AN ABSTRACT OF THE PROJECT OF

William Maxwell Davis for the degree of Master of Science in Electrical and Computer Engineering presented on May 26, 2020.

Title: Applications of Magnetic Materials in Soft Robotics

Abstract approved:

____

Pallavi Dhagat

Magnetic materials can be used in modern soft robotics as a method for external stimulus actuation and motion control. By combining aspects of biology and mechanics, devices are fabricated to create a structure capable of complex movement. Applications that these devices are subject to can be broken down into four groups to summarize magnetics influence. These groups are flexible soft robotics, rigid design approaches, liquid metal groups, and novel stimulus methods. Flexible soft robotics involve magnetic materials placed into different elastomers primarily for use in locomotion. The resulting torque from the ferromagnetic particles in an external magnetic field will deform the elastomer causing locomotion. Rigid design approaches

will use a hybrid of hard and soft magnetic materials to create a switch for gripping payloads. The process of actuating the switch is done by manipulating the magnetization of the soft material so that it is attracted or repelled from its hard material counterpart. Attaching paramagnetic particles to this device will allow locomotion for payload delivery applications. Liquid metal groups utilize both gallium-based compounds due to their low melting points and ferrofluid in both magnetic and fluid mechanic applications. Lastly, the novel stimulus methods include a variety of stimulus events such as varying light, temperature, and pH levels to modify magnetics influence on the device.

Applications of Magnetic Materials in Soft Robotics

By

William Maxwell Davis

A PROJECT

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Presented May 26, 2020

Commencement June 2020

Master of Science project of William Maxwell Davis presented on May 26, 2020

APPROVED:

Major Professor, representing Electrical and Computer Engineering

Director of the School of Electrical Engineering and Computer Science

Dean of the Graduate School

I understand that my project will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my project to any reader upon request.

William Maxwell Davis, Author

ACKNOWLEDGEMENTS

I would like to thank Dr. Pallavi Dhagat for giving me inspiration from the very beginning to do my best work. Her determination in my progress has allowed me to achieve more than I ever could have imagined.

I am grateful for the time my committee members have put aside in their busy schedules to help me along the way. I would also like to thank the members of the Applied Magnetics Laboratory for answering the many questions I had, no matter the hour.

Finally, I would like to thank my friends and family for always being there when I needed them the most.

TABLE OF CONTENTS

Page

1 INTRODUCTION 13

2 MATERIAL PHYSICS 14

2.1 Magnetic Materials 14

2.1.1 Hard Magnetic Materials 15

2.1.2 Soft Magnetic Materials 16

2.2 Physical and Magnetic Properties 17

2.2.1 Rare Earth Compounds 18

2.2.2 Iron (II, III) oxide 19

2.2.3 Ferrites 19

2.3 Applications in Soft Robotics 20

2.3.1 Flexible 20

2.3.2 Ferrofluid 21

2.3.3 Rigid 21

2.3.4 Novel Use 22

2.4 Materials Advantage 22

3 MANUFACTURING CONDITIONS 26

3.1 Materials Consideration 26

3.1.1 Curing Agents 27

TABLE OF CONTENTS (CONTINUED)

Page

3.1.2 Photocurable 27

3.2 Properties of Specific Elastomers 28

4 APPLICATIONS 28

4.1 Biomimicry 30

4.2 Biomedical Targeted Drug Control 31

4.3 Technology Gaps 33

4.3.1 Scaling 33

4.3.2 Durability 33

4.3.3 Performance 34

5 CONCLUSION 34

BIBLIOGRAPHY 35

LIST OF FIGURES

Figure Page

Figure 1 Magnetization profile of the device is shown in four different orientations for simplification. The magnetic material represents one domain for the ferromagnetic particles embedded in the elastomer……………………………………………………23

Figure 2 An external magnetic field is applied to the device. Ideal conditions have a uniform field created by a Helmholtz coil or electromagnetic actuator (EMA)……..24

Figure 3 Simplification of the magnetization is shown with north and south poles for both the device and external magnetic field. ………….…………………………….24

Figure 4 With the external magnetic field replaced with a north and south magnetic pole, an electromagnetic force due to oppositely charged particles will deform the device in the resulting figure. ……………………………………………………..25

Figure 5 Changing the orientation of the external magnetic field will create a force that will push the device forward to create locomotion……………………………...25

Figure 6 Helmholtz coil responsible for producing magnetic flux density for locomotion of the device under test. Flux density is determined by Equation 6. ……………………………………………………………………………………..29

LIST OF TABLES

Table Page

Table 1 Magnetic Materials Classification……………………………………….. 17

LIST OF SYMBOLS

Symbol	Name	SI Unit
Hc	Coercivity	Amperes/Meter (A/m)
ρ	Resistivity	Ohm-Meter (Ωm)
M	Magnetization	Amperes/Meter (A/m)
B	Magnetic Flux Density	Tesla (T)
H	Magnetic Field Strength	Amperes/Meter (A/m)
μ_0	Permeability of Free Space	Henry/Meter (H/m)
m	Magnetic Moment	Amperes*Meter ^{2} (Am^2)
θ	Theta	Degrees (°)
F	Force	Newtons (N)
T	Torque	Newton-Meter (Nm)
E	Youngs Modulus	Newton/Meter ^{2} (N/m^2)
σ	Stress	Newton/Meter ^{2} (N/m^2)
ε	Strain	Unitless
N	Number of Turns	Unitless
I	Current	Amperes
R	Radius	Meters

LIST OF ACRONYMS

Acronym	Name
LM	Liquid Metal
PDMS	Polydimethylsiloxane
PEGDA	Poly (ethylene glycol) Diacrylate
PHEMA	Poly 2-hydroxyethyl Methacrylate
PLGA	Polylactic-co-glycolic Acid
EMA	Electromagnetic Actuator
FDA	Food and Drug Administration
PVDF	Polyvinylidene Fluoride
Ppy	Polypyrrole
NW	Nanowire

1. INTRODUCTION

Soft robotics is a branch of robotics that utilizes highly flexible materials to achieve locomotion and actuation control where rigid bodies are unable. Soft materials such as silicon rubber [1,5,26], PDMS [24,30,35,47], and PEGDA [2,24,82] will make up most of the device as to maximize its potential in soft applications. These applications are most prevalent in the biomedical field [9,10,18,27,70] with further research in the design of these devices to improve locomotion using biomimicry [1,17,18,25]. The biomedical field includes drug delivery [2], peristaltic pump control [12,21], and endoscopy [9,10]. Biomimicry includes land based [1,9,10] and water based [3,18] locomotion. Elastomers for biomimicry will include PEGDA and PLGA since they are photocurable, for use in 3D printing for fast manufacturing of designs to test. The field of magnetics is crucial to the advancement of modern soft robotics to provide control to these devices as they scale to microscopic proportions. External magnetic fields can be used to actuate the soft robot. Thus, no hardware needs to be included in the robot allowing for it to be miniaturized.

2. MATERIAL PHYSICS

This section will cover the materials that are most used in soft robotic applications, while describing the physical and magnetic properties. Advantages and disadvantages of these materials are evaluated based on previous design approaches. Equations used to derive the fundamental forces at work to create locomotion have also been included.

2.1 Magnetic Materials

Three basic properties of magnetic materials are paramagnetic, diamagnetic, and ferromagnetic or ferrimagnetic materials. Of these basic properties, the primary type used for soft robotics are ferromagnetic or ferrimagnetic materials due to their ability to retain magnetization even after an external magnetic field is removed. This gives the ability to implant a permanent magnet capable of supplying a localized field embedded in the elastomer. When embedding certain magnetic materials into elastomers, they are fabricated using melt spinning process development among other tools to create small particles. These particles can be uniformly distributed to make a flexible magnetic responsive material.

The main difference between these materials is ferrimagnetic materials can produce a field similar or weaker to that of ferromagnetic materials. This is because the magnetization of one magnetic dipole moment is antiparallel to that of neighboring magnetic dipole moments. Because the two magnetizations are of unequal strength, there is a net spontaneous magnetization [71]. Another distinction that can be made from these ferrimagnetic/ferromagnetic materials is their ability to resist a change in magnetization. This resistance is defined as the coercivity of a material. Materials that have a small coercivity (Hc < 1,000 A/m) are denoted as soft magnetic materials, where large coercivity (Hc > 100,000 A/m) is denoted as a hard magnetic material. Different magnetic materials used in applications reported in research papers are discussed below.

2.1.1 Hard Magnetic Materials

Hard ferromagnetic materials will produce large magnetic fields with minimal material mass. Since hard magnetic materials have high coercive fields that prevent demagnetization, they will perform well in environments with background magnetic interference or high temperatures. The main goal is to produce a constant magnetic field for use in high repulsion or attraction to other magnetic fields. Such materials are typically compounds of rare earth metals including neodymium (Nd-Fe-B) [4,7,8,25,34], praseodymium-iron-boron (Pr-Fe-B) [1], and samarium-cobalt (Sa-Co). Before the development of rare earth metals, iron alloys like alnico (Al-Ni-Co) were used.

Continuing the analysis on hard magnetic materials, a large magnetic field is not always desirable. These demagnetization resistant fields can be manipulated by only allowing a certain percentage of the magnetic dipole moments in a material to align, which produce ferrimagnetic properties. The ferrimagnetic components to these hard magnetic materials will include various iron oxides (γFe_2O_3), strontium hexaferrite ($SrFe_{12}O_{19}$), and barium ferrite ($BaFe_{12}O_{19}$) [4].

2.1.2 Soft Magnetic Materials

Soft ferromagnetic materials are nanocrystalline and amorphous alloys with lower coercive fields due to the weaker alignment of magnetic dipole moments created by the electrons orbiting the atoms of a material. Since coercive fields are smaller than that of hard magnetic materials, the magnetization from this material can be reversed if exposed to an external field greater than that of its own. This property allows for switching of the magnetization of the soft materials while nearby hard magnetic materials will retain their magnetization orientation. Applications in gripping/drug delivery are explored in Section 4 using this technique. These materials include iron (Fe), iron cobalt alloys (Fe-Co), and nickel-iron alloys (Ni-Fe) that will have high specific saturation magnetization and curie temperatures resulting in the ability to use higher magnetic fields in the applications previously described [17].

These materials will be implemented in microscale devices where the external fields needed for control are very small. This allows for increased range of use since the magnetic fields produced by external devices will exponentially decrease as distance increases. Such applications are in the medical industry where these devices will go in-vivo environments used as payload delivery tools [9,10,18,27,70]. These materials are soft ferrimagnetic ferrites are comprised of materials like iron (II,III) oxide (Fe_3O_4) [2,3], manganese-zinc (Mn-Zn), and nickel-zinc (Ni-Zn). Benefits also include low cost and stability [76] of the magnetic field that is caused by unintentional magnetic interference.

Table 1: Magnetic Materials Classification

	Hard Magnetic Materials	Soft Magnetic Materials
Ferromagnetic	Neodymium, Praseodymium, Samarium-Cobalt, Alnico	Iron, Iron-Cobalt Alloys, Nickel-Iron Alloys
Ferrimagnetic	Iron Oxides, Strontium Hexaferrite, Barium Ferrite	Magnetite, Nickel-Zinc, Manganese-Zinc

Of these materials, three specific alloys present key properties needed in soft robotics. Manufacturing companies and product numbers are provided for further information on these materials and how the mixtures of elements can change the magnetic properties of the materials.

2.2 Physical and Magnetic Properties

The physical characteristics of materials include the mass/volume concentration, mean particle size if in particulate form, and vendor names to verify the elemental composition.

Magnetic characteristics include the demagnetization field required to flip the magnetic dipole moments in the material, saturation magnetization to find the highest possible dipole moment orientation of such magnetic material, and energy product to compare the strength of each magnetic material against one another.

2.2.1 Rare Earth Compounds

Neodymium is a rare-earth metal that can produce hard ferromagnetic properties if combined with compounds like iron and boron (Nd-Fe-B) to stabilize the magnetization of the material in room temperature applications exposed to oxidation. Among all other rare-earth metals, neodymium has the highest power density capable of supplying the highest magnetic field given a set mass. The specific neodymium compound used in research projects by *Diller et al.* was manufactured using micromoulding techniques to be integrated into a micro gripper arm in combination with soft magnetic materials to form a payload delivery system. Application in gripping/drug delivery are explored in Section 4. The material was purchased from Magnequench *product number MQP-15–7*.

Praseodymium (Pr-Fe-B) is a second rare-earth metal that provides small scale integration into elastomers to create flexible magnetic field responsive material. Examples produced from *Venkiteswaran et al.* use isotropic powder with a mean particle size of 5-10μm. While the elastomer is curing, the particles can be oriented in a specific direction to allow different magnetic domains within the same elastomer. Applications in locomotion are explored in Section 4. The material was also purchased from Magnequench *product number MQFP-16-7-11277*.

Permanent magnet applications for these alloys are the most common with varying power densities in larger scale devices (sub millimeter) [4,7,8,25,34].

2.2.2 Iron (II, III) oxide

Iron (II, III) oxide (also known as magnetite) is a soft magnetic material with an elemental compound of Fe_3O_4. This material exhibits paramagnetic properties unlike the previously mentioned compounds. Paramagnetism means the iron (II, III) oxide is attracted to externally applied magnetic fields, but is unable to produce a magnetic field of its own.

The specific material used in research projects by *Li et al.* was manufactured by Sigma-Aldrich *product number 637106*. This project implemented the iron oxide within biodegradable and bio-compatible hydrogels for simple attraction to a magnetic field to create locomotion in aqueous environments. This effect combined with other materials that exhibit non-magnetic stimulus events allowed for a novel method of drug delivery. The iron oxide particles used had a diameter of 100nm.

2.2.3 Ferrites

Ferrites are ceramic compounds consisting of iron oxide and elements like barium, cobalt, nickel, or silicon. Ferrites magnetization can be switched at moderate fields of about 120-477kA/m [4,86] at room temperature allowing for dynamic remagnetization of this single material.

The range of coercive fields corresponds to different materials mixed in with the iron oxides. An example of this classification would be $BaFe_{12}O_{19}$ with a coercive field of 400ka/m [4]. This material has been used in prior research projects [4] purchased from Hoosier Magnetics, particle size ranges from 5-10 μm. Higher resistance to demagnetization creates the possibility for low frequency switching applications to perform best.

2.3 Applications in Soft Robotics

Soft robotics will utilize a variety of magnetic materials depending on application conditions. Some conditions may include biocompatibility of these devices to be used in-vivo experiments, structural integrity for long lasting devices, and low-cost for large scale applications. In the section below, the different variety of magnetic materials is discussed.

2.3.1 Flexible

Flexible field of soft robotics uses hard magnetic materials such as neodymium (Nd-Fe-B) [4,7,8,25,34], praseodymium-iron-boron (Pr-Fe-B) [1], and iron oxide (Fe_3O_4) [2,3] that are integrated into flexible elastomers. During manufacturing, these elastomers are in a liquid form allowing the magnetic powder to be uniformly distributed along the device. When an external magnetic field is applied, the particles will physically move their magnetic moments in the direction of the field which is then cured in place to align in a single direction. Combining different domains of cured elastomer together will result in a device with multiple domain orientations of magnetization. These directions of each domain influence the interactions between the elastomer and the external field to produce a desired magnetic response.

2.3.2 Ferrofluid

Ferrofluids groups need liquid metals (LM) in microfluidic systems for mechanical actuation. These materials are gallium based [16,19,33] compounds for low melting temperatures typically below room temperature. These liquid metals can achieve beneficial properties from both magnetics and fluid mechanics fields. Mixing these LM materials with other alloys will influence the properties to provide longer lifetime of the material, resistance to oxidation, or viscosity of the metals in liquid form for improving microfluidic techniques [16,19,33]. Since the metals are liquid, they are not bound by a specific structure. The fluid metal can merge into different orientations as needed from application specific tasks.

2.3.3 Rigid

Rigid design approaches have a hybrid integration of hard and soft magnetic materials that are micromoulded into place [4]. Micromoulding is a manufacturing technique to create a miniature mold of a device that will be filled with magnetic material in liquid form. This material will harden to form some desired shape. Shaping the orientation of the mold will determine the shape of such device to match the mechanical properties needed to function as a switch for payload delivery applications [4]. Different orientations of the magnetization of these metals are applied after the micromoulding process has occurred.

2.3.4 Novel Use

These basic magnetic materials can be mixed with other elements to make them responsive to pH [2,40], light [35,63], or other stimulus events [66]. Multiple layers of different material will allow actuation and locomotion techniques to be utilized.

Examples include pH responsive material to expand/contract when the pH level of the surrounding fluid changes. This effect combined with the layers of magnetic material allows for interactions with the surrounding environment. Light is a second stimulus event that can be used to heat the materials. This temperature change will also influence the magnetization of specific materials to respond when they are exposed to this event [35,63].

2.4 Materials Advantage

Power density, torque, and mean particle size are specific metrics tracked to provide advantages from one magnetic material to the next. This section will cover the basis of locomotion and the forces involved that can change depending on different magnetic materials embedded into the elastomer.

The magnetization of a material can be found from the magnetic moment produced by the material integrated over the volume of that material as shown in equation 1.

$$M = \frac{dm}{dV} \tag{1}$$

This quantity can also be obtained by measuring the magnetic flux density (B-field) that the material will produce given a known external magnetic field (H-field) to the material where μ_0 is the magnetic permeability of free space shown in equation 2.

$$M = \frac{B}{\mu_0} - H \tag{2}$$

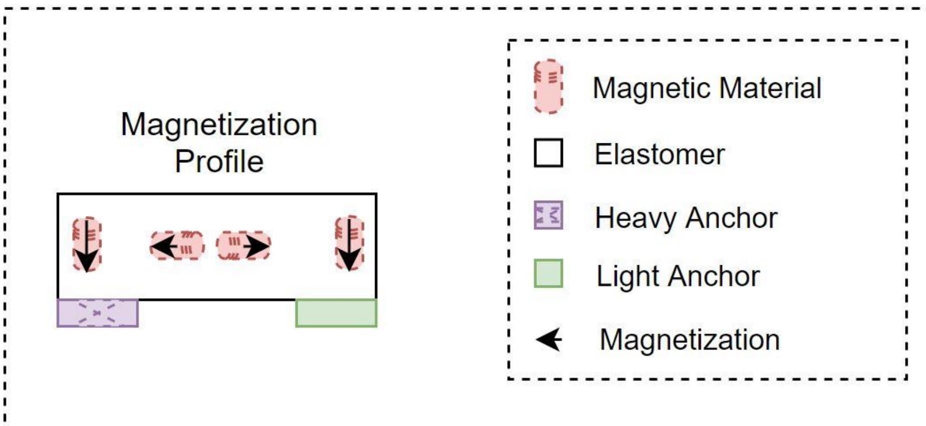

Figure 1: Magnetization profile of the device is shown in four different orientations for simplification. The magnetic material represents one domain for the ferromagnetic particles embedded in the elastomer.

Applying these concepts to soft robotics, the basis of movement is defined by a magnetic materials orientation in each elastomer design. With magnetic materials spread through the device as shown in Figure 1, each dipole moment in the magnetic material will exhibit torque while under an external magnetic field. The applied magnetic field (Figure 2) is applied at some *angle* θ to the device. This will cause the surrounding elastomer to twist (deformation) that will create strain.

$$T_m = m \times B \tag{3}$$

$$T_m = m * Bcos\theta \quad (4)$$

With the proper elastomer design, this strain can be utilized for propulsion. Examples of this device in action include an "inch-worm" design shown in Figures 1-5.

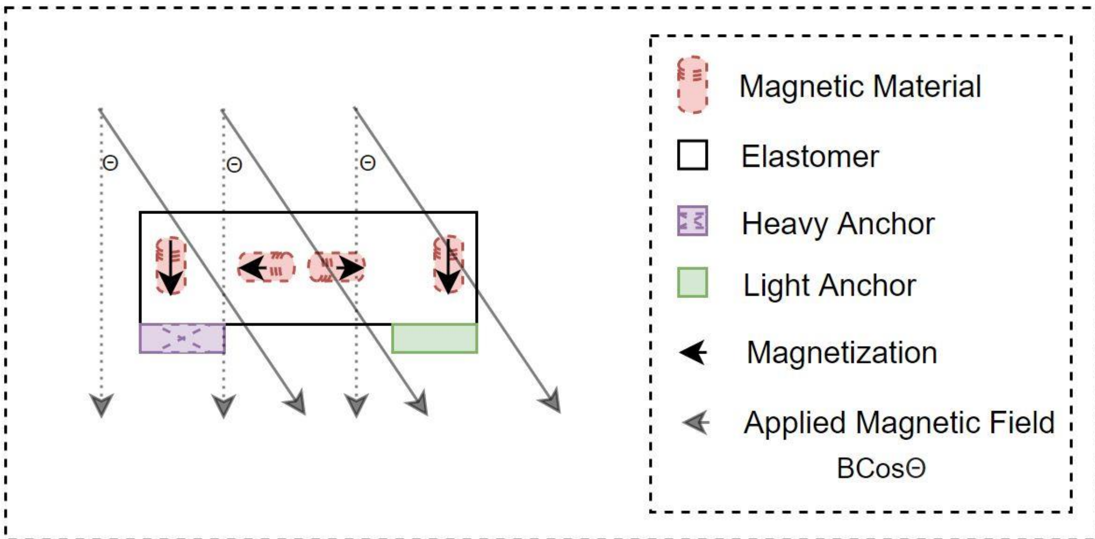

Figure 2: An external magnetic field is applied to the device. Ideal conditions have a uniform field created by a Helmholtz coil or electromagnetic actuator (EMA).

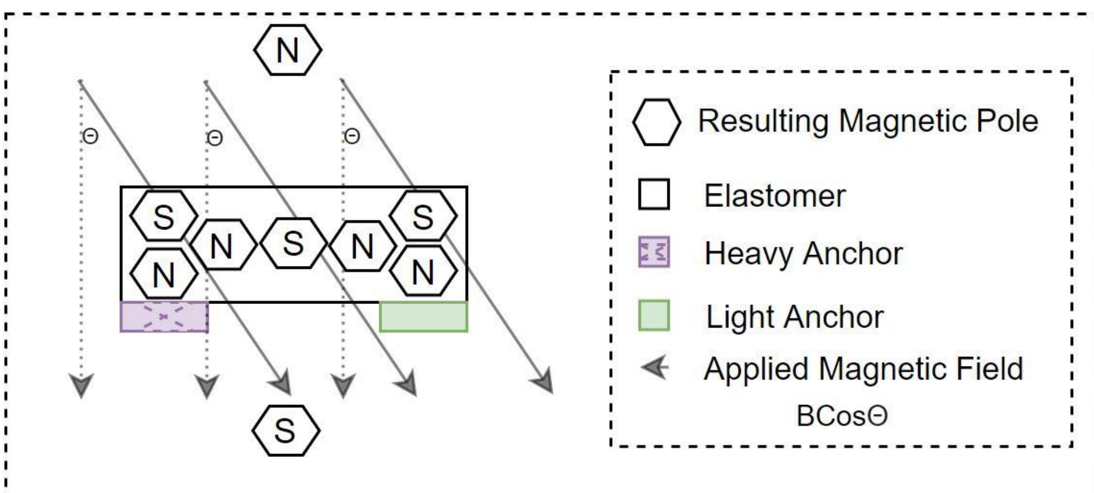

Figure 3: Simplification of the magnetization is shown with north and south poles for both the device and external magnetic field.

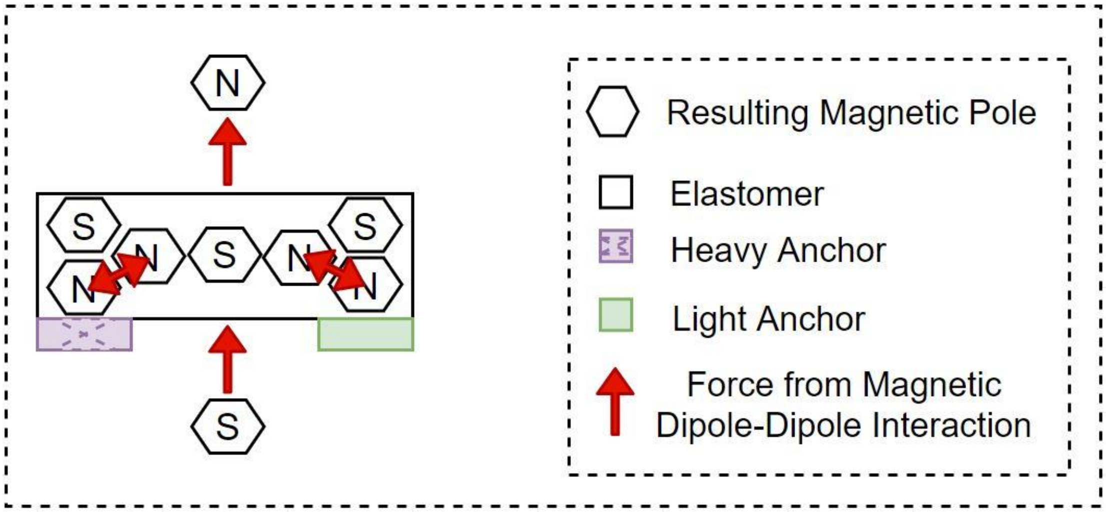

Figure 4: With the external magnetic field replaced with a north and south magnetic pole, an electromagnetic force due to oppositely charged particles will deform the device in the resulting figure.

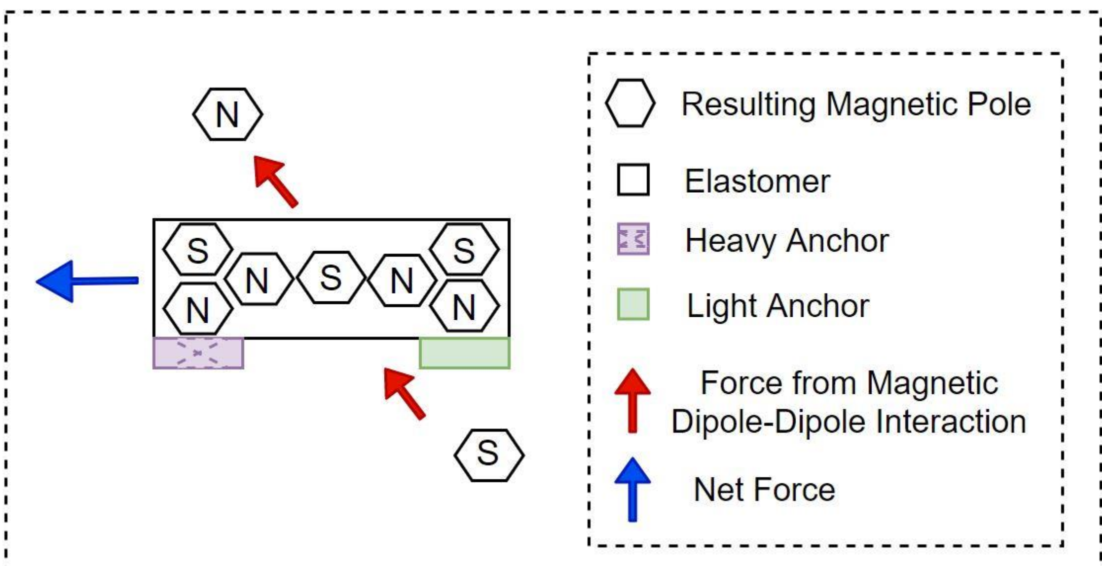

Figure 5: Changing the orientation of the external magnetic field will create a force that will push the device forward to create locomotion.

3. MANUFACTURING CONDITIONS

The following section will cover manufacturing considerations for embedding magnetic materials into elastomers for use in soft robotics. Elastomers are also explored for important characteristics as well as what physical properties make them necessary for soft robotics. One important property of the elastomer is flexibility, while having no interference with the magnetic properties of the material encased.

3.1 Materials Consideration

Elastomers are made from a base polymer mixed with a curing agent to produce different physical properties of the material like heat and chemical resistance, temperature performance, and elastic modulus. As the base polymer mixes with the curing agent, the elastomer can be poured across some molding that allows magnetic materials to be embedded within the structure. After the elastomer is in the desired shape and orientation, the curing agent will solidify the material in place. This can be done through liquid curing agents, high temperatures, or photolithographic techniques.

Important characteristics include the density of the material, magnetic permeability, biocompatibility, and melting point. These characteristics will impact the performance of the magnetic material's response to external fields. Considerations of these materials will also vary with different molecular weights. Longer polymer chains will have higher molecular weights yielding different properties of elastic modulus.

3.1.1 Curing Agents

Polydimethylsiloxane (PDMS) is one type of elastomer that will use a curing agent mixed with the base elastomer to harden. Mixing different ratios of base elastomer and curing agent will change the elasticity of the material. This is also known as the Young's modulus of the material. Traditional applications involve IC packaging and medical applications. Ecoflex ™ 00-10 will be used in place of PDMS for applications requiring higher tolerance for deformation at a low elastic modulus [1,11].

3.1.2 Photocurable

Poly(ethylene glycol) diacrylate (PEGDA) is another type of photocurable resin that allow embedded (ferro)magnetic particles in the elastomer to be used in lithography for shaping the device with a uniform layer of the particles. This photocuring technique is widely used for 3D printing complex designs to optimize the actuation techniques to improve speed and reliability of motion.

PEGDA was used as crosslinking agent for the photopolymerization of poly 2-hydroxyethyl methacrylate (PHEMA) in order to obtain PHEMA/PEGDA-based hydrogels [82]. The first layer of PHEMA will expand in low pH environments and contract in high pH environments. With some mechanical engineering of the structure, the soft robot will actuate based on strains that this expansion/contraction creates. The other layer of PEGDA has Fe_3O_4 iron oxide particles embedded within it. With the use of an external field, locomotion of the soft micro robot is possible. This locomotion will transport the micro-robot from a high pH area (normal body pH) to a low pH environment (associated with tumor cells).

Polylactic-co-glycolic acid (PLGA) is the most desirable elastomer for biocompatible applications (FDA approved [83]) from biodegradable properties. Mixed with magnetic materials like Iron (II, III) oxide particles, the manufactured device can be left in-vivo environments without causing harmful effects.

3.2 Properties of Specific Materials

Elastomers are chosen based on the mechanical property called elastic modulus that represents the amount the material is able to flex under load. This load can be measured from the stress σ and strain ε that is put on the elastomer to cause deformation.

Materials with high elastic modulus are rigid in nature. This is because they require higher force defined as stress to generate the same amount of strain or deformation. Rigid bodies have infinite Young's modulus [84].

In soft robotic applications, higher torque from the magnetic material in an external field will cause the strain of the elastomer to propel the device forward.

$$E = \frac{\sigma}{\varepsilon} \tag{5}$$

4. APPLICATIONS

Some example applications are summarized in this section. One process worth mentioning is the creation of the uniform magnetic field through a device called a

Helmholtz coil. This coil will envelop the device under test to provide a uniaxial orientation of the magnetic field for applications in locomotion where the magnetic materials will be forced to move in a single direction [25]. Multiple Helmholtz coils can be constructed with a 90° rotation about the center axis to provide x/y control in 3d space.

$$B_z = \frac{\mu_0 N I R^2}{2}\left[\frac{1}{\left[\left(z-\frac{l}{2}\right)^2+R^2\right]^{\frac{3}{2}}}+\frac{1}{\left[\left(z+\frac{l}{2}\right)^2+R^2\right]^{\frac{3}{2}}}\right] \tag{6}$$

Equation 6 [87] represents the flux density that will be applied to the magnetic materials. This field will change depending on the current I, number of turns per loop N, radius of each coil R, distance from one coil to another l, and distance from the center point z.

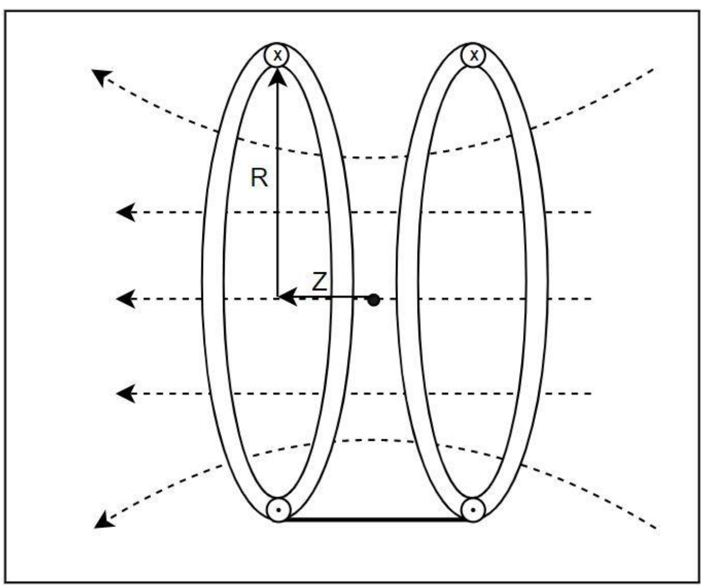

Figure 6: Helmholtz coil for producing magnetic flux density for locomotion of the device under test. Flux density is determined by *Equation 6* [87].

The second device used to produce an external magnetic field is an electromagnetic actuator (EMA). This EMA can provide a uniaxial magnetic field near the origin of the EMA. The benefit over its counterpart is the ability to create this field without requiring a structure to be surrounding the device. This EMA will be used for triggering events that can cause the magnetic field of one material to reverse. This is used in drug control/release applications [6,22].

4.1 Biomimicry

Soft robotics uses the design mechanisms found in nature to produce an elastomer embedded with magnetics that allows for optimized locomotion techniques. These techniques involve producing some stress on the surrounding elastomer from an electromagnetic force applied on the magnetic material that is embedded within the elastomer. This stress will cause parts of the elastomer to contract. Once the electromagnetic force is taken away, the contraction will correct itself to form the original elastomer shape. Depending on the design of the elastomer, this event can cause forward motion in the elastomer.

Some key designs worth mentioning are mimicked from inchworms [1,17], turtles [1], fish [25], and electric eels [18]. The reason for different designs is based on the environment the device is placed in. Friction can be used in combination with contraction to launch the device forward like that of an inchworm. Somersaults can be ideal for harsh terrain on land, and swimming techniques are explored from eels to move these devices around in liquid environments.

Performance metrics from *Venkiteswaran et al.*[1] include the specimens average speeds to vary between 0.15-0.37 mm/s. This was under a 60mT field in any specific direction with a bandwidth of 40hz. The mass of these specimens are calculated based on the area times density of elastomer with magnetic particles embedded. The millipede specimen was the smallest area at 1000 mm^3 with the largest speed of 0.37mm/s while the quadruped was 1400 mm^3 at a speed of 0.15mm/s. Density of silicon rubber is 2.3*10^{-12} grams per cubic millimeter. This results in a mass of 2.3*10^{-9} grams for the millipede and 3.22*10^{-9} grams for the quadruped.

All these designs utilize an externally generated magnetic field. Helmholtz coils perform well to move the magnetic material from one location to the next in one direction (somersault techniques). EMAs will be used to control specific portions of the device like the legs of a centipede.

4.2 Biomedical Targeted Drug Control

The biomedical field has generated new methods for targeted drug delivery using magnetics. Selective drug delivery is important for drugs that can produce harmful side-effects when mixed with healthy tissues in the body. Using actuation techniques to only release the payload of drugs when the device is in the correct position will allow a higher concentration of the drug to work in a smaller area.

One method of targeted drug release is proposed with artificial nano-eels [18]. These nano-eels have a flexible tail made from polyvinylidene fluoride (PVDF)-based copolymer linked to a polypyrrole (PPY) nanowire head. This device contains nickel rings that are attracted to external magnetic fields. This attraction will pull the device from one location in space to another through a series of “tumbling, wobbling, and cork-screwing” movements in an aqueous environment as described by *Mushtaq et al.* [18]. After the device is in the proper area to release its payload, a second rotating magnetic field will cause the nickel rings to oscillate causing deformation in the tail. This deformation is a piezoelectric strain of the PVDF material which will cause the repulsion of oppositely charged RhB drugs stored in the device allowing targeted drug release. Fabrication techniques allow for a large quantity of these devices to be produced at an average device size of 15μm [18], making applications in the biomedical field possible.

Another type of device will physically attach itself to the drug from a mechanical stress. Multiple layers of different material will allow actuation and locomotion techniques to be utilized. The first layer consists of Poly [2-hydroxyethyl methacrylate] or PHEMA for short that can expand in low pH environments and contract in high pH environments. With some mechanical engineering of the structure, the soft robot will actuate based on strains that this expansion/contraction creates to release the drug stored inside. These types of structures will move when a uniform field is applied around the device from a Helmholtz coil.

4.3 Technology Gaps

4.3.1 Scaling

Research groups for soft robotics will manufacture devices at large scales (millimeter level) [1,2,9,10,25] to make proof of concept models. With these models, devices for endoscopy [9,10] and targeted drug release [2] should be minimized to allow less discomfort when used in a medical scenario. *Hao Li et al* [2] states the goal for mobility in these settings is to reduce the size from sub millimeter to less than 8μm to match the diameter of the capillaries located in the body, which are the smallest blood vessels in the circulatory system.

4.3.2 Durability

Hard robotics has advantages from the rigidity of materials used for common applications to maintain composure under harsh working environments. Elastomers on the other hand will break down over time if exposed to extreme temperatures and sporadic motion. This has benefits when used in parallel with humans since soft robotics cannot harm the user compared to that of hard components. Durability may be factored in the design if the device is biocompatible, such that it will break down over time so that it may naturally leave the body. Another branch would be liquid metal systems. Since the metals are in a liquid state at room temperature, they can conduct current without potential for disconnections like physical metal wires where the connections can be broken from too much deformation. Microfluidic channels still rely on elastomers that are subject to breakdown as they contain the liquid metals.

4.3.3 Performance

Metrics in speed and power stroke are constantly evolving to maximize the power delivery from external fields to the magnetic materials embedded in devices. Materials with higher saturation magnetization can improve the range of speeds used in torque control for locomotion while different variations of electromagnetic actuators can be implemented closer to the device for low power requirements.

5. CONCLUSION

Magnetics applications in soft robotics combines aspects of biology and mechanics to create a structure capable of complex movement. This movement is possible with the use of magnetics embedded within different materials such that the material will exhibit magnetic properties. Utilizing the biomedical devices such as drug delivery [2], peristaltic pump control [12,21], and endoscopy [9,10] that can be placed in vivo environments will allow medical professionals to control stimulus events for minimal harm done. Locomotion techniques shown in the application section 4 will help these delivery devices to reach their destination, ideally utilizing micro scale devices so that transportation through capillaries are possible. Most areas of research are exploring the locomotive side of magnetics to control the direction of the devices embedded within the body. There are very few cases that will use magnetics for both locomotion and actuation techniques, which has the most potential for automated uses of treatment where a Helmholtz coil can generate magnetic fields at different axis programmed by a computer to navigate a prior mapped environment. Large scale devices [1,2,9,10,25] as mentioned in section 4.3.1 have been shown to work, but fabrication techniques are not yet perfected to create small and reliable devices.

BIBLIOGRAPHY

[1] V. K. Venkiteswaran, L. F. P. Samaniego, J. Sikorski, and S. Misra, "Bio-Inspired Terrestrial Motion of Magnetic Soft Millirobots," IEEE Robotics and Automation Letters, vol. 4, no. 2, pp. 1753–1759, Apr. 2019. http://dx.doi.org/10.1109/LRA.2019.2898040

[2] H. Li, G. Go, S. Y. Ko, J.-O. Park, and S. Park, "Magnetic actuated pH-responsive hydrogel-based soft micro-robot for targeted drug delivery," Smart Materials and Structures, vol. 25, no. 2, p. 27001, Jan. 2016. http://dx.doi.org/10.1088/0964-1726/25/2/027001

[3] R. Tognato et al., "A Stimuli-Responsive Nanocomposite for 3D Anisotropic Cell-Guidance and Magnetic Soft Robotics," Advanced Functional Materials, vol. 29, no. 9, p. 1804647, Dec. 2018, doi: https://doi.org/10.1002/adfm.201804647

[4] E. Diller and M. Sitti, "Three-Dimensional Programmable Assembly by Untethered Magnetic Robotic Micro-Grippers," Advanced Functional Materials, vol. 24, no. 28, pp. 4397–4404, Apr. 2014, doi: https://doi.org/10.1002/adfm.201400275

[5] T. N. Do, H. Phan, T.-Q. Nguyen, and Y. Visell, "Miniature Soft Electromagnetic Actuators for Robotic Applications," Advanced Functional Materials, vol. 28, no. 18, p. 1800244, Mar. 2018. http://dx.doi.org/10.1002/adfm.201800244

[6] S. Doerger and C. Harnett, "Force-Amplified Soft Electromagnetic Actuators," Actuators, vol. 7, no. 4, p. 76, Oct. 2018, doi: https://doi.org/10.3390/act7040076

[7] J.-Y. Lee and K.-J. Cho, "Development of magnet connection of modular units for soft robotics," in 2017 14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), 2017. http://dx.doi.org/10.1109/URAI.2017.7992886

[8] S. W. Kwok et al., "Magnetic Assembly of Soft Robots with Hard Components," Advanced Functional Materials, vol. 24, no. 15, pp. 2180–2187, Dec. 2013, doi: https://doi.org/10.1002/adfm.201303047

[9] S. Yim and M. Sitti, "Design and Rolling Locomotion of a Magnetically Actuated Soft Capsule Endoscope," IEEE Transactions on Robotics, vol. 28, no. 1, pp. 183–194, Feb. 2012, doi: https://doi.org/10.1109/tro.2011.2163861

[10] Sehyuk Yim and M. Sitti, "Shape-Programmable Soft Capsule Robots for Semi-Implantable Drug Delivery," IEEE Transactions on Robotics, vol. 28, no. 5, pp. 1198–1202, Oct. 2012, doi: https://doi.org/10.1109/tro.2012.2197309

[11] T. S. Zhang, A. Kim, M. Ochoa, and B. Ziaie, "Controllable x2018;somersaultx2019; magnetic soft robotics," in 2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS), 2015. http://dx.doi.org/10.1109/MEMSYS.2015.7051141

[12] M. M. Schmauch, S. R. Mishra, B. A. Evans, O. D. Velev, and J. B. Tracy, "Chained Iron Microparticles for Directionally Controlled Actuation of Soft Robots," ACS Applied Materials Interfaces, vol. 9, no. 13, pp. 11895–11901, Mar. 2017, doi: https://doi.org/10.1021/acsami.7b01209

[13] A. D. Marchese, C. D. Onal, and D. Rus, "Soft robot actuators using energy-efficient valves controlled by electropermanent magnets," in 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2011, doi: https://doi.org/10.1109/iros.2011.6095064

[14] Sangok Seok, C. D. Onal, R. Wood, D. Rus, and Sangbae Kim, "Peristaltic locomotion with antagonistic actuators in soft robotics," in 2010 IEEE International Conference on Robotics and Automation, 2010. http://dx.doi.org/10.1109/ROBOT.2010.5509542

[15] Z. Chen, C. Zhao, Y. Zhang, Y. Zhu, J. Fan, and J. Zhao, "CBalls: A Modular Soft Robot Connected and Driven via Magnet Forced," Journal of Physics: Conference Series, vol. 1207, p. 12006, Apr. 2019, doi: https://doi.org/10.1088/1742-6596/1207/1/012006

[16] J. Shu, S.-Y. Tang, Z. Feng, W. Li, X. Li, and S. Zhang, "Unconventional locomotion of liquid metal droplets driven by magnetic fields," Soft Matter, vol. 14, no. 35, pp. 7113–7118, 2018. [17] R. P. Singh and P. R. Onck, "Magnetic field induced deformation and buckling of slender bodies," International Journal of Solids and Structures, vol. 143, pp. 29–58, Jun. 2018, doi: https://doi.org/10.1016/j.ijsolstr.2018.02.029

[18] F. Mushtaq et al., "Motile Piezoelectric Nanoeels for Targeted Drug Delivery," Advanced Functional Materials, vol. 29, no. 12, p. 1808135, Feb. 2019, doi: https://doi.org/10.1002/adfm.201808135

[19] T. Tone and K. Suzuki, "Surface Deformation Control of a Ferrofluid-Based Robotic Sheet for Object Handling," IEEE Transactions on Automation Science and Engineering, vol. 16, no. 2, pp. 851–862, Apr. 2019, doi: https://10.1109/tase.2018.2868741

[20] T. Kimura, Y. Umehara, and F. Kimura, “Magnetic field responsive silicone elastomer loaded with short steel wires having orientation distribution,” Soft Matter, vol. 8, no. 23, p. 6206, 2012. http://dx.doi.org/10.1039/c2sm25442e

[21] S. Dirven, M. Stommel, R. Hashem, and W. Xu, “Medicallyinspired approaches for the analysis of soft-robotic motion control,” in 2016 IEEE 14th International Workshop on Advanced Motion Control (AMC), 2016, doi: https://doi.org/10.1109/amc.2016.7496378

[22] E. Diller, J. Giltinan, G. Z. Lum, Z. Ye, and M. Sitti, “Six-degree-of-freedom magnetic actuation for wireless microrobotics,” The International Journal of Robotics Research, vol. 35, no. 1–3, pp. 114–128, Jun. 2015. http://dx.doi.org/10.1177/0278364915583539

[23] D. J. Kang, S. An, A. L. Yarin, and S. Anand, “Programmable soft robotics based on nano-textured thermo-responsive actuators,” Nanoscale, vol. 11, no. 4, pp. 2065–2070, 2019, doi: https://doi.org/10.1039/c8nr08215d

[24] J. Kim, S. E. Chung, S.-E. Choi, H. Lee, J. Kim, and S. Kwon, “Programming magnetic anisotropy in polymeric microactuators,” Nature Materials, vol. 10, no. 10, pp. 747–752, Aug. 2011, doi: https://doi.org/10.1038/nmat3090

[25] S. H. Kim, K. Shin, S. Hashi, and K. Ishiyama, “Magnetic fish-robot based on multi-motion control of a flexible magnetic actuator,” Bioinspiration Biomimetics, vol. 7, no. 3, p. 36007, May 2012, doi: https://doi.org/10.1088/1748-3182/7/3/036007

[26] M. Khoo and C. Liu, “Micro magnetic silicone elastomer membrane actuator,” Sensors and Actuators A: Physical, vol. 89, no. 3, pp. 259–266, Apr. 2001, doi: https://doi.org/10.1016/s0924- 4247(00)00559-8

[27] R. Fuhrer, E. K. Athanassiou, N. A. Luechinger, and W. J. Stark, “Crosslinking Metal Nanoparticles into the Polymer Backbone of Hydrogels Enables Preparation of Soft, Magnetic Field-Driven Actuators with Muscle-Like Flexibility,” Small, vol. 5, no. 3, pp. 383–388, Feb. 2009, doi: https://doi.org/10.1002/smll.200801091

[28] C. Christianson, N. N. Goldberg, D. D. Deheyn, S. Cai, and M. T. Tolley, “Translucent soft robots driven by frameless fluid electrode dielectric elastomer actuators,” Science Robotics, vol. 3, no. 17, p. eaat1893, Apr. 2018, doi: https://doi.org/10.1126/scirobotics.aat1893

[29] R. F. Shepherd et al., “Using Explosions to Power a Soft Robot,” Angewandte Chemie International Edition, vol. 52, no. 10, pp. 2892–2896, Feb. 2013, doi: https://doi.org/10.1002/anie.201209540

[30] C. Yamahata, C. Lotto, E. Al-Assaf, and M. A. M. Gijs, “A PMMA valveless micropump using electromagnetic actuation,” Microfluidics and Nanofluidics, vol. 1, no. 3, pp. 197–207, Aug. 2004, doi: https://doi.org/10.1007/s10404-004-0007-6

[31] G. Z. Lum et al., “Shape-programmable magnetic soft matter,” Proceedings of the National Academy of Sciences, vol. 113, no. 41, pp. E6007–E6015, Sep. 2016, doi: https://doi.org/10.1073/pnas.1608193113

[32] Y. Kim, H. Yuk, R. Zhao, S. A. Chester, and X. Zhao, “Printing ferromagnetic domains for untethered fast-transforming soft materials,” Nature, vol. 558, no. 7709, pp. 274–279, Jun. 2018, doi: https://doi.org/10.1038/s41586-018-0185-0

[33] Y. Yu and E. Miyako, “Frontispiece: Recent Advances in Liquid Metal Manipulation toward Soft Robotics and Biotechnologies,” Chemistry - A European Journal, vol. 24, no. 38, Jul. 2018. http://dx.doi.org/10.1002/chem.201883862

[34] P. Cremer, H. Lowen, and A. M. Menzel, “Tailoring su- ¨ perelasticity of soft magnetic materials,” Applied Physics Letters, vol. 107, no. 17, p. 171903, Oct. 2015, doi: https://doi.org/10.1063/1.4934698

[35] M. Li et al., “Flexible magnetic composites for lightcontrolled actuation and interfaces,” Proceedings of the Na- tional Academy of Sciences, vol. 115, no. 32, pp. 8119–8124, Jul. 2018, doi: https://doi.org/10.1073/pnas.1805832115

[36] S. Bi, A. Sutor, R. Lerch, and Y. Xiao, “A measurement setup for acquiring the local magnetic properties of plastically deformed soft magnetic materials,” Journal of Applied Physics, vol. 109, no. 7, p. 07E306, Apr. 2011, doi: https://doi.org/10.1063/1.3535549

[37] Quaranta, P. (2015). Morphing, Self-Healing and Other Electric-to-Material Applications. Military Technology, 39(6), 76. http://search.ebscohost.com.ezproxy.proxy.library.oregonstate.edu/login.aspx?direct=true&db=aph&AN=108491570&site=ehost-live

[38] H. K. Yap, N. Kamaldin, J. H. Lim, F. A. Nasrallah, J. C. H. Goh, and C.-H. Yeow, “A Magnetic Resonance Compatible Soft Wearable Robotic Glove for Hand Rehabilitation and Brain Imaging,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 25, no. 6, pp. 782–793, Jun. 2017. http://dx.doi.org/10.1109/TNSRE.2016.2602941

[39] M. A. Willard, M. Daniil, and K. E. Kniping, “Nanocrystalline soft magnetic materials at high temperatures: A perspective,” Scripta Materialia, vol. 67, no. 6, pp. 554–559, Sep. 2012, doi: https://doi.org/10.1016/j.scriptamat.2011.12.043

[40] J. C. Breger et al., “Self-Folding Thermo-Magnetically Responsive Soft Microgrippers,” ACS Applied Materials Interfaces, vol. 7, no. 5, pp. 3398–3405, Jan. 2015. http://dx.doi.org/10.1021/am508621s

[41] H. Miura and H. Kang, “Application of metal injection moulding to soft magnetic materials,” Powder Metallurgy, vol. 56, no. 1, pp. 38–45, Feb. 2013. http://dx.doi.org/10.1179/1743290112Y.0000000031

[42] G. Mohler, A. W. Harter, and R. L. Moore, “Micromagnetic study of nonlinear effects in soft magnetic materials,” Journal of Applied Physics, vol. 93, no. 10, pp. 7456–7458, May 2003, doi: https://doi.org/10.1063/1.1557362

[43] A. B. Subramaniam et al., “Noncontact orientation of objects in three-dimensional space using magnetic levitation,” Proceedings of the National Academy of Sciences, vol. 111, no. 36, pp. 12980–12985, Aug. 2014, doi: https://doi.org/10.1073/pnas.1408705111

[44] A. Dwivedi, A. Ramakrishnan, A. Reddy, K. Patel, S. Ozel, and C. D. Onal, “Design, Modeling, and Validation of a Soft Magnetic 3-D Force Sensor,” IEEE Sensors Journal, vol. 18, no. 9, pp. 3852–3863, May 2018, doi: https://doi.org/10.1109/jsen.2018.2814839

[45] T. Chen, O. R. Bilal, K. Shea, and C. Daraio, “Harnessing bistability for directional propulsion of soft, untethered robots,” Proceedings of the National Academy of Sciences, vol. 115, no. 22, pp. 5698–5702, May 2018. http://dx.doi.org/10.1073/pnas.1800386115

[46] J. J. Abbott, O. Ergeneman, M. P. Kummer, A. M. Hirt, and B. J. Nelson, “Modeling Magnetic Torque and Force for Controlled Manipulation of Soft-Magnetic Bodies,” IEEE Transactions on Robotics, vol. 23, no. 6, pp. 1247–1252, Dec. 2007, doi: https://doi.org/10.1109/tro.2007.910775

[47] S. Nagahama, K. Migita, and S. Sugano, “Soft Magnetic Powdery Sensor for Tactile Sensing,” Sensors, vol. 19, no. 12, p. 2677, Jun. 2019. http://dx.doi.org/10.3390/s19122677

[48] M. A. Woodward and M. Sitti, “Universal Custom Complex Magnetic Spring Design Methodology,” IEEE Transactions on Magnetics, vol. 54, no. 1, pp. 1–13, Jan. 2018, doi: https://doi.org/10.1109/tmag.2017.2759099

[49] K. E. Peyer, E. Siringil, L. Zhang, and B. J. Nelson, “Magnetic polymer composite artificial bacterial flagella,” Bioinspiration Biomimetics, vol. 9, no. 4, p. 46014, Nov. 2014. http://dx.doi.org/10.1088/1748-3182/9/4/046014

[50] L. Wang et al., “Controllable and reversible tuning of material rigidity for robot applications,” Materials Today, vol. 21, no. 5, pp. 563–576, Jun. 2018. http://dx.doi.org/10.1016/j.mattod.2017.10.010

[51] H. Wang, Y. Liang, W. Gao, R. Dong, and C. Wang, “Emulsion Hydrogel Soft Motor Actuated by Thermal Stimulation,” ACS Applied Materials Interfaces, vol. 9, no. 49, pp. 43211–43219, Dec. 2017, doi: https://doi.org/10.1021/acsami.7b08661

[52] L. Jamone, L. Natale, G. Metta, and G. Sandini, “Highly Sensitive Soft Tactile Sensors for an Anthropomorphic Robotic Hand,” IEEE Sensors Journal, vol. 15, no. 8, pp. 4226–4233, Aug. 2015, doi: https://doi.org/10.1109/jsen.2015.2417759

[53] D. Son, S. Yim, and M. Sitti, “A 5-D Localization Method for a Magnetically Manipulated Untethered Robot Using a 2-D Array of Hall-Effect Sensors,” IEEE/ASME Transactions on Mechatronics, vol. 21, no. 2, pp. 708–716, Apr. 2016.

[54] Y. Kim, S. S. Cheng, M. Diakite, R. P. Gullapalli, J. M. Simard, and J. P. Desai, “Toward the Development of a Flexible Mesoscale MRI-Compatible Neurosurgical Continuum Robot,” IEEE Transactions on Robotics, vol. 33, no. 6, pp. 1386–1397, Dec. 2017, doi: https://doi.org/10.1109/tro.2017.2719035

[55] D. Zhang, J. Xiao, Y. Qiu, J. Yang, and Q. Guo, “InitiatorIntegrated 3-D Printing of Magnetic Object for Remote Controlling Application,” IEEE Transactions on Magnetics, vol. 53, no. 5, pp. 1–9, May 2017. http://dx.doi.org/10.1109/TMAG.2017.2666777

[56] F. Ongaro et al., “Autonomous planning and control of soft untethered grippers in unstructured environments,” Journal of Micro-Bio Robotics, vol. 12, no. 1–4, pp. 45–52, Sep. 2016, doi: https://doi.org/10.1007/s12213-016-0091-1

[57] M. Luo et al., “Slithering towards autonomy: a self-contained soft robotic snake platform with integrated curvature sensing,” Bioinspiration Biomimetics, vol. 10, no. 5, p. 55001, Sep. 2015. http://dx.doi.org/10.1088/1748-3190/10/5/055001

[58] S. Yim and M. Sitti, “SoftCubes: Stretchable and selfassembling three-dimensional soft modular matter,” The International Journal of Robotics Research, vol. 33, no. 8, pp. 1083–1097, May 2014, doi: https://doi.org/10.1177/0278364914527630

[59] Z. Ren, W. Hu, X. Dong, and M. Sitti, “Multi-functional softbodied jellyfish-like swimming,” Nature Communications, vol. 10, no. 1, Jul. 2019. http://dx.doi.org/10.1038/s41467-019-10549-7

[60] J. Kim et al., “Simultaneous Monitoring of Sweat and Interstitial Fluid Using a Single Wearable Biosensor Platform,” Advanced Science, vol. 5, no. 10, p. 1800880, Aug. 2018, doi: https://doi.org/10.1002/advs.201800880

[61] S. Ijaz et al., “Magnetically actuated miniature walking soft robot based on chained magnetic microparticles-embedded elastomer,” Sensors and Actuators A: Physical, vol. 301, p. 111707, Jan. 2020, doi: https://doi.org/10.1016/j.sna.2019.111707

[62] K. B. Yesin, K. Vollmers, and B. J. Nelson, “Modeling and Control of Untethered Biomicrorobots in a Fluidic Environment Using Electromagnetic Fields,” The International Journal of Robotics Research, vol. 25, no. 5–6, pp. 527–536, May 2006, doi: https://doi.org/10.1177/0278364906065389

[63] J. A.-C. Liu, J. H. Gillen, S. R. Mishra, B. A. Evans, and J. B. Tracy, “Photothermally and magnetically controlled reconfiguration of polymer composites for soft robotics,” Science Advances, vol. 5, no. 8, p. eaaw2897, Aug. 2019. http://dx.doi.org/10.1126/sciadv.aaw2897

[64] D. Garcia-Gonzalez, “Magneto-visco-hyperelasticity for hardmagnetic soft materials: theory and numerical applications,” Smart Materials and Structures, vol. 28, no. 8, p. 85020, Jul. 2019, doi: https://doi.org/10.1088/1361-665x/ab2b05

[65] S. Shian, K. Bertoldi, and D. R. Clarke, “Dielectric Elastomer Based ‘Grippers’ for Soft Robotics,” Advanced Materials, vol. 27, no. 43, pp. 6814–6819, Sep. 2015. https://search.library.oregonstate.edu/permalink/f/1g9lfhc/TN_dash1/17694369

[66] Kim, Park, Won, Jeon, and Wie, “Contactless Manipulation of Soft Robots,” Materials, vol. 12, no. 19, p. 3065, Sep. 2019, doi: https://doi.org/10.3390/ma12193065

[67] Q.-H. Gao et al., “Label-free manipulation via the magnetoArchimedes effect: fundamentals, methodology and applications,” Materials Horizons, vol. 6, no. 7, pp. 1359–1379, 2019, doi: https://doi.org/10.1039/c8mh01616j

[68] P. Dario, R. Valleggi, M. C. Carrozza, M. C. Montesi, and M. Cocco, “Microactuators for microrobots: a critical survey,” Journal of Micromechanics and Microengineering, vol. 2, no. 3, pp. 141–157, Sep. 1992, doi: https://doi.org/10.1088/0960-1317/2/3/005

[69] S. Martel, “Magnetic nanoparticles in medical nanorobotics,” Journal of Nanoparticle Research, vol. 17, no. 2, Feb. 2015. https://doi.org/10.1007/s11051-014-2734-2

[70] F. Blyakhman et al., “The Contribution of Magnetic Nanoparticles to Ferrogel Biophysical Properties,” Nanomaterials, vol. 9, no. 2, p. 232, Feb. 2019, doi: https://doi.org/10.3390/nano9020232

[71] Vahak Marghussian. (2015). 4 - Magnetic Properties of NanoGlass Ceramics. In Nano-Glass Ceramics (pp. 181-223). Elsevier. https://search.library.oregonstate.edu/permalink/f/1g9lfhc/TN_elsevier_sdoi_10_1016_B978_0_323_35386_1_00004_9

[72] Calais, T., Valdivia Y Alvarado, P. (2019). Advanced functional materials for soft robotics: Tuning physicochemical properties beyond rigidity control. Multifunctional Materials, 2(4), 042001. https://doi.org/10.1088/2399-7532/ab4f9d

[73] Inaba, M., Corke, Peter I. (2016). Robotics research : The 16th International Symposium ISRR (Springer tracts in advanced robotics ; 114). Switzerland: Springer. https://search.library.oregonstate.edu/permalink/f/ueodtl/CP71258558250001451

[74] Solymar, L., Walsh, D., Syms, R. (2018). Magnetic materials. In Electrical Properties of Materials (p. Electrical Properties of Materials, Chapter 11). Oxford University Press. https://doi.org/ 10.1093/oso/9780198829942.001.0001

[75] Sanchez-De Jes ´ us, F., Bolar ´ ´ın-Miro, A., Cort ´ es Escobedo, ´ C., Torres-Villasenor, G., Vera-Serna, P. (2016). Structural ˜ Analysis and Magnetic Properties of

FeCo Alloys Obtained by Mechanical Alloying. Journal of Metallurgy, 2016, 1-8. https://doi.org/10.1155/2016/8347063

[76] Okamoto, A. (2009). The Invention of Ferrites and Their Contribution to the Miniaturization of Radios. 2009 IEEE Globecom Workshops, 1-6. https://doi.org/10.1109/GLOCOMW.2009.5360693

[77] Mishra, S., Dickey, M., Velev, O., Tracy, J. (2016). Selective and directional actuation of elastomer films using chained magnetic nanoparticles. Nanoscale, 8(3), 1309-1313. https://doi.org/10.1039/c5nr07410j

[78] Lockette, Lofland, Biggs, Roche, Mineroff, Babcock. (2011). Investigating new symmetry classes in magnetorheological elastomers: Cantilever bending behavior. Smart Materials and Structures, 20(10), 10. https://doi.org/10.1088/0964-1726/20/10/105022

[79] Moss, G., Gullick, Darren R., Wilkinson, Simon C. (2015). Predictive methods in percutaneous absorption. Heidelberg: Springer. https://search.library.oregonstate.edu/permalink/f/ueodtl/CP71230444960001451

[80] Armani, D., Liu, C., Aluru, N. (1999). Re-configurable fluid circuits by PDMS elastomer micromachining. Technical Digest. IEEE International MEMS 99 Conference. Twelfth IEEE International Conference on Micro Electro Mechanical Systems (Cat. No.99CH36291), 222-227. https://doi.org/10.1109/MEMSYS.1999.746817

[81] Zellander, A., Zhao, C., Kotecha, M., Gemeinhart, R., Wardlow, M., Abiade, J., . . . Engler, A. (2014). Characterization of Pore Structure in Biologically Functional Poly(2- Hydroxyethyl Methacrylate) - Poly(Ethylene Glycol) Diacrylate (PHEMA-PEGDA). PLoS ONE, 9(5), E96709. https://doi.org/10.1371/journal.pone.0096709

[82] Gonzalez-Henr ´ ´ıquez, C., Pizarro, G., Sarabia-Vallejos, M., Terraza, C., Lopez-Caba ´ na, Z. (2019). In situ-preparation and ˜ characterization of silver-HEMA/PEGDA hydrogel matrix nanocomposites: Silver inclusion studies into hydrogel matrix. Arabian Journal of Chemistry, 12(7), 1413-1423. https://doi.org/ 10.1016/j.arabjc.2014.11.012

[83] Makadia, H., Siegel, S. (2011). Poly Lactic-co-Glycolic Acid (PLGA) as Biodegradable Controlled Drug Delivery Carrier. Polymers, 3(3), 1377-1397. https://doi.org/10.3390/polym3031377

[84] Quantities, Units and Symbols in Physical Chemistry : Blackwell, Oxford, 2nd edn., 1993 (ISBN 0-332-03583-8). ix 167 pp. (1994). Analytica Chimica Acta, 288(3), 284. https://doi.org/10.1016/0003-2670(94)80152-5

[85] Brand, H., Martinoty, P., Pleiner, H. (2012). ChemInform Abstract: Physical Properties of Magnetic Gels. ChemInform, 43(49) https://doi.org/10.1002/chin.201249266

[86] Fukumasa, O., Kurita, M., Yamashita, T. (2005). Synthesis of fine ferrite particles from powder mixtures by using wellcontrolled thermal plasmas. In Novel Materials Processing by Advanced Electromagnetic Energy Sources (pp. 261-264). Elsevier. https://doi.org/10.1016/B978-008044504-5/50054-4

[87] web.mit.edu, “Sources of Magnetic Fields.” [Online]. Available: http://web.mit.edu/viz/EM/visualizations/notes/modules/guide09.pdf