ABSTRACT

KAPLAN, REBECCA CARYN. Impact of Scalability on Laser Tissue Ablation in Minimally Invasive Surgery. (Under the direction of Dr. Edward Grant).

Over recent decades, the medical field has become heavily involved, interested with, and improved by the use and incorporation of robotics, as well as certain physics applications, such as the use of optical fibers and lasers for microsurgeries. Based on research previously done by Alperen Acemoglu and Leonardo S. Mattos, a magnetic laser scanning tool was built to be tested for use in endoscopic scanning laser microsurgery [1] and the impact of scalability on this design and application was examined. Current technology for laser microsurgery is classified in two types of systems: free-beam system and fiber-coupled systems. The system developed here is a fiber-coupled laser system, which utilizes an optical fiber to carry the laser beam light to the surgical area. Consisting of five ring permanent magnets, which the flexible optical fiber was placed through, and four miniature electromagnetic coils (two pairs), placed orthogonally to each other around the optical fiber and permanent magnets. Actuation was based on the interaction between the generated electromagnetic field and the permanent magnets. The bending of the optical fiber with magnetic torque allowed for controlled and high-speed laser scanning. Therefore, achieving a much smaller actuator than those typically utilized, which are large, located outside the patient, and requiring direct line-of-sight to the microsurgical area.
Impact of Scalability on Laser Tissue Ablation in Minimally Invasive Surgery

by
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DEDICATION

To my parents, brother and all the rest of my family, for your constant support and unconditional love. I love you guys and could not have done it without you.

“We may not have it all together, but together we have it all!”
BIOGRAPHY

Rebecca Caryn Kaplan was born on December 12, 1994 to Mr. Howard J. Kaplan and Mrs. Judith L. Kaplan, in White Plains, New York. Upon completion of her high school education, Rebecca went on to pursue a Bachelor’s degree in Applied Physics with a minor in Spanish at Towson University, in Towson Maryland. She graduated in the Spring of 2016 [on May 20, 2016], only a month after being inducted into the National Physics Honors Society, Sigma Pi Sigma. In the Fall of 2016 she moved to Raleigh, NC to pursue a Masters degree at North Carolina State University in Electrical Engineering. She will receive her Masters degree in the Fall of 2017 [on December 15, 2017]. She intends to begin her career in engineering and soon return to North Carolina State University to pursue a Ph.D. degree under the direction of Dr. Edward Grant.
ACKNOWLEDGMENTS

I want to thank my parents and brother for all their love, support, faith and encouragement of me and my dreams throughout my life and throughout this process of receiving my Master’s degree. Also, I want to thank my grandparents, aunts, uncles, cousins and all the rest of my family for always believing in me and my dreams, and for always supporting and encouraging my decisions. Additionally, I want to thank Abdullah for being there when I really needed somebody and for helping me get through my moments of high-stress and uncertainty, and for being a true friend and wonderful person my entire time here at NC State.

I thank Hamed Mohammadbagherpoor for all his help throughout the control, coding and programming process, and for assisting me and working with me on this project and to obtain more precise results.

Last, but not least, I thank my advisor Dr. Edward Grant for being the best, most supportive, personable, encouraging and funniest advisor anybody could ask for. I do not think I could have made it through this program without his words of encouragement, helpfulness, and constant funny stories to keep smiles on all our faces; and the hugs I received whenever he could see I was stressed or just feeling down, they were definitely needed and appreciated! Dr. Grant has given me confidence in my
abilities academically and otherwise. He made my experience here more enjoyable and for that I thank him.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>A/m</td>
<td>Amps per Meter</td>
</tr>
<tr>
<td>NCSU CAMAL</td>
<td>NCSU Center for Additive Manufacturing and Logistics</td>
</tr>
<tr>
<td>fps</td>
<td>Frames per Second</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-red</td>
</tr>
<tr>
<td>LASER</td>
<td>Light Amplification by the Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>LD</td>
<td>Laser Diode</td>
</tr>
<tr>
<td>Maser</td>
<td>Microwave Amplification by the Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>MCU</td>
<td>Micro Controller Unit</td>
</tr>
<tr>
<td>mm</td>
<td>Millimeter</td>
</tr>
<tr>
<td>MMF</td>
<td>Multimode Fiber</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infra-red</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer</td>
</tr>
<tr>
<td>T</td>
<td>Tesla</td>
</tr>
<tr>
<td>TIR</td>
<td>Total Internal Reflection</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VIS</td>
<td>Visible</td>
</tr>
<tr>
<td>V/m</td>
<td>Volts per Meter</td>
</tr>
<tr>
<td>(\mu_0)</td>
<td>Permeability of Free Space</td>
</tr>
<tr>
<td>(\mu_m)</td>
<td>micrometer</td>
</tr>
</tbody>
</table>
CHAPTER 1 - INTRODUCTION

1.1 — Motivation & Inspiration

The medical field, over recent decades, has become heavily involved with and improved by robotics, as well as with various physics applications, such as the use of optical fibers and various types of lasers. These are typically applied to microsurgical and endoscopic applications. Commonly used and available actuators for performing scanning laser microsurgery are restricted, in the confined workspaces which they must operate, by their large size. Many of these actuators are, therefore, typically located outside the patient and necessitate a direct line-of-sight to the surgical area.

Currently, lasers are typically used for surgery on delicate organs requiring high-precision; such as the eyes and throat. Utilizing scanning lasers, the quality of laser microsurgery is increased, enabling fast and efficient laser ablation with less potential of causing thermal damage to healthy tissue.

![Figure 1. Diagram showing how lasers can be utilized for corrective eye surgery.](image)
A few specified benefits of using lasers for these soft tissue surgeries are: improved post-operative function, decreased morbidity (disease), better hemostasis (coagulation, changing blood from a liquid to a gel), and minimal peripheral tissue injury [9], [10]. Currently, the technology for laser microsurgery is classified into two types of systems; free-beam systems and fiber-coupled systems.

Based on recent research conducted by Alperen Acemoglu and Leonardo S. Mattos, a magnetic laser scanner was re-designed, scaled down slightly and built. It was then later tested for potential use in scanning laser microsurgery. In addition, the impact of scalability was also observed to ensure the device could be scaled down to the size of a conventional endoscopic tool [1], typically ranging in size from around 8 mm to 10 mm, and maintain the precision actuation necessary. Specifically, the tool was designed to be used for laser tissue ablation purposes. The tool, fitted with two small electromagnetic coil pairs (four coils), as well as five small ring permanent magnets, attached to an optical fiber was controlled via actuation based on the interaction between the electromagnetic field of the coils and the permanent magnets. Via bending of the optical fiber utilizing magnetic torque, high-speed and controlled scanning was achieved. The use of lasers, as well as these actuation techniques could enable medical professionals to perform surgeries with significantly smaller incisions.
and, therefore, allow for a shorter healing time and hospital stay for the patients, amongst various other benefits, such as those stated above.

1.2 — Thesis Goals

This research focused on the development and re-creation of a fiber-coupled magnetic laser scanning system to be used in endoscopic laser scanning microsurgery, based on the previous research done by Alperen Acemoglu and Leonardo S. Mattos [1]. However, in the work done by Alperen Acemoglu and Leonardo S. Mattos [1] the current control was achieved via pairing the coils which were orthogonal to each other. Here, the four coils were controlled and supplied a current individually in an attempt to achieve finer laser control. Additionally, the research aimed to focus on the scalability of the tool for future design as an endoscopic tool to be used for laser tissue ablation (microsurgery). The goal of this being to observe the impact on functionality and precision actuation, of scaling this device down to the size of traditional endoscopic tools (approximately 8 to 10 mm).

Consisting of four miniature electromagnetic coils and five ring permanent magnets placed on a flexible optical fiber, actuation was based on the interaction between the generated electromagnetic field and the permanent magnets. Advantages to using this actuation method include; non-contact actuation (the device does not come into contact with the tissue being ablated), high scanning speed, high resolution,
and simple control. The external electromagnetic field is produced via the use of the two pairs of orthogonally placed electromagnetic coils; a current is applied to each coil individually, causing the electromagnetic field to be generated. Permanent magnets were attached to a cantilevered optical fiber, and the electromagnetic field produced by the coils were precisely controlled. This electromagnetic field caused reactions in the permanent magnets, leading to a bending of the optical fiber which they were attached. Bending of the optical fiber with use of the magnetic torque allowed for controlled and high-speed laser scanning. Therefore, achieving a much smaller actuator than those typically utilized, which are large, located outside the patient, and requiring a direct line-of-sight to the microsurgical area.

To collimate and focus the laser light, two small plano-convex lenses were used. Execution of precise laser scanning motions were achieved via deflection of the optical fiber cantilever and the motion of the laser spot onto the target, as the electromagnetic field was changed. This was done via the use of a simple circuit, Arduino DUE, and a control board connected to a Texas Instruments BOOSTXL-EDUMKII, which contains a joystick. The joystick on the board was used to change the amount of current supplied to each coil, therefore changing its electromagnetic field. An additional goal was to modify the system so as to be able to actuate the
scanning tool in three dimensions (x-, y-, and z-planes), instead of the two dimensions (x- and y-planes) used in the original research.

1.3 — Outline of Thesis

Chapter 2 of this thesis provides broader knowledge of the research topic via some literature review. Laser systems, the effects of lasers on tissue, optical fibers and their actuation via various techniques are all discussed in Chapter 2. Chapter 3 provides equations, simulations and models of the tools and equipment used. Chapter 4 provides details concerning the design of the laser system and its various components. Chapter 5 gives an analysis of the system via explanations of experiments performed as well as their results. To conclude, Chapter 6 presents conclusions and future research.
CHAPTER 2 — LITERATURE REVIEW

2.1 — Brief History of Lasers

The idea for a process with which to create what we now know as a laser, called stimulated emission, was initially proposed in 1917 by Albert Einstein. Primarily, Einstein proposed an excited, isolated, atom could emit photons and thereby return to a lower energy state; he called this spontaneous emission. Additionally, he postulated that when light passes through a substance, it can stimulate the emission of more light. Einstein also hypothesized that photons favor travelling together in the same state. Therefore, if an individual has a vast collection of atoms which contain a large excess of energy, they will be prepared to emit a photon at random. Nevertheless, the passing by of a wandering photon of correct wavelength will cause the atoms to be stimulated and release their photons early. These photons will then travel in the same direction with an identical frequency and phase to the original stray photon. This, thereby, causes a chain reaction in which a horde of identical photons will move through the rest of the atoms, causing more photons to be emitted from the atoms and then to join the horde. In the case of lasers, this stray photon is fired at an atom already in an excited state, causing this release of photons and therefore, the laser beam which can be seen [11].
It was not until 1951 when Charles Hard Townes conceived his idea of a “MASER”, an acronym for a process which consisted of Microwave Amplification via Stimulated Emission of Radiation. In 1954, the first optical maser (what we now call a laser) was designed and demonstrated at Columbia University by Townes, Herbert Zeiger and James Gordon. Gordon Gould, a student at Columbia University at the time, wrote down ideas for a laser and became the first to use the term “LASER” in his notebook in 1957. The term or acronym stands for Light Amplification by the Stimulated Emission of Radiation.

A laser can be described as any device which generates and intensifies a narrow and focused beam of light whose photons are coherent. In a laser, atoms or molecules of the medium being used for lasing — can be a crystal (such as ruby or garnet), a gas, or a liquid — are “propelled” so more of them will be at higher (excited) energy levels than at their ground state. This results in a sudden burst of coherent light as these atoms rapidly discharge in a chain reaction. This is the process called stimulated emission.
Figure 2. Diagram showing the process through which Stimulated Emission occurs. [4]

Figure 3. Diagrams showing and explaining the process of Stimulated Emission. [5]
The first laser was constructed by Theodore H Maiman in 1960. Approximately six months later (in December of 1960), three researchers at Bell Labs; Ali Javan, William Bennett Jr., and Donald Herriott, developed a helium-neon laser, and became the first to generate a continuous beam of light. This led to the creation of lasers utilizing different chemical elements over the years and decades since, such as; Thulium, yttrium aluminum garnet (YAG), neodymium glass (Nd:glass), and neodymium-doped YAG (Nd:YAG).

In 1961 lasers were used on humans for medical purposes for the first time. The first operation was performed at Columbia-Presbyterian Medical Center by Dr. Charles J Campbell and Charles J. Koester, who destroyed a retinal tumor with the use of a ruby laser [12]. By 1964 the Carbon Dioxide (CO₂) laser was developed and by the 1970’s early surgical versions were being engineered and used with articulated robot arms for delivery of the laser beam to the tissue being targeted. During the 1970’s to the 1980’s Dr. Kathy Laakmann-Crothall invented the all-metal RF-excited carbon dioxide laser, as well as flexible waveguides for use with carbon dioxide lasers. Carbon Dioxide lasers are currently some of the most high-powered and efficient lasers available [13].
Figure 4. The four main wavelength regions of optical fibers. The first and second windows have the greatest optical loss limit.

Technology currently used for laser microsurgery is classified into two types of systems; free-beam systems and fiber-coupled systems. The use of lasers for surgical purposes has many advantages, such as; greater accuracy of incisions, they are extremely precise and can be tuned to function at the micro-scale, and they can be easily inserted into the body as well as have incisions be guided by a computer, eliminating some of the risk associated with human error (such as hand tremors) during surgeries. In addition to these reasons, these procedures tend to take less time, cost less money, and the heat which the laser generated is capable of keeping the surgical site germ free, therefore reducing the risk of infection [6]. Disadvantages include; the individual (doctor or surgeon) performing the procedure must be thoroughly trained and highly skilled at controlling the laser. There are also certain risks and
complications which can occur during laser surgery, such as; careless or un-safe surgical practices which can lead to unintentional damage or burns to the patient’s tissues or organs, risk of fires and ignition of clothing or paper by the laser, and electric shock caused by the high voltage required to power the lasers.

Table 1. Table showing the most commonly used lasers for surgery, their wavelengths and their main uses and advantages in surgeries[2].

<table>
<thead>
<tr>
<th>Type of Laser</th>
<th>Wavelength</th>
<th>Surgical Uses</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>10,600 nm (Infrared)</td>
<td>Seals blood vessels &amp; lymphatics, incising and excising tissue use. Use for maxilla-facial and plastic surgery, urology and gynecology.</td>
<td>Converts light energy to heat, strong enough to minimize bleeding while cutting through or vaporizing tissue.</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1,060 nm (Infrared Coherent)</td>
<td>Mainly used in tracheobronchial, gastrointestinal &amp; urologic pathology for treatment of stenosis, granulomas, benign tumors &amp; reduction of malignant tumors.</td>
<td>Penetrates tissue more deeply, enables blood to clot quickly. Tissue destruction with good hemostasis; &amp; provides control of normal and abnormal blood vessels.</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>488 nm &amp; 514 nm</td>
<td>Commonly used in ophthalmology for ontological microsurgery in treatment of otosclerosis &amp; tympanosclerosis.</td>
<td>Limited penetration, good for eye surgery and superficial skin disorders, and can use light-sensitive dyes to shrink or dissolve tumors.</td>
</tr>
</tbody>
</table>

2.2 — Free Beam vs. Fiber-Coupled Laser Systems

Free-beam laser systems are used to ablate tissue from relatively large distances; typically, on the scale of hundreds of millimeters. Due to these large distances, direct line-of-sight to the surgical area, as well as high quality focusing optics (to focus the laser energy on the tissue being targeted), are required by these systems. Usually equipped with scanning capabilities as well, there is the capability
to minimize tissue carbonization and thermal damage to surrounding tissue. Ultimately this leads to cleaner laser cuts and enhanced surgical outcomes [14].

Figure 5. Examples of free-beam laser system.

Fiber-coupled surgical lasers, on the other hand, tend to be flexible and capable of delivering the laser energy required when performing tissue ablation within closer proximity to the surgical sight, making them an ideal choice for minimally invasive and endoscopic surgeries. Scanning capabilities, however, are not currently offered, thus limiting them regarding the quality of laser-tissue ablations which can be provided.

Figure 6. Example of a Fiber-Coupled Laser System.
2.3 — Effects of Lasers on Tissue

The type of laser and specific wavelength utilized for minimally invasive surgeries is dependent upon the surgery being performed as well as the tissue it is being performed on. For example, in laryngeal surgeries, lasers which operate in the infrared spectrum (such as the Thulium laser and diode lasers) are typically used. Carbon Dioxide (CO₂) gas lasers, which have longer wavelengths, are commonly used for a variety of different types of surgeries, including: oral surgery, dermatology, and ophthalmology. Argon and Nd:YAG lasers, which also have longer wavelengths, a larger capacity for coagulation, and an increased potential for perforation, make them ideal for use in endoscopic hemostasis [15].

Figure 7. Diagram showing different techniques and their effects on the tissue possible with a Thulium Fiber-Coupled Laser emitting a 2μm wavelength beam, which is strongly absorbed by water (which is present in all tissue)[6].
Coagulation, vaporization, carbonization or melting can occur when tissue is illuminated and heated by laser light, depending on the peak power and wavelength of the laser, as well as the thermal properties of the biological tissue being operated on. Contraction of arteries may also occur with use of the laser via rapid heating methods which weld the walls of the vessels together. Prior to heat delivery a Bipolar Circumactive Probe (a thermally active contact or heating probe) may be used to compress the artery of interest. Photocoagulation may also be achieved; focusing the laser beam on a bleeding point to cause rapid tissue heating and therefore producing blood coagulation, as well as tissue necrosis [15].

The normal temperature of tissue is around 37° C, most biological effects which occur beyond 60° C are irreversible. When increased to a range of 40° C to 50° C, hyperthermia occurs. During hyperthermia, some molecular bonds are destroyed and the membrane is altered, a reduction in enzyme activity is also observed. Denaturation of proteins and collagen can occur between 35° C and 90° C. Tissues coagulate and cells necrotize between 60° C and 65° C. At around 100° C vaporization of water occurs, in which the temperature of water does not change but gas bubbles are formed. This causes thermal decomposition (ablation) of tissue fragments. Beyond 100° C carbonization occurs. This is when, if all water molecules are vaporized, carbon atoms are released and adjacent tissues are blackened. As a result of this, smoke rises from
the skin. At temperatures beyond 300°C melting of the tissue can occur [16]. This raise in tissue temperature occurs via the absorption of the laser energy by the ‘targets’ (water, melanin, and blood; i.e. tissue) [16].

![Diagrams showing incisions/ablations made with a focused beam and coagulation caused with the use of an unfocused beam; both displaying the effects of a surgical flexible-fiber (optical fiber) CO₂ laser handpiece.][1]

**2.4 — Optical Fiber Characteristics and Equations**

The main function of optical fibers is the efficient transmission of light at operational wavelengths. Total Internal Refraction (TIR) must occur for the light to be able to remain in the core of an optical fiber. Total Internal Reflection occurs when a propagating light beam encounters the boundary of a medium at an angle larger than a particular critical angle. The critical angle is the angle of incidence above which Total Internal Reflection occurs, given by:

\[ \theta_c = \arcsin \frac{n_2}{n_1} \]  

[1]
and is only defined when $\frac{n_2}{n_1}$ is less than 1. When incident on an optical fiber at an angle of incidence larger than the critical angle, the light will remain trapped within the glass strand and be capable of traveling over long distances without significant loss. Optical fibers can thus be used for a variety of applications, including: surgical and biomedical applications, telecommunication, fiber lasers, imaging techniques in various fields, as well as countless other applications.

Figure 9. TIR allows light to remain in core of fiber.[7][17]

This research utilized a multimode step-index optical fiber with a core diameter of approximately 300 $\mu$m. The core of step-index fiber has uniform index of refraction up to the cladding interface where the index changes in a step-like manner. To avoid problems with modal dispersion, data transmission distances must be kept short because different modes in step-index fiber travel different path lengths while traveling through the fiber. Step-index fibers, are well suited to applications requiring high power densities, such as medical and industrial power delivery [7].
Single-mode fibers differ from multimode fibers in that only the fundamental zero-order mode will be transmitted. Additionally, in single-mode fibers the light beam will travel straight through the fiber without any reflections from the core-cladding sidewalls. In single-mode fibers modal dispersion is eliminated since it only propagates the fundamental mode. Therefore, the bandwidth is much higher with a single-mode fiber than that of a multimode fiber. This means pulses can be transmitted much closer together in time without overlap, making them very desirable for use in long-range communication systems. Their typical core diameters are much smaller than that of a multimode fiber, ranging between 5 and 10 µm [7].

![Diagram of Single-Mode and Multimode Fibers](image)

Figure 10. Diagrams showing the difference between Single-Mode and Multimode Optical Fibers. [17]

The real number of modes, M, which can be propagated through a fiber depends on the core diameter, numerical aperture and the wavelength of the light being transmitted. [7] This number can be approximated via the equations:

\[ M = \frac{V^2}{2} \]  
\[ V = \frac{2\pi a (NA)}{\lambda} \]

Eqn. [1]  
Eqn. [2]
\[ \text{NA} = n \sin(\theta_{acc}) = \sqrt{n_{core}^2 - n_{clad}^2} \quad \text{Eqn. [3]} \]

Where \( M \) is the number of modes supported by the optical fiber, \( V \) is the \( V \)-number which is the normalized optical frequency, \( a \) is the fiber core radius, \( \lambda \) is the free space wavelength, \( \text{NA} \) is the numerical aperture (a dimensionless quantity used to specify the acceptance angle of an optical fiber), \( \theta_{acc} \) is the acceptance half-angle, \( n \) is the index of refraction of air, \( n_{core} \) is the index of refraction of the core, and \( n_{clad} \) is the index of refraction of the cladding.

![Diagram showing the beginning process of the propagation of light through an optical fiber.](image)

Optical fibers, however, are not perfect and do experience attenuation. Attenuation is the loss or decrease in intensity of light as it propagates through the optical fiber\cite{18}. This loss can be quantified to estimate the total transmitted power lost within the fiber optic setup. There are many factors which can contribute to attenuation, such as: absorption, scattering (i.e. Rayleigh and Mie Scattering), and bending losses (i.e. macro-bending and micro-bending losses).
Scattering losses are those which occur when light encounters a change in the refractive index of the medium. These changes can be extrinsic (impurities, particulates, bubbles, etc.) or intrinsic (fluctuating glass density, composition, phase state, etc.) [8]. Bending losses are those which occur due to changes in the external and internal geometry of the fiber. Macro-bending losses are associated with the physical bending of the fiber (ex: rolling the fiber into a tight coil can cause losses if the bend radius is smaller than the recommended value for that fiber). Micro-bending losses are those which arise from internal geometrical changes of the fiber; particularly the core and cladding layers. Random variations (or “bumps”) in the fiber’s structure can disrupt the conditions necessary for total internal reflection to occur, therefore causing the propagating light to couple into a non-propagating mode which leaks from the fiber [8].

![Diagram of light coupling](image)

Figure 12. Diagrams showing the effects of micro-bending (left) and macro-bending (right). [8]

2.5 — Scaling Laws

When size becomes extremely small, Newtonian mechanics fails, and quantum mechanics must be utilized in order to study these physical systems. However, even
prior to this level of miniaturization, there are numerous special aspects which one must consider for the successful design and analysis of these micro-systems [3]. In modern engineering, due to the emergence of Microsystems, formal studies of the changes in characteristics of objects and systems with a change in their size (scale) is necessary. Dimensional Analysis is another name for the basic ideas behind scaling laws, in which the characteristics of a system are able to be expressed as an amalgamation of various parameters, making each group dimensionless. Changes in size or scale, therefore, have no effect on the magnitudes of these quantities. Based on the performance of a similar system of different size, the performance of the system can then be predicted.

In today’s technologies, a drastic increase in sensory data is required to achieve higher degrees of intelligence and autonomy, demanding the need for miniaturized sensors to be able to fit a large quantity in small spaces. This must be done without exceeding energy consumption and cost limitations. The same is true of actuators for these devices, a large number must be employed in a small space, therefore requiring miniaturization of these actuators. However, the study of these scaling laws really began will Galileo Galilei who discovered, amongst many things, for example: that large ships will break (when not in water) under their own weight but a scale model of said ship designed of the same wood will not. He also saw that a thin
small board, made of material heavier than water, will float when the piece is small enough; this lead him to argue that when downsized its area (which is proportional to its weight) will decrease quicker than the rate at which its perimeter (receives the support from the waters’ surface tension) will decrease.

Essentially, there are two types of scaling laws; one which is related to the scaling of physical size of objects, and the other which is related to the scaling of phenomenological behavior of objects and/or machines. “Isomorphic” or “isometric” scaling is when all aspects of the device scale in a similar way and the geometric integrity is maintained with size. “Allometric” scaling is when differing elements of a system with different functionalities do not scale in similar ways. Generally, in a system, the various subsystems performances will scale differently, leading to different appearance of the system as size becomes smaller. Another aspect to be taken into consideration is that different physical phenomena become predominant as scale changes; i.e., relative importance changes with size.

Taking the example of scaling a cantilever beam which has a length (L), a width (w), and a thickness (h); the deflection/displacement of the tip (δ) can be found when there is a force acting on the beam. The stiffness of the beam is represented by s. If the material used remains the same, the stiffness of the beam will scale proportionally as the scale of the length (l) does; s ∝ l. If stiffness must be found under the beam’
weight, then the deflection force will be proportional to its weight, which scales as $l^3$.

Smaller beams, therefore, will behave stiffer than larger ones [3].

![Diagram showing the forces on a cantilever beam.](image)

Figure 13. Diagram showing the forces on a cantilever beam.

Various types of forces are involved in solving dynamical problems, each of which scale in a manner different to one another. Electrical resistance for a given material can be shown to scale as $l^{-1}$, inductance is shown to scale as $l^1$, and current is shown to scale as $l^2$.

<table>
<thead>
<tr>
<th>Force</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension</td>
<td>$l^1$</td>
</tr>
<tr>
<td>Fluid force/electrostatic force</td>
<td>$l^2$</td>
</tr>
<tr>
<td>Weight/inertia force/electromagnetic</td>
<td>$l^3$</td>
</tr>
<tr>
<td>Electromagnetic force (constant current density)</td>
<td>$l^4$</td>
</tr>
</tbody>
</table>

Table 2. This table shows some common forces and the manner in which they scale.
Figure 14. Plot showing how each of these four common forces scales.
Table 3. Table showing the scaling laws for various physical quantities: $P = l^n$ [3].

<table>
<thead>
<tr>
<th>Physical quantity, $P$</th>
<th>Scaling exponent “$n$”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending stiffness</td>
<td>1</td>
</tr>
<tr>
<td>Mass</td>
<td>3</td>
</tr>
<tr>
<td>Mass moment of inertia</td>
<td>5</td>
</tr>
<tr>
<td>Second moment of area</td>
<td>4</td>
</tr>
<tr>
<td>Strength</td>
<td>2</td>
</tr>
<tr>
<td>Shear stiffness</td>
<td>1</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>-1</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>2</td>
</tr>
<tr>
<td>Electrical resistance</td>
<td>-1</td>
</tr>
<tr>
<td>Electrical capacitance</td>
<td>1</td>
</tr>
<tr>
<td>Inductance</td>
<td>1</td>
</tr>
<tr>
<td>Surface tension, van der Walls force</td>
<td>1</td>
</tr>
<tr>
<td>Fluid force</td>
<td>2</td>
</tr>
<tr>
<td>Inertia force</td>
<td>3, 4</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>3 (Const. speed), 5</td>
</tr>
<tr>
<td>Potential energy (gravitational)</td>
<td>4</td>
</tr>
<tr>
<td>Elastic potential energy</td>
<td>2</td>
</tr>
<tr>
<td>Strength to weight ratio</td>
<td>-1</td>
</tr>
<tr>
<td>Resistance power loss</td>
<td>1</td>
</tr>
<tr>
<td>Thermal time constant</td>
<td>2</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>3</td>
</tr>
<tr>
<td>Electric field energy</td>
<td>-2</td>
</tr>
<tr>
<td>Available power</td>
<td>3</td>
</tr>
<tr>
<td>Power loss/power available</td>
<td>-2</td>
</tr>
<tr>
<td>Electromagnetic force</td>
<td>3</td>
</tr>
<tr>
<td>Electrostatic force</td>
<td>2</td>
</tr>
</tbody>
</table>

The scaling laws presented here, as well as those not stated above, play a crucial role in the design and development of micro-sized systems and devices. These laws assist in the development of a “micro-intuition” for the designer of the system. Finally, it should be noted that completely different concepts may be necessary for the design of a miniaturized system, guidance to which will come from these scaling laws. [3].
CHAPTER 3 — OUTLINE OF DESIGN

3.1 — Development of Prototype [Scanning Tool & Optical Design]

To build this prototype laser scanning tool a variety of components were required, designed and purchased. Those which were designed, via SolidWorks, were 3D printed by the industrial engineers in NC State’s CAMAL Lab. The items required included: an optical fiber, lenses, lens holders and lens casings, a casing to hold the optical elements and the optical fiber, a separate casing to hold the coils, permanent magnets, a camera, a laser and laser source, an Arduino DUE as well as a custom-made circuit board (for current supply and control to the electromagnetic coils), as well as a variety of smaller parts (such as; wires, resistors, capacitors, ferromagnetic cores for the coils, etc.).

Figure 15. Photos of the coils which were custom ordered for this research project; made of 35 AWG copper wire and consisting of 150 turns.
For the optical element, a *Collimated Laser Diode 635-nm Module*, from Thorlabs, was purchased and used. The laser was powered and mounted via use of the *CPS08K, CPS085-EC CPS Laser Diode Mounting Kit*, also from Thorlabs. The optical fiber used was a multimode optical fiber with 300 µm core diameter and 0.39 NA, the Thorlabs *FT300EMT*. The fiber has a silica core, 12.5 µm hard polymer cladding layer, and a 180 µm coating layer. The two lenses purchased were each 6 mm in diameter, one with a focal length of 10-mm and the other with a 30-mm focal length; these lenses were used to further collimate and focus the laser light. The lenses were each epoxied into a lens holder and then placed into individual cylindrical lens casings, which were then placed inside the optical elements casing designed. (It is also important to note that these lenses caused the laser beam direction to be inverted.)

![Image](image.png)

Figure 16. Photos showing the laser source and mount used (left), as well as the laser diode used (right) for this research.
Figure 17. Photos showing the lenses in their lens mounts and lens casings.

To adapt the fiber optic cable to be used with the laser purchased, a cylindrical piece of metal was held in place over the patched end of the fiber optic cable with electrical tape. This cylindrical piece was then placed in the laser mount with the laser.

The coils used in this project were custom ordered. They were made from 35 AWG copper wire and contained 150 turns each with an inner diameter of approximately 1.42 mm, an outer diameter of approximately 2.88 mm, and a length of approximately 6 mm. They initially also contained an air core. In the work done by Alperen and Mattos [1], the coils used were made from 36 AWG copper wire; here we chose 35 AWG because it has a slightly better current carrying capability. When initial tests were performed using the coils with an air core; it failed to produce results significant enough to consider (only about 1-mm of movement was noticeable). To correct this, ferromagnetic cores were ordered to be place in the center of the coils.
The ferromagnetic cores, made of Ferrite 77 Material, were successfully used to strengthen the generated electromagnetic field.

Initially, via the use of SolidWorks, a rectangular casing with a cylindrical cutout through the center was designed and 3D printed with the intention of being used to hold the optical elements. This design was later modified to better resemble that of the original work done by Alperen Acemoglu and Leonardo S. Mattos [1]. The design was changed to a completely cylindrical casing; however, the original rectangle was still used to keep all of the elements steady on the table. Additionally, designed was
a small cylinder with a hole through the middle. This was used to place the optical fiber through and be able to keep it stable and centered in the casing.

Figure 19. Initial design for casing in which the portion of the optical fiber with permanent magnets, the casing containing the coils, as well as the optical elements were placed. Measurements in diagram of dimensions are shown in inches.

Figure 20. SolidWorks design for optical fiber stabilizer; consisting of two portions, one which is large enough to hold stable the orange tubing placed around the fiber to patch it to a connector and therefore the laser, and the other smaller hole to be able to fit just the fiber and keep it stable and centered. Measurements in diagram of dimensions are shown in inches and are representative of the diameter measurements.

Figure 21. SolidWorks design of final casing to hold electromagnetic coils, with a hole in the center through which the optical fiber with permanent magnets will be placed. The dimensions were made to have a smaller distance between the coils and the permanent magnets, as well as to be able to fit inside the cylinder designed to hold the lenses in their cases. This design went through multiple iterations.
each time the holes in which the coils are placed needed to be made closer to the center hole
containing the fiber, and the center hole for the fiber made smaller, in order for the generated EM field
to be strong enough to move the PM’s & therefore the optical fiber. Measurements in the diagram
are shown in inches and are representative of the diameter measurements.

The five axially magnetized ring permanent magnets were placed on the optical
fiber and positioned in the center of the cylindrical casing. The two lenses, in their
holders and cases were placed in the cylindrical casing, after the free end of the optical
fiber, and the coils (with the ferromagnetic cores place in their center) were placed
inside the casing designed for them and around the optical fiber and permanent
magnets. This completed the setup which was used for later experimentation.
3.2 — Laser Spot Detection

Laser spot detection was performed via the use of an AKASO EK7000 4K Ultra HD video action camera. A piece of millimetric paper was placed behind the optical elements casing, where the laser spot exited, and behind this the action camera was strategically placed. Due to the low power of the laser used, the camera and millimetric paper were placed in very close proximity to where the laser beam exited. Using the cameras 60 frames per second (fps) capability at a resolution of 1080 by 1080 pixels, the motion of the laser through the millimetric paper was captured as the precision control of the laser via application of current to the electromagnetic coils was tested.

In the original research performed, [1] a SpeedCam HiSpec 1 — Fastec Imaging camera with a capability of 120 frames per second at a resolution of 880 by 512 pixels,
was used. For this research project, however, this level of precision videography was unnecessary at these early stages.

Figure 23. Photos of the laser beam spot taken by the AKASO EK7000 4K Ultra HD video action camera.

Figure 23a. Photos of the AKASO EK7000 4K Ultra HD video action camera.
CHAPTER 4 — EQUATIONS, SIMULATION & MODELING

4.1 — Coil & Magnet Equations [Induced Magnetic Field & Beam Deflection]

In this study, four identical electromagnetic coils (two pairs) were professionally formed and then placed orthogonal to each other in the experimental setup surrounding the permanent magnets located on the optical fiber. All four coils were made of 35 AWG copper wire and contained 150 turns each.

The magnetic field induced via a circular current loop, such as the coils used here, whose axis lies along the z-axis, a single loop place in the \( z = z_0 \) plane, can be expressed in cylindrical coordinates \((r, \theta, z)\) by the equations below [Eqn (4a), (4b), and (4c)]. These equations are found by finding the curl of the magnetic vector potential;

\[
\vec{B} = (\nabla \times \vec{A}) = \text{curl}(\vec{A}) \quad [19].
\]

The vector potential, \( \vec{A} \), of the magnetic field produced by a circular coil in the case stated above, with a current of \( I \) amperes is represented by the equation [17];

\[
\vec{A} = \frac{\mu_0 I}{2\pi} \int_0^\pi \frac{\cos \Phi d\Phi}{\left(\alpha^2 + r^2 + (z-z_0)^2 - 2ar \cos \Phi\right)^{1/2}} \quad \text{Eqn. [i]}
\]

Which can be expressed as;

\[
\vec{A} = \frac{\mu I}{k\pi} * \frac{\alpha \pi}{r} \left[ \left(1 - \frac{k^2}{2}\right) K(k^2) - E(k^2) \right] \quad \text{Eqn. [ii]}
\]

The equations for \( \vec{B} \) are thus;
\[ B_r = \frac{\mu_0 I}{2\pi r} \left[ \frac{r^2 + a^2 + (z-z_0)^2}{(r-a)^2 + (z-z_0)^2} E(k_c) \right] \quad \text{Eqn. [4a]} \]

\[ B_z = \frac{\mu_0 I}{2\pi} \left[ K(k_c) - \frac{r^2 - a^2 + (z-z_0)^2}{(r-a)^2 + (z-z_0)^2} E(k_c) \right] \quad \text{Eqn. [4b]} \]

\[ B_\theta = 0 \text{ due to symmetry in cylindrical coordinate system} \quad \text{Eqn. [4c]} \]

Where to simplify slightly:

\[ [R^2 + z^2]^{\frac{1}{2}} = [(r + a)^2 + (z - z_0)^2]^{\frac{1}{2}} = \text{magnitude of vector } r \]

= distance between differential current element & point on the axis "P"

And:

\[ k_c^2 = \frac{4ar}{(r+a)^2 + (z-z_0)^2} \quad \text{Eqn. [4d]} \]

In the above equations, \( \mu_0 \) represents the permeability of free space (\( \mu_0 = 4 \times \pi \times 10^{-7} \text{ Wb/A } \)), \( a \) is the radius of the coil, and \( I \) is the current. \( K(k_c) \) represents the first kind of elliptical integral function, and \( E(k_c) \) signifies the second kind of elliptical integral function; each have simple polynomial approximations. Using equations [4a] and [4b] it is possible to calculate the magnetic field components, \( B_r \) and \( B_z \), for any \( r \) and \( z \). The elliptical integral functions will equal \( \frac{\pi}{2} \) for any point in the z-axis (indicating, \( r = 0 \) and therefore \( E(0) = K(0) = \frac{\pi}{2} \)). For the special condition, \( z_0 = 0 \), the magnetic field strength can then be derived:

\[ B_z = \frac{\mu_0 I}{2} \frac{a^2}{[a^2 + z^2]^{\frac{1}{2}}} \quad \text{Eqn. [5]} \]

With the use of vectorial summation of the contributions from each coil, the total magnetic field strength, \( B \), can be calculated. When placed in this external magnetic
field \( \mathbf{B} \), a permanent magnet which has a magnetic dipole moment \( \mathbf{m} \) it will the experience a force and a torque:

\[
F = \nabla (\mathbf{m} \cdot \mathbf{B}) \quad \text{Eqn. [6]}
\]

and

\[
\mathbf{T} = \mathbf{m} \times \mathbf{B} \quad \text{Eqn. [7]}
\]

This torque produced aims to align the magnets with the magnetic field, while the force produced pulls it towards the directions of the magnetic field gradient. It is assumed spatial variation of the field is small enough that the net force on the magnets can be considered to be negligible. The cantilever beam is kept straight via the elastic forces of the cantilever body. This balances the magnetic torque and keeps it at an equilibrium configuration. This is when considering a cantilever which has no contact with the tissue. Any cross-section along its length will have a bending moment equal to the magnetic torque, while the twisting moment will be equal to zero [20].

![Figure 24. Interaction of the cantilever beam with an induced magnetic field.](image)

Since the magnetic field variation is negligibly small the net force on the permanent magnets induced by the coils will be neglected, taking this into account.
Identical currents are to be fed to the coils facing each other, therefore inducing a uniform magnetic field within the workspace. The beam bending is generally dependent on the magnetic torque. The magnitude of magnetic torque and bending moment of the cantilever beam become equal when in the equilibrium condition. The bending angle of the cantilever beam can therefore be calculated via the formula:

$$\theta = \frac{|T_m| \cdot l}{E \cdot I_m}$$  \hspace{1cm} \text{Eqn. [8]}

In this equation, $I_m$ is the moment of inertia of the cantilever beam, $l$ is the length of fiber between the fixed end and the permanent magnets, and $E$ is the elasticity modulus. The displacement is represented by $\delta$ and can be calculated by integrating the above equation, Eqn. [8], over the length of the beam, giving:

$$\delta(k) = \frac{|T_m| \cdot k^2}{2E \cdot I_m}$$  \hspace{1cm} \text{Eqn. [9]}

In which, $0 \leq k \leq l$. A relationship is therefore established between the moment acting on the tip and the displacement being observed at length $k$ [21]. The deflection angle of the cantilever beam, $\varphi$, can then be computed via the equation:

$$\varphi = \tan^{-1}\left(\frac{\delta(l)}{l}\right)$$  \hspace{1cm} \text{Eqn. [10]}

In order to validate this model against deflections obtained experimentally an equation, Eqn. [11], which is linear with respect to field strength is utilized:

$$\frac{\theta}{\sin(\gamma - \theta)} = \frac{||m|| ||B|| l}{EI}$$  \hspace{1cm} \text{Eqn. [11]}
The left side of Eqn. [11] represents the deflection which can be computed for a measured cantilever beam deflection. The left side can then be compared to the right side of the equation which is representative of the model quantity. Therefore, through the use of this equation, the displacement of the cantilever beam can be described as a function of the magnetic field strength within the work space[21].

4.2 — Current Control

In order to supply a current to each of the four electromagnetic coils, as well as to control this current for the manipulation of the optical fiber, a circuit board needed to be designed and created. Below is a schematic of the circuits on the board designed to supply a current to each of the coils individually. Despite only using four coils for this particular research project, this board in particular was designed to be able to supply a current to six separate coils in case of future addition of coils for forward and backward motion. In this design a DC-DC converter, three MCP4922-E/P (MCP) digital-to-analog converters, and six OPA541AP (OP-AMP) power current amplifiers were utilized in an open-loop control system. The DC-DC converter was used to regulate the voltage which was input into the circuit. The MCP’s were used to supply a current to each of the four coils; where each MCP is capable of controlling two coils separately. However, the MCP’s can only handle a current of up to 20-mA and we required a current of 200-mA to be supplied. This issue was fixed with the OP-
AMP's which were used as our current controllers; they were capable of amplifying this 20-mA current to our desired 200-mA current.

This custom designed board was then hooked up to a circuit, and connected to an Arduino DUE, which was connected, initially, to the joystick on Texas Instruments Educational BoosterPack MKII microcontroller unit. The joystick was used, along with a code which was written on the Arduino platform, to control which coil was being supplied a current and how much it was being supplied.

With the code tested, complete, and functional, initial tests were performed; supplying a current to the coils with an air core and the initial setup (the initial setup was the same as that in that in the final setup, Figure 22, with the subtraction of the ferromagnetic cores). This initial testing of the prototype was done to see if the electromagnetic fields of the coils was strong enough to move the position of the optical fiber. When this testing failed to work the first thing to be changed was the setup; the coil casing was redesigned to place the coils in much closer proximity to the hole which the optical fiber and permanent magnets would go though (shown above in Figure 21.).

With the new setup tests were run another time; this testing proved the electromagnetic fields were still not strong enough to deflect the fiber as much as was needed; it was only able to move the fiber and beam approximately one millimeter. To
strengthen the generated electromagnetic fields, four small ferromagnetic cylindrical cores, with diameters of 1.5 mm, were bought and placed in the center of each coil. The ferromagnetic cores were made of Ferrite 77 Material, MnZn.

With the new 3D printed design (shown in Figure 21, above) as well as the ferromagnetic cores placed inside the electromagnetic coils, we were able to attempt testing once again. These tests proved that with the addition of the ferromagnetic cores, the electromagnetic field produced was strong enough to cause displacement of the permanent magnets and therefore the optical fiber and laser beam as well. However, the electromagnetic field was still very week and the amount which it was able to move the optical fiber was extremely small. (Images of the final setup are shown in Figure 22.)
Figure 25. Schematic diagram of the circuit board designed and used to control the currents supplied to the four individual electromagnetic coils.
4.3 — Simulation and Modeling

Simulation and modeling was performed via the use of COMSOL Multiphysics 5.2a software. Initially, one of the four coils, which are identical, was modeled and then the magnitude and direction of its magnetic flux density (T) was simulated with the use of the various physics studies available to use in COMSOL. Different plotting methods were used in order to clearly show how the magnetic flux density changes through the coils and to display the expected uniformity of the coils magnetic flux density.
Figure 26. Screenshots showing three separate views of a contour plot on which the Magnetic Flux Density (in Tesla) of the coil is shown.
Figure 26a. Screenshots showing different representations of the Magnetic Flux Density (T) of the coil. One shows the Magnetic Flux Density as a representation of arrows (top), another shows a multi-slice view (bottom left), and the last one shows a multi-slice view with streamlines to represent the uniformity of the magnetic flux density (bottom right).

Figure 27. Diagrams showing; direction of Magnetic Field (A/m) of Permanent Magnets (left) and the uniformity of the Magnetic Field of the Permanent Magnets via the use of field lines (right).
Figure 28. Diagrams showing the Magnetic Field (A/m) of the Permanent Magnets via the use of; a contour plot (left) and a multi-slice plot (right).

Figure 29. Diagrams showing the Magnetic Flux Density (in Tesla) of the Permanent Magnets via the use of; a contour plot (left) and a multi-slice plot (right).

Figure 30. Diagrams showing contour plots of the Magnetic Field (A/m) with an effective mode index equal to 1.4585 (2) (left) and the Electric Field (V/m) with an effective mode index equal to 1.4585 (1) (right) of the optical fiber.
Figure 31. Diagram showing a surface plot of the Electric Field (A/m), in the z-direction, of the optical fiber with an effective mode index equal to 1.4585 (2) (left) and diagram showing a surface plot of the Magnetic Field (A/m), in the z-direction, of the optical fiber with an effective mode index equal to 1.4585 (1) (right).

Figure 32. Diagram showing a combination of a contour plot and a surface plot of the Magnetic Field (A/m) and the Electric Field (V/m), respectively, in the z-direction, of the optical fiber with an effective mode index equal to 1.4585 (2) (left) and diagram showing a combination of a contour plot and a surface plot of the Electric Field (V/m) and the Magnetic Field (A/m), respectively, in the z-direction, of the optical fiber with an effective mode index equal to 1.4585 (1) (right).
Figure 33. Diagram showing a combination of an arrows (surface) plot, arrows (boarder) plot and a streamline plot of the Magnetic Field (A/m), in the x- and y-directions, of the optical fiber with an effective mode index equal to 1.4585 (1).
CHAPTER 5 — EXPERIMENTS AND RESULTS

5.1 — Teleoperation

To observe how precise our control of the device would be with the initial setup and to observe the functionality, the joystick was used to move the fiber in each direction to observe how much it was deflected. This was done via a code written in the programming language Arduino, a version of ‘C’, and provided real-time control and assessment of the laser spot position.

5.2 — Repeatability

Once the setup was made steadier, and alignment was made more precise (allowing for a larger displacement observed in the laser beam), a circle was drawn on a piece of millimetric paper with the goal of following the outline of the circle as closely as possible using this magnetically actuated fiber-coupled laser system. Additionally, a square was also outlined with the laser. These were both accomplished by modifying the original Arduino code to supply current directly to the coils in a manner which would create the desired shapes.

The shapes of a circle and a square were initially chosen to test the repeatability of the laser scanner because they are simple shapes which were fairly simple to write a code for in Arduino and obtain results.
5.3 — Results

5.3.1 — Teleoperation Results

Initially results of teleoperation, deflection of the beam via use of a joystick, proved that our setup and code were both functional. However, it was clear while performing these experiments that there were a few issues, such as; a lack of permanency in the actual setup (it was easily displaced) and the need for the optical fiber to be exactly centered between the four coils for the actuation to be highly effective (this was very difficult to achieve). Additionally, due to the fact that the ferrite cores were simply placed inside each coil and not originally designed as a part of the coil, they were loosely fitted inside and a bit longer than the coils. This caused them to at times move towards the fiber, as opposed to the fiber moving towards them. This was a major issue because when this occurred it means there was no displacement of the optical fiber and, therefore, the laser beam was not being actuated. This issue was fixed by sanding down the cores to the size of the coils.

Issues were also encountered with the displacement downward. This was found to be an issue with one of the coils itself and was fixed by reversing the current to that coil.
5.3.2 — Repeatability Results

During the repeatability experiments the number of permanent magnets was changed from five to six to observe a greater displacement in the laser beam and the optimal placement of the permanent magnets on the fiber was found to be when the first permanent magnet is approximately 5-mm from the free-end of the fiber. Many of the same issues encountered with the Teleoperation experiments were also encountered in the Repeatability experiments.

The Arduino codes for both the circle and the square were tested and verified as functional. The main issues still encountered in the results had to do with the inability to get the fiber exactly centered between the four coils; this lead to the fiber being more actuated in the direction of the coils it was located closer towards. This can be seen in the image sequence of the circle; which appears to look more like an oval. In the image sequence of the square it appears as though one of the sides of the square is angled in an awkward manner.
Figure 34. Screenshot of the code used to generate a circular pattern.

Figure 35. Image sequence taken from the video capture of the laser making a circle.
Figure 36. Screenshot of the code used to generate a square pattern.

Figure 37. Image sequence taken from the video capture of the laser making a square. (Shape is hard to see due to the small size of the displacement; ~2-mm).
CHAPTER 6 — CONCLUSIONS & FUTURE RESEARCH

6.1 — Conclusions

Ultimately, the device was able to function according to the desired requirements; actuation of the laser via the use of a joystick, as well as via automation of the current control and therefore actuation of the fiber-coupled laser system were both achieved. However, there were many issues encountered with the setup of the device itself and the precision necessary for the fiber and laser beam to be displaced. With the current setup it is very difficult to achieve the results desired, however, was not impossible and can easily be made more exact with time.

6.2 — Future Research

As we move towards the future and progress with this research there are many directions in which this can be built upon. The main embellishments being a more steady and uniform setup, the use of feedback control instead of the open-loop control which was used here, as well as the potential additional capability to move the fiber-coupled laser forward and backward. This forward and backward motion would make it possible for the device to keep closer proximity to infected tissue when performing laser ablations and therefore reduce the risk of damaging any surrounding tissue which
may be healthy. Additionally, the code written for the creation of a square shape can be modified in order to make the shape created by the laser more accurate.

Furthermore, since this thesis was mainly focused on the building, development and initial testing of this system, more accurate design, testing and experimentation to produce more precise results will be completed.
REFERENCES


[22] “opa541.pdf.”

[23] “21897a-70809.pdf.”

APPENDICES
Appendix A — Equipment & Materials Utilized (Datasheets & Designs)

Materials required to design and build this system:

- FT300EMT Optical Fiber (ThorLabs)
- Permanent Magnets (x5) — axially magnetized
- Custom Coils — 35-AWG Copper Wire; 150 turns each
- Ferrite Toroids (x4) — Ferrite 77 (MnZn)
- Laser — 635-nm Collimated Laser Diode Module (ThorLabs)
- Laser Mount — CPS085-EC CPS Laser Diode Mounting Kit (ThorLabs)
- Lenses (x2) — 6-mm diameter (ThorLabs)
  - Focal Length =10-mm & Focal Length = 30-mm
- Lens Holders (x2) & Cases (x2) (ThorLabs)
- Camera — AKASO EK7000 4K Ultra HD Video Action Camera
- Custom Circuit Board
  - OPA541 — (x6)
  - MCP4922-E/P — Digital-to-Analog Converter (x3)
- Texas Instruments Educational Booster Pack MKII — Joystick used

Below are Datasheets, Diagrams & Designs of some of the Materials used to Build the Laser Scanning Device:
59
### MCP4922-E/P

<table>
<thead>
<tr>
<th>MCP4922 Pin No.</th>
<th>Symbol</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V_{DD}$</td>
<td>Positive Power Supply Input</td>
</tr>
<tr>
<td>2</td>
<td>NC</td>
<td>No Connection</td>
</tr>
<tr>
<td>3</td>
<td>CS</td>
<td>Chip Select Input</td>
</tr>
<tr>
<td>4</td>
<td>SCK</td>
<td>Serial Clock Input</td>
</tr>
<tr>
<td>5</td>
<td>SDI</td>
<td>Serial Data Input</td>
</tr>
<tr>
<td>6</td>
<td>NC</td>
<td>No Connection</td>
</tr>
<tr>
<td>7</td>
<td>NC</td>
<td>No Connection</td>
</tr>
<tr>
<td>8</td>
<td>LDAC</td>
<td>Synchronization input to transfer DAC settings from serial latches to output latches.</td>
</tr>
<tr>
<td>9</td>
<td>SHDN</td>
<td>Hardware Shutdown Input</td>
</tr>
<tr>
<td>10</td>
<td>$V_{OUTB}$</td>
<td>DAC&lt;sub&gt;B&lt;/sub&gt; Output</td>
</tr>
<tr>
<td>11</td>
<td>$V_{REFB}$</td>
<td>DAC&lt;sub&gt;B&lt;/sub&gt; Voltage Input (AV&lt;sub&gt;SS&lt;/sub&gt; to $V_{DD}$)</td>
</tr>
<tr>
<td>12</td>
<td>AV&lt;sub&gt;SS&lt;/sub&gt;</td>
<td>Analog Ground</td>
</tr>
<tr>
<td>13</td>
<td>$V_{REFA}$</td>
<td>DAC&lt;sub&gt;A&lt;/sub&gt; Voltage Input (AV&lt;sub&gt;SS&lt;/sub&gt; to $V_{DD}$)</td>
</tr>
<tr>
<td>14</td>
<td>$V_{OUTA}$</td>
<td>DAC&lt;sub&gt;A&lt;/sub&gt; Output</td>
</tr>
</tbody>
</table>

![Diagram](image1)

![Diagram](image2)
Appendix B — Equations, Derivations & Definitions

Magnetic Field:

\[\vec{B} = (\nabla \times \vec{A}) = \text{curl}(\vec{A})\]

\[\Rightarrow \text{SI Units; } \nabla = \frac{1}{\text{meters}}, \vec{A} = T \cdot m = Wb \cdot m^{-1} = N \cdot A^{-1}, \text{ and } \vec{B} = \text{Tesla}\]

\[\Rightarrow 1 \text{ Tesla} = 1 \frac{N}{A \cdot m} = 1 \frac{\text{Newton}}{\text{Amp} \cdot \text{meter}}\]

Definition of Curl in Cylindrical Coordinates:

\[(\nabla \times \vec{A}) = \text{curl}(\vec{A}) = \left(\frac{1}{r} \frac{\partial A_z}{\partial \theta} - \frac{\partial A_\theta}{\partial z}\right) \hat{r} + \left(\frac{1}{r} \frac{\partial A_r}{\partial \theta} - \frac{\partial A_\theta}{\partial r}\right) \hat{\theta} + \frac{1}{r} (A_\theta + r \frac{\partial A_\phi}{\partial r} - \frac{\partial A_r}{\partial \theta}) \hat{z}\]

Or

\[(\nabla \times \vec{A}) = \begin{vmatrix} 1/r & 1_\phi & k/r \\ \partial r & \partial \theta & \partial z \\ E_r & rE_\theta & E_z \end{vmatrix} \text{ where; } k \text{ is the unit vecot in the } z-\text{direction}\]

Vector Potential of a Solenoid:

It is known that the EM field inside a solenoid is along its z-axis & zero outside. Taking a circular path of radius, s, centered along its axis, the flux through the circular area is shown to be; \(\Phi_B = \pi s^2 B = \pi \mu_0 n s^2\). Additionally, because \(A\) (the vector potential) is along the direction of current, which is circumferential, the line integral of the vector potential is, \(2\pi rsA_\phi\). [24]

For \(s < R\), the vector potential is therefore; \(\vec{A} = \mu_0 n l \frac{\phi}{2} \hat{\phi}\). Despite the fact that the field outside is zero, the vector potential does not disappear outside the solenoid. The reason for this being, if we take a circle with radius \(s > R\), the flux through the circular area will be \(\pi R^2 B = \pi R^2 \mu_0 n l\), where flux is contributed only from the inside of the solenoid. Therefore the vector potential for \(s > R\) is; \(\vec{A} = \mu_0 n l \frac{R^2}{2s} \hat{\phi}\), this falls off as the inverse of the distance from the axis. [24]
Appendix C — Arduino Code Written for Current Supplied to the Coils

(Current Supplied to Coils via Use of Joystick)

Arduino_currentControlFinalJoystick.ino
#include <SPI.h>
#include <math.h>
#include <DueTimer.h>
#include <PID_v1.h>

int JOy_LaserControl(int16_t);
int JOy_LaserControl2(int16_t);
int JOy_LaserControl3(int16_t);
int JOy_LaserControl4(int16_t);
void AnalogOut1(double);
void AnalogOut2(double);
void AnalogOut3(double);
void AnalogOut4(double);
void AnalogOut5(double);
void AnalogOut6(double);
double Controller(double, double);

double Error = 0;
byte address = 0x00;
int CS1 = 13;

//CS = Chip Select.
//CS1 connected to pin 13 in DUE.
//CS2-->pin 12. CS3-->pin 11.

int CS2 = 12;
int CS3 = 11;
//int CS2 = 9;
int Joy_DataOut = 0;
int Joy_DataOut2 = 0;
int Joy_DataOut3 = 0;
int Joy_DataOut4 = 0;

int16_t Joy_X = 0;
int16_t Joy_Y = 0;

int FREQ_1Hz = 2000;
double Time = 0;
float Data=0;
int Data_int =0;

float Read_Current = 0;
float Voltage = 0;
int Read_Voltage_int = 0;

//Define Variables we'll be connecting to
double Setpoint, Input, Output;

//Define the aggressive and conservative Tuning Parameters
double aggKp=.3, aggKi=7, aggKd=0;
double consKp=.1, consKi=0, consKd=0;

//Specify the links and initial tuning parameters
//PID myPID(&Input, &Output, &Setpoint, consKp, consKi, consKd, DIRECT);

void myHandler()
{
  Time += 0.01;
}

void setup()
{
  Timer3.attachInterrupt(myHandler);
  Timer3.start(10000); // Calls every 10ms

  pinMode (CS1, OUTPUT);
  pinMode (CS2, OUTPUT);
  pinMode (CS3, OUTPUT);
  SPI.begin();
  //pinMode (CS2, OUTPUT);
  SPI.setBitOrder(MSBFIRST);
  SPI.setDataMode(1);
  SPI.setClockDivider(21); // 4MHz

  Setpoint = 100;
  // myPID.SetOutputLimits(0, 255);
  // myPID.SetSampleTime(1);
  //turn the PID on
  // myPID.SetMode(AUTOMATIC);

  Serial.begin(9600); // setup serial
}
void loop()
{
    Joy_Y = analogRead(A0);   // read the input pin
    Joy_X = analogRead(A1);   // read the input pin

    Joy_DataOut = Joy_Right_Up(Joy_X);  
    Joy_DataOut2 = Joy_Left_Down(Joy_X);  
    Joy_DataOut3 = Joy_Right_Up(Joy_Y);  
    Joy_DataOut4 = Joy_Left_Down(Joy_Y);  

    Data = 1.5 * sin( 1.57 * Time) + 1.5; 
    Data = Data *(125/3); 
    Setpoint = Data; 
    Read_Voltage_int = analogRead(A7); 
    Voltage = Read_Voltage_int   * (3.3/1023); 
    Read_Currect = (Voltage/10)*1000; 
    Input = Read_Currect; 

    /*
     * if (gap < 1)
     * {  //we're close to setpoint, use conservative tuning
     *    myPID.SetTunings(consKp, consKi, consKd);
     * }
     * else
     * {
     *    //we're far from setpoint, use aggressive tuning
     *    myPID.SetTunings(aggKp, aggKi, aggKd);
     * }
     
     myPID.Compute();
     */
     
     for(int i=0;i<255;i++){

    //AnalogOut(Joy_DataOut) --> To check output data of right and left
    //AnalogOut(Joy_DataOut2) --> To check output data of up and down
    AnalogOut1(Joy_DataOut);  //Coil 1
AnalogOut2(Joy_DataOut2); //Coil 2...right/left b/c
Joy_DataOut
  AnalogOut3(Joy_DataOut3); //Coil 3
  AnalogOut4(Joy_DataOut4); //Coil 4
  // delay(100);
  // }
  // Serial.print("Input = ");
  // Serial.print(Input);
  // Serial.print("    Setpoint = ");
  // Serial.println(Setpoint);

  Serial.print("Joy_X:");
  Serial.print(Joy_X);
  Serial.print("Joy_Y:");
  Serial.print(Joy_Y);
  Serial.print("  ");
  Serial.println(Joy_DataOut);
  //ln=line or new line
  // Serial.print(Error);
  // Serial.print("    ");
  // Serial.println(Input);

}
int8_t msg1 = 0x00;
int8_t msg2 = 0x00;

msg1 = 0xD0 | ((int)value)>>8); //High Byte
msg2 = (((int)value) & 0xFF); //Low Byte
digitalWrite(CS1, LOW);

SPI.transfer(msg1, SPI_CONTINUE);
SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS1, HIGH);

void AnalogOut3(double value)
{
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | ((int)value)>>8); //High Byte
    msg2 = (((int)value) & 0xFF); //Low Byte
digitalWrite(CS2, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS2, HIGH);
}

void AnalogOut4(double value)
{
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0xD0 | ((int)value)>>8); //High Byte
    msg2 = (((int)value) & 0xFF); //Low Byte
digitalWrite(CS2, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS2, HIGH);
}
void AnalogOut5(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | (((int)value)>>8); // High Byte
    msg2 = (((int)value) & 0xFF); // Low Byte

digitalWrite(CS3, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS3, HIGH);
}

void AnalogOut6(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0xD0 | (((int)value)>>8); // High Byte
    msg2 = (((int)value) & 0xFF); // Low Byte

digitalWrite(CS3, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS3, HIGH);
}

int JOy_LaserControl(int16_t JoyData){
    int Output = 0;
    if (JoyData>514 && JoyData<517){
        JoyData = 515;
    }

    Output = map(JoyData, 0, 1023, 0, 1500);
    return Output;
}

int Joy_Right_Up(int JoyData) //For Coil #2 or #1...X-Right, same as Y-Up
if (JoyData>=517)
    Output = map(JoyData, 517, 1023, 0, 1500);
else
    Output = 0;
return Output;

int Joy_Left_Down (int JoyData) //For Coil #3 or #4...X-Left, 
same as Y-Down
{
    if (JoyData<=512)
        Output = map(JoyData, 514, 0, 0, 1500);
    else
        Output = 0;
    return Output;
}

double Controller(double Input_Data, double Setpoint__Data)
{
    double Out_Data = 0;
    Error = Setpoint-Input; //distance away from setpoint
    Out_Data = aggKp * Error;
    if(Out_Data >= 125)
        Out_Data = 125;
    else if( Out_Data <= -125)
        Out_Data = -125;
    Out_Data += 125;
    return Out_Data;
}

(Arduino supplied to coils directly)

Arduino_currentControlCircle.ino
#include <SPI.h>
#include <math.h>
#include <DueTimer.h>
//#include <PID_v1.h>

int JOy_LaserControl1(int16_t);
int JOy_LaserControl21(int16_t);
int JOy_LaserControl3(int16_t);
int JOy_LaserControl4(int16_t);
void AnalogOut1(double);
void AnalogOut2(double);
void AnalogOut3(double);
void AnalogOut4(double);
void AnalogOut5(double);
void AnalogOut6(double);
double Controller(double, double);
void Force1_Control(void);
void Force2_Control(void);
void Force3_Control(void);
void Force4_Control(void);

double Error = 0;
byte address = 0x00;
int CS1 = 13; // CS = Chip Select. CS1 connected to pin 13 in DUE. CS2-->pin 12. CS3-->pin 11.
int CS2 = 12;
int CS3 = 11;
  //int CS2= 9;
int Joy_DataOut = 0;
int Joy_DataOut2 = 0;
int Joy_DataOut3 = 0;
int Joy_DataOut4 = 0;

int16_t Joy_X = 0;
int16_t Joy_Y = 0;

void control_cycles(void);

int FREQ_1Hz = 2000;
double Time = 0;
float Data = 0;
int Data_int = 0;

float period = 5; //Seconds
int n_period = 0;
uint16_t A_1 = 2000; //Amplitude - Down
uint16_t A_2 = 2000; //Left
uint16_t A_3 = 2000; //Up
uint16_t A_4 = 2000; //Right
float F1 = 0, F2 = 0, F3 = 0, F4 = 0;
float freq = 1/period; //Frequency (Hz)
float pi = 3.14158;

float Read_Currect = 0;
float Voltage = 0;
int Read_Voltage_int = 0;

//Define Variables we'll be connecting to
double Setpoint, Input, Output;

//Define the aggressive and conservative Tuning Parameters
double aggKp=.3, aggKi=7, aggKd=0;
double consKp=.1, consKi=0, consKd=0;

//Specify the links and initial tuning parameters
//PID myPID(&Input, &Output, &Setpoint, consKp, consKi, consKd, DIRECT);

void myHandler(){
  Time += 0.01;
}

void setup(){
  Timer3.attachInterrupt(myHandler);
  Timer3.start(10000); // Calls every 10ms
  pinMode (CS1, OUTPUT);
  pinMode (CS2, OUTPUT);
  pinMode (CS3, OUTPUT);
  SPI.begin();
  //pinMode (CS2, OUTPUT);
  SPI.setBitOrder(MSBFIRST);
  SPI.setDataMode(1);
  SPI.setClockDivider(21); // 4MHz
  Setpoint = 100;
  // myPID.SetOutputLimits(0, 255);
  // myPID.SetSampleTime(1);
  //turn the PID on
  // myPID.SetMode(AUTOMATIC);
  Serial.begin(9600); // setup serial
}

void loop(){
  /* Joy_Y = analogRead(A0); // read the input pin //Right
  and Left */
Joy_X = analogRead(A1); // read the input pin  //Up and Down
Joy_DataOut = Joy_Right_Up(Joy_X); //Up
Joy_DataOut2 = Joy_Left_Down(Joy_X); //Down
Joy_DataOut3 = Joy_Right_Up(Joy_Y); //Right
Joy_DataOut4 = Joy_Left_Down(Joy_Y); //Left
*/
// Data = 1.5 * sin( 1.57 * Time) + 1.5;
// Data = Data *(125/3);
// Setpoint = Data;
// Read_Voltage_int =  analogRead(A7);
// Voltage = Read_Voltage_int * (3.3/1023);
// Read_Current = (Voltage/10)*1000;
// Input = Read_Current;
/*
// if (gap < 1)
// {  //we're close to setpoint, use conservative tuning
parameters
  // myPID.SetTunings(consKp, consKi, consKd);
// } // else
// { //we're far from setpoint, use aggressive tuning
parameters
  // Output = Controller(Input,Setpoint);
  myPID.SetTunings(aggKp, aggKi, aggKd);
// }
myPID.Compute();
*/
// for(int i=0;i<255;i++){

//AnalogOut(Joy_DataOut) --> To check output data of right and left
//AnalogOut(Joy_DataOut2) --> To check output data of up and down
  // AnalogOut1(Joy_DataOut);  //Coil 1, fiber-right, laser-left
  // AnalogOut2(Joy_DataOut2);  //Coil 2, fiber-down, laser-up
  // AnalogOut3(Joy_DataOut3);  //Coil 3, fiber-left, laser-right
// AnalogOut4(Joy_DataOut4); //Coil 4, fiber-up, laser-down

// delay(100);
// }
Serial.print("F1 = ");
Serial.print(F1);
Serial.print(" F2 = ");
Serial.print(F2);
Serial.print(" F3 = ");
Serial.print(F3);
Serial.print(" F4 = ");
Serial.println(F4);

Force1_Control();
Force2_Control();
Force3_Control();
Force4_Control();

control_cycles();

/*Serial.print("Joy_X:");
Serial.print(Joy_X);
Serial.print("Joy_Y:");
Serial.print(Joy_Y);
Serial.print(" ");
Serial.println(Joy_DataOut); */
//ln=line or new line

// Serial.print(Error);
// Serial.print(" ");
// Serial.println(Input);

}

void AnalogOut1(double value)
{
  int16_t data =0x0000;
  int8_t msg1 = 0x00;
  int8_t msg2 = 0x00;

  msg1 = 0x50 | (((int)value)>>8); //High Byte
  msg2 = (((int)value) & 0xFF); // Low Byte
digitalWrite(CS1, LOW);
SPI.transfer(msg1, SPI_CONTINUE);
SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS1, HIGH);
}

void AnalogOut2(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0xD0 | (((int)value) >> 8); // High Byte
    msg2 = (((int)value) & 0xFF); // Low Byte
    digitalWrite(CS1, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

    digitalWrite(CS1, HIGH);
}

void AnalogOut3(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | (((int)value) >> 8); // High Byte
    msg2 = (((int)value) & 0xFF); // Low Byte
    digitalWrite(CS2, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

    digitalWrite(CS2, HIGH);
}

void AnalogOut4(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;
msg1 = 0xD0 | (((int)value)>>8);  //High Byte
msg2 = (((int)value) & 0xFF);  // Low Byte
digitalWrite(CS2, LOW);

SPI.transfer(msg1, SPI_CONTINUE);
SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS2, HIGH);
}

void AnalogOut5(double value)
{
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | (((int)value)>>8);  //High Byte
    msg2 = (((int)value) & 0xFF);  // Low Byte
digitalWrite(CS3, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

    digitalWrite(CS3, HIGH);
}

void AnalogOut6(double value)
{
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0xD0 | (((int)value)>>8);  //High Byte
    msg2 = (((int)value) & 0xFF);  // Low Byte
digitalWrite(CS3, LOW);

    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);

    digitalWrite(CS3, HIGH);
}

int JOy_LaserControl(int16_t JoyData){
    int Output =0;
if ( JoyData > 514 && JoyData < 517) {
    JoyData = 515;
}

    Output = map(JoyData, 0, 1023, 0, 2000);
    return Output;
}

int Joy_Right_Up ( int JoyData) //For Coil #2 or #1 ... X-Right, same as Y-Up
{
    if (JoyData >= 517)
        Output = map(JoyData, 517, 1023, 0, 2000);
    else
        Output = 0;
    return Output;
}

int Joy_Left_Down ( int JoyData) //For Coil #3 or #4 ... X-Left, same as Y-Down
{
    if (JoyData <= 512)
        Output = map(JoyData, 514, 0, 0, 2000);
    else
        Output = 0;
    return Output;
}

double Controller(double Input_Data, double Setpoint__Data)
{
    double Out_Data = 0;
    Error = Setpoint - Input; //distance away from setpoint
    Out_Data = aggKp * Error;
    if (Out_Data >= 125)
        Out_Data = 125;
    else if (Out_Data <= -125)
        Out_Data = -125;
    Out_Data += 125;
    return Out_Data;
}

void control_cycles (void){
    AnalogOut1(F1);
    AnalogOut2(F2);
AnalogOut3(F3);
AnalogOut4(F4);
/*
if(Time<=(n_period*period+(period/4)))
{
}
else if(Time>(n_period*period+period/4) &&
Time<=(n_period*period+(2*period/4)))
{
AnalogOut1(0);
AnalogOut2(F2);
AnalogOut3(F3);
AnalogOut4(0);
}
else if (Time>(n_period*period+2*period/4) &&
Time<=(n_period*period+(3*period/4)))
{
AnalogOut1(0);
AnalogOut2(0);
AnalogOut3(F3);
AnalogOut4(F4);
}
else if (Time>(n_period*period+3*period/4) &&
Time<=(n_period*period+(4*period/4)))
{
AnalogOut1(F1);
AnalogOut2(0);
AnalogOut3(0);
AnalogOut4(F4);
if (Time==(n_period+1)*(period))
{
    n_period++;
}
}
*/
}

void Force1_Control(void)
{
    F4 = (A_4 * cos (2* pi * freq * Time));
    if (F4<=0)
        F4 =0;
}

void Force2_Control(void)
F3 = (A_3 * sin(2 * pi * freq * Time));
if (F3<=0)
    F3 =0;
}

void Force3_Control(void){
    F2 = (A_2 * sin(2 * pi * freq * (Time - (period/4))));
    if (F2<=0)
        F2 =0;
}

void Force4_Control(void){
    F1 = (A_1 * sin(2 * pi * freq * (Time - (period/2))));
    if (F1<=0)
        F1 =0;
}

Arduino_currentControlSquare.ino
#include <SPI.h>
#include <math.h>
#include<DueTimer.h>
//#include <PID_v1.h>

int JOy_LaserControl(int16_t);
int JOy_LaserControl2(int16_t);
int JOy_LaserControl3(int16_t);
int JOy_LaserControl4(int16_t);
void AnalogOut1(double);
void AnalogOut2(double);
void AnalogOut3(double);
void AnalogOut4(double);
void AnalogOut5(double);
void AnalogOut6(double);
double Controller(double , double );
void Force1_Control(void);
void Force2_Control(void);
void Force3_Control(void);
void Force4_Control(void);

double Error =0;
byte address = 0x00;
int CS1= 13; //CS = Chip Select. CS1 connected to pin 13 in DUE. CS2-->pin 12. CS3-->pin 11.
int CS2= 12;
```c
int CS3 = 11;
//int CS2 = 9;
int Joy_DataOut = 0;
int Joy_DataOut2 = 0;
int Joy_DataOut3 = 0;
int Joy_DataOut4 = 0;

int16_t Joy_X = 0;
int16_t Joy_Y = 0;

void control_cycles(void);

int FREQ_1Hz = 2000;
double Time = 0;
float Data = 0;
int Data_int = 0;

float period = 5; //Seconds
int n = 0;
uint16_t A_1 = 2000; //Amplitude - Down
uint16_t A_2 = 2000; //Left
uint16_t A_3 = 2000; //Up
uint16_t A_4 = 2000; //Right
float F1 = 0, F2 = 0, F3 = 0, F4 = 0;
float freq = 1 / period; //Frequency (Hz)
float pi = 3.14158;

float Read_Current = 0;
float Voltage = 0;
int Read_Voltage_int = 0;

//Define Variables we'll be connecting to
double Setpoint, Input, Output;

//Define the aggressive and conservative Tuning Parameters
double aggKp = 0.3, aggKi = 7, aggKd = 0;
double consKp = 0.1, consKi = 0, consKd = 0;

//Specify the links and initial tuning parameters
//PID myPID(&Input, &Output, &Setpoint, consKp, consKi, consKd, DIRECT);

void myHandler()
{
    Time += 0.01;
}
```

```cpp
void setup()
{
    Timer3.attachInterrupt(myHandler);
    Timer3.start(10000); // Calls every 10ms

    pinMode(CS1, OUTPUT);
    pinMode(CS2, OUTPUT);
    pinMode(CS3, OUTPUT);
    SPI.begin();
    //pinMode (CS2, OUTPUT);
    SPI.setBitOrder(MSBFIRST);
    SPI.setDataMode(1);
    SPI.setClockDivider(21); // 4MHz

    Setpoint = 100;
    //myPID.SetOutputLimits(0, 255);
    //myPID.SetSampleTime(1);
    //turn the PID on
    // myPID.SetMode(AUTOMATIC);

    Serial.begin(9600); // setup serial
}

void loop()
{
    /* Joy_Y = analogRead(A0); // read the input pin //Right and Left
       Joy_X = analogRead(A1); // read the input pin //Up and Down
       Joy_DataOut  =  Joy_Right_Up(Joy_X); //Up
       Joy_DataOut2 =  Joy_Left_Down(Joy_X); //Down
       Joy_DataOut3  =  Joy_Right_Up(Joy_Y); //Right
       Joy_DataOut4 =  Joy_Left_Down(Joy_Y); //Left
    */
    // Data = 1.5 * sin( 1.57 * Time) + 1.5;
    // Data = Data *(125/3);
    // Setpoint = Data;
    // Read_Voltage_int =  analogRead(A7);
    // Voltage = Read_Voltage_int * (3.3/1023);
    // Read_Current = (Voltage/10)*1000;
    // Input = Read_Current;
```
/*
   // if (gap < 1)
   // { //we're close to setpoint, use conservative tuning
   //   myPID.SetTunings(consKp, consKi, consKd);
   // }
   // else
   // {
   //   //we're far from setpoint, use aggressive tuning
   //   Output = Controller(Input, Setpoint);
   //   myPID.SetTunings(aggKp, aggKi, aggKd);
   // }

   myPID.Compute();
*/

// for(int i=0;i<255;i++){

   //AnalogOut(Joy_DataOut) --> To check output data of right and left
   //AnalogOut(Joy_DataOut2) --> To check output data of up and down
   // AnalogOut1(Joy_DataOut);  //Coil 1, fiber-right, laser-left
   // AnalogOut2(Joy_DataOut2);  //Coil 2, fiber-down, laser-up
   // AnalogOut3(Joy_DataOut3);  //Coil 3, fiber-left, laser-right
   // AnalogOut4(Joy_DataOut4);  //Coil 4, fiber-up, laser-down

   // delay(100);
   // }
Serial.print("F1 = ");
Serial.print(F1);
Serial.print("  F2 = ");
Serial.print(F2);
Serial.print("  F3 = ");
Serial.print(F3);
Serial.print("  F4 = ");
Serial.println(n);
control_cycles();
/*Serial.print("Joy_X:");
Serial.print(Joy_X);
Serial.print("Joy_Y:");
Serial.print(Joy_Y);  
Serial.print("  ");
Serial.println(Joy_DataOut); */

//ln=line or new line

//  Serial.print(Error);
//  Serial.print("      ");
//  Serial.println(Input);

}

void AnalogOut1(double value)
{
  int16_t data =0x0000;
  int8_t msg1 = 0x00;
  int8_t msg2 = 0x00;

  msg1 = 0x50 | (((int)value)>>8); //High Byte
  msg2 = (((int)value) & 0xFF); // Low Byte
  digitalWrite(CS1, LOW);

  SPI.transfer(msg1,SPI_CONTINUE);
  SPI.transfer(msg2,SPI_LAST);

  digitalWrite(CS1, HIGH);
}

void AnalogOut2(double value)
{
  int16_t data =0x0000;
  int8_t msg1 = 0x00;
  int8_t msg2 = 0x00;

  msg1 = 0xD0 | (((int)value)>>8); //High Byte
  msg2 = (((int)value) & 0xFF); // Low Byte
  digitalWrite(CS1, LOW);

  SPI.transfer(msg1,SPI_CONTINUE);
  SPI.transfer(msg2,SPI_LAST);
digitalWrite(CS1, HIGH);
}

void AnalogOut3(double value) {
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | (((int)value)>>8);  // High Byte
    msg2 = (((int)value) & 0xFF);  // Low Byte
    digitalWrite(CS2, LOW);

    SPI.transfer(msg1,SPI_CONTINUE);
    SPI.transfer(msg2,SPI_LAST);

    digitalWrite(CS2, HIGH);
}

void AnalogOut4(double value) {
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0xD0 | (((int)value)>>8);  // High Byte
    msg2 = (((int)value) & 0xFF);  // Low Byte
    digitalWrite(CS2, LOW);

    SPI.transfer(msg1,SPI_CONTINUE);
    SPI.transfer(msg2,SPI_LAST);

    digitalWrite(CS2, HIGH);
}

void AnalogOut5(double value) {
    int16_t data =0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;

    msg1 = 0x50 | (((int)value)>>8);  // High Byte
    msg2 = (((int)value) & 0xFF);  // Low Byte
    digitalWrite(CS3, LOW);
SPI.transfer(msg1, SPI_CONTINUE);
SPI.transfer(msg2, SPI_LAST);

digitalWrite(CS3, HIGH);
}

void AnalogOut6(double value)
{
    int16_t data = 0x0000;
    int8_t msg1 = 0x00;
    int8_t msg2 = 0x00;
    
    msg1 = 0xD0 | (((int)value)>>8); //High Byte
    msg2 = (((int)value) & 0xFF); // Low Byte
    digitalWrite(CS3, LOW);
    
    SPI.transfer(msg1, SPI_CONTINUE);
    SPI.transfer(msg2, SPI_LAST);
    digitalWrite(CS3, HIGH);
}

int JOy_LaserControl(int16_t JoyData)
{
    int Output = 0;
    if (JoyData>514 && JoyData<517){
        JoyData = 515;
    }
    
    Output = map(JoyData, 0, 1023, 0, 2000);
    return Output;
}

int JOy_Right_Up (int JoyData)  //For Coil #2 or #1 ... X-Right, same as Y-Up
{
    if (JoyData>=517)
        Output = map(JoyData, 517, 1023, 0, 2000);
    else
        Output = 0;
    return Output;
}

int JOy_Left_Down (int JoyData)  //For Coil #3 or #4 ... X-Left, same as Y-Down
{
if (JoyData<=512)
    Output = map(JoyData, 514, 0, 0, 2000);
else
    Output = 0;
return Output;
}

double Controller(double Input_Data, double Setpoint__Data)
{
    double Out_Data = 0;
    Error = Setpoint - Input;  //distance away from setpoint
    Out_Data = aggKp * Error;
    if(Out_Data >= 125)
        Out_Data = 125;
    else if( Out_Data <= -125)
        Out_Data = -125;
    Out_Data += 125;
    return Out_Data;
}

void control_cycles(void){
    float t = Time - n*period;

    if (t <= (period/8)){
        F3 = 2000;
        F2 = (-2000/(period/8)) * t + 2000;
    }
    else if (t > (period/8) && t <= (2*period/8)){
        F3 = 2000;
        F4 = (2000/(period/8)) * (t - (period/8));
    }
    else if (t > (2*period/8) && t <= (3*period/8)){
        F4 = 2000;
        F3 = (-2000/(period/8)) * (t - 2*(period/8)) + 2000;
    }
    else if (t > (3*period/8) && t <= (4*period/8)){
        F4 = 2000;
        F1 = (2000/(period/8)) * (t - 3*(period/8));
    }
    else if (t > (4*period/8) && t <= (5*period/8)){
        F1 = 2000;
F4 = (-2000/(period/8)) * (t - 4*(period/8)) + 2000;
}
else if (t > (5*period/8) && t <= (6*period/8)){
    F1 = 2000;
    F2 = (2000/(period/8)) * (t - 5*(period/8));
}
else if (t > (6*period/8) && t <= (7*period/8)){
    F2 = 2000;
    F1 = (-2000/(period/8)) * (t - 6*(period/8)) + 2000;
}
else if (t > (7*period/8) && t <= (8*period/8)){
    F2 = 2000;
    F3 = (2000/(period/8)) * (t - 7*(period/8));
}
if (Time >= (n + 1)*period){
    n++;
}

AnalogOut1(F1);
AnalogOut2(F2);
AnalogOut3(F3);
AnalogOut4(F4);