{H} \cdot \vec{B})dV$$  

3-6

It is important to remember that the dot product of two vectors $(\vec{B} \cdot \vec{B} = B_x B_x + B_y B_y + B_z B_z = B_x^2 + B_y^2 + B_z^2 = \|\vec{B}\|^2)$ is a scalar and the gradient operator (of a scalar) result in a vector, as defined by:

$$\nabla(\vec{B} \cdot \vec{B}) = \frac{\partial}{\partial x} (B_x^2 + B_y^2 + B_z^2)\hat{x} + \frac{\partial}{\partial y} (B_x^2 + B_y^2 + B_z^2)\hat{y} + \frac{\partial}{\partial z} (B_x^2 + B_y^2 + B_z^2)\hat{z}$$  

3-8

$$d\vec{F} = \frac{\chi_m}{\mu_0} \|\vec{B}\|^2 dV$$  

3-9

Constant and not aligned

In some applications when calculating the force over ferromagnetic materials, it is common to search for expressions that consider the material when the magnetization saturates at a constant value (referred as saturation magnetization $M_s$). In this case the magnetization becomes $\vec{M} = M_s \hat{n}_M$, were $\hat{n}_M$ is the unitary vector describing the direction of this scalar saturation magnetization. The force expression is then:
\[ d\vec{F} = M_s \nabla (\hat{M}_M \cdot \vec{B}) dV \] (3-10)

**Constant and aligned**

Most of the multiphysics simulations over super paramagnetic nanoparticles assume that the magnetization of the particles aligns instantaneously with the external magnetic field (sometimes this is a very rough approximation). In these cases, it is possible to describe the external magnetic flux density vector as the norm and direction of the unitary vector: \( \vec{B} = \|\vec{B}\| \hat{n}_B \) and if the field and magnetization are aligned then \( \hat{n}_B = \hat{M}_M \). Therefore, \( \hat{M} \cdot \vec{B} = M_s \|\vec{B}\| \|\hat{n}_B\| = M_s \|\vec{B}\| \) because \( \hat{n}_B \cdot \hat{n}_B = 1 \) and the force expression simplifies as:

\[ d\vec{F} = M_s \nabla \|\vec{B}\| dV \] (3-11)

**Nonlinear and not aligned**

Not all the ferromagnetic applications consider the saturation magnetization of the material. Most of the times, the magnetization behavior of a material is presented by a magnetization function (hysteresis curve in case of permanent magnets). When this happens, the magnetization is represented as a vector function of the external magnetic field \( \vec{M} = \vec{M}(\vec{H}) \). This case is the one that should be considered in most of the finite element model simulations where it is desired to include measured properties of materials. The general force equation became:
\[ d\vec{F} = \nabla(\vec{M}(\vec{H}) \cdot \vec{B})dV \]  

3-12

**Nonlinear and aligned**

Finally, when the magnetization vector function is aligned with the external field, the dot product of them can be simplified as \( \vec{M} \cdot \vec{B} = \|\vec{M}(\vec{H})\| \hat{\vec{n}}_B \cdot \|\vec{B}\| \hat{\vec{n}}_B = \|\vec{M}(\vec{H})\| \vec{B} \)

because \( \hat{\vec{n}}_B = \hat{\vec{n}}_M \) and \( \hat{\vec{n}}_B \cdot \hat{\vec{n}}_B = 1 \). The expression for the force in this case is:

\[ d\vec{F} = \nabla\|\vec{M}(\vec{H})\| \vec{B}dV \]

3-13

The following figure (Figure 3-5) summarizes the expressions of the magnetic force based on the direction and behavior of the material magnetization in an external magnetic field.

### Figure 3-5: Magnetic force expressions based on the behavior and direction of the magnetization of the material.

<table>
<thead>
<tr>
<th></th>
<th>Linear</th>
<th>Constant</th>
<th>Nonlinear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Aligned</td>
<td>( \chi_m \nabla(\vec{H} \cdot \vec{B})dV )</td>
<td>( M_s \nabla(\hat{\vec{n}}_M \cdot \vec{B})dV )</td>
<td>( \nabla(\vec{M}(\vec{H}) \cdot \vec{B})dV )</td>
</tr>
<tr>
<td>Aligned</td>
<td>( \frac{\chi_m}{\mu_0} \nabla|\vec{B}|^2dV )</td>
<td>( M_s \nabla|\vec{B}|dV )</td>
<td>( \nabla|\vec{M}(\vec{H})| \vec{B}dV )</td>
</tr>
</tbody>
</table>

3.3 **Analytical Solution of the Force Between Two Magnets**

In the previous section the force generated by an external magnetic field over a magnetic object was explained, but in some applications, the magnetic field is produced by another magnetic object. An example of this case is the force between two cuboidal magnets. The solution is not trivial, it is related to the relative position of both magnets and in most cases, it is better to use finite element model to compute that force.
In 1984 Akoun and Yonnet [82] provided a 3D analytical solution for this problem and experimental verification showing astonishing match. A later solution for the force between two cylindrical magnets was presented by [83]. These generic calculations were used to generate a “map” of the magnetic force in the space, by fixing the position of one of the magnets and calculate the force in each point of the space meanwhile the other magnet is displaced [84]. Based on these calculations, Robertson et al. [85], [86] created a public framework for calculating forces between magnets and create a 2D plot of these forces as a function of the position of one of the magnets. Using this framework, a simplified case of one magnet separating from other in x axis is presented in Figure 3-6.

Figure 3-6 Analytical solution for the force between two cuboidal magnets. Magnets displacement in x axis only.

Advancing the understanding of the magnetic forces, the following experiment was made: If the moving magnet is orders of magnitude smaller (almost as a “differential” magnetic volume) than the fixed one, then it is possible to raster it through
the entire area of the big magnet and obtain a 3D representation of the magnetic force. Figure 3-7 illustrate this concept by calculating the magnetic force between a 3 mm × 3 mm × 0.4 mm NdFeB magnet (grade N42) and a 150 µm x 150 µm x 8 µm CoPt magnet (not shown in the figure). The magnet separation is 296 µm. Because the superposition of magnetic fields, this technique is useful to estimate the forces generated by multipole-arrays of magnets. As it will be demonstrated later in section 3.5, these results not only provide a better understanding of the array of magnets, but also serve as a proof of concept for an alternative “force measurement” method. The forces between two magnets can be used to characterize magnetic constructions at micro scales, such as microrobots.

Figure 3-7: 3D representation of the analytical solution for the magnetic force between two cuboidal magnets when one magnet is one order of magnitude bigger that the other. Magnet separation is 296 µm.

3.4 Diamagnetic Levitation

Because of its curiosity, repulsive forces generate by magnetic fields over diamagnetic materials are of high interest. According to Jiles [87], “Diamagnets are solids with no permanent net magnetic moment per atom…Diamagnetism leads to very weak magnetization which opposes the applied magnetic field”. A priori analysis of this
statement will lead to think that it is trivial to use these repulsive forces to suspend (levitate) a magnet over a diamagnetic material or vice versa. Unfortunately, it is not.

The first setback is theoretical. For many researchers, levitating a magnet appears to be a violation of the Earnshaw theorem [88]. In 1839 Earnshaw demonstrated mathematically that a stable free suspension of a collection of particles with the characteristics of a permanent magnet in vacuum is not possible. Earnshaw proved that a configuration consisting of bodies that attract or repel one another with a force proportional to the inverse square of the distance between them is always unstable. The stability will come with the addition of other attractive or repelling forces such as induced by currents. In a personal interpretation of this theorem, this will be true if we are trying to find a stable state (suspension) in a configuration of only particles (or permanent magnets) with the same characteristics. (In a satirical note: it is important to recognize the limitations of the time when this paper was published and the fact that it is trying to explain the constitution of the luminiferous ether).

An expanded theory of the possibilities and the conditions for free levitation was given by Braunbeck [89], where it was stated that stable levitation is indeed possible when a diamagnetic material is involved because the introduction of repulsive forces that balance the attractive forces of the magnet. With this premise in mind, several attempts to pursue diamagnetic levitation have been made. A complete history of diamagnetic levitation can be found in [90], [91] where the concept has been used in applications as diverse as sensors for structural monitoring in civil engineering [92], energy harvesting [80], microfabricated rotors [93], biomedical applications [94],
acceleration sensors [95] and even to levitate frogs [96] (very iconic and controversial research that won the IG Nobel Prize in 2000).

Although many of the elements in the periodic table are diamagnetic (copper, gold, silver), not all are used for diamagnetic levitation. The two commonly used materials for levitation are bismuth and pyrolytic graphite [97], because they are the materials with the highest magnetic susceptibility at room temperature, with 

\[ \chi_m = -16.6 \times 10^{-5} \] and \[ \chi_m = -40.9 \times 10^{-5} \] respectively [98]. There are four configurations to obtain diamagnetic levitation:

1) By levitating the diamagnetic material on top of an array of magnets with alternated poles [95], [99], [100]. A variation of this technique is to use a single magnet with selectively magnetized regions to obtain multiple poles [101].

2) By levitating a magnet using the diamagnetic material and additional magnets to balance the forces (also called assisted levitation) [102], [103], [104].

3) An assisted levitation but replacing the balancing magnets by electric coils to induce magnetic fields [105], [106].

4) To levitate the magnet over the diamagnetic material without balancing forces [107], [108]. It is important to recognize the first to demonstrate the feasibility of levitate a magnet over diamagnet without balancing forces was Pelrine in [109]. This technique was used to fabricate levitated microrobots [110]. The microrobot is an array of cuboidal magnets with alternated magnetic poles (checkerboard pattern), such as the one presented in Figure 3-8.
Figure 3-8: Stray magnetic field of an array of magnets intended for diamagnetic levitation. Simulation obtained in COMSOL.

Using the charge model presented in section 2.2.6 (Figure 2-16) it is possible to calculate the stray magnetic field produced by the array of magnets to be levitated as microrobots. Additionally, following analysis on section 3.2.2 to calculate the magnetic forces, the diamagnetic force can be understood by considering the magnetization of the diamagnetic material always aligned with the applied magnetic field and with a linear behavior for any applied field (negative susceptibility $\chi_m$). Therefore, a differential expression of such forces will be described by Equation 3-9: $d\vec{F} = (\chi_m / \mu_0) \nabla \|\vec{B}\|^2 dV$.

This analytical solution was experimentally confirmed by [80].

An analytical model is then created to predict the diamagnetic force produced by the array of magnets, levitating on top of a diamagnetic surface. An example with
magnets 3x3 NdFeB magnets (1 mm x 1 mm x 0.4 mm) with remanent magnetization
~1,051 kA/m over a pyrolithic graphite surface (4.8 mm x 4.8 mm x 2.4 mm) with susceptibility \( \chi_m = 41 \times 10^{-5} \) was modeled. The parameters involved in the levitation will be: the thickness and susceptibility of the diamagnetic material, the order of the magnetic poles (+- or -+), thickness, size and magnetic properties (remanence magnetization) of the magnets. Figure 3-9 present a comparison of a magnetic array reducing all parameters in half, the reference sample is the array called (- + -). This model is a powerful tool to predict trends in the behavior of the magnetic force and will be used later in this document.

![Figure 3-9: Analytical solution to calculate the diamagnetic force. Sample is a 3 x 3 magnet array with alternated poles. Variation of all the parameters involve in the model.](image-url)
A more versatile model is desired, therefore finite element models (COMSOL) were used to calculate the diamagnetic force, three steps are required. 1) Calculate the quasistatic solution of the stray magnetic field (as in Figure 3-8). 2) Generate a map of the magnetic force density in the space surrounding the magnets. This could be obtained by calculating \( \frac{\chi_m}{\mu_0} \nabla \| \vec{B} \|^2 \) on each point of the space, using the magnetic susceptibility of the diamagnetic material. The force density units are N/m\(^3\). 3) Integrate the force density values in the volume corresponding to the diamagnetic material. This method simplifies the computational burden of the diamagnetic force, enabling the calculation of diamagnetic forces in complex magnetic patterns.

Figure 3-10 illustrates the technique by presenting a cross section of the magnetic force density generated by the magnets. To calculate the force generated by the magnets suspended over block of pyrolytic graphite, it is only necessary to integrate this force density function over the volume occupy by the pyrolytic graphite. As hypothetical example, the diamagnetic force (if they were touching each other) between an array of magnets and a block of pyrolytic graphite (5 mm x 5 mm x 2.5 mm), with susceptibility \( \chi_m = -4 \times 10^{-4} \), will be 1.8 mN.
Figure 3-10: Representation of the magnetic force density. A) Cross section simulation of the magnetic force density contours. B) The volume where the force density will be integrated to obtain the total force of $F_m = 1.8 \text{ mN}$.

3.5 Direct Measurement and Microscale Mapping of NanoNewton to MilliNewton Magnetic Forces

This section describes the direct measurement and mapping of magnetic forces/fields with microscale spatial resolution by combining a commercial microforce sensing probe with a thin-film permanent micromagnet. The main motivation of this work is to fill a critical metrology gap with a technology for direct measurement of magnetic forces from nN to 10’s of mN with sub-millimeter spatial resolution. This capability is ideal for measuring forces (which are linked to magnetic field gradients) produced by small-scale magnetic and electromagnetic devices including sensors, actuators, MEMS, micromotors, microfluidics, biomedical devices. This new measuring technique is validated by comparison of measured forces from small permanent magnets with the analytical models.
3.5.1 Measuring Magnetic Forces at Microscale

Ongoing technological advancements in microscale devices motivate the need for magnetic force metrology at small spatial scales. Atomic force microscopy (AFM) provides force sensing capability with sub-micron spatial resolution [111] and two variants of scanning probe microscopy are capable of measuring forces produced by magnetic fields: magnetic force microscopy (MFM) [112]–[121] and magnetic resonance force microscopy (MRFM) [122]. While these techniques are well suited for measuring forces at the micrometer and nanometer length scales, they are generally limited to forces on the order of ~1 nN or smaller [123].

For measurements of larger forces in the nN to \( \mu \text{N} \) range, microfabricated microelectromechanical systems (MEMS) force-sensing approaches are well suited [70], [124], [125], [126]. Contact-based microscale force measurements have been made using vision-based (optical) [127], [128], [129] and capacitance sensing mechanisms [130], [131]. However, non-contact magnetic force sensing at the microscale has not been widely explored, but rather forces are inferred from magnetic field measurement methods using Hall probe [132] or magneto-optical imaging (MOI) [133] techniques. To infer forces from magnetic field measurements it is necessary to calculate the magnetic field gradient (as described in Equation 3-4), which requires multiple scans at different heights (at least two). Furthermore, noise and/or resolution limitations in the measurement of \( \vec{B} \) can lead to significant errors in calculating the gradient, and hence force, especially if the field gradients are small. Therefore, in certain applications a direct force measurement is desired to decrease the measurement time and potentially increase the accuracy.
This work reports the combination of a microforce capacitive sensing probe (FemtoTools FT-S1000) with a microfabricated permanent magnet as a sensing probe yielding uniaxial magnetic force mapping capabilities at any point in space, with microscale spatial resolution and nanometer positional accuracy. A similar construction for sensing forces using MEMS devices and magnetic materials was previously explored,[134], [135] but not intended as a force mapping tool. To validate the construction of the proposed magnetic force sensing technique, an analytical model of the force between two magnets was implemented and compared with experimental measurements.

3.5.2 Experimental

As shown in Figure 3-11, an $L_{10}$ CoPt micromagnet (~150 µm x 150 µm x 8 µm) with out-of-plane magnetization serves as the “probe magnet” and is attached to a microforce sensing probe (FemtoTools FT-S1000) [131]. The force probe is factory calibrated to sense forces in the z-direction in a ±1000 µN range with 50 nN resolution and cross-axis rejection factor of >30. The micromagnet is detached from the silicon substrate on which it was formed and glued on the end tip of sensing probe using UV-curable glue. The micromagnet is oriented such that attractive or repulsive forces acting on the magnet are directed along the sensing direction of the force probe (along the probe shank). The probe is then rastered at different vertical heights (from 25 µm to 200 µm) above a magnetic sample via a micromechanical testing station (FemtoTools FT-MTA02) that facilitates a three-dimensional scanning range of 26 mm and minimum step size of 1 nm in all three directions. Microforce sensing probes can be exchanged in order to extend the force range from ±100 µN (5 nN resolution) up to 100 mN (5 µN
resolution). This means that the proposed technique can potentially measure magnetic forces ranging from 5 nN to 100 mN.

Figure 3-11: Direct magnetic force measurement mechanism and overall experimental schematic. Force range 5 nN to 100 mN and displacement range of 26 mm in xyz.

The size, shape, magnetization direction, and material properties of the probe micromagnet determine the magnitudes of the forces on the force sensor, as well as the spatial resolution of the measurement. Figure 3-12A shows the micromagnet topology as measured using an optical profilometer (Bruker Contour GT-I). Measurements of the stray magnetic field at the surface of the micromagnet are made using a MOI method (Figure 3-12B) [133]. The magnetization curves (Figure 3-12C) are measured using a vibrating sample magnetometer (VSM) (ADE Technologies EV9) evidencing: \( B_r = 0.65 \, T \), \( H_{c} = 405.8 \, kA/m \), \( H_{ci} = 726 \, kA/m \), \( B_{H_{max}} = 52 \, kJ/m^3 \) and remanent magnetic moment \( m = 74 \, \mu emu \).

Figure 3-12: Micromagnet characterization. A) Optical profilometer analysis. B) MOI measurements of the micromagnet \( B_z \) field and cross section values. Inset is
a microscope image of the micromagnet. C) Magnetization curves for material out of plan and in-plane.

To create an “interesting” test sample for field mapping purposes, a 3 mm × 3 mm × 0.4 mm N52 grade NdFeB magnet (BJA - Bob Johnson Associates, Inc.) was used, exhibiting preferential out-of-plane magnetic properties, measured by VSM to be $B_r=1.16$ T, $H_{ci}=899$ kA/m, $BH_{max}=170$ kJ/m$^3$. The magnet sample was mechanically polished to a surface roughness ($R_a$) of ~20 nm and then selectively magnetized using the procedures described in Chapter 4 and by Velez, et al. [137] to imprint stripe-like alternating negative and positive poles in the out-of-plane direction (perpendicular magnetization). In brief, the magnet was initially magnetized upwards at 7 T and then selectively reversed (downwards) using a 1-mm-thick low-carbon steel sheet (ASTM A108) magnetizing mask subjected to a 1.5 T reversal field. The result of this process is a patterned magnetic substrate where the imprinted poles have an estimated magnetization of $\mu_0 M_r=\pm 0.27$ T. The stray magnetic field ($B_z$) generated by the selectively magnetized test sample was characterized using magneto-optical image (MOI) measurements at three different heights: 0 µm, 50 µm and 300 µm (Figure 3-13).

![Figure 3-13](image.png)

Figure 3-13: Magneto-optical image measurements of the magnetic field ($B_z$) produced by the 3 mm × 3 mm × 0.4 mm selectively magnetized test sample at different measurement heights. Comparative cross section plot (right).
An analytical model is used for comparison and validation of the measurements made with the proposed force measurement technique (as presented in section 3.3). For calculating the 3D forces acting on the force probe, the Akoun-Yonnet model [82] is employed in a publicly available computational tool [85]. The force calculation assumes uniform magnetization of two cuboidal magnets ($\mu_0 M_r$=0.65 T for micromagnet and $\mu_0 M_r$=0.27 T for sample magnets) and determines the gradient of the energy equation to find the force expression. At any given point in space, the force acting on the probe micromagnet is calculated to be the superposition of the forces from the three stripe poles from the magnet test sample with zero gap between the poles.

### 3.5.3 Results and Discussion

Multiple scans were made using 100 µm steps (in the xy direction) at different z heights (25 µm, 100 µm, and 200 µm) above the test sample. Figure 3-14 illustrates the measured forces in the z direction ($F_z$) in both 2D and 3D representations. At 25 µm from the surface, forces ranging between -80 to 50 µN meanwhile at 200 µm, the forces range between -10 and 10 µN. Distinct spatial variations are observed when nearer the test sample at 25 µm, whereas at 200 µm the fields look much smoother due to spatial averaging. The spatial asperities with spatial size scales of ~100 µm, are also evident in the MOI field measurements (Figure 3-14). These local field variations are attributed to a combination of two factors: 1) magnetic microstructures created by the magnetocrystalline material grains of the NdFeB, and 2) imperfect magnetization due to the selective magnetization process (i.e. not saturating the poles in the test sample).
Figure 3-14: Force measurements at a different scan height above the test sample.

Figure 3-15 shows a comparison between the micromagnetic force measurements (performed with 50 µm step size for maximum resolution) and an analytical calculation [85]. The measurements show good general agreement with the force model and prove the concept of direct magnetic force measurement.
The limits of the proposed technique are calculated by hypothetically varying the micromagnet size by changing the edge length from 1 µm to 1 mm, while keeping the magnet thickness constant at 8 µm and assuming a constant out of plane magnetization of the magnetic material ($M_r = 426$ kA/m). The force equation $F = \nabla(M \cdot \vec{B})$, reduced in one dimension to $d\vec{B}_z/dz = F_z/(V \cdot M_r)$, where $V$ is the volume of the micromagnet. Figure 3-16 shows the range of measurable field gradients ($d\vec{B}_z/dz$) versus magnet size. The red region indicates the maximum and minimum possible force resolvable by the microforce sensor platform using different probes (5 nN to 100 mN). The purple region indicates the max and min force by the specific probe used in the results presented here (50 nN to 1 mN). The field gradient range obtained from the fabricated magnet (150 µm
edge length) is also highlighted from 0.7 T/m to 13,500 T/m). This plot highlights the tradeoff between spatial resolution and field gradient resolution.

Figure 3-16: Magnetic field gradient limits detected by the proposed technique as a function of the micromagnet edge length. The equipment, the probe and the fabricated magnet detection ranges are highlighted.

3.6 Summary

This chapter described the relevant forces at small scale and highlighted the importance of magnetic forces for microrobotic applications. The magnetic forces were explained and a set of equations intended to be used in simulation models were derived. The diamagnetic levitation was explained and calculated for a set of simulations. A magnetic force sensing technique for force range of ±1000 µN with 50 nN resolution and with a minimum step size of 50 µm has been demonstrated. The actuation principle is by attaching a micromagnet (~150 µm x 150 µm x 8 µm) to a commercial micro-force measuring probe (FemtoTools FT-S1000) and controlled by a micromechanical testing station (FemtoTools FT-MTA02). Resulting magnetic forces
measured using this method were compared with the analytical solution of the forces between two magnets (with one fixed and the other raster the surface). Measurements and an analytical model present a good agreement.
This chapter contextualize some of the techniques used nowadays by researchers to solve the problem of creating magnetic field patterns at small scale. An alternative technique called selective magnetization (briefly described in Chapter 1) will be presented as a batch fabrication process for magnetic patterns. A simulation model for the process will be presented and experimental results will confirm the existence of an ideal reversal magnetic field for this process.

4.1 Patterning Magnetic Fields

The use of permanent magnets in MEMS (micro electro mechanical systems) has been amply discussed by [138] and can track its origins back to the 1990’s with the first implementations of micromotors [139]–[142]. Later on an extensive review on the fabrication methods for integrating magnetic materials in MEMS was made by [143]. One important application of permanent magnets in microsystems is as part of microscale power generators [144], and energy harvesting systems [145]. More recently these power sources with permanent magnets as driving mechanism, have found specific applications in bioengineering as energy generators for implantable medical devices [146], powering biomedical sensors [147], and biomedical devices [148].

The use of permanent magnetic materials in MEMS was originally restricted to a single magnetization direction, i.e. the entire magnet is “poled” in only one direction. In contrast, at the macroscale, much more complex, three-dimensional magnetic field arrangements are typically used to create desirable magnetic field patterns, such as

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* This section contains excerpts from reference [8].
Halbach arrays [149]. These arrangements generally enable stronger magnetic fields and/or field gradients, which enhance device-end effect performance. The ability to create complex magnetic field patterns with sub-millimeter or even micrometer features in MEMS can significantly broaden the utility of magnetic materials, and also enable new microscale device architectures.

Previous attempts for creating complex magnetic structures (patterning) with sub-millimeter features began with machining permanent magnets, individually magnetizing, and assembling them [150]–[152]. Due to the high attractive forces between magnetic poles the assembly is troublesome; furthermore, the lack of batch processing makes large-scale manufacturing difficult. A more recent alternative is the inkjet-print of micro-magnets [153], but this approach still requires additional permanent magnets to guarantee a certain field orientation.

The solution presented in this work is to pattern (magnetically) permanent magnet layers by “writing” magnetic poles with desired shape and orientation. As mentioned by [144] and [154], this magnetic patterning is still one of the ongoing challenges with this technology. For instance, Figure 4-1 shows three types of power generation and all of them relay on the fabrication of complex magnetic shapes and magnetized pole patterns that are difficult to integrate in a batch fabrication process. Another example is the complex magnetic pattern for inertial rotation-based generators presented in [147].
Figure 4-1: Three different types of permanent magnet power generation technology. Blue sections represent regions where pole patterns are required. © 2007 IEEE. Reprinted, with permission, from D. P. Arnold, “Review of microscale magnetic power generation,” IEEE Transactions on Magnetics, vol. 43, no. 11, pp. 3940–3951, 2007 [144].

The five mechanisms that are mainly used for magnetic micro-patterning are described below. This literature review describes these mechanisms and presents the most relevant work up to date.

First, poles can be created by generating spatially varying magnetic fields with current-carrying conductors. This mechanism, published in 1998 by [155], proposed a magnetization feature based on the magnetic field generated by passing current in a conductor (Figure 4-2). The magnet was made out of plastiform flexible NdFeB and the magnetized poles had minimum size of 42 mm (inner length for each one of the 6 segments in the ring). Magnetic flux densities were measured using a Hall effect gaussmeter.

In [156], [157], the magnetization of 0.5 mm thick NdFeB magnets with 1 mm pole pitch was reported. Poles were obtained by using pulse magnetization using wire windings. Remanent induction of the patterns was measured using Hall probe scanning and magnetic field reconstruction was made by software.

Using a configuration of wire windings and a soft ferromagnetic magnetizer, [158] [159] present a planar micro-generator. A 8 mm diameter and 0.5 mm thickness disk made of SmCo₅ was magnetized with 15 pairs of poles. No direct measurement of the magnetic fields generated by the magnet was documented. So far all groups working with windings recognize that scalability below 1 mm is an issue.
In the second mechanism, the composition of the magnetic material is modified in order to locally change the coercivity of the material. If the material has predefined areas with lower coercivities than others, then all the material can be strongly magnetized in one direction and after, the field can be switched to a negative value greater than the coercivity of sections with higher coercivity, but less than that of the areas with lower coercivity. In order to create pole patterns. This mechanism was presented by [160]. The entire permanent magnet was electrodeposited, but the regions with different coercivity were generated by using patterned electrodes (with the desired shape of the poles) that will alter the current conditions during the electrodeposition. The current changes induce chemical modification of the magnet composition, therefore the coercivity alterations. Poles of 450 µm were generated and the stray fields were measured using a Hall probe.

The third mechanism to magnetize patterns on a permanent magnet is the thermomagnetic patterning [161]. This method aims to reduce the coercivity of the magnet by increasing the temperature locally, using laser irradiation through a mask. If this heating process is done in the presence of external magnetic field (in the opposite direction of the magnet’s magnetization), then the segments exposed to the laser will change the orientation of their magnetization. This process is illustrated in Figure 4-3. NdFeB films with thickness of 4 µm were magnetized with 50 µm pitch [162]. Scanning Hall probe microscopy was used to measure the stray magnetic fields of the patterned structures [162]. One drawback of this technology is the depth of magnetization reversal, which was estimated to be 1.1 ± 0.2 µm. Later on, in [163] this depth was
increased to 1.3 μm. Thermomagnetic patterning has been mainly used in microfluidic applications [163], particle capturing applications [164], [165], and cell capturing [166], [167].


In order to increase the magnetization depth, a variation of the thermomagnetic patterning was made by [168]. The external magnetic DC field was applied by an array of permanent magnets and the heat process was conducted by laser beam scanning (speed of 12m/s). A 4.5 μm thick NdFeB/Ta magnet over glass was magnetically patterned with features between 70 μm and 100 μm. Magnetic flux density of the patterns was measured using a Hall element.

The fourth mechanism relays on ion implantation or irradiation for patterning magnetic films. This mechanism pertains the change in magnetization of selected areas using ion irradiation or implantation results in a reduction of the magnetic anisotropy
The mechanism is explained in figure Figure 4-4. This mechanism, has a bottom-up approach and it is more suitable for nanoscale magnetic patterning, but because it’s relevance in the field it worth to be mentioned. Depth and size of the magnetized patterns are still in the order of hundreds of nanometers, and is a useful technique for patterning thin magnetic films.

Figure 4-4: Sketch of the irradiation induced intermixing at the upper and lower Co/Pt interface. Reprinted from J. Magn. Magn. Mater., vol. 320, no. 3–4, J. Fassbender and J. McCord, Magnetic patterning by means of ion irradiation and implantation, pp. 579–596, Copyright 2008, with permission from Elsevier [169].

Lastly, in the fifth mechanism the magnetic fields can be shaped using soft-magnetic magnetizing heads to selectively magnetize poles into magnetic layers. This mechanism does not involve wire windings or altering physical properties of the magnet, instead it uses ferromagnetic magnetized heads to imprint patterns on magnets. This method was originally proposed by [175] [176] to pattern a SmCo magnet. Eight poles were magnetized in a disk of 9.5 mm diameter and 0.5 mm thickness. A Hall sensor measures the magnetic field. Dr Arnold’s group at University of Florida has continued working on improving this method by varying the magnetization mask according to the needs of the application. A laser and mechanical machined Hiperc050 mask (with 200
µm trenches) mask was used to magnetize 10 µm thick Co-Pt magnetic films with 250 µm features [177], [178]. Scanning Hall probe measurements were made to quantify the magnetic films. A laser machined magnetic foil mask was implemented by [179]. Sub-100 µm features on a 10 µm thick CoPt film were demonstrated. More recently, a microfabricated mask (electroplated) was used to magnetize patterns down to 50 µm in 15-µm-thick CoPt films and 5-µm-thick NdFeB films [180]. A variation of this process is conceived by Correlated Magnets [181], where the mask is a simple small circle and by repetition of the magnetization process and displacement of the mask in the space it will be possible to “write” any pattern in printer-like way. The equivalent to a pixel in a printer will be a “maxel” (magnetic pixel) in this selective magnetization process.

The selective magnetization process using shaped magnetizing heads has been shown to be widely adaptable to different pole sizes (microns to millimeters), materials (ultra-thin magnetic layers, electroplated thick films, bulk rare earth materials), and geometries (simple stripes to complex shapes) This complexity leads to the introduction of a simulation approach for modeling the process and the resultant magnetic structures [182].

4.2 Selective Magnetization Process

The selective magnetization technique to imprint relatively arbitrary magnetic pole patterns onto hard magnetic substrates using soft magnetic “magnetization masks” was proposed by [183] and [184]. The method is depicted in Figure 4-5. The soft magnetic mask (hereafter the mask) can be made of nickel or carbon steel. To imprint magnetic pole patterns in a substrate using this method, first the substrate is uniformly pre-magnetized out-of-plane (upward) first, using a 6 T pulsed magnetic field. Then a soft magnetic “magnetization mask” is placed in contact with the substrate, and a
reversal (downward) magnetic field pulse is applied (in the order of hundreds of mT). The high permeability of the magnetization mask concentrates the magnetic flux in the poles of the mask, thereby flipping the magnetization down in those areas. In the other regions (between the poles underneath the air gaps of the mask), where the fields are weaker, the magnetization remains in the original upward orientation.

Figure 4-5: Schematic of selective magnetization process. Magnetic tape is strongly magnetized up (6 T). Then the magnetization mask is placed on top of the substrate, and a reverse magnetic field is applied. This reversal field selectively reverses the direction of the magnetization on the substrate, only in the areas underneath the mask.

The mask can be optimized by simulating feature sizes, separation between structures, materials, and mask thickness. Every parameter variation involve in the magnetization process can be simulated by using finite element method in COMSOL Multiphysics.

4.2.1 COMSOL Simulation

The selective magnetization process is modeled using COMSOL Multiphysics using a 2D simulation. The finite-element method is used to solve the magneto-quasi-static Maxwell equations, following the methods reported in [182]. The experimentally measured nonlinear magnetic properties of the substrate and mask materials (magnetization curves) are used in the simulations.
Simulations are divided in two consecutive and dependent steps: first, the application of the reversal magnetic field (Figure 4-6, top row), followed by second, the stray field generated by the remanent magnetization in the substrate after selective magnetization (Figure 4-6, bottom row). In the first step, the substrate is initially considered uniformly magnetized up, and the simulation models the fields during the peak of the downward selective reversal pulse. The result of this first step is then used to calculate the conditions for second step. Following Samwel., et al. [185], the remanent magnetization at every point in the substrate is calculated using the DCD curve. The DCD curve relates the peak field from step one to the resultant residual magnetization used in step two. Step two of the simulation computes the stray fields for the selectively magnetized substrate (with the magnetizing mask no longer present).

Figure 4-6: Selective magnetization process simulation (during magnetization – top row) and stray B field generated by the magnetic substrate after selective magnetization (after magnetization – bottom row). The M field inside the magnetic substrate and the mask.
The sensitivity of the magnetization process with respect to the reversal B field amplitude is evident in simulations shown in Figure 4-7, comparing reversal fields of 100 mT, 400 mT, and 700 mT. Figure 4-7 shows the profile of the predicted $B_z$ stray fields at 50 µm above the surface of the substrate for the same three cases. For the 400 mT case, the simulations indicate that it is possible to selectively reverse the substrate through its entire thickness, as compared to the thermomagnetic patterning [161], [163], which was limited to ~1 µm in depth. This case also yielding the strongest magnetic stray field contrast. These simulations suggest there exists an ideal (optimal) reversal magnetic field at which the substrate sections underneath the mask reverse without affecting the magnetizations of the remaining substrate. Consequently, a parametric series of simulations and experiments are conducted, varying the reversal B field from 50 to 1100 mT in order to determine the optimal field.

Figure 4-7: Simulations of the stray magnetic field comparison at 50 µm above the substrate for three reversal magnetic fields.
4.2.2 Magnetization Mask Machining and Model Validation

Figure 4-8 shows the magnetizing mask used in this section and the resulting pole pattern of a selectively magnetized substrate. The mask has a simple stripe pattern and is conventionally machined (using Sherline CNC) from AISI 1018 mild/low carbon steel (relative permeability $\mu_r=102$) with the feature size (line/space) of 1 mm and feature depth of 0.6 mm. The magnetic substrate for selective magnetization is a flexible iron oxide material with 0.57 mm thickness, remanence of $B_r=180$ mT, and coercivity of $H_{ci}=125$ kA/m ($\mu_0H_{ci}=0.16$ T).

Figure 4-8: Low aspect ratio magnetization mask. A) Schematic of the magnetization mask (gray) over magnetic substrate (orange). Red dashed lines represent the simulation line and the images taken using magneto optical images at 50 $\mu$m of the surface (shown late). B) Magnetization mask. C) Magnetized pattern on flexible iron oxide observed using magnetic viewer paper.

Magnetization fields from 100 mT to 1000 mT are applied using a pulse magnetizer on independent samples. Magneto-optical images of each sample are taken [65] using a 250 mT saturation magneto-optical indicator film at 50 $\mu$m above the surface of the substrate. Figure 4-9A presents an example 3D representation of the field pattern after magnetization, and Figure 4-9B presents the average measurement of the
B\textsubscript{z} field across the feature line (average of 1240 profiles). Figure 4-9C shows the average B\textsubscript{z} field (measured at 50 μm) generated by samples experimentally magnetized at 88 mT, 411 mT, and 926 mT. The values B\textsubscript{min} and B\textsubscript{max} defined in this figure correspond to the fields measured in the center of the mask pole and air gap, respectively.

Figure 4-9: Magneto-optical images of the selectively magnetized sample (at 411 mT) taken at 50 μm above the surface. A) Magneto optical topographical view of the B\textsubscript{z} field. B) Magneto optical image of the B\textsubscript{z} field and average profile along the x axis. C) B\textsubscript{z} field profiles for samples magnetized with different external magnetic fields.

Figure 4-10A compares B\textsubscript{z} field simulation and experimental values. The maximal values of B\textsubscript{max} and B\textsubscript{min} were 45 mT and -23 mT, measured on sample magnetized with 411 mT. The results show the simulations accurately predict the general trends of the fields. However, there is some discrepancy in the absolute field magnitudes; the simulations under-predict the measurements. Discrepancies in the magnitude of the B fields between simulation and measurements can be attributed to experimental inaccuracies in the magneto-optical measurements; underestimation of the B fields generated by the mask during simulations; or oversimplifications in the simulation model (e.g. only permits magnetization in the z-direction).
As an overall figure of merit for the magnetization process, the magnetic contrast is defined as [186]: \[ C = \frac{B_{\text{max}} - B_{\text{min}}}{B_{\text{max}} + B_{\text{min}}} \]. Figure 4-B shows a comparison between the B field contrast from simulations and the experimental measurements. These results confirm the existence of an optimal external magnetic field value at which the contrast is maximized (~500 mT in this case). A contrast difference between simulations and measurements is on the order of 29%.

4.2.3 Variations on the Selective Magnetization

To improve the selective magnetization procedure and make it viable for magnetic substrates with high intrinsic coercivity and remanence (such as NdFeB), some variations of the process were considered. It is necessary to remark that none of the following configurations were used in future experiments, although they show important learning lessons for future applications.

The intention of this set of experiments is to compare the selective reversal magnetizations (were the initial state of the substrate is fully magnetized up) with two techniques where the magnet has no initial magnetization (zero-base magnetization).
One sample will be magnetized in one step and the other sample will be magnetized in two steps with opposite field direction, as depicted in Figure 4-11.

Figure 4-11: Zero-base magnetization experiment description. Inset represents the cubical soft magnetic mask used for magnetization.

For this experiment, we used a 3 mm x 3 mm x 0.4 mm NdFeB diced magnet (magnetic properties described before in Chapter 2) and a cuboidal mask of iron oxide of 1 mm x 1mm x ~1 mm. We demagnetize samples by rising the temperature to 327ºC. The applied magnetic field was selected from DCD measurements. Magnetized samples were measured using MOI technique. Figure 4-7 compares the field measurements of the three samples with a COMSOL 3D simulation of an ideal square fully magnetized in a middle of the 3 mm x 3 mm substrate. We shifted all results to the same field level for comparison. Results were very encouraging because showed the possibility to increase the magnetic field amplitude by simply selectively magnetize the substrate that is originally demagnetized.
Another variation that was considered during the reversal magnetization process was the inclusion of a soft magnetic back plate (same material of the magnetization mask). Unfortunately, this experiment didn’t show significant improvement, as can be observed in Figure 4-13. The back plate increases the resulting maximum stray magnetic field, but also increases the minimum magnetic fields reducing significantly the contrast.

Figure 4-13: Inclusion of a soft magnetic back plate during the magnetization.

Another experiment performed in the search of alternatives for increasing the magnetic field generated by the selectively magnetized sample was the inclusion of a
soft magnetic back plate. The hypothesis was that the plate could close the magnetic flux lines in one side (top side of the checkerboard) and enhance the stray magnetic field in the opposite side (bottom side). A manually assembled checkerboard pattern was used for this experiment and a soft ferromagnetic back plate with similar dimensions (thickness ~140 µm) of the magnet array was machined. Figure 4-14 presents the comparison of the magnetic field generated by the manually assembled checkerboard array with and without back plate (measured using the MOI). Even though the field is relatively stronger with back plate, the results were inconclusive and lower than expected (it was intuitively expected to double the fields).

![Graph showing comparison of magnetic field with and without back plate.]

Figure 4-14: Comparison between manually assembled micro-robot with and without back plate and picture of the micro-robot with the back plate.

### 4.3 Summary

A process for imprinting magnetic pole patterns on permanent magnets was proposed called selective magnetization. The fabrication process was modeled using simulations and validated with experiments showing very good agreement and the potential to be used in the microfabrication of magnetic microsystems such as microrobots.
CHAPTER 5
MICROROBOT FABRICATION: BOTTOM-UP APPROACH

By the time the research reported in this chapter was conducted, the idea of working on the microrobotics field was not contemplated by the researchers related with this project. Later involvement in this field, reveals that the product of our work (called releasable magnetic microstructures in this chapter) is in fact another form of microrobots. The fabrication approach presented here is called bottom-up (piecing together of elements to give origin a more complex system), because uses the physics of nanostructured materials to conform structures with micrometer dimensions and observe the behavior in the macro world.

This chapter describes a versatile method to fabricate magnetic microstructures with complex two-dimensional geometric shapes using magnetically assembled iron oxide (Fe$_3$O$_4$) and cobalt ferrite (CoFe$_2$O$_4$) nanoparticles. Magnetic pole patterns are imprinted into magnetizable media, onto which magnetic nanoparticles are assembled from colloidal suspension into defined shapes via the shaped magnetic field gradients. The kinetics of this assembly process are studied by evaluation of the microstructure features (e.g. line width and height) as a function of time, particle type, and volume fraction. After assembly, the iron oxide particles are crosslinked in situ, and subsequently released by dissolving a sacrificial layer. The free-floating magnetic structures are shown to retain their patterned shape during manipulation with external magnetic fields. Figure 5-1 summarize the intention of this research.

Figure 5-1: A method is presented to batch-fabricate complex, free-floating magnetic microstructures from magnetic nanoparticle feedstocks. Magnetically patterned substrates using selective magnetization technique are used to assemble the nanoparticles into complex geometric shapes. Particles are then crosslinked \textit{in situ}, creating rigid magnetic microstructures that are released as free-floating structures for external magnetic manipulation.

5.1 Magnetic Assembly and Cross-Linking of Nanoparticles for Releasable Magnetic Microstructures

Magnetically directed and self-assembly of magnetic micro/nanoparticles in one, two, and three dimensions[187] is of increasing interest owing to the unique stimuli-responsive behavior of the resultant micro/nanostructures. For example, in sensors and electronics,[188] assembly of magnetic nanoparticles into microstructures is desirable to tailor the properties of the structure (\textit{e.g.} photoelectrical activity,[189] surface morphology,[190] electrochemical response,[191] surface enhanced Raman scattering
[192] or surface plasmon [193]). For microelectromechanical systems (MEMS),[194] structural characteristics of the assembled microstructures and the mechanical deformation of the structures in the presence of magnetic fields can be used for manipulation and actuation. In the biomedical field, there is interest in microstructures fabricated with magnetic nanoparticles for targeted delivery of therapeutic agents and for more effective diagnosis techniques that extend the limits of molecular diagnostics.[195] Magnetic nanoparticle assembly has also been used in photonics for obtaining periodic structures, designed to have a strong interaction with light.[196], [197]

In the above examples, externally applied magnetic fields are used to drive the assembly of the particles. Methods for magnetically-directed assembly can be generally classified as colloidal-assembly techniques and surface-patterning techniques. In the former, magnetic dipole-dipole interactions are used to drive the assembly of particles (typically microparticles) in suspension, while in the latter, magnetic media with a pre-determined field gradient pattern is used to drive assembly of particles (typically nanoparticles) onto a surface.

The formation of magnetically-directed colloidal superstructures with multipole symmetry, consisting of paramagnetic and diamagnetic microparticles assembled mediated by induced dipole-dipole interactions in a magnetic nanoparticle suspension, has been demonstrated.[198] Depending on the relative sizes and induced dipole moments of the constituent particles, a variety of shapes have also been demonstrated.[199]–[201] However, it is not possible to generate complex asymmetric shapes using this approach, and the structures reported thus far do not retain their shape once the magnetic field is removed,[202] except when fixing them to the
substrate. Magnetic dipole-dipole interactions have also been used to drive colloidal assembly of superparamagnetic microparticles into chain-like structures.[203], [204] Crosslinking of the microparticles using complementary DNA strand hybridization and by chemical means has been reported to yield microparticle chains that retain their form once the magnetic field is removed.[205] These structures can also be manipulated using applied magnetic fields, in order to actuate their rotation and vibration,[204] and applications in mixing of microfluidic systems have been reported.[206] However, this method of magnetically-directed assembly and crosslinking appears limited to formation of linear structures and lacks control over the length of the resulting linear aggregates. Thus, it would seem that current methods of colloidal magnetically-directed assembly are limited to particles with high degree of symmetry or to chain-like aggregates, and the current methods are difficult to extend to obtaining structures with complex asymmetric shapes.

For more complex shapes, the use of patterned magnetic media templates to drive the assembly of magnetic particles from solution to the surface of the media has also been reported. Experiments have demonstrated assemblies with micron[207] and sub-micron feature sizes,[208]–[212] and simulations have indicated that assembly for such small structures occurs in millisecond time scales.[213], [214] Most commonly, a magnetic pattern is recorded in magnetic recording media (e.g., magnetic tape or a hard drive surface) using a magnetic write head.[215] The resulting magnetization pattern then generates magnetic field gradients that capture particles from solution, resulting in linear or bit-like patterns.[216] These patterns can be transferred to a polymer film substrate, which can be lifted-off and used, for example, as a diffraction grating.[217]
Although these techniques are promising, to date the complexity of the patterns of assembled magnetic particles has generally been limited to the geometry of the magnetic bit of the respective recording medium.[217] Furthermore, although basic shapes can be obtained using this method, they are confined to a surface or film, and fabrication of free-floating magnetic microstructures has not been demonstrated using these techniques.

In this contribution, we report a method that combines the potential of magnetically-directed assembly of magnetic nanoparticles on a substrate with in situ nanoparticle crosslinking to obtain releasable free-floating complex magnetic microstructures. The magnetic field gradient patterns required to drive magnetic nanoparticle assembly into complex shapes are obtained using a selective magnetization technique to imprint relatively arbitrary magnetic pole patterns onto hard magnetic substrates using soft magnetic “magnetization masks”. [183] By chemical crosslinking, the magnetically assembled structures retain their shape after release from the substrate even in the absence of a magnetic field. They can also be manipulated through applied magnetic stimulus, enabling control of their translational and rotational motion in suspension, and their deformation, depending on their shape and degree of crosslinking. By changing the polymer linkers in combination of selected drug molecules a magnetically-triggered drug release mechanism can be envisioned, as reported recently[210], [218]–[222]. The reported method is a simple, low cost, and scalable route to generating free-floating magnetically assembled complex microstructures of crosslinked magnetic nanoparticles. Furthermore, refinement of the selective magnetization and crosslinking steps should enable generating structures with sub-
micrometer features. Finally, the process flow could conceivably be adapted for continuous, e.g. roll-to-roll, fabrication of the magnetic microstructures.

5.2 Results and Discussion

The fabrication method of magnetic microstructures is illustrated schematically in Figure 5-2, where magnetic nanoparticles are assembled via the magnetic fields from a magnetically patterned substrate (in this case a Hi8MP video cassette tape). The particles preferentially assemble in the higher magnetic gradient regions at the boundaries of the magnetic poles, allowing for the generation of complex two-dimensional shapes.

Both iron oxide (Fe₃O₄) and cobalt ferrite (CoFe₂O₄) nanoparticles were used in this work, in an effort to explore how different magnetic relaxation mechanisms may influence the assembly process [187], [203], [223], [224]. During the assembly process,
particles will translate and rotate as they respond to the magnetic field gradient generated by the magnetic pole pattern. The iron oxide nanoparticles used in this study respond to magnetic fields through internal dipole rotation, known as Néel relaxation, whereas the cobalt ferrite nanoparticles used in this study respond to magnetic fields by rigid body rotation, known as Brownian relaxation. We expected possible differences in the rate of assembly of the Néel and Brownian particles due to the differences in magnetic torques and the corresponding hydrodynamic translation/rotation coupling. However, as will be seen upon discussion of our results, there were no measurable differences in the assembly rates of the two types of nanoparticle.

The iron oxide and cobalt ferrite nanoparticles were each synthesized by thermal decomposition.[225], [226] The hydrodynamic diameter distributions were obtained by dynamic light scattering (DLS) using a Brookhaven Instruments 90Plus/BIMAS. For the analysis, oleic acid coated nanoparticles were suspended in toluene and then filtered with 0.1 mm PTFE filter syringes prior to measurement. Typical number-weighted hydrodynamic diameters for the oleic acid coated particles used in the experiments were 19 ± 3.9 nm iron oxide and 20 ± 3.3 nm for cobalt ferrite.

The particle’s core diameter distribution was determined by fitting the diameter histograms measured by TEM (JEOL 200CX microscope, operating at 120 kV acceleration voltage) to a lognormal size distribution, indicating the particles had narrow size distributions, with average core diameters of 17 ± 5.6 nm for iron oxide and 13 ± 2.9 nm for cobalt ferrite.

Some of the iron oxide nanoparticles were transferred to the aqueous phase by cleavage of the oleic acid double bond to obtain nanoparticles with surface carboxylic
acid groups. The resulting nanoparticles were now colloidally stable in aqueous media and possessed reactive carboxylic acid groups that were subsequently used to crosslink the structures. After transferring the particles to the aqueous phase, the particle hydrodynamic diameter remained practically the same, confirming that there was no particle aggregation.

Equilibrium magnetization measurements at 300 K for aqueous nanoparticle suspensions, made using an MPMS-3 superconducting quantum interference device (SQUID) magnetometer (Quantum Design), demonstrated superparamagnetic behavior in the samples. By fitting the data to the Langevin function using the procedure suggested by Chantrell,[227] the average magnetic diameter was 8 ± 5.2 nm for iron oxide and 13 ± 3.3 nm for cobalt ferrite, while the volume fraction (ϕ) of magnetic nanoparticles in the stock solutions were determined to be 0.19% and 0.14%, respectively. After transferring the iron oxide nanoparticles to the aqueous phase, the average magnetic diameter was 9 ± 4.5 nm, and the magnetic volume fraction (ϕ) in the stock solution was 0.062%.

The poles in the magnetic tape were created by a selective magnetization technique using soft magnetic “magnetization masks”. [184] A magnetization mask (hereafter mask) was fabricated by electroplating 45-µm-thick Ni structures on a silicon wafer. Different shape and size structures were included in the mask, as shown in Figure 5-3. However, detailed analysis focused on 175-µm-wide squares and 150-µm-wide crosses with minimum edge-to-edge distance between structures of 225 µm. It is important to remark that the magnetic mask can be reused, thereby reducing fabrication time and cost associated with lithography steps. A magnetic reversal field of ~200 mT
was used to generate the magnetization pattern in the magnetic tape substrate. Because experimental measurement of the resultant microscale magnetic field gradients is quite difficult, simulations[67] were used to estimate orders of magnitude of the magnetic field and magnetic field gradient in a typical boundary between two opposing magnetic poles.

Figure 5-3: Magnetically assembled iron oxide nanoparticles and crosslinked microstructures over the magnetic tape substrate before release.

The kinetics of the assembly process and the resultant microstructural features were studied for three process variables: (1) assembly time, (2) volume fraction of the particles in suspension, and (3) iron oxide vs. cobalt ferrite nanoparticles. Figure 5-4 shows the average deposited line height as a function of time for different volume fractions and particle types. As expected, the line height increases with increasing collection time and increasing particle concentration. The line height is greater for the iron oxide particles (Figure 5-4A) as compared to the cobalt ferrite particles (Figure 5-4B) under all conditions tested. This observation was initially unexpected, considering that iron oxide exhibited a smaller magnetic core diameter than the cobalt ferrite (8 ± 5.2 nm vs. 13 ± 3.3 nm). Because of their larger magnetic core diameter, the cobalt ferrite particles would experience a larger magnetic force during assembly. However, the two
particles have unequal hydrodynamic diameters, so additional analysis was performed to estimate the number of particles collected.

Figure 5-4: Time dependence of the line height for different volume fractions. A) Iron oxide nanoparticles with Néel relaxation mechanism and B) cobalt ferrite nanoparticles with Brownian relaxation mechanism.

Figure 5-5 shows the number of particles assembled per unit length as a function of assembly time for different volume fractions and particle types. The roughness of the substrate and the detection limits of the profilometer caused significant statistical variation in the data. The most reliable results were generated by samples with larger numbers of particles accumulated on the substrate, e.g. the experiments with maximum collection time ($10^5$ s) and maximum volume fractions of particles in solution (0.19% for iron oxide and 0.14% for cobalt ferrite). Figure 5-6 further illustrates these maximal cases for direct comparison between the two particle types. It is worth noting that the order of magnitude of number of particles collected is the same for both particle relaxation mechanisms. However, the iron oxide particles exhibit a larger line height because the core diameter is greater than the cobalt ferrite particles (17 nm vs. 13 nm).
As was pointed out earlier, we expected possible differences in the rate of assembly of nanoparticles with Néel (iron oxide) vs Brownian (cobalt ferrite) relaxation mechanisms. However, the results of Figure 5-6 indicate that particles with either relaxation mechanism are captured at essentially the same rate. Consequently, it was
decided to carry out subsequent experiments demonstrating crosslinking and release solely with the iron oxide nanoparticles.

To demonstrate fabrication of free floating structures, an assembly experiment was conducted using the iron oxide nanoparticles that had been transferred to the aqueous phase ($\phi = 0.062\%$) and an assembly time of 19 hr. The resulting structures had typical line height and width of $230 \pm 80$ nm and $3.9 \pm 1$ µm, respectively. After assembly, the carboxylic acid groups present on the nanoparticle surface were crosslinked with the primary amines present in branched polyethylenimine (PEI).[228]–[231] A schematic of the process from phase transfer to crosslinking is shown in Figure 5-7. Structure release was achieved by dissolving an underlying sacrificial layer of polydimethylglutarimide-based resist added before particle assembly. Figure 5-8 illustrates the results by showing free-floating structures and demonstrating the successful crosslinking of particles forming a structure. Additional magnetic characterization of the resulting free-floating structures demonstrated that structures have superparamagnetic properties similar to those of the nanoparticles used in their formation. Superparamagnetic behavior is desirable because micrometric-size structures will be magnetized in the presence of external fields (higher susceptibility than counterpart paramagnetic structures) but structure agglomeration and unwanted structure-structure interaction in the absence of magnetic field will be prevented due to the absence of residual magnetization.
Figure 5-7: Schematic of the crosslinking process on iron oxide nanoparticles, starting from the formation of the oleic acid after particle thermal decomposition. The cleavage of the double bond in the oleic acid creates a terminal carboxylic group that can be used to crosslink particles using a poly-amine such as PEI, via EDC chemistry.

Figure 5-8: Examples of released structures free-floating in water after crosslinking iron oxide nanoparticles with 25kDa PEI.
The free-floating magnetic microstructures were shown to retain their geometric shape, even under response to an applied magnetic field. Figure 5-9 illustrates the displacement of one of those structures in the presence of an applied magnetic field generated by a permanent magnet. The displacement of the structure was in the direction of higher field gradient, due to magnetic forces exerted on the magnetic nanoparticles within the structure.[232] In other experiments the direction of the applied magnetic field was changed, and the microstructures were shown to move along different axes (rotate and flip) depending on the direction of magnetic field rotation, as illustrated in Figure 5-10. These observations demonstrate the potential utility of these structures that can be remotely actuated, and retain their shape after the magnetic field is removed.

Figure 5-9: Superimposed snap-shots of a single microstructure translated towards a magnetic field generated by a permanent magnet (images extracted from video). Structure made of iron oxide nanoparticles.
Figure 5-10: Rotation of a microstructure by rotating the magnetic field (TOP). Microstructure flipping produced by the change of direction of the rotation in the magnetic field (Bottom). Images extracted from video. Structure made of iron oxide nanoparticles.

5.3 Experimental Methods

5.3.1 Magnetization Mask Fabrication

The mask is manufactured using micromachining techniques as described by [233], using photolithographic patterns and 45 µm electrodeposited and polished Nickel. Figure 5-11 depicts the microfabrication process followed for the fabrication of the magnetization mask. The first step is to remove the native oxide from a Si 100 wafer using BOE. Then clean it using nitrogen and Asher (Power of 300 W for 300 s with 600 sccm O₂ at 1200 mtorr). Then sputter (KJL CMS-18) an adhesion-promoter layer of
TI (30 nm), an electroplating seed layer of Cu (30 nm), and a protective layer of Ti (30 nm) to avoid oxidation. A positive photolithographic process is conducted using KMPR 1025 (static 300 rpm by 10 s / 3000 rpm by 30 s / 12 min soft bake at 100°C) and exposition of the mask using MA6 (157.4 s at 4.1 mW/cm²). 2 min post bake at 100°C are recommended. Photoresist development using 1.38% of TMAH solution (AZ300MIF) for 30 min. Additional Asher treatment (100 W for 120 s with 10 sccm of O₂ at 25 mtorr). The photoresist thickness was confirmed at 45.6 µm.

Right before the electroplating, the Ti is etched using 1:1 solution of HF 49% and Di water for 30 sec. A commercial Ni plating bath (Techni Nickel “S”) is used under constant agitation at 100 rpm at room temperature. The conditions on the power supply are: current 10.56 mA and 1.3 V for 4 hours. (30 mA/cm² for an estimated area of 0.35cm²). Mechanical polish (microcut silicon carbide P2400/ micromesh AO1200 / Alumina powder 0.05 µm and 20 N of force) was conducted to planarize the final mask.

Figure 5-11: Microfabrication process for the selective magnetization mask.
5.3.2 Substrate Magnetization

Using the methods described by Garraud et al.,[183] a nickel magnetization mask (hereafter the mask) is used to create the desired magnetic patterns (shapes) on a magnetic substrate (Hi8MP video cassette tape). The mask was optimized by simulating the magnetization process using the finite element method in COMSOL Multiphysics in order to minimize magnetic field interference between structures. Size, separation between structures and mask thickness were simulated. To imprint the geometric shapes of the mask as magnetic pole patterns in the tape, a selective magnetization method reported by Oniku et al.,[184] was used. In this method, first a tape is uniformly pre-magnetized out-of-plane (6 T, upward), then the mask is placed in contact with the tape to apply reverse (downward) magnetic field pulse. Patterns were generated using reversal fields of 200 mT, which yielded the best results.

5.3.3 Nanoparticle Synthesis and Phase Transfer

Two different magnetic nanoparticles representing two different relaxation mechanisms were studied: iron oxide nanoparticles with predominant Néel relaxation mechanism (i.e. magnetic dipole alignment with the applied field without physical particle rotation) and cobalt ferrite with predominant Brownian relaxation mechanism (i.e. particle physical rotation due to magnetic dipole alignment).

Iron oxide nanoparticles were synthesized by thermal decomposition of an iron-oleate precursor as described by Park et al.[225] An iron-oleate was prepared by mixing sodium oleate (72 mmol) and iron (III) chloride hexahydrate in 3:1 molar ratio with water (36 mL), hexane (84 mL) and ethanol (48 mL). The mixture was kept at 70 °C for 4 hr under reflux and further washed with water to remove unreacted reagents. Thermal decomposition of the iron-oleate in a high boiling point solvent in presence of oleic acid...
yielded iron oxide nanoparticles coated with a monolayer of oleic acid and narrow size distributions. Triocetylamine was used as the solvent and the temperature maintained at 345 °C for 1 hr. After synthesis, magnetic nanoparticles were suspended in chloroform and precipitated with acetone to remove the excess of solvent and free oleic acid, and finally dried at room temperature to remove excess solvent.

Cobalt ferrite nanoparticles with predominant Brownian relaxation mechanism were synthesized by thermal decomposition of organo-metallic precursor at 320 °C in the presence of oleic acid using 1-Octadecene as solvent.[226]. The iron/cobalt oleate was prepare using a 2:1 molar ratio of iron (III) chloride hexahydrate to cobalt (II) in a mixture of 50 mL of deionized water, 100 mL of hexane and 50 mL of ethanol at 67 °C under reflux condenser during 4 hours., and then aged for 3 days. 1-Octadecene was used as the solvent and the temperature maintained at 320 °C for 3 hr. After synthesis, the reaction product was washed using the same procedure was for iron oxides nanoparticles.

The as-synthesized iron oxide and cobalt ferrite nanoparticles were soluble only in organic solvents due to oleic acid coating their surface. In order to crosslink the nanoparticles in their magnetically assembled patterns, a reactive group is necessary on the particle surface. Furthermore, most applications of interest require particles that are compatible with an aqueous environment. Therefore a phase transfer procedure described by Wang et al.[234] was used to cleave the double bond in the oleic acid chain, simultaneously transferring the particles to the aqueous phase and introducing a reactive carboxylic acid group on the outer surface of the nanoparticles. In a typical procedure, dried particles (100 mg) were suspended in toluene (10 mL) and mixed with
a mixture of ethyl acetate/acetonitrile, 1:1 volume ratio (8 mL), and a solution of sodium periodate (6 mL of NaIO₄ 0.28 molar). The mixture was placed under ultrasound for 20 min, and the product was magnetically decanted to remove excess solvent. For particle assembly over the magnetized substrate, a stock solution was prepared by suspending particles in water (10 mL). This procedure is equally effective for iron oxide and cobalt ferrite nanoparticles, although only the results for the iron oxide nanoparticles are reported herein.

5.3.4 Nanoparticle Assembly

The patterned substrate was immersed in a suspension of magnetic nanoparticles and after a specified assembly time, the substrate was removed from the particle suspension, washed with water at the same pH of the particle solution, and dried at room temperature. Serial stock dilutions of 1:1 / 1:5 / 1:10 / 1:50 and 1:100 were prepared in order to study the effect of nanoparticle volume fraction on the assembly process.

The volume fraction was calculated from the measured magnetization curve using superconducting quantum interface device (SQUID). Particles were collected over independent substrates (for different relaxation mechanism and different volume fraction), during: 32s / 100s / 316s / 1,000s / 10,000s and 100,000s.

5.3.5 Analysis of Nanoparticle Assemblies

The microstructural features of the assembled structures were evaluated by optical profilometry measurements. An optical profilometer (Contour GT-I, Bruker) was used to measure the hill-like profile of the collected nanoparticles over the substrate. Post-processing analysis converted the 3D-profile map into a series of cross-sections. From this, the average line widths (at the base of the hill) and average line heights were
calculated for different experimental conditions. Each experimental condition was analyzed using cross-sections from 5 different square microstructures. Using these averaged profiles, it was possible to estimate the number of particles collected by unit of length.

### 5.3.6 Nanoparticle Crosslinking

For the nanoparticle crosslinking, iron oxide nanoparticles in the water phase, described before, were assembled for 19 hr by immersing the tape in a particle suspension. A gentle wash process with deionized water over the inclined surface was necessary after assembly to remove free particles from the surface. Once the particles were deposited, a solution of branched polyethyleneimine (PEI, 25wt% and molecular weight of 2.5 kDa), was used to crosslink the carboxylic acid groups present on the nanoparticle surfaces with the primary amines in the polymer chains, using 1-ethyl-3-[3-dimethylaminopropyl] carbodiimide hydrochloride (EDC) chemistry (0.03 mmol). To catalyze the reaction, N-hydroxysulfo succinimide (Sulfo-NHS) was added to the solution at an EDC: Sulfo-NHS (0.1 molar ratio). The reaction was carried out by adding this solution on top of the substrate containing magnetically assembled microstructures and the reaction was allowed to occur for 1 hr. A final rinse with deionized water and acetic acid was used to remove free polymer (process described in Figure 5-2).

### 5.3.7 Structure Release

In order to release structures the magnetizable tape was coated with a 350 nm-thick sacrificial layer of LOR 3B (polydimethylglutarimide based resist), after the selective magnetization step. After magnetic assembly and crosslinking of nanoparticles on top of the sacrificial layer, this underlying sacrificial layer was dissolved in AZ300 MIF developer (tetra-methyl ammonium hydroxide), releasing the magnetic
microstructures into solution. Samples were very gently agitated to accelerate
dissolution of the LOR 3B layer.

5.4 Summary

A fabrication technique to obtain free-floating magnetic microrobots by in situ
crosslinking of magnetically assembled nanoparticles (bottom-up approach) was
demonstrated. Complex two-dimensional geometric shapes were obtained by using a
selective magnetization technique to define structure boundaries. Squares and crosses
were obtained with external dimensions of 175 µm and 150 µm, respectively, with
boundary line dimensions of 230 ± 80 nm in height and 3.9 ± 1 µm in width. The
magnetic microstructures were successfully released from the substrate and retained
their shape in suspension during manipulation with external magnetic fields.
CHAPTER 6
MICROROBOT FABRICATION: TOP-DOWN APPROACH

The University of Florida collaborated with the company SRI International in a project called: “Levitated Microfactories for High Speed Adaptive Microassembly”. This project is under the umbrella of the DARPA’s Atoms to Product (A2P) program. The A2P program is looking to develop technologies and processes to assemble nanometer-scale pieces, whose dimensions are near the size of atoms, into systems, components, or materials that are at least millimeter-scale in size.

The “Levitated Microfactories for High Speed Adaptive Microassembly” project focuses on assembling micron-sized ($\sim 10^{-6}$ m) feedstocks into at least millimeter scale ($\sim 10^{-3}$ m) components (micron to millimeter), using a revolutionary microfactory concept developed by SRI International [110]. A microfactory is a platform for displacement and accurate positioning of swarms of small-scale robots.

Figure 6-1 shows the schematic of the microfactory with an inset picture of the levitated robots and the magnetic force patterns generated by the platform to manipulate each robot. Diamagnetic levitation was explained in Section 3.4.

The state of the art for these diamagnetic levitated robots, as developed by SRI International, combines two parts: (1) A manually assembled/glued square magnets forming a magnetic base. The simplest magnetic base is composed by a 2x2 magnet array. Each magnet has the opposite magnetic orientation of its immediate neighbors and the same magnetic orientation of its diagonal neighbor, forming a magnetic checkerboard pattern. (2) The manually bent end effectors made of 0.005 inch thick (chemically etched) stainless steel [235], which are glued or simply rested on top of the magnetic bases.
The contribution of University of Florida researchers in this project is to develop a batch fabrication technique for the robots to operate under the microfactory platform provided by SRI International. This dissertation will continue considering each robot as an integration of two parts, therefore the fabrication of the magnetic bases will be presented in this chapter, meanwhile the fabrication of the end effectors will be discussed in Chapter 7.

Figure 6-1: Diamagnetic levitated robots. A) Schematic of diamagnetic levitated robot system; actual board uses two layers each for x and y offset by 0.5 mm (four trace layers total; two not shown for clarity); colors on robot indicate vertical magnetization polarity in these “checkerboard” arrays B) Magnetic force patterns on robot due to trace currents; x and y motion is obtained by phasing traces while vertical z force is adjusted using trace current amplitude. © 2007 IEEE. Reprinted, with permission, from R. Pelrine, A. Hsu, A. Wong-Foy, B. McCoy, and C. Cowan, “Optimal control of diamagnetically levitated milli robots using automated search patterns,” in 2016 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS), 2016, pp. 1–6 [236].
A manually assembled 2x2 SRI microrobot (using 1 mm x 1 mm x 0.4 mm NdFeB magnets from BJA magnetics) was characterized using magneto optical image technique. Figure 6-2 presents the topological surface of the measured field at 500 µm and compares cross sections of the $B_z$ field at different heights of the magnet array surface.

Figure 6-2: $B_z$ field magneto optical image measurement of a 2x2 magnets array. A) 500 µm from the array surface and B) comparison at different heights.

6.1 The Magnetic Substrate

The most important part of the levitated microrobot is the magnetic base. One of the goals of this project is to fabricating this magnetic base from a single magnet (this magnet will be called substrate). Therefore, choosing the right magnetic material is fundamental for the evolution of this project. Several commercial materials and fabrication process were evaluated to find the thinnest magnet possible (bellow 500 µm) with the highest energy product. Figure 6-3 shows a comparison for four vendors that could offer magnets with this thickness. Unfortunately, none of the companies offering high energy product materials (solid lines in the figure) guarantee that those magnets
could be micromachined to target the project needs. Based on our exploration, only one company offers the fabrication capabilities to create machinable magnetic materials, with high energy product, with thicknesses of \(~400 \, \mu m\): BJA magnetics.

BJA magnetics produces their N42 grade NdFeB “micro-magnets” by sintered the magnetic elements using strip casting. They pulverize the strips (using a 600 grit grinding wheels) to obtain bigger and uniform grain size powders in the order of hundreds of microns. Finally a process called hydrogenation disproportionation desorption recombination (HDDR) is used to obtain an isotropic powder with grainsizes around \(~0.3 \, \mu m\) [237]. The mechanism to compact this powder into the final shape of the magnet (sintering, pressing, etc.) was not disclosed by the vendor.

A custom-made batch of magnets with sizes of 10 mm x 10 mm x 0.4 mm was used for this project. This material will be called substrate hereon. The magnetization curve for this material was measured using a vibrating sample magnetometer (VSM). Measurements corroborate the magnetic grade of the material (N42). Figure 6-4
compares the magnetization of the magnets used by SRI (1 mm x 1 mm x 0.4 mm BJA magnetics) in the manually assembled robots with the new custom-made batch magnets provided by BJA magnetics. The energy product of the magnets used in the batch fabrication process of the micro-robots is 39.6 MGOe, whereas the magnets provided by SRI before this project was 21.3 MGOe (possibly due to aging).

![Magnetic characterization comparison for SRI and BJA magnets. A) Out of plane magnetization and B field curves. B) Energy product curves.](image)

Figure 6-4: Magnetic characterization comparison for SRI and BJA magnets. A) Out of plane magnetization and B field curves. B) Energy product curves.

It was of interest of this project to measure magnetic properties of the BJA substrate at different temperatures. The reason was based on the success of heat-assisted magnetic recording [238] to enhance the local magnetization of a material, by reducing the coercivity after increasing the temperature locally. It was intended to evaluate viability of this technique during the selectively magnetization process, to improve the final magnetization pattern. Two sets of measurements were performed: (1) The remanent magnetization recoils and (2) the DC demagnetization curves.

For the magnetic recoils (1), the cycle was: Sample was fully magnetized, the temperature was raised, the magnetization was measured, and then the temperature was reduced to room temperature and the remanent magnetization was again
measured. Additionally, the hysteresis loops were measured at different temperatures, and it was observed that the maximum temperature for the substrate to be exposed before magnetic degradation is 47ºC. Higher temperatures will generate more than 5% reduction (i.e. considered to be irreversible) on the remanent magnetization, as shown in Figure 6-5.

![Figure 6-5: Magnetization characterization at different temperatures. A) Remanent magnetization recoils and B) hysteresis loops.](image)

By using this information, a second set of measurements was conducted: (2) the DC-demagnetization curves (DCD explained in section 2.2.4). The DCD curves were measured at different temperatures, to understand the effect of temperature on the remanent coercivity (field which $M_r(H)/H$ changes sign). The remanent coercivity is very important for the selectively magnetization process. This value is related with the reversal magnetic field to be applied for generating the selectively magnetized patterns.

At room temperature, the BJA substrate remanent coercivity is 1.5 T. By evaluating the remanent coercivity at different temperatures, it was discovered that the remanent coercivity was reduced only by 227 mT by raising the temperature above 47ºC (maximum temperature before reducing 5% in the coercivity).
Figure 6-6 presents the DCD measurements at different temperatures making emphasis on the remanent coercivity. Because the reduction in remanent coercivity (227 mT) is not significant (only 15% of the NdFeB remanent coercivity at room temperature), this technique proves to be not cost effective for this project goal, therefore was not further considered.

Figure 6-6: DCD at different temperatures. A) DCD demagnetization curves at different temperatures. B) Remanent coercivity fields at different temperatures. Data extracted from the DCD curves.

6.2 Machining the Magnetic Substrate

Two steps were necessary to guarantee batch fabrication of magnetic bases using the same substrate (monolithic fabrication): dicing the substrate in individual bases after fabrication (singulated) and polishing the surface.

A semiconductor dicing saw (from ADT) was used to singulated the substrate. The dicing blade was a hubbed resin bond diamond blade. 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 ~214 µm wide kerf and 422 µm deep). Figure 6-7 shows the results of the dicing process for the magnetic substrate.

There are two caveats of this technique. (1) The substrate is constantly exposed to water. This could generate oxidation on the surface which may require removal via polishing. (2) If the substrate is magnetized before singulation, multiple residual particles will accumulate on the edges or each base. It is necessary to thoroughly clean bases with adhesive tape to eliminate any debris.

Figure 6-7: Successful dicing of the BJA NdFeB material, producing 9 magnetic bases per substrate.

The next 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. Figure 6-8A shows a difference between the unpolished and the polished sample. An original concern was that the polishing process could reduce the magnetization of the substrate. Figure 6-8B shows two selectively magnetized samples and a magnetic viewing paper before and after polishing. No apparent variation was observed.
Some magnetic imperfections over the surface of the magnet were observed during the magneto-optical image of the selectively magnetized samples, even after polishing. These imperfections were originally attributed to material roughness; therefore, roughness characterization was conducted. Results are presented in Figure 6-9 showing microscopy images of the surface and cross-section (after cleaving).

Figure 6-9: Optical microscopy image of the BJA magnet surface, top view and cleaved cross section. Magneto-optical image at the surface of a selectively magnetized sample (similar image for polished and unpolished samples).

Magneto-optical images of a selectively magnetized sample were taken before and after polishing and magnetic fields remain almost the same (right image in Figure 6-9). This confirms that the magnetic imperfections were not produced by the material roughness and suggest that the selectively magnetization process is not completely magnetizing the poles on the substrate. This gives evidence that there is still room for improvement on the selective magnetization process.

To accurately evaluate the effectiveness of the polishing, two samples (polished and unpolished) were analyzed using an optical profilometer (Bruker, Contour GT-I).
The unpolished sample has an average $R_a=770$ nm (surface roughness), while the polished sample $R_a=20$. Results presented in Figure 6-10.

![Optical profilometer image of polished and unpolished 3 mm × 3 mm magnet (BJA).](image.png)

From these results, it is concluded that NdFeB magnets grade N42 provided by BJA, are the best candidates to be a substrate in the mass fabrication of magnetic bases for levitated microrobots. To the date of this research, this is the material that offers higher magnetic energy product, lower thickness and better qualities for machining.

### 6.3 Adapting Selective Magnetization for Microrobot Bases

As explained in Chapter 4 of this document, selective magnetization is a technique to reverse the magnetization of selected areas of a magnet by “imprinting” magnetic patterns using a magnetization mask meanwhile a reversal field is applied. This process is ideal for the batch fabrication of the robot bases with checkerboard magnetic patterns, because it will eliminate the manual assembly of individual 1 mm x 1 mm square magnets. Manual assembly is difficult and time consuming due to attractive and repelling forces of the magnets.
6.3.1 Improving Magnetization: Simulations

The selective magnetization process was simulated using COMSOL multiphysics (2D quasi-static simulations in COMSOL), as described in section 4.2.1. These simulations provide a fast evaluation mechanism for different design parameters. The first parameter to be evaluated is the mask material. Different soft ferromagnetic materials will have different saturation magnetization. A higher saturation magnetization will produce a higher magnetic field underneath the mask during the reversal magnetization. The hypothesis is that higher magnetic field under the mask will result in an increase of magnetic contrast (defined as \( C = (B_{\text{max}} - B_{\text{min}}) / (B_{\text{max}} + B_{\text{min}}) \)), therefore the magnetic patterns quality will be improved.

During section 4.2.1. Carbon steel was used to magnetize flexible iron oxide (at 0.5 T). The saturation magnetization of the carbon steel was not a limiting factor, but the magnetic substrate (NdFeB) requires a high reversal magnetic field of ~1.5 T. By simulating the magnetization process at different reversal fields and measured the peak magnetic field underneath a simple 1 mm x 1 mm square mask, it is possible to compare the effectiveness of different mask materials. Figure 6-11, compares the magnetic field produced underneath masks fabricated with 2V permendur, supermendur, low carbon steel 1018, and permalloy. The magnetic properties for these various materials were from the COMSOL library and/or measured in the laboratory. The reversal magnetic fields used during selective magnetization are highlighted.
Figure 6-11: Set of materials to take into consideration for the magnetization mask fabrication.

Although it is possible to increase the reversal magnetic field underneath the mask by selecting a different material such as supermendur or 2V permendur rather than carbon steel, the reality is that this increment (9% for 2V permendur and 6% for supermendur) does not worth the extra cost and difficult machinability of these two materials for this project. Therefore, carbon steel will continue to be the designated material for the mask.

Variations on the mask thickness were also simulated. The magnetic contrast will be used as figure of merit. Figure 6-12 confirms that it necessary to fabricate thicker masks to increase magnetic fields. Increasing the fields will generate better magnetic patterns with sharper edges. Simulations indicated that a minimum aspect ratio (mask pole height / pole width) of 3 is necessary for achieving good magnetic contrast.
Figure 6-12: Selective magnetization simulation model. A) COMSOL simulations of $B_z$ field generated by a magnetization mask, parametric with thickness. B) Contrast calculation for different mask thickness (at the middle section of the magnet).

Another important parameter that was simulated was the importance of using one magnetization mask in comparison with two aligned magnetization masks (beneath and underneath the magnetic substrate). Comparative simulations are presented in Figure 6-13A. Double mask showed better performance in terms of magnetic contrast underneath the patterns. It is easy to appreciate how strong and uniform is the magnetic field (across the thickness of the magnet) when using double mask. A numeric comparison of the magnetic field at the center of the magnet is presented in Figure 6-13B. Double mask generates a higher magnetic contrast underneath the mask features.
6.3.2 Improving Magnetization: Field Selection

The following steps will describe variation process for the selective magnetization procedure and experiments conducted after selecting carbon steel as material for the magnetization mask. To have a better control over the applied magnetic field and to reduce Eddy currents during the magnetization (that could potentially reduce the total magnetization of the sample), we proposed to use DC magnetic field instead of a pulse magnetizer. We used a vibrating sample magnetometer (VSM – ADE technologies) to generate the external reversal field.

Considering the DC-demagnetization curve of the substrate for the magnetic bases (NdFeB), we compared three reversal fields (1 T, 1.5 T and 2 T). A magnetization mask with stripe-like patterns and pole width of 1 mm was used for the experiment. Figure 6-14 present MOI measurements of the substrate after selective magnetization of the three reversal fields, confirming that ~1.5 T will be the best reversal field to obtain...
magnetic pole patterns of the same size and fields with the same absolute value (symmetric magnetization pattern with positive magnetic field equal to the negative magnetic field).

Figure 6-14: DC magnetization of lines, varying the applied magnetic field. MOI measurements at 500 µm from surface.

6.4 The Magnetization Mask

6.4.1 Mask Fabrication Exploration

The most important job is to fabricate 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. The mask fabrication is a critical step towards obtaining multiple magnetic bases from a single magnetic substrate (batch-fabrication). The first set of magnetization masks was designed to magnetize four robots (each one as an array of 3x3 alternated poles of 1 mm side) in the same substrate.
As presented in the top row of Figure 6-15, four variations were made on the mask: Mask 1_1 was designed with squares made with a 1/64” commercial end mill; Mask 1_2_1 and Mask 1_2_2 were made with simple circles using 1/32” end mill and 1mm drill bit respectively, and Mask 1_3 was made with simple circles using 1/64” end mill. All masks were made from the same material (AISI 1018 mild/low carbon steel). Top row on Figure 6-15 shows schematics and bottom row presents pictures of the resulting masks.
Figure 6-16: Magneto optical images measured at 50 µm of magnetized samples. Samples magnetized using the same field (1.5 T) and four different masks. $B_z$ comparison for substrates at similar height (200 µm) but different mask. The manually assembled 2x2 magnet array was also measured and compared (SRI sample in green).

Samples were magnetized using different masks. The substrates in this experiment were 4.9 mm x 4.9 mm x 0.7 mm NdFeB magnets. The reversal magnetic field was 1.5 T. Individual 3x3 bases were not diced for this experiment. Figure 6-16 summarizes the stray magnetic field ($B_z$) measured using magneto optical images at 50 µm from surface. Additional measurement (200 µm from surface) of a manually assembled magnetic base was included for comparison (2x2 magnet array sample provided by SRI – line in green). The results look promising; $B_z$ fields are in the same order of magnitude for most of the masks (except small 1/64” circles mask that remains lower).
6.4.2 Low Aspect Ratio Magnetization Mask

The aspect ratio of the mask will be designated as the thickness over feature length. If a square with 1 mm side and 1 mm depth is machined, then the aspect ratio will be 1. A square patter mask was selected to complain with the specifications of the microfactory base. Differing from design in Figure 6-15, all the robots have the same magnetic pattern. Resulting magnetic square poles at individual bases should have 1 mm side. A total of 9 magnetic bases (3 mm x 3 mm) can be fabricated in the selected 10 mm x 10 mm substrate. Robot distribution over a substrate is presented in Figure 6-17A. With this distribution, it will take 22 substrates to fabricate 200 robots.

As mentioned in section 6.3.1, it was clear that the next step was to design and fabricate a double side magnetization mask. Technical drawings were made using solid works. Figure 6-17B shows the desired pattern and the 3D model of one side of the mask.

Figure 6-17: Modeling the log aspect ratio mask. A) Desired pattern for batch fabrication of 9 micro-robots per substrate. B) 3D representation of the magnetization mask to generate the desired pattern.

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 layer. Figure 6-18A 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. This mask was machined using a Sherline 2000 CNC and 1/64”-two flutes end mills. Figure 6-18B shows the final machined mask disassembled.

![Carbon steel diagram](image)

**Figure 6-18**: Model and fabrication of double side mask. A) Schematic of the double side magnetization mask used to produce 9 micro-robots. B) Fabricated magnetization mask (disassembled).

### 6.4.3 High Aspect Ratio Magnetization Mask

As mentioned in Figure 6-12, the higher the aspect ratio of the mask the better magnetic field quality will be generated during the reversal magnetization. With this premise in mind, it is necessary to fabricate different magnetization masks, but this raises a fabrication problem. It is very complicated to 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.
A laminated design was proposed to obtain high aspect ratios: Use the 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 mm$^3$ poles and other with 3 x 1 mm$^3$ 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 6-19. This fabrication concept was originally tested using laser cut over stainless steel (easier to machine) and then implemented in carbon steel using CNC. As shown in Figure 6-19C, the saturation magnetization of stainless steel is lower than the carbon steel.

Figure 6-19: Laminated mask approach. A) 3D design of the mask and CNC program to produce every layer of the mask. B) Laser machined stainless steel mask C) VSM measurement comparison of low carbon steel (CNC), stainless steel (laser cut) and NdFeB (BJA) magnet.

The optimal reversal magnetic field for the high and low aspect ratio masks are different. Both high aspect ratio masks (stainless steel and carbon steel) were used to magnetize individual magnetic bases (3 mm × 3 mm x 0.4 mm). Variations on the reversal magnetic field were made to find the optimal magnetization (higher contrast).
For these two masks the best external magnetic field was selected as 1T, as shown in Figure 6-20.

Figure 6-20: Finding the right external magnetic field used during the selective magnetization. Stainless steel and carbon steel masks.

A comparison of three substrates magnetized with the fabricated masks is presented in Figure 6-21. Contrary to expectations, the high aspect ratio did not provide significant improvement over the low aspect ratio mask. Even though the shape of the
magnetization pattern was improved, the absolute values of the magnetic fields produced by the selectively magnetized arrays were not significantly different.

Figure 6-21: Magneto optical image of a selectively magnetized samples using each of the machined masks. Measured at 500 µm from magnet surface. S1 corresponds to low aspect ratio carbon steel, S2 is the high aspect ratio, laser cut stainless steel, and S3 is the high aspect ratio CNC machined.

To understand the discrepancy between the results using low and high aspect ratio masks, it was necessary to generate a 3D simulation model (2D simulations have been used so far), as depicted in Figure 6-22. We simulated the magnetic fields generated between two (aligned) high aspect ratio masks, separated by an air gap of 400 µm, in a constant external magnetic field of 1 T over the z-axis (to simulate pulse magnetizer and VSM). Under these circumstances we observed that the difference of magnetic field between exposed and unexposed areas (by the mask) was only 600 mT. Generating a very low magnetic contrast ~0.2. We then noticed that unexposed areas were experiencing very high fields contributing to reversing the overall magnetization of the sample.

To overcome these difficulties and to increase the magnetic contrast during the selective magnetization process, results in a task that exceeds the scope of this project. Future development on this specific area will be described at the end of this dissertation in Chapter 9. To advance with the batch fabrication of magnetic bases, the only
magnetization mask that will be used hereafter is the double side low aspect ratio presented in Figure 6-18.

Figure 6-22: 3D simulation of the laminated mask (double mask) under permanent external B field. External field = 1 T. A) Perspective view, B) horizontal cross section in the middle of the air gap, and C) Bz field measurement.

6.5 Characterization of Microrobot Bases

Using selective magnetization process to create magnetic bases (at 1 T reversal field), the following results are presented: Figure 6-23 shows the magnetization of the BJA magnetic layer using the machined double mask. Two magneto optical image techniques were used: A) and B) were obtained using magneto optical (MO) sensor of 38 mT saturation field in the “Minimo” magnetic camera (Matesy). These pictures show a manually assembled 3x3 magnetic bases, a selectively magnetized base, and the entire substrate (10 mm x 10 mm x 0.4 mm) before being singulated. The images are crisper and the magnetic poles are well defined, because the magnetic sensor saturates at magnetic fields lower than the produced by the magnets. This images confirms that the selectively magnetization process is not fully magnetizing the alternated poles.

Figure 6-23C is using the magneto optical image developed in Dr. David Arnold’s group [133]. The advantage of this technique is that the intensity of the magnetic field can be quantified. The magneto optical image taken at 500 µm from the substrate was
superpose over the micrograph image of the substrate to demonstrate the success of selectively magnetization process.

Figure 6-23: Magneto optical image of the selective magnetization of BJA substrates. A) Comparison between manually assembled and selectively magnetized bases. B) Selectively magnetized substrate containing 9 robots (before dicing). C) In house magneto optical image, superpose over a micrograph of the magnetic substrate.

By quantifying the stray magnetic field from the magneto optical image, a comparison between manually assembled micro-robots and selectively magnetized micro-robots is presented in Figure 6-24. 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 6-24: MOI measures. Assembled and selectively magnetized levitated micro-robot’s comparison. Measurements at 600 µm.

Two batches of magnetic bases were fully produced. A ~280 µm and a ~400 µm thick batches, with 9 bases each. Figure 6-25 shows the fabrication results. The fabrication process can be summarized in the following steps:

- 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 magnetize the substrate up (7T).
- Reverse magnetization using low aspect ratio, carbon steel double side mask (1.2 T).
- Substrate singulation into nine micro-robot bases using dicing saw.
- Manually cleaned, separation and packaging.
Figure 6-25: Fabrication of nine micro-robots per batch. A) None polished magnetic base after dicing, with a magneto optical image (MOI) inset of one of the base. B) Singulated and polished robots ready for shipping.

The stray magnetic field of each base was measured using magneto optical imaging technique and presented in Figure 6-26, for evaluation of the process reproducibility.

Figure 6-26: MOI characterization of samples from the same batch (280 μm thickness). A) Images obtained at 500 μm from surface. B) Quantification of the B field cross section for all robots in the batch.
An additional stray magnetic field characterization technique was used to validate results: scanning hall probe. Figure 6-27 depicts an example of this characterization technique by comparing a manually assembled robot with a batch-fabricated one. Scanning hall probe confirms that selective magnetization of 280 µm thick substrates generates patterns with only ~39% of the magnetic field strength of the manually assembled patterns.

![Image of scanning hall probe measurements](image)

**Figure 6-27:** Scanning hall probe measurements of manually assembled and selectively magnetized sample.

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 [239]. 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 (build on 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 we will register this force as weigh in the balance. Figure 6-28 illustrate the experiment and results.

Figure 6-28C compares measurements of the magnetic force with COMSOL simulations and charge model calculations (as presented in section 3.4). 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 6-28C 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.
Although the selectively magnetized fields and the diamagnetic forces are weaker than the manually assembled counterparts, experiments conducted using SRI microfactory (Figure 6-29) 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 6-29: Characterization of batch fabricated robots at SRI. Left, assisted levitation and right, assisted sliding.
6.6 Summary

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. Enthought the fabricate 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).
A common challenge for microrobotic platforms is adding more functionality and the need of fixturing and gripping strategies to better interact with external micro-parts. Most of the strategies used to address this problem rely on some form of microgrippers that are very difficult to customize because of the system complexity. However, there are many microrobotic manipulation tasks that do not require grabbing, such as dispensing droplets and micropositioning, which are the target of this work.

The primary solution for enabling multi-functional interactions in macroscale robotics is the use of end effectors. An end effector is the protrusion of a robot intended to interact with the environment and perform a task. This end effector can be fixed or replaceable, and translating this concept to the field of micro/milli robotics is of high interest. In small scales, there is the same need for simple, task-specific end effectors that can be exchangeable for addressing different tasks (i.e. pick and place, scanning surfaces) or interacting with objects with different properties (i.e. solids, liquids, different sizes). Fabrication techniques capable to create end effectors with micrometer resolution features will bridge the gap between millirobots and micro-part assembly. Exchangeability is also desirable in case of damage or part wear.

Wafer-level microfabrication is desirable for realization of hundreds or thousands of microrobots that can complete complex tasks by working in parallel, such as “microfactory” or “swarm” concepts. Because magnetic actuation is fairly common for

* This section contains excerpts from reference [240].
micro/milli robots [40], [46], [246] and based on the successful advances in functionality, complexity and reproducibility developed by SRI International [110], [235], the end effectors developed here are designed for compatibility with these magnet-array microrobot platforms operating under the diamagnetic levitation principle. However, the general concepts presented here could be modified for other microrobotic platforms.

Previews attempts of end effectors used by SRI international in their levitated microrobots were described at [247]. Those attempts included tungsten wires (electrochemically etched), polyamide (photolithography) and a combination of polyimide and soft elastomer styrene-butadiene-styrene -SBS- (dip-coated). The former one used to increase the surface area upon contact and the pick strength of the end effector. In Figure 7-1, commercial end effectors are compared with an electroplated end effector fabricated following procedures described in this chapter. The primary parameter for maintaining the microrobot’s levitation is that the mass of the end effector should be <5% of the robot’s mass.

![Figure 7-1: Comparison between fabricated end effector (Copper) and commercially available end effectors: tungsten wire, polyamide and a combination of polyamide and SBS elastomer [247].](image)

A microfabrication process for batch production of magnetically attached (exchangeable) end effectors for micro/milli robots is describe in this chapter. The end effectors make use of soft ferromagnetic materials to enable interchangeable and
adjustable attachment to magnetic bonding surfaces on robotic bases. The end
effectors have overall dimensions in the millimeter scale (8 mm and 7 mm length), but
employ microstructured tools (eight shapes) for manipulation of objects below 10 µm
with micro and nano scale precision. Three materials—copper, nickel and SU-8—are
used for forming the end effector body, and nickel is used as the magnetic attachment
material in all cases. An additional fabrication method called hybrid produced end
effectors with nickel body and tips made of SU-8. The end effectors are assembled onto
diamagnetically levitated microrobot bases in order to demonstrate the versatility of the
exchangeable end effector technology.

7.1 End-effector Design and Fabrication

7.1.1 Design Considerations

A first goal for the end effector is to enable task-specific function, while
minimizing the weight (payload) of the end effector. Another long-term goal is to provide
for multiple functionalities (electrical, mechanical, thermal, etc.), so three types of
materials are considered for the main end effector body: a non-magnetic metal (copper),
a ferromagnetic material (nickel), and a dielectric material (SU-8 photo-patternable
epoxy). A comparison of each material’s Young’s modulus, density and weight (based
on end effectors fabricated for 3x3 and 4x4 magnets arrays) is presented in Table 7-1.

Even though SU-8 is the lighter material, it also has a lower Young’s modulus, making it
less rigid and potentially mechanically unstable for long thin end effectors.

Table 7-1. End effector material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus [GPa]</th>
<th>Density [g/cm³]</th>
<th>Mass (3x3) [µg]</th>
<th>Mass (4x4) [µg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>220</td>
<td>8.9</td>
<td>140</td>
<td>283</td>
</tr>
<tr>
<td>Copper</td>
<td>117</td>
<td>8.9</td>
<td>140</td>
<td>284</td>
</tr>
<tr>
<td>SU-8</td>
<td>2</td>
<td>1.2</td>
<td>19</td>
<td>38</td>
</tr>
</tbody>
</table>
In the case of the SRI microrobots, the stray fields from the magnetic base are used to attach end effectors without affecting the properties or function of the robot base. Since the microrobot base is an array of permanent magnets, soft ferromagnetic nickel is incorporated in the end effector enabling it to easily and reversibly snap onto the base. To enable attachment to other types of microrobots, permanent magnet materials could be used instead of nickel.

The microfactory concept involves multiple robots, potentially working in close proximity to one other and even co-manipulating the same part. To avoid unwanted attractive forces between magnetic bases, the end effectors are designed with shanks that protrude at least 2 mm away from the base. Additionally, in order to manipulate objects smaller than 10 µm, finely shaped, high-precision end effectors are required (~10 µm). Together, these requirements demand fabrication of long, slender structures, which can be prone to bending. Consequently, the mechanical robustness of the long end effectors is a key area for investigation. Figure 7-2 shows an end effector (nickel) magnetically attached to the magnetic base (here, a 2 x 2 array of permanent magnets). End effectors are designed to have the center of mass at the same x and y position as the center of mass of the magnetic base. Two sizes of end effectors are developed: 7.1 mm and 8.6 mm in overall length (for 3 x 3 and 4 x 4 magnet bases with 2 mm shank).
7.1.2 Fabrication

Two generations of end effectors were proposed: In the first generation, the end effector (containing magnetic attachment features) and the tip are fabricated in the same material. In the second generation, the end effector and the tip are fabricated with different materials, therefore it will be called hybrid.

**First generation: Single material for end effector and tip**

To enable heterogeneous integration of multiple materials (one for magnetic attachment, the other for the main structure), a two-step fabrication process is used. The first step employs electroplating to form the nickel magnetic attachment structures, and the second step forms the shank and tool tip. Figure 7-3 shows cross-section schematics of the three different materials.
Figure 7-3: Cross section schematic and layer thicknesses of the three different end effector types: copper, nickel and SU-8 (not drawn to scale).

For the first step, a seed layer of Ti/Cu (100 nm/50 nm) is sputtered (Multi-Source RF and DC Sputter System CMS-18, Kurt J. Leskar), 9.5-µm-thick photoresist (AZ9260) is patterned using a first lithography mask, and a ~2.5 µm nickel layer is electroplated using a commercial bath (Nickel Sulfamate RTU, 33 mA/cm² current density, nickel anode). The Ti layer serves as adhesion layer between the Cu and the Si during the electroplating and also serves as a sacrificial layer during the releasing step.

In the second step, the process flow depends on the material. For the Cu and Ni structures electroplating is again used, so it is necessary to sputter a second seed layer of Ti/Cu (100 nm/50 nm) on top of the existing features. An ~8-µm-thick photoresist (AZ9260) is photo-patterned with a second lithography mask, and the metal (Cu or Ni) is electroplated. Cu uses a solution of copper (II) sulfate pentahydrate and sulfuric acid (10 mA/cm² current density, copper anode). Ni uses the same bath conditions as
before. Alternatively, the SU-8 end effectors are made by spin coating OmniCoat™ (MicroChem) and a ~10 μm layer of SU-8 over the sample, followed by lithographic patterning. For all three materials, the final structures are released from the substrate by dissolving the Ti/Cu seed layer in a bath of ammonium hydroxide saturated with copper sulfate (blue etch) [etches Cu] followed by hydrofluoric acid (HF) [etches Ti].

**Second generation: Hybrid materials for end effector and tip**

For the second generation of end effectors the fabrication process is divided in two main layers (therefore 2 lithography masks): (1) The first layer form a nickel end effector body that was electroplated. (2) The second layer is intended to produce the tips and tethers that support the end effectors and it was fabricate by spin coating SU-8.

Both layers were produced following procedures described in the first generation of end effectors, except for the structure release were different sacrificial layers were used. Two sacrificial layers were compared during this generation: Titanium and LOR 3A (polymeric lift off resist by MicroChem). A cross section comparison of both sacrificial layers before releasing is presented in Figure 7-4A. The reason to eliminate Ti as a sacrificial layer, is to avoid using hydrochloric acid and improve the quality of the produced structures (prolonged exposures to HCl will swallow the SU-8). A polymeric sacrificial layer will also speed up the releasing process and increment the yield of the produced structures.

It is important to mention that second generation of end effectors will not have additional magnetic attachment structures because the entire body is made of nickel, simplifying the fabrication and reducing one lithographic mask. Cross section and top view schematics of the end effector after release are presented in Figure 7-4B. Final
recipe used to produce the first layer of end effectors (second generation) is presented in Figure 7-5 and the second layer is presented in Figure 7-6.

Figure 7-4: End effector fabrication schematics. A) Cross section schematic of the materials for the end effector body (no SU-8), before releasing. Comparisons of two sacrificial layers: Ti and LOR. B) Schematic of the hybrid end effectors after release, were the tip is made of SU-8 and the body of nickel.
1 End effector level (electroplating)

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<th>Step</th>
<th>Procedure</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Si Wafer cleaning</td>
<td>Bake for 5 min in HS61 hotplate at 95ºC (no Al foil)</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Coat LOR 3A layer (aprox 700nm)</td>
<td>Spin for 30 sec, 3000rpm</td>
<td><strong>30</strong></td>
</tr>
<tr>
<td>1.3</td>
<td>Seed layer deposition (Cu)</td>
<td>Dwell time (s)</td>
<td><strong>417</strong></td>
</tr>
<tr>
<td>1.4</td>
<td>AZ9260 (+) patterning (~10 µm)</td>
<td>Lamp (mW/cm²)</td>
<td><strong>10.1</strong></td>
</tr>
<tr>
<td>1.5</td>
<td>Ni electroplating (~2.5 µm)</td>
<td>Dose @ 6 µm</td>
<td><strong>110-140 mJ/cm²</strong></td>
</tr>
</tbody>
</table>

Figure 7-5: Fabrication recipe for hybrid (Nickel + SU-8) end effector with LOR as a sacrificial layer. First layer: the nickel electroplated end effector body.
2 Tip level (SU-8)

<table>
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<th>Step</th>
<th>Procedure</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>2.1</td>
<td>Si Wafer cleaning</td>
<td>Print 3000 bath at 70°C for 3 minutes in solvent bench</td>
<td></td>
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<tr>
<td></td>
<td>Triple water rinse in solvent bench</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>N blow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asher treatment for: 300 W, 300 s, O2 at 600 sccm, ~1200 mtorr (Anatech Barrel SCE600)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Bake for 3 min in hot plate at 112°C. Rehydrate for 24 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Coat OmniCoat</td>
<td>HMDS treatment (hot plate 3 min / HMDS 30 s / hot plate 2:30 min / out side 30 s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dispense static, covering 90% of wafer in Headway spinner</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spin for 15 sec, 500rpm</td>
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<td></td>
<td>Spin for 30 sec, 3000rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bake for 1 min in Wencesco hotplate at 200°C</td>
<td></td>
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<td>2.3</td>
<td>SU-8 2005 (-) patterning (~ 6 µm)</td>
<td>Dispense SU-8 2005 static, covering 90% of wafer in Headway spinner</td>
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<td></td>
<td>Spin for 15 sec, 500rpm</td>
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<td>Spin for 30 sec, 3000rpm</td>
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<td></td>
<td>Soft bake for 5 min in HS61 hotplate at 95°C (no Al foil)</td>
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<td></td>
<td>Expose mask, hard contact, Algap=50 µm and wec=0 (Karl Suss MA6)</td>
<td>Lamp (mW/cm²)</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Post exposure bake for 3 min in HS61 hotplate at 95°C (no Al foil)</td>
<td>Exposure time (s)</td>
<td>31</td>
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<tr>
<td></td>
<td>Develop using SU-8 developer for 2 min under agitation</td>
<td>Develop time (m)</td>
<td>2:00</td>
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<td>Stop process rinsing IPA for 10sec</td>
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<td></td>
<td>Hard bake for 15 min in oven (Despatch) at 150°C</td>
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<td></td>
<td>Measure photoresist thickness using profilometer on test area (Dektak 150)</td>
<td>Thickness (µm)</td>
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<tr>
<td>2.4</td>
<td>Structure releasing</td>
<td>Develop OmniCoat using AZ 300 mil developer for 30 sec under agitation</td>
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<td>Rinse with water 2 min</td>
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<td></td>
<td>Asher treatment for: 100 W, 60 s, O2 at 600 sccm, ~1200 mtorr (Anatech Barrel SCE600)</td>
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<td></td>
<td>Etch Cu using Ammonium hydroxide saturated with copper sulfate (blue etch) 2 min under agitation</td>
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<td>Rinse with water for 2 min</td>
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<td></td>
<td>N blow</td>
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<td></td>
<td>Etch LOR using AZ 422 mil, room temp, no agitation, for at least 1 hour. Full release will take 6 h.</td>
<td>Releasing time (h)</td>
<td>6:00</td>
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<td></td>
<td>Rinse with water</td>
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<tr>
<td></td>
<td>Assembly to final robots</td>
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Figure 7-6: Fabrication recipe for hybrid (Nickel + SU-8) end effector with LOR as a sacrificial layer. Second layer: the spin coated SU-8 tip.

7.2 Fabrication Results

7.2.1 Magnetic Attachment and (Lack Of) Self-alignment

In order to evaluate a possible self-alignment behavior between the end effectors and the magnetic base, three types of magnetic attachment designs were considered: full nickel layer, lines of nickel on the magnetic field high gradients (produced by the boundary of the magnets at the base with opposite magnetic poles), and crosses of nickel on the corners of the magnets intersections. Figure 7-7 illustrates all the combinations of magnetic attachment evaluated (with additional layer of SU-8 representing the end effector). All three designs and all combinations of materials and thickness withstand the weight of the magnetic bases without detaching from the end effector (meaning the robot base could be lifted up by the end effectors). It was also possible to detach the end effectors without causing damage to the structures, by
holding the magnetic bases and sliding the end effectors laterally. This proves the concept of manual detachability and exchangeability of end effectors.

Figure 7-7: Three designs of magnetic attachment to the magnetic base: full nickel covering the entire area of the support, nickel on the lines where the higher magnetic gradients will be located and at the corners where adjacent magnets will be located.

End effector assembly onto manually assembled and selectively magnetized magnetic bases was performed. As presented in Figure 7-8, the end effectors can be attached to the bases by bringing end effector to the magnet (potential damage to bend the end effector by the generated forces) or by bringing the magnet to the end effector. End effectors can be manually attach/detach easily by hand, making viable the process of replacing broken tips.

Notably, the desired self-alignment behavior was not observed. The explanation is that the vertical clamping forces are substantially higher than the lateral (horizontal) alignment forces. Overall, the full nickel design was the most practical structure in terms of fabrication process because it prevents delamination of the Ni structures.
Figure 7-8: End effectors assembly tests. A) Attachment by bringing end effector to magnet or magnet to end effector. B) Attachment strength to manually assembled and selectively magnetized magnetic base. C) Replacement/detachability of broken end effector.

7.2.2 Supporting Tethers and Sacrificial Layer

Variations on the end effectors design were made to include tethers with notches to support the structures during the releasing step. These variations were made when introducing hybrid materials (SU-8 and nickel) for the second generation of end effector. In this second generation of end effectors it was also evaluated a polymeric sacrificial layer instead of the titanium. By using LOR (lift off resist) it was possible to reduce the releasing time and enhance the fabrication yield. Figure 7-9 compares samples with both sacrificial layers and the usage of the tethers before releasing. Thicknesses of
each material involved in the fabrication of the second generation of end effectors were measured using profilometer (Tencor AS500) and presented in Table 7-2.

![Figure 7-9: Examples of end effectors fabricated in the second generation. A) Using Ti and B) LOR as sacrificial layer. Unreleased structures.](image)

| Table 7-2. Thickness measurement of each material in the end effector. |
|---------------------------------|------------------|------------------|
| Material                       | Ti sacrificial layer | LOR sacrificial layer |
| Nickel                         | 13 µm             | 11 µm             |
| SU-8                           | 6 µm              | 6 µm              |
| SU-8 + Nickel                  | 18 µm             | 16 µm             |
| Seed layer                     | 243 nm            | 262 nm            |

7.2.3 End Effector Materials

Examples of fully fabricated end effectors in the four proposed techniques are presented in Figure 7-10, with an example end effector array (before releasing) demonstrating a batch microfabrication process. Cu and Ni successful resulted in rigid structures that can protrude over 2 mm without bending with the weight of the beam itself (as shown in Figure 7-2). However, end effector deformation (curling) was observed in SU-8 structures during structure release. It is feasible to obtain successful end effectors made of SU-8, but they may require much thicker structural layers.
Young’s modulus and mass for 4 mm x 4 mm end effectors (Ni/Cu/SU-8) are 220 GPa/117 GPa/2 GPa and 283 µg/284 µg/38 µg, respectively. The hybrid end effector successfully combines the rigidity of the nickel structure with the better feature definition, transparency, and dielectric characteristics of the SU-8.

![Image](image_url)

Figure 7-10: Released end effectors fabricated in four different techniques. Following materials were used: Copper, nickel, SU-8 and hybrid (nickel+SU-8). Example of nickel end effectors batch fabrication for 4 mm x 4 mm magnetic bases.

## 7.2.4 End Effector Tips

Aiming to fabricate replaceable end effectors, it is possible to create any number of exchangeable tips that fulfill the needs of a micro/milli robot task. In the first generation devices, tips were formed in the same fabrication step as the end effector body, and using three materials (SU-8, copper and nickel). Six different tip designs were explored, as shown in Figure 7-11 (here, fabricated in SU-8): a loop with notch for carrying and dispensing liquids, a 10 µm loop for carrying spheres, a sharp V-shape to accurately position smaller spheres, a round V-shape tip for controlling of bigger spheres, a sharp single beam for fine positioning of objects under 10 µm, and round single beam for moving objects larger than 15 µm.
Additional geometries were designed for the second generation of end effectors, including liquid handling capabilities in a pen-like shape, a ~7 µm loop with a notch and a fork to better manipulation of spherical objects. Examples of the designs fabricated in nickel are presented in Figure 7-12. The smallest tip diameter obtained with nickel end effectors was 4.7 µm.
Successful hybrid end effectors were fabricated and released. Three configurations of SU-8 and nickel were tested and represented in Figure 7-13: (1) Were the SU-8 is totally contained inside the boundaries of nickel structure, forming 3D structure (Out-plane circle). (2) The SU-8 has a conformable shape surrounding the nickel structure (fork and sharp V-shape). (3) The active section of the tip is fabricated in SU-8 and is protruding from the nickel (liquid handling and square). The minimum tip diameter obtained in the SU-8 section of the hybrid tip was 3.8 µm. This result confirms an improvement on feature size resolution between first and second generation of end effectors.

![Image of hybrid end effector tips](image)

**Figure 7-13:** Hybrid end effector tips made of nickel and SU-8. The SU-8 can be positioning in three configurations: Totally contained inside the nickel structure (Out of plane circle), conforming the nickel structure (fork and sharp V-shape) and with the active section protruding from the nickel (liquid handling and square).

### 7.3 End Effector Testing

First generation nickel end effectors were magnetically attached to magnetic bases, creating a fully assembled levitated microrobot. End effector tips were dip-coated
in styrene-butadiene-styrene (SBS) following procedures in [247] to enhance adhesion with objects to be manipulated. To facilitate the process, the SBS was dissolved in toluene before dip coating. After coating the toluene is evaporated at room temperature. Figure 7-14 illustrates the usage of the end effectors to manipulate a 10 µm gold wire A) and a 1005-package surface mount technology (SMT) resistor (1 mm x 0.5 mm). For demonstration purposes, the end effectors were mounted with the cooper seed layer facing up in Figure 7-14A and the nickel facing up Figure 7-14B therefore the difference in color. The functionality of the end effectors was unaltered when flipping the end effectors.

Figure 7-14: Top view of nickel end effector mounted on magnetic bases and manipulating objects. A) Sharp single beam tip carrying 10 µm diameter gold wire. Seed layer facing up. B) Sharp V shape tip carrying a SMT resistor. Nickel facing up. Adhesion is enhanced by using SBS polymer (elastomer).

The assembled levitated microrobots with nickel end effectors were successfully tested using the SRI microfactory platform, proving that there was no deleterious electromagnetic interference between the driving platform and the end effectors, nor interference with the levitation of the magnetic base. End effectors were successfully used to manipulate a nickel square test piece (150 µm x 150 µm x 11 µm) and transport it to a sticky surface as presented in Figure 7-15.
An automated sequence was programmed to insert the end effector in a liquid droplet and retrieve back the end effector from the droplet. Because the surface tension forces of the droplet increase dramatically in the microscale, some considerations must be taken for this experiment: The liquid used was a solution of alcohol and water (to reduce surface tension), and the end effector was introduced from the side following a concave trajectory lowering the tip meanwhile entering the droplet. The opposite steps
were followed to retrieve the end effector. Clips from a video demonstrating the procedure were organized in a sequence presented in Figure 7-16.

![Image of end effector entering and leaving a droplet solution of alcohol and water](image)

Figure 7-16: Sequence of the end effector entering and leaving a droplet solution of alcohol and water (for reducing surface tension).

Another interesting application for the end effectors is the possibility to use them for micro electro discharge machining (µEDM) [248], [249]. By connecting in series, the electrically conducive end effectors (nickel or copper) to a high voltage circuit ended in a conductive thin film layer (gold-coated polyamide tape), the circuit could only be closed if the pointy tip of the end effector reach the film layer (Figure 7-17). Right before touching the film, the end effector will discharge energy used to create an eroding spark that will consume the gold layer. The precision, position and direction of the erosion are dependent on the microrobot positioning and electrical circuit. µEDM is beyond the scope of this dissertation. The experiment reported at Figure 7-17 was conducted as a proof of concept at SRI laboratories but experiment conditions were not shared with researches at University of Florida for confidentiality reasons.
Herein we demonstrate successful batch fabrication of two generations of detachable/exchangeable end effectors. The first generation made of Cu, Ni and SU-8 had thickness between 10-13 µm and minimum tip diameter of 4.7 µm. The second hybrid generation is fabricated on Ni with SU-8 tips were 6 µm thick and minimum tip diameter of 3.8 µm. The Cu and Ni end effectors prove more robust than the SU-8. Fully assembled microrobots are achieved by attaching the end effectors to magnetic bases.
using nickel attachment structures embedded in the end effector bodies. This magnetic attachment can withstand the weight of \(~12\) mg (magnetic base of 2x2 magnets) when lifting the robot by the end effector. End effectors are entirely fabricated using standard microfabrication techniques, therefore demonstrating the possibility of batch fabrication of hundreds of interchangeable end effectors in the same lot. Eight different end effector tips (tools) with micrometer scale features are successfully implemented, demonstrating the potential of having multiple exchangeable tools designed for specific tasks.

The end effectors fully assembled on levitated microrobots proved to be useful for manipulated objects at milli-scale (gold wire and SMT resistors), further tests must be conducted to demonstrate manipulation of objects at the micro-scale. Fabricated robots also proved to have a straightforward interaction with the microfactory platform (no electromagnetic interference), and no interference with the levitation.
ELECTROPERMANENT MAGNETS

Electropermanent magnets (EPM) can play an important role on microgrippers, microrobot end-effectors, microfluidic systems, mechanobiology, MEMS and actuators. This work describes the simulation, fabrication, and experimental demonstration of the smallest reported EPM and subsequent simulation as an actuator for microgrippers. Highly miniaturized EPMs— a NdFeB EPM (900 µm x 2000 µm x 500 µm) and a flexible iron oxide EPM (790 µm x 1000 µm x 500 µm, one order of magnitude smaller than state of the art)—are fabricated using precision dicing and microassembly of bulk magnetic materials. The stray fields from the as-fabricated EPM devices are measured, demonstrating a 15x ratio for the fields between the “on” and “off” states. Additionally, theoretical and simulation models predict the function as actuation mechanism in microgrippers.

A second section of this chapter will describe the fabrication of sub-millimeter axisymmetric electropermanent magnets (EPMs), introducing for the first time a fabrication technique for EPM that involves flexible magnets and bonded magnetic powders. Two different bonded magnets were investigated: NdFeB and SmCo, obtaining magnetic field on/off ratios of 2.8 and 4.6 respectively. Compared to magnet assembly, the fabricated axisymmetric EPM provides: 1) symmetric magnetic field along the magnetization axis, as opposed to the asymmetric fields in the transverse direction, 2) a path for future microfabrication, and 3) an alternative for mass production using roll-to-roll process.

* This section contains excerpts from reference [250]. Special thanks to Catlin Beker, Zahira Gonzalez, Lars Tatum and Dr. Johann Osma for their contribution on this chapter.
8.1 Electropermanent Magnet

An electropermanent magnet (EPM) is a switchable magnet that only consumes power during transition between the on/off states. The concept of switchable magnet was first achieved using mechanical rotation of magnet sandwiched between two soft magnetic shunt plates to turn “on” or “off” a magnetic latching field [251], as in Figure 8-1.

![Figure 8-1: Concept of switchable magnets.](image)

Rather than a physical rotation, an EPM makes use of a pair of magnets where pulse of current in a coil (Figure 8-2) is used to flip the magnetization of one of the pair [252] (avoiding unnecessary interactions with surrounded entities). EPMs at small scale were previously investigated by [253] who reported a manual assembled 2.5 mm x 4 mm x 2.3 mm EPM based on Alnico and NdFeB, used as actuators/latches for
microrobots and programmable matter. Padovani et al. [254] presented a 3.2 mm x 4 mm x 3.6 mm EPM application for the control of a droplet inside a microfluidic system and generated a magnetic field of 50 mT.

Figure 8-2: Concept of electropermanent magnet. The EPM will remain in the designated state in the absence of electrical currents.

There are multiple application drivers for miniaturization of this component such as actuators/latches for microrobots and programmable matter [3], ferrofluid droplet manipulations in microfluidic devices [4], and more. This work focus is the permanent magnet array and explores a novel axisymmetric EPM fabrication technique that is amenable to miniaturization, building on the design principles previously proposed by the authors in [5].
8.2 Sub-millimeter Electropermanent Magnets for Microgripper

Microgrippers [243] have been used for precise manipulation and assembly of microscale elements and the most common actuation mechanisms are electrostatic [255], electro-thermal expansion[256], thermos-magnetically[257], piezoelectric [242], [258] and magnetic [241], [259]. Magnetic actuation results very attractive for the ability to generate high forces through remote actuation. A previously reported magnetically actuated microgripper [260] used a permanent magnet on one side of the gripper and a ferrite on the other side (reverting the ferrite to attract them). A pulsed external magnetic field on the surrounding environment is required. This work proposes an alternative actuation mechanism to build a microgripper by using a magnet that can be remotely turned on/off.

This work explores the feasibility of employing an EPM as an on/off microgripper as shown in Figure 8-3. By placing the EPM at the end of a cantilever (top jaw of the gripper) and an iron foil in front (bottom jaw). When the EPM is switched “off”, there is no magnetic force and the gripper is open; when the EPM is switched “on”, the magnetic force between the EPM and iron foil will bend the cantilever and close the jaws of the gripper.
8.2.1 Experimental Results

EPM Fabrication

An order-of-magnitude size down-scaling of EPMs using semiconductor dicing technology (ADT dicing saw) is proposed. Two magnetic materials (hard ferromagnets) were machined: (1) NdFeB magnets 650 µm x 1000 µm x 500 µm (thick/width/depth), with remanence of \( B_r = 1.16 \) T, and coercivity of \( H_{ci} = 899 \) kA/m (\( \mu_0 H_{ci} = 1.13 \) T), and (2) flexible iron oxide magnets 540 µm x 500 µm x 500 µm, with remanence of \( B_r = 180 \) mT, and coercivity of \( H_{ci} = 125 \) kA/m (\( \mu_0 H_{ci} = 0.16 \) T). Two iron foils (soft ferromagnets) were machined, with 125 µm of thickness, covered the magnets to conduct the magnetic flux.

Two EPMs were successfully assembled with the two magnetic materials as presented in the insets of Figure 8-4. Each EPM consist of two magnets of the same size and material, in between two iron foils. The NdFeB EPM was 900 µm x 2000 µm x 500 µm, and the flexible iron oxide EPM was 790 µm x 1000 µm x 500 µm. EPMs were manually assembled and the switching magnet was mechanically rotated to change on/off states. This consideration was made as initial approach to constraint the problem.
analysis to the magnetostatic domain and to focus on the behavior of the magnetic materials without considering external currents.

A test bench with computer interface platform was built using a commercial Hall effect sensor (SSE49) to measure the magnetic flux density ($\mathbf{B}$ field) produced by the EPM after fabrication. According to these measurements, calculations for using a single-turn solenoid and a straight wire circuits were made to generate the necessary field to electrically switch the state of the EPM.

**Measurement of EPM magnetic fields**

The measured magnetic fields for each EPM are shown in Figure 8-4 for on/off states. As expected, the NdFeB EPM presented a larger magnetic flux density at the surface during “on” state (2.7 mT) in comparison with the iron oxide EPM (0.75 mT). On the other hand, the NdFeB EPM presented lower on/off ratio (9) than the flexible iron oxide (15). It is strongly suspected that the “off” state magnetic field of the iron oxide EPM is in the resolution limits of the measurement system therefore, future measurements of the magnetic fields with higher resolution equipment are suggested.
According to the measured fields, the necessary current to invert the magnetization direction of the flexible iron oxide magnet, when using a single-turn solenoid of 750 µm radius and a straight wire circuits were calculated (currents of 187 A and 895 A respectively). Future work will be dedicated to evaluate the strategies to generate such currents and to flip the magnetization direction of the magnets.

8.2.2 Simulation Results

Three sets of finite element model simulations were implemented using COMSOL® Multiphysics. (1) A 2D magnetostatic simulation predicted the stray magnetic field generated by the EPM at on/off states. (2) By placing an iron foil in front of the magnet and change the separation, it is possible to estimate the total force generated by the EPM at each state (on/off) as a function separation. (3) Knowing the
force generated by the magnet it is possible to simulate the gripper deflection towards the iron foil.

**Magnetic Field Simulation**

Simulations of the stray magnetic field at on/off states for the strongest EPM (NdFeB) are presented in Figure 8-5. Simulations include an iron foil in front of the EPM and two independent configurations with different EPM-foil separations were evaluated: 1 mm and 0 mm separation. Figure 8-6A summarizes simulation results for the “on” state of the EPM at multiple separations. The maximum force when the EPM is “on” and separation is 1 mm (microgripper will change from open to close) is \( \sim 686 \) mN. When the EPM is “on” and separation is 0 mm (microgripper is touching the surface) the magnetic force is \( \sim 881 \) mN.

![Figure 8-5: NdFeB 1500 \( \mu \)m x 2000 \( \mu \)m x 500 \( \mu \)m EPM magnetic field lines simulation for “on” and “off” states when the distance between the EPM and the iron foil is zero.](image)
Figure 8-6: COMSOL simulation results for a NdFeB EPM (540 µm x 1000 µm x 500 µm) at “on” state: A) Magnetic force vs gap distance. B) Beam displacement vs applied magnetic force.

**Microgripper Mechanical Simulation**

The beam dimensions were chosen considering the size and weight of the EPM and the desire deflection produced by the magnetic force at 1 mm of distance. Using the force values simulated above, it is possible to simulate the mechanical response of cantilever beam by applying different point force loads at the tip of the beam.

Considering the EPM dimensions, the beam height and thickness were constrained to 800 µm and 300 µm respectively. Considering the possibility of having symmetrical beams (jaws) in the microgripper and each one bending half the separation gap, an analytical solution for bending the beam 500 µm was found. The beam length is obtained by solving Equation 8-1, the maximum deflection equation ($\delta_{\text{max}}$).

$$
\delta_{\text{max}} = \frac{F_{\text{EPM}} \cdot L_b^3}{3 E_s I}
$$

where $F_{\text{EPM}}$ is the magnetic force made by the EPM at “on” state, $L_b$ is the length of the beam, $E_s$ is the Silicon young’s modulus and $I$ is the moment of inertia.
\[ I = W_b \cdot H_b^3 / 12 \]. An appropriate length of \(~8.6\) mm was calculated to meet the desire requirements. Thus, the beams with those dimensions are expected to suffer a deformation of \(500\) µm when a magnetic force of \(674\) mN is applied. Simulations confirmed the beam deflection as shown in Figure 8-7. Additionally, beam deflection simulations for all forces calculated under section III. A. (Magnetic field simulation) for different EPM separations were made and presented in Figure 8-6B.

![Figure 8-7: Simulation of the beam stress and deflection when the EPM is “on”](image)

The weight of the EPM was considered for the beam deformation analysis. The weight of each iron foil was \(22.62\) mg and each NdFeB magnet was \(2.79\) mg, thus, the total EPM mass was \(50.84\) mg equivalent to a weight force of \(~499\) µN, which is negligible compared to the magnetic forces acting on the beam. The deflection of the beam due to the weight of the EPM was simulated to be \(0.37\) µm and also confirmed by calculations.
8.3 Axisymmetric Sub-millimeter Electropermanent Magnet

A design and fabrication of sub-millimeter axisymmetric electropermanent magnets (EPMs) will be presented in this section. Figure 8-8 shows the operation principle of the traditional EPM, and compares the conventional (transversal field [252]–[254]) vs. the new (axisymmetric field) architectures. The axisymmetric architecture aims to generate stray B fields and latching forces along the axis, using two concentric permanent magnets and two soft magnetic cap plates.

![Operational concept of the conventional and new axisymmetric EPM architectures showing the ON and OFF states.](image)

8.3.1 Simulations of the Axisymmetric EPM

Using 2D simulations in COMSOL Multiphysics, the B fields and latching forces of both architectures are studied as a function of several design variables: outer radius, permanent magnet aspect ratio and radius ratio, and cap plate thickness. For this investigation, the following materials were assumed: grade N52 NdFeB as fixed inner magnet, grade 5 Alnico for the outer switching magnet, and mild/low-carbon steel (AISI 1018) for the cap plates. The cap plate thickness was found to be an important variable for tuning the on/off latching force ratio. Figure 8-9 shows the final proposed dimensions...
as a function of the magnetic layer thickness (T). These dimensions were selected to maximize the on/off latching force ratio for a given cap plate thickness.

Figure 8-9: Example EPM configuration yielding maximum latching force on/off ratio

Simulations of the stray magnetic field of the optimal EPM evidence ~10x difference in B field near the EPM poles in the on/off states (Figure 8-8A). Figure 8-8B shows the magnitude of the on/off B-fields along the central axis with and without the cap plates. Additional modeling is used to predict the latching force to a semi-infinite steel plate. Figure 8-8C shows how the on/off latching force ratio can be tuned by changing the thickness of the cap plates. Simulations of the new configuration (dimensions used in Figure 8-9) suggest an on/off force ratio of 450, with the ability for tuning this ratio from 1 up to 784, for sizes between 8 mm³ and 34 mm³, respectively. These results suggest the new axisymmetric design may afford hundred-fold higher latching force ratio than conventional EPM architectures in 1/10th the volume.
Simulations and optimization of sub-millimeter axisymmetric electropermanent magnets (EPMs) predicting a latching force on/off ratio of 784 with total volume of 34 mm³. Compared to conventional architectures, the axisymmetric design provides: 1) better performance in a smaller form factor, 2) symmetric magnetic field along the magnetization axis, as opposed to the asymmetric fields in the transverse direction, 3) a path for future microfabrication, and 4) large tunability of the magnetic field on/off ratio (therefore the force) as a function of design variables (e.g. radii and thickness).

8.3.2 Fabrication of the Axisymmetric EPM

The concentric magnets on the EPM are fabricated by punching ~1 mm diameter holes (using a cutting cannula) on flexible iron oxide (switching magnet) magnetic substrate, previously demagnetized. Bonded magnets (fixed magnet) are fabricated on these holes using permanent magnet powder as the magnetic material and cyanoacrylate glue as bonding agent (applied on both sides), following technique described in [261]. Finally, a ~2 mm cutting cannula is aligned to punch the outer ring. The resulting assembly (called EPM core) is presented in Figure 8-11. Two different bonded magnets were analyzed: NdFeB (6 µm) and Sm₂Co₁₇ (~15 µm). EPM cores are
magnetically characterized by using vibration sample magnetometer (VSM) and magneto optical images (MOI). A pulse magnetizer is used to switch the EPM cores from ON state (pulsing 7 T in the axial direction) to OFF state (by pulsing -700 mT for SmCo or -440 mT for NdFeB EPMs). Mild/low-carbon steel (AISI 1018) plates are milled and glued to the EPM core to finish the EPM.

Figure 8-11: Fabrication of the EPM core. A) Top view and B) cross section. C) Frontal view of the EPM including caps.

8.3.3 Characterization of the Axisymmetric EPM

A switchable 2.1 mm diameter and 0.8 mm thickness EPM was fabricated using the proposed technique. Magnetic characterization of the EPM cores using VSM (Figure 8-12), showed that the SmCo EPM presented higher remanence ($\mu_0 M_r = 117$ mT) and lower intrinsic coercivity ($H_{ci}=210$ kA/m) than the NdFeB EPM (75 mT and 252 kA/m).
Figure 8-12: Magnetization curve (VSM) of two EPM core configurations: with NdFeB and SmCo as bonded magnets.

MOI characterization (Figure 8-13) of the ON and OFF states demonstrate that it exists a reversal magnetic field capable to switch the magnetization of only one of the concentric magnets (flexible iron oxide) without switching the fix magnet (bonded magnet). Cross section measurements of the B field suggest that the average ON/OFF ration of the magnetic cores for the SmCo (27.3 mT/-6 mT) and NdFeB (23 mT/8.3 mT) EPM cores are 4.6 and 2.8 respectively. These are fundamental advances in the small-scale fabrication of EPMs and an important demonstration of the working principle for the axisymmetric EPM design.
Figure 8-13: Stray magnetic field (MOI) for ON and OFF states of the EPM. A) Two configurations with different bonded magnets are measured: NdFeB and SmCo. B) Cross section measurement over the X axis.

Different reverse magnetic fields were applied to each sample of NdFeB and SmCo EPM and MOI measures were made. A full magnetization of (7 T) was always applied before the reversal field (Figure 8-14A). Post processing treatment from MOI data was made to calculate the magnetic flux (in units of nWb). For this calculation, the outer diameter of the EPM was manually selected for each image (constant diameter through all images). The integral of the magnetic flux density field (through the selected circular area) was used to define the magnetic flux. A plot of the magnetic flux as a function of the reversal magnetic field for each sample is presented in Figure 8-14B. This plot demonstrates that it exists a reversal magnetic field that cancel completely the magnetic flux of the EMP. This is a prove of concept of the feasibility of obtaining an “off” state from the EPM. This reversal magnetic field to turn the EPM off is 430 mT for the NdFeB sample and 300 mT for the SmCo sample.
Figure 8-14: EPM magnets after applying different reverse magnetic fields. SmCo and NdFeB samples were fully magnetizing before each test. Magnetic flux density calculated from MOI data. MOI of EPM magnets (inset).

Fully assembled EPMs with the caps were used to measure the magnetic flux in the on and off state (by applying the reversal magnetic field found below). Carbon steel plates proved to be a bad choice because their dimensions generate leakage magnetic fields that interfere with the accuracy of the measurement. Instead, 150 µm thick film made of steel, was used to create the plates. The film was laminated (top and bottom of the magnet) before punching the EPM. This technique self-align the core of the EPM with the plates and guaranty the same diameter. Figure 8-15 illustrates the result of the magnetic flux measurements for the fully assembled EPM. The proof of concept of a EPM that can be turned “on” and “off” was demonstrated and magnetic flux on/off ratio of ~2 were achieved for both samples (NdFeB and SmCo).

Future efforts should be made to optimize the reversal field value for the fully assembled EPM and to maximize the on/off ratio.
This work demonstrates successful design of a microgripper based on EPM actuation using NdFeB magnets to obtain higher magnetic field. It also demonstrates the fabrication of the two smallest EPM reported to date, a NdFeB EPM (900 µm x 2000 µm x 500 µm) and a flexible iron oxide EPM (790 µm x 1000 µm x 500 µm). The structure generates an estimate magnetic field on/off ratio of 9 and 15 respectively. Future magnetic field measurements with higher resolution are required to confirm this ratio. An application of the EPM as a microgripper is demonstrated using finite-element model simulations. These promising results validate a future microfabrication path of such microgrippers and enable the technology advance towards smaller scales.

A novel axisymmetric configuration of EPM was proposed. A fabrication technique that enables the batch microfabrication of this components was also demonstrated. Two fully assembled EPM (SmCo and NdFeb) with magnetic flux on/off ratio of ~2 were achieved.
CHAPTER 9
CONCLUSIONS

The presented work advanced the field of microrobotics by developing of a micro-magnetic field pattern fabrication process called selective magnetization. The process imprinted pre-designed mini/micro-scale patterns on hard magnetic thick films. This process was modeled via the finite-element method to solve the magneto-quasi-static Maxwell equations using the measured nonlinear magnetic properties of the materials (magnetization curves) and successfully validated using experimental characterization with two techniques: magneto-optical imaging and a scanning Hall probe. The model predicted the general trends observed in the experimental results.

Using the selective magnetization process, two applications were demonstrated in this work: 1) the magnetic assembly of nanoparticles (bottom-up) for the manufacture of releasable magnetic microstructures and 2) the batch fabrication of diamagnetic levitated microrobots (to-down). Selective magnetization proved to be fundamental enhancing both sub-millimeter fabrication approaches: Bottom-up and top-down.

Solutions for two fundamental problems in the field were presented: 1) A successful batch fabrication process of microrobots, to counteract the low throughput of manually assembled robots. 2) The creation of exchangeable end effectors and magnetic actuators, to counteract the lack of functionality.

9.1 Summary of Research Contributions

A selective magnetization process was successfully implemented, with the versatility to create complex magnetic field patterns to be used in nano/micro application. The technology core is the magnetization mask. Three different alternatives to produce these masks were presented: 1) A microfabricated nickel mask, with 150 µm
feature size, successfully magnetizing magnetic recording media. 2) A low aspect ratio (0.6), with 1 mm feature size, fabricated using end mill machining and successfully magnetizing flexible iron oxide and NdFeB magnets, and 3) a high aspect ratio (10), with 1 mm feature size, laser machined that successfully magnetized NdFeB.

Using selective magnetization, a novel fabrication technique was demonstrated to obtain free-floating magnetic microrobots by in situ crosslinking of magnetically assembled nanoparticles. Microrobots with square and cross shape were obtained with external dimensions of 175 µm and 150 µm, respectively, with boundary line dimensions of 230 ± 80 nm in height and 3.9 ± 1 µm in width. The magnetic microrobots were successfully released from the substrate retaining their shape in suspension during manipulation with external magnetic fields.

Additionally, using selective magnetization, a process was successfully implemented to fabricate 9 diamagnetically levitated microrobots per batch. The millimeter-scale robots utilized a checkerboard magnetic pole pattern imprinted into a 400-µm-thick NdFeB substrate. Fabricated microrobots were capable of assisted levitation (external magnetic field bias) and operation in sliding mode (lateral movement using microfactory platform).

A magnetic force sensing technique for force range of ±1000 µN with 50 nN resolution and with a minimum step size of 50 µm was also demonstrated. Resulting magnetic forces measured using this method were compared with the analytical solution of the forces between two magnets (with one fixed and the other raster the surface). Measurements and an analytical model present a good agreement. The results
demonstrate this technology could be a valuable contribution to close the technological gap for microscale magnetic force sensing.

Next, magnetically detachable/replaceable end effector were developed. A fabrication recipe for these end effectors was created and successfully standardized (over 4” wafer) to produce structures with nickel body and SU-8 tip tools. End effectors accomplished the manipulation of objects at microscale and were successfully used to perform micro-electro discharge machining (µEDM) with the microrobots.

Finally, the usage of electropermanent magnets as actuators for microrobot was successfully demonstrated, by designing an EPM-based microgripper. The two smallest EPM reported to date in literature were fabricated: a NdFeB EPM (900 µm x 2000 µm x 500 µm) and a flexible iron oxide EPM (790 µm x 1000 µm x 500 µm). Furthermore, a novel axisymmetric configuration of EPM was proposed (leading to the filing of a patent) and a fabrication technique that enables the batch microfabrication of this components was also demonstrated.

9.2 Future Work

There is always room for improvement in research. It was fortunate that most of the individual efforts described in this dissertation successfully demonstrated a proof of concept of the respective technology. However, each effort has the potential for follow-on work (especially in the emerging, infant-stage field of microrobotics). For example, in the case of electropermanent magnets, it was demonstrated that the configuration of magnets in the axisymmetric EPM can be magnetized to turn on/off the external magnetic flux. Despite that, a full microfabrication of the EPM should be pursued in future research projects. Another example is the work conducted with the bottom-up approach of fabricating releasable magnetic structures can be continued by exploring
biomedical applications for the technique. What if before releasing, the structures are coated with some medicine and they are remotely manipulated after release (i.e. using magnetic resonances images MRI), to be used as drug delivery mechanism into cells, tumors or damaged tissue.

9.2.1 Selective Magnetization

From all the topics covered in this document (and because of its broad relevance and applicability), the one requiring special discussion of future work is the selective magnetization process. Future work towards enhancing the selective magnetization process must address alternatives to increase the magnetic fields (therefore diamagnetic force) produced by selectively magnetized bases and make them levitate. The alternative hypothesis to solve the problem is: during the reversal magnetization, the magnetic field experienced by the substrate under the unexposed areas (magnetic mask) is so high (between 1 T and 1.5 T), that the material start to demagnetize and loose magnetic field. This problem is observed either using pulse magnetizer or VSM.

An alternative solution is to reduce the magnetic field in the unexposed areas. One way to do it is to follow developments by the company called Correlated Magnetics. This company has produced devices called PolyMagnets (cm size selectively magnetized NdFeB magnets). They use a fabrication procedure [181], were they induce magnetic field on a single ferromagnetic tip by driving current trough a coil and magnetizing an individual square (pixel like). By displacing the tip in x and y and repeating the magnetization they will “imprint” any designated pattern.

An alternative could be to combine Correlated Magnetics’ approach the selective magnetization propose in this dissertation. To fabricate a magnetization mask in the form of a C-shape transformer (like the one proposed by Figure 9-1), with a 450 µm
gap. The rationale is that an electric current pulse will generate a concentrated magnetic field only under the mask patterns, reducing the external magnetic field in the areas without the presence of a magnetization mask, leading towards the selective magnetization of the substrate.

A proof of concept of the proposed C-shape transformer with a coil (transformer configuration with the magnet substrate to be magnetized placed in the air gap) was simulated. This configuration will potentially increase the field underneath the mask but keep almost 0 T field everywhere else. A cross section of the 3D COMSOL simulations are presented in Figure 9-2. The current and number of wire loops was selected so the field in the gap was ~1.5 T.
Figure 9-2: Cross section of a 3D simulation of the $B_z$ field generated by a coil and the mask.

As a control simulation, a laminated C shape core with no pattern was also simulated. Figure 9-3A compares the $B_z$ fields observed at the air gap in: the control simulation (coil and core), the mask under surrounding external field (external field) and the coil, the core and the mask (coil and mask). The results showed that by using a coil, the field outside the patterns can be dramatically reduced by ~750 mT, and therefore the magnetic contrast can be enhanced. Figure 9-3B presents the minimum and maximum fields obtained and the calculated contrast superimpose over the DC demagnetization curve of substrate. These results are encouraging because the contrast was immediately duplicated. Further investigation is required to find the right conditions to maximize the magnetizations of the patterns.
By observing Figure 9-3A a new concern arises: The separation between poles in the mask during reversal could affect the contrast. Three peaks can be observed in the figure, the ones at the sides observe a contrast of ~0.8 meanwhile the one in the middle has a contrast of ~0.4. A minimum separation between features in the mask could exist to maximize contrast. If this is true, a single reversal magnetization will not be enough to solve the problem. Multiple masks with the minimum separation between poles should be aligned and used at different times to magnetize the designated pattern and obtain levitation.

### 9.2.2 End Effectors

For future fabrications of end effectors, the authors suggest to make the following modifications on the process: (1) Use LOR as a sacrificial layer, this will improve the quality of the resulted structures and reduce fabrication time. (2) Use AZ 422 MIF for dissolving the LOR sacrificial layer. Other commercial stripper or developers (such as
AZ 312 mif or PG remover) might etch the copper seed layer or detach the SU-8 from the nickel. (3) Eliminate Ti as a protective material in the seed layer (replace this step by etching the copper oxide using a 1:10 solution of hydrochloric acid and water), this will prevent the peeling of end effectors during electroplating. (4) Avoid using magnetic attachment structures, it was proven that these structures will not generate a self-alignment of the end effector and not having them will simplify the process. (5) Fabricate the body of the end effectors in nickel. As show before, the nickel offered magnetic adhesion to the robot bases and high stiffness to support objects. (6) Keep two separated steps for end effectors and tips but fabricate the tips by electroplating nickel or copper (depending on the application). This will improve the adhesion between end effector and tip, increasing yield and making the tethers more robust. (7) Invert the order of the layers. Electroplate the tips first (smaller feature size) and then electroplate the end effector body (bigger feature size). This will guaranty that the surface of the tip (the one in direct contact with manipulated objects) will be flatter and smoother.

In a broader vision of future work on end effectors, it is relevant to remember that their functionality is totally dependable on the applications. New applications will require different tools, therefore is necessary to continue improving this technology to create alternatives that are more customizable by the end user. An interesting direction of this concept is making the body end effector with the planar fabrication technologies presented here, but using micro-nano scale 3D printing (i.e. Nanoscribe technology) for creating the final tips.

9.3 Final Conclusions

Microrobotics is a ~30 years old field that technologically is still in its infancy stage. Many physical phenomenon at the micro/nano level are not fully understood and
technical/technological challenge remain unsolved. Even though there are many and fantastic potential applications (mainly in industrial manufacturing, military and bioengineering) they still need more momentum to be considered opportunities for the industry or governments and invest full steam in their development. It is the time for the research community to take advantage of this fertile soil, numerous questions to solve and infinite opportunities to explore. Microrobotics is living now the prophesy of Richard Feynman that drove the semiconductor industry, fortify the microsystems community and exploit in the nanotechnology potential: There's Plenty of Room at the Bottom.

The research presented in this dissertation, advanced another step towards the realization of the dreams associated with microrobotics providing clever engineering solutions to tackle technological two challenges: the batch fabrication of microrobots and their functionality. The vehicle to advance this step is name “selective magnetization”, a technique so versatile that proved to be useful to fabricate structures with the two existing approaches: bottom-up (assembly nanoparticles into free floating microrobots) and top down (machining centimeter magnets into levitated microrobots).

The importance of this work relays in the link between academia and industry. Any technology looking to impact industry in a certain stage, necessary requires advances in batch fabrication and that was precisely the direction of this work. Contributions made in this research can potentially be used by industry to fabricate and test (with the magnetic force measuring technique) better and more functional magnetic devices at nano and micro scale.

This research carries the hope that the fabricated microrobots themselves can be used in two scenarios: the free floating magnetically responsive microstructures, can
potentially be used by researchers in biomedical applications for drug delivery or even theranostic applications, where is required precise remote manipulation of cell-size-structures. By the other hand, the levitated robots are very close to contribute manufacturing and 3D positions of complex devices with sub-micron accuracy. Detachable end effectors will be indispensable to give customization and versatility to the final customer.

The other inspiring technology brought by this research is in the direction of functionality. The presented proof of concept of the microfabricated electropermanent magnet, could inspire the research community with the idea of “digital micro magnets”. This component is an actuator that could enhance the microrobots by giving them “smart” tools.

The author of this dissertation, firmly believes that the true potential of microrobotics will come when the advances in electronics start bridge the gap between the promises of the micro/nano world and functionality of the meter scale world. And that is the reason this research contributed towards the functionally of the next generation of microrobots. Ultimately, humanity will continue pushing the limits of the small scale, and only connecting the dots between independent technologies (i.e. the nano – micro gap) we will be able to deliver the promises and vision to create enhanced human-size products starting from atoms.
REFERENCES


BIOGRAPHICAL SKETCH

Camilo Velez Cuervo is a researcher who received his Ph.D. in the electrical and computer engineering department of University of Florida in 2017. He worked on Dr. David Arnold’s group at the Interdisciplinary Microsystems Group (IMG). He is hoping to further apply his expertise on magnetic microsystems in the field of microrobotics, as a stepping stone toward a faculty position. Skilled researcher in microsystems, MEMs, microfluidics and electronics engineering. He strength any team by bringing creativity, innovation, entrepreneurship, and leadership. His curriculum include 9 years of research experience in micro/nano device fabrication, 2 years of industry experience in Siemens healthcare diagnostics, teaching experience for more than 20 courses at graduate and undergraduate level covering more than 13 areas at 3 different universities, he is a co-author on 14 papers, he has participation in 18 conferences, he has 2 provisional patents filed, plus 1 additional invention disclosure, and he is also a co-founder of a startup company (Real NanoMicro).

Camilo was awarded the Gator Engineering Award for Creativity (awarded annually to only one PhD student in the entire UF College of Engineering), his bachelor graduation work at Pontifícia Universidad Javeriana received honorable mention and he has won two best poster awards. Camilo is also Magister in Science from UF, a Magister in Engineering at Universidad de los Andes and has a bachelor degree in Electronic Engineering from Potificia Universidad Javeriana in Colombia.