Portable Coilgun

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1. Executive Summary

Coil guns have been challenging home design projects for the electronic hobbyist for many years. Carl Friedrich Gauss, who developed a mathematical description of the magnetic effect of coils on a projectile, first thought of the concept of a coil gun. A Norwegian Physicist Kristian Birkeland created the first operational coil gun in 1904. A Texas inventor named Virgil Rigsby designed a stationary coil gun in 1933 that was developed to be used like a machine gun. Coil guns over the years have typically had limited portability and therefore are limited to a stationary mount design. The purpose of our project is to redesign the coilgun so that it has complete portability. We aim to reduce the size and weight of the coil gun as compared to its predecessors to create a coil gun that can be handled and maneuvered with ease. The main goal of the Portable Coilgun project is to untether the coil gun and to develop a level of portability that could lead to further research and interest in the coil gun as a practical gun.

The project will begin with a plastic frame of the coil gun created with plastic piping and sheet plastic. A capacitor bank will be built using the capacitors themselves and a plastic molding. This capacitor bank will be attached to the frame of the coil gun and be integrated into the design of the frame of the coil gun. The coil gun will feature an LCD display that will display when the capacitors have been fully charged and the coil gun is ready to fire. When the user picks up the coil gun to use it, a switch will have to be moved from the safety position to the charge position. The coil gun will proceed to charge and will alert the user once a maximum charge has been reached and the coil gun is ready to be fired. The user can then fire the ferromagnetic projectile at a target with confidence in the accuracy of the coil gun. To be able to fire a projectile, the coils must accelerate the ferromagnetic projectile, which will be done by generating a current that will run through the coils to create a magnetic field in the center of the coils. More than one set of coils will be used, therefore the current going through each set of coils must be meticulously controlled in order to ensure the maximum amount of acceleration through the barrel. This will require the use of infrared sensors and a microcontroller. This microcontroller will be attached to the frame of the gun in a place that is out of sight.

A budget of five hundred dollars was established and this is one of the few constraints we have. We estimated this budget and we intend on remaining at or below the five hundred dollar limit. Since we will be dealing with high voltage equipment, there is a chance of electric shock to the group members. The design and implementation of the circuits will be with safety in mind. After completing a full design of the coil gun and defining all the requirements and specifications for the project, a prototype of the coil gun will be built to test the design and specifications the group has created. If the prototype is successful and meets the requirements and specifications laid out by the group, then our goal will be a success; to create a portable coilgun that will provide the user with a great deal of accuracy.

In the process of creating this document and defining all the specifications for this project, the group might need to use another individual's intellectual property. To prevent intellectual theft and plagiarism, any time a piece of work or property belonging to another entity is necessary to utilize, we will obtain proper consent and will give the entity due credit when referencing the piece of work.

2. Project Description

In this section we will be discussing the specifics of the project. We will define the main motives and reasons that led us to decide to pursue the design and construction of a coil gun. A description of the objectives of this coil gun project will be provided, such as how each component will work under a variety of circumstances and how the coil gun will function overall. The basic project requirements, such as individual conditions needed for each component to work, will be provided in this section as well. We hope to gain skills, knowledge and experience that we can apply to the career paths that we choose.

2.1 Project Motivation and Goals

After brainstorming the different areas of interest of the group members, we ultimately decided that we would work on a coil gun. This coil gun project contains several components and will allow all the group members to utilize their areas of expertise. This will also allow group members to set individual goals to be met throughout the design and building stages of the project.

The coil gun market or industry has yet to have a breakthrough in mass production. A coil gun has not been designed that has the specifications or marketability to be mass-produced. We believe this might have something to do with the portability of most of the designs for previous coil guns. Another factor that might be contributing is the efficiency and capability of most modern day guns. When researching past senior design projects, we found that there have been a few groups who take on the designing and building of a coil gun. However, most of these groups have failed to achieve complete portability. The coil gun we are designing is being designed with portability, accuracy, and power as the major goals. We want to create a coil gun that could potentially lay the groundwork for future research and development of the coil gun as a weapon to be used by the military.

A major goal of all the group members is to learn and acquire various skills and experience from the project that they could put on their resume. We would like to acquire skills that will benefit us in the workplace and possibly in future research as a student. We hope that this class and project will be a learning experience that we can take with us into our careers or the furthering of our education. Communication between the members of the group is crucial to the success of this project. It is a very important goal to maintain a level of communication. If members research a topic, they should share the findings of their research with all of the other members of the group. This is important because every group member is going to have a different level of experience in different fields or aspects of the project. The sharing of information will provide a learning experience for all of the other members, as well as keeping everyone in the loop and up to date on all information.

Microcontrollers contain a circuit printed on a circuit board around the central processor. The combination of the processor, circuit, and all of the components on the circuit board form an integrated circuit that is referred to as an FPGA. FPGA is an acronym for a Field Programmable Gate Array. After looking at previous designs of coil guns, it was determined that a microcontroller would play an essential role in the design of our coil gun. That being said, being able to integrate a microcontroller into the gun became a large motivating factor for the group. The microcontroller controls the LCD display and the infrared sensors that will ultimately determine how well the coil gun performs. This is due to the fact that the microcontroller will determine the timing of the power to each of the coils we will have. We believe working with a microcontroller will give us a great amount of applicable experience to be used when we go into the workforce, which could give us an advantage over other members of the workforce who may not have had an opportunity to work with a microcontroller.

Programming is also another critical part of this coil gun project. The timing circuit of the coil gun is going to be controlled by the microcontroller. Without a properly coded timing circuit, the coil gun will not fire correctly. So, being able to successfully code a timing circuit and LCD display will be crucial to the success of the project. We will need to be able to create tasks and assign jobs through the use of a programming language that will allow the microcontroller to communicate and designate to the other components of the coil gun. The group is comprised of two electrical engineers and two computer engineers. The computer engineering students will take the lead on the programming and integration of the microcontroller into the coil gun, but it is expected that the two electrical engineering students also apply the concepts they have learned and contribute to the design an integration of the microcontroller. This is a critical component of the coilgun, so it is imperative that all group members work together to create a working prototype and final design and build.

The electrical components of the coilgun we will be using will have a wide range of specifications that we will have to merge with each other. We will be evaluating and comparing several options for the powering of the electronics on the coilgun. We will be looking at quite a few different DC batteries and comparing power output, charging speeds, and rechargeability. We will also be determining how many batteries we will need and how to integrate them into the final design. The capacitor bank is a major part of the electrical components. We will be researching available capacitors in the market and determine which capacitors we will use based on charge storing, size, and discharging capabilities. After doing our research and coming to a conclusion on what option we will use to power the electrical components, we hope to have gained enough experience and knowledge to be confident in our decision. We also hope to have gained enough knowledge to be able to articulate why we chose the option we did and for what reasons.

2.2 Objectives

With the design of this portable coilgun, there were several objectives that we had to meet to ensure proper functionality of the coilgun. These objectives are centered around our main goals for the overall senior design project. This is what we will be focusing on to maintain the overall vision for the project and to keep the group members focused on achieving these objectives once the project is completed. These objectives include portability, high power, accuracy, easy to use, and multiple firing modes. The objectives of the project are discussed below in more detail.

Portability- Portability was an important factor in the design of the coilgun. As portability was one of the main goals of our project, we designed the coilgun based around the achievement of portability. Our design was thought up with portability in mind. We want to create a coilgun that is able to be easily carried around and transported from location to location. This is what we believe sets our coilgun apart from previous projects that have been undertaken.

High Power- The coils need to be able to generate enough power to ideally fire the projectile at around 60 feet per second.This velocity was determined by the group due its realistic and achievable value in the completed design of the project. We also chose this value because we designed our gun for close range accuracy and this velocity should be powerful enough to meet those specifications. This velocity can be generated with a voltage around 400 volts. The past projects we have been using as references have designed coilguns around these values and we believe we can achieve these values as well.This will be discussed more in the design section of our paper.

Accuracy- All guns are typically made with accuracy in mind. Therefore, accuracy was another key objective in our design of the coilgun. The coilgun needs to be reliable and able to successfully strike targets at a close range distance. We design our coilgun to be accurate at up to 20 feet within a boundary of up to 6 inches in any direction. This can be achieved with the velocity we rated the coilgun at and the rifling of the barrel we plan to implement on the final design. This will be discussed further in the design section of our paper.

Easy to use- The coilgun must be easy to use if we wish to market it as a product to a suitable market. It is not practical to have a gun that is complex and complicated to use because of the situations the gun might have to be used in. This goes for any successful product. The coilgun must allow the user to quickly and efficiently charge the capacitors to be able to run current across the coils and fire the loaded projectile. If this process does not run smoothly or the user cannot seem to figure out how the process works, then the product will ultimately fail.

Multiple Firing Modes- The ability for the coilgun to be switched between multiple fire modes was discussed at length by all of the group members. We are designing the coilgun to ultimately fire a projectile once, but if we wish to have a product that can be marketed to a larger market, then we need to attempt to integrate multiple firing modes into the coilgun. If we only have a single firing mode, then the gun will completely discharge the capacitors each time it fires the projectile. This design might not be practical for use on a larger scale or in a larger market, so we will attempt to design the coilgun to be able to be switched between multiple firing modes in an attempt to increase marketability. This will be discussed further in the design section of our paper.

2.3 Requirements and Specifications

As with any project, there is a set of specifications and requirements that need to be met and followed in order for the final design and build to be successful. In this section, we will discuss the basic requirements and specifications that we determined were important in order to successfully design the coil gun. We have spent several hours going over these requirements and specifications, from the moment we first thought of the idea and through several meetings since then.

2.3.1 Power Specifications

The largest component of the project, which is the component that will be charged up and will provide power to the coils upon discharge, are the capacitors. The capacitors were determined to be a requirement of the project because of their importance and role they will play in the ultimate success of the project. There are many different capacitors to choose from and many different sizes and ratings to consider. Some examples include farad ratings, physical size, charge storage, and discharge capabilities. We also need a battery source to power the microcontroller and charge the capacitors after each shot

2.3.2 Hardware Specifications

The components of the hardware will not only have to accomplish their goals but must account for the high voltage/high temperature and portability goal. We want to achieve a lightweight coil gun where the user can hold it in there hand for a long period of time and shoot it comfortably. To achieve this we want to keep the weight below 10 kg (22 lbs), we feel comfortable that this weight will achieve portability from that standpoint. We must also make the coilgun comfortable to hold and not too bulky or long or undistributed weight. We are considering using an air soft gun frame or paintball frame but if we can't find one that fits we will be 3D printing the frame. After we need to choose the barrel we want to use for the coilgun. Length of the barrel will be important and also the material we use for the barrel. Next the projectile will be a drill bit and our goal is to achieve 100 ft/s for the projectile.

2.3.3 Software Specifications

All the software will be written on the microcontroller. The first aspect of the software is to set up all the libraries we may have for the LCD display, microcontroller and any other hardware we may have. We need to figure out what codebase we will be using, what compliers, and what IDE we will be using to even get our software going. After we have the ability to test the microcontroller and program the microcontroller. We have many options as to what the microcontroller will be doing since we are leaving a big budget for it. We are faced with our biggest choice and that is powering the coils that launches the projectile through the microcontroller or using a firing circuit. There are tradeoffs for both options and we must weigh both options. The next aspect is building a volt meter for the user to see when the capacitors have charged up. This is where the LCD Display will come to use. We also want to explore the possibility of displaying more data like temperature,speed of projectile, and projection to the user to help with the overall user experience.

3. Research Related to Project

3.1 Past Projects

As mentioned before, the coil gun has been a home project for the electronic enthusiast for a few years now. The coil guns that have been produced by these enthusiast range from clunky, large, and heavy to elegantly sleek products. It's clear that the more time and research the enthusiast would correlate with a more polished design.

Hobbyist and now engineer Jason Murray is the main inspiration for our project with his design of two coil guns. The first design is the CG-33 1.25kJ Coilgun, which is a single stage, bolt action coil gun that was finished in July of 2010. **Figure 3.1** is a picture of Murray's design. Since the gun is a single stage coilgun that means that there is only one large coil that is used to accelerate the projectile. Since only one coil is being used the design does not require the use of either a timing circuit or software to turn on and off the multiple stage of the coil. This design uses four 3,900 microfarad capacitors with a maximum voltage rating of 400 V producing 1.248 kJ of stored energy. Unfortunately Murray's design gets about 2.02% coil efficiency which means that the projectile's kinetic energy is only a mere 25.20J. Another drawback or Murray's design the use of the capacitor bank. The capacitors take around 30 seconds to charge.[2]

Figure 3.1: Jason Murray's "CG-33"
(Permission to reprint from Jason Murray)

Murray's second design is the "CG-42" Gauss Machine Gun, which is a fully automatic 8 stage coil that was finalized July 2013. **Figure 3.2** is Murray's CG-42. This design included 8 different coils along the length of the barrel. The 8 coils were implemented because of need for high energy without the use of a capacitor bank. Since the CG-42 doesn't use a capacitor bank it does not run into the issue of long charging time like the CG-33. Infrared sensor were placed at the end of each coil so when the projectile broke the sensors path it would shut off the previous coil, thus allowing the projectile to accelerate throughout the remainder of the barrel. Since the CG-42 didn't use a capacitor, the main power source is two 22.2 Volt, 3600mAh, 50C Lithium Polymer battery packs. The battery pack was tested to be able to fire two-hundred projectiles before needing to be recharged again. A drawback to both of Murray's coilgun is that he didn't not design the barrel to introduce rifling. The lack of rifling hurts the gun's accuracy and range. [2]

Figure 3.2: Jason Murray's "CG-42"
(Permission to reprint from Jason Murray)

Most coilgun projects include the same elements shown above with small variations in the design. There are two common variations in coil gun designs. the first one is the use of either a battery pack or a capacitor bank. The battery pack allows for the quick firing and multiple firing modes. While the capacitor banks allows for high voltage and power being supplied to the coils. The second major variation is the number of stages. The number of coils increases the efficiency of the gun overall. Therefore the more coils that are introduced the more energy and velocity the projectile is going to have when fire.

Another project we referenced was a project that was completed by a designer by the name UZZORS2K. This designer's project was referenced because he designed a charging circuit similar to the circuit we would need to charge our coilgun. The circuit is based off of and centered around the Mazzilli flyback driver circuit. The designer used this circuit with a voltage monitor that cut the circuit off once a terminal voltage was reached. When the capacitor voltage is below the threshold the Mazzilli driver circuit drives the transformer. The capacitor bank voltage is sampled using a TL431 voltage reference to set the reference. According to UZZORS2K, this gives a stable voltage reference over a wide supply range. This is a circuit we are going to be referencing to design our charging circuit and we will be utilizing this design when we design our circuit. Figure 3.3 is the transformer created by UZZORS2k for his boost converter.

This designer calculated the charge time to 430V on a 3.29mF capacitor bank at 6.3s. So 304J in 6.3s is roughly 50W of average charging power at only 12V. UZZORS2K stated that the charger to be 70%-80% efficient, which means more mileage with batteries and less heating. According to UZZORS2K, with a maximum supply voltage of up to 30V, the power can be increased much greater than 50W.[37]

Figure 3.3: Transformer Designed by UZZORS2K (Public Domain)

3.2 Main Components

3.2.1 Frame

3.2.1.1 Material

Traditional frames are made using one of three materials: aluminum, polymer (plastic) and, most commonly steel.

Aluminum was the common metal to use before World War II. There are many downsides with using aluminum as the base material. For one, it is extremely expensive to refine from the raw ore. Also, it is not as durable and not as strong as steel. Another downfall is that aluminum alloys being used must be carefully chosen, and must be fifty percent thicker when using it for the cross section. The reason for this for a pistol is because of balance and grip width. Also, in terms of using aluminum, it is less resistant to flame cutting and stretching versus steel. In addition, aluminum frames tend to have larger recoils [31].

However, it does provide the benefit of being lighter. When looking at revolvers and hand-held guns, aluminum-framed arms saves about thirty-five to forty percent in weight versus steel. This makes a difference for gun users, especially cops because they must pack this weight every day for long periods of time. Thus, in some cases aluminum has been seen to be a popular alternative for a frame.

Guns that use aluminum as their base metal is usually surfaced with some form of hard-anodizing process. This allows the frame to be more resistant to corrosion and wear while not increasing the weight at all. Other common finishes include nickel and hard chrome.

Another type of material for using frames is polymer or plastic. Initially, it was limited to small parts of the gun such as grips and recoil spring guides. But in the mid-1970s, a German firm called Heckler and Kosh introduced a polymer framed model for their gun. The true advancement began when the Gaston Glock's use of a polymer frame, and using polymer for some of the smaller parts.

There was some reaction against using polymer guns. At the time, those who favored anti-gun policies tried arguing that plastic guns were not metal detectable. However, all plastic guns have some degree of steel in its functioning parts, and it still shows up on an X-ray screen. A Glock, well, still looks like a glock.

There are many benefits to using a polymer based frame. For one, it saves a lot of weight. Also, in a manufacturing sense, it is pretty cheap. Although precision injection molds are expensive, once the molds are done, the parts are cheap to make. Companies save money since they don't have to invest on metal cutting equipment. Plastic tends to be damage resistant, and because of its thermal neutrality, they can be exposed to a wider temperature range without suffering any damage [31].

However, at the same time, there are some downsides to a plastic-based frame. For one, it has less tensile strength, meaning that compared to steel or aluminum, the frame can straight up break and is more susceptible to failure. On a performance scale, their lightweight means that the gun will have higher recoil and less aiming stability. As a result, it means that its overall accuracy decreases.

Steel serves as an appropriate frame, and probably is the most common material that the army uses. Though it can be expensive, there's many benefits to steel-constructed frames. Tensile strength is very high and the material design itself is durable. It's heavier weight may make carrying of the gun a little harder, but it helps out in the control and aiming steadiness, meaning better overall accuracy.

There are some drawbacks to the gun, weight already mentioned, but the need for lubrication and protection from corrosion, and the fact that it can't be exposed to super hot or super cold temperatures for too long. In a performance point of view, the steel guns fare better, but in terms of maintainability versus plastic, guns with steel-based frames have to be kept better maintained.

Based on looking at these materials, we feel that the best solution would probably be something of a plastic-based material. Despite the lightweight, we feel that since our gun is using electromagnets to accelerate the gun rather than gunpowder, which creates an explosive force, kickback should not be something we would have to worry about. Therefore, using plastic should not decrease the performance or the accuracy of the gun. Also, we feel that the cost of creating a plastic-based frame should be cheaper than using steel.

Creating a plastic frame also is a lot easier than creating a metal based frame because we would not be using any metal-cutting tools which can be expensive if we do not have access to it already. However, to create a plastic-based frame, the University of Central Florida has a 3d printer available for students that allow us to print out frames, making it a feasible solution for us.

Though this holds to be our current route of action for our choice of material, there is a possibility for us to upgrade the frame to be steel or aluminum based if we feel that we need the extra performance boost of our gun. This comes at the cost of being more expensive materials, so we will continually evaluate this decision.

3.2.1.1 PCB Design

In our implementation we used a PCB for our voltmeter. To Design our PCB, we used the KiCad EDA because of its ease of use and completely open source. We used two-layer copper board to separate our power and ground planes. The Front Copper layer is dedicated to the power and logic traces while the back copper layer is dedicated to the ground plane. Because we have mixed signal chip with analog inputs and digital outputs we need to take into account noise from the digital signals. We created two dedicated ground planes, one for analog and the other for the digital. We also route all of our logic traces on the front copper layer within their respective ground planes. We also have two different power supplies on the MCU one Vcc for analog supply and another Vcc for digital supply. We use an LC network to reduce the noise from the digital

3.2.1.2 Frame Design

The purpose of the frame is to keep all the components of the gun in tact, hidden from view. Because we will have batteries, wires, microcontrollers and other electronics within the gun, we must design a frame that will be able to hold it all together and keep it sealed. The frame is important for many reasons:

aesthetics - this makes the overall gun look better and more appealing
exposure - the frame prevents the internal components of the gun to be exposed to possible outside damage such as heat
stability - when we fire the gun, we want to make sure that no component comes loose in the process
ease-and-reusability - we want the gun to be easily usable, requiring very few steps to prepare the gun and to reprepare it for the next shot

Our frame's shape should be designed to mimic that of a paintball gun. The guns are relatively stable and they are designed to handle launching projectiles through use of CO2. A standard paintball gun looks like as follows in **figure 3.4**:

Figure 3.4: Standard Paintball gun

The major modification we would make to this design is not having the hopper on the gun (the top component of the paintball gun, purpose is to feed paintballs into the barrel). With this design, we can take advantage of the space created by the grip and where the clip would be. For the grip, we could store the capacitors, and for the clip, we could design it to hold possibly the batteries.

Therefore, we will create dimensions of the frame that will be able to hold the required amount of capacitors and batteries for the grips and then some in case we need to make modifications due to miscalculations. The barrel will have to be encased as well so the coils are not exposed to outside air since copper is susceptible to rust.

The current design of the barrel is to be fourteen inches long with about four coils. Even though the barrel is this long, the coils would be placed in the first half of the barrel where the frame encases it. Each coil is about an inch long, with half an inch length for the sensors about half an inch long to be attached at the end of each coil (see the section on coils). A small slot, probably a half an inch by an inch will be designed for us to insert the projectile. For the moment, the we are designing the gun to act like a one-shot rifle. (Load the bullet, fire it, load the bullet again). Therefore, we would have roughly a main frame of 8 by 2 by 2 inches.

Below the main body, will be where we design a frame for the capacitors. The capacitors we plan on using is about five inches in height and two inches in width, with four capacitors (one for each coil). Therefore, the frame we have to design below the barrel will be about 5.5 by 8.5 by 2 inches to allow space for wiring and possibly other components and to match the width of the main body's frame.

Behind the main body we will add another frame, whose job is to hold the microcontroller in the inside, and the LCD display on the outside. Now, the dimensions of the frame are 4 by 2 inches. Also, the dimensions of the LCD is 2.1by 3.2 inches. Since we have to design a frame that can hold the microcontroller, this will naturally be able to hold the LCD display. Therefore, the frame should be 4.5 by 2.5 by 2 inches to match the frame for the barrel and to make room for extra wires.

The base of the frame, right behind the trigger, would be our frame for the batteries. Standard 12 V Duracell batteries are 2 inches in height and half an inch in diameter. Assuming we use three batteries, two to supply the power to the coils and one to supply the microcontroller, the base would only need to be 2 by 2 by 2 inches, again extra space for miscalculations and to provide space for wiring and other components.

Our prototype design currently for the frame looks like as shown in **figure 3.5** below:

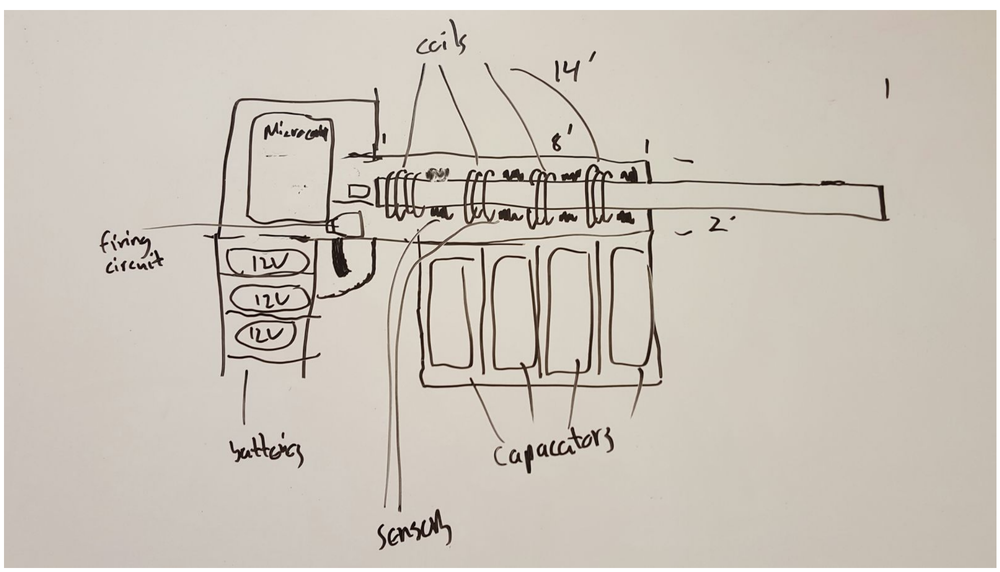


Figure 3.5: Proposed Schematic of Gun Frame

Ideally, we will make this initially out of plastic, using the 3d printer provided by the University of Central Florida as mentioned before.

In the end, we used a wood cut frame thanks to makercase.com. We found that using a laser cutter on wood would be much more efficient than using a 3d printer. The boxes made from this website allowed for interlocking joints, which with wood glue, made a stable frame. In the end, the frame consisted of three layers, one for the 2 capacitors, one for the barrel and all the components, and one for the PCB.

3.2.2 Barrel

Traditional firearms are usually constructed using a metal barrel. Since most bullets are generally made out of metal this allow for a low amount for friction between the barrel and the projectile. In the case of a coil gun, the barrel could not be made out of a ferromagnetic material. This is because the barrel has to allow the magnetic field that is produced by the coils to be passed through to the projectile.

The next material to be considered as the barrel would be a metal. the issue with a metal barrel would be conductive. This would lead to the creation of eddy currents along the barrels. Like mentioned above the creation of eddy currents would impede the acceleration of the projectile due to the induced magnetic field. Slots made along the side of barrel could reduce the amount of eddy currents that are created. The slots themselves could lead to the issue of the projectile getting jammed into the slot and never leaving the rifle. This would be less than ideal because not only does it not fire the projectile but requires the disassembly of the coil gun to alleviate the issue.

Another option that will be considered is the use of a non-conductive material. A barrel constructed out of a non-conductive material would not create any eddy currents which would remove that constraint but compromise with the strength of the barrel itself. Since the coils are going to dissipate the extra electrical energy into thermal heat, the use of a non-conductive material like plastic or paper would be less than ideal due to the fear of the barrel melting. Also, the friction between the projectile and the non-conductive material could be considerable more than between the a metal barrel and the projectile. The barrel of a gun can be seen in **figure 3.6.**

Figure 3.6: Rifling inside of Glock 18 Barrel

The barrel of the traditional firearms affects the muzzle velocity and accuracy. Propulsion in a traditional projectile inside a rifles is caused by the explosion of the gunpowder. This explosion creates a buildup of pressure which accelerates the projectile through the barrel, because of this the length of the barrel is extremely important with respects to the muzzle velocity of the projectile.

Generally, as one increases the length of the barrel the muzzle velocity also increases. Since the propulsion of our projectile does not originate from an explosion inside the barrel it's easy to think that the barrel length won't affect the muzzle velocity when compared to a traditional firearm. In reality, if the length of the barrel is to increase the coil gun could be outfitted with either a longer coil or more stages along the barrel. Which would net an increase in the time the projectile will be accelerated before leaving the barrel. Almost all of the accuracy of a traditional firearm comes from the rifling of the barrel.

Rifling is the arrangement of helical grooves inside the barrel. Rifling causes the projectile to spin when firing. The spin of the projectile will allow the projectile to fly in straight path, given that there are no other forces acting on it. If rifling is not introduced into the design of the barrel then then the projectile will tumble while leaving the barrel. If the projectile is tumbling while in the air, more of the projectile's surface area will be exposed therefore leading to more drag caused by air, quicker loss of velocity, and a considerable loss of range.

There are three methods to rifle a barrel:

Button forged rifling - is a rifling method that was being development during the 19th century and was not perfect until 1940 by Remington It is currently the most common method of manufacturing rifled barrels in the united states. A barrel is button forged by passing a button through the length of the barrel. The button is a tool that is made out of hardened steel or titanium and is the negative image of the barrel. **Figure 3.7** is a picture of an actual button forged rifling tool. The button could either be pushed or pulled through the barrel to carve out the grooves but it is thought that pulling the button through the barrel could cause it to break inside. Most manufacturers decided to push the button to bypass any issue of a button getting stuck inside the barrel.

After the grooves have been cut out the barrel must be stress relieved because button rifling puts a lot of stress on the barrel. If not done the barrel could split or deform during later use. Stress relieving is done by heating the barrel in a furnace to upwards of 525 degrees celsius. The reason why button forged rifling is the most common manufacturing technique in the United States is because it is quick and easy and the only disadvantage is that the barrel's uniformity has to be taking into consideration before starting the process. Not doing so could result in a deformed barrel.

Figure 3.7: Button Tool for Rifling
(Public Domain)

Hammer-Forged rifling - another rifling method that was invented by germans in 1939, and to it success spread throughout the rest of Europe. Unlike button forging the barrel is pounded into shape from the outside. The process is done by taking a barrel that hasn't been rifled yet and then place a mandrel, with the negative image of the barrel, with in the barrel.

Once the mandrel is in place, the hammers begin to beat on the outside of the barrel. The hammers beat the barrel somewhere between one thousand to two thousand times per minutes. While being beat, the barrel is being rotated and repositioned until the entire length of the barrel has been beat by the hammes. Just like button forging this method introduces a lot of stress into the barrel so it must also be treated like a button forged barrel. The advantages to hammer forging is the accuracy of the groove dimensions are accurate to what is desired. **Figure 3.8** is an illustration of the hammer-forging process.

Also, if the proper technology is being used the whole process takes less than ten minutes. The biggest disadvantage of hammer forged rifling is the starting price of the machinery.

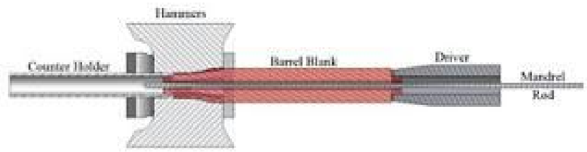


Figure 3.8: The Process of Hammer Forged Rifling
(Public Domain)

Cut rifling - is one of the oldest method of rifling and dates back to 16th century. Cut rifling is achieved by taking a cutting tool and running it through the inside of a barrel removing steel along the way. Each time the tool is pulled through the barrel it removes a very small amount of metal, so it takes many times pulled through to achieve the groove diameter that is desired.

This process can take many hours to complete. Since each groove is carved out individually, cut rifling produces very accurate groove diameter and uniform twist. Opposite to the other two methods, cut rifling does not stress the barrel. Therefore, the barrel does not have to be heated as a protective measure. The only real disadvantage to this technique is that that length of time that is required to complete ony barrel.[21][22][23]

3.2.3 Ferromagnetic Projectile

The effectiveness of the coil gun highly depends on the type of projectile that is chosen to be fired. The materials, dimensions and shape of the projectile are critical to the efficiency of the coils. The type of the material is probably the most important thing to decide when choosing the projectile. One must take into consideration the magnetic permeability, reluctivity and friction of the material. Magnetic permeability is a measure of the ability to support the formation of a magnetic field within itself. **Figure 3.9** below shows the materials with their relative permeabilities.

	Material	μ_r (H/m)
Diamagnetic	bismuth gold silver copper water	0.99983 0.99986 0.99998 0.999991 0.999991
Paramagnetic	air aluminum platinum	1.0000004 1.00002 1.0003
Ferromagnetic (nonlinear)	cobalt nickel iron (99.8% pure) iron (99.96% pure)	250 600 5000 280,000

Figure 3.9
(Obtained permission from Dr.Shady Elashab)

As can be seen from the above table, different materials are affected by magnetic fields in different ways. Diamagnetic materials include bismuth, gold, silver, copper, and water. Diamagnetic materials are comprised of atoms that have only shared electrons in their outer orbital. According to the hyperphysics website, the motion of the electrons in diamagnetic materials creates tiny atomic current loops. These current loops are responsible to the production of the magnetic fields. In diamagnetic materials, if an external magnetic field is applied to the material, the current loops will arrange themselves in a way that opposes the applied external magnetic field. These induced magnetic fields are in the direction opposite of the applied external magnetic field. Therefore, these materials are classified as diamagnetic which also means they are not paramagnetic or ferromagnetic.

Paramagnetic materials can form an internal induced magnetic field if an external magnetic field is applied to the material. The internally induced magnetic field will be in the direction of the applied magnetic field. According to the hyperphysics website, paramagnetic materials exhibit a magnetization that is proportional to the external magnetic field that is being applied to the material. Paramagnetic materials are said to follow Curie's Law. Curie's Law states that the magnetization for a fixed value of the field is inversely proportional to the temperature. If a material is heated the proportionality is reduced. Mathematically this is represented by **equation 3.1:**

$$M= C*(B/T) \qquad (3.1)$$

Ferromagnetic materials are the materials that will be used in our design for the coilgun. Ferromagnetic materials contain unpaired electrons in their outer orbital and an ordering phenomenon occurs at the atomic level that causes the unpaired electrons spins to line up parallel with each other in a region called a domain. Inside a domain, the magnetic field is intense. However, in the absence of an external magnetic field, the whole material will usually be unmagnetized because many of the domains will be randomly oriented with respect to other domains. If an external magnetic field is applied, even a small field, the magnetic domains will line up with one another and this will cause the material to become magnetized.

The relative permeability of the material will have a large effect on the multiplication of the external field by the alignment of the domains contained within the ferromagnetic material. Ferromagnetic materials will tend to remain magnetized to a certain extent after having an external magnetic field applied to them. The name for this tendency is hysteresis.

Hysteresis is the lack of retraceability of a magnetization loop. The ferromagnetic material must be brought back to zero magnetization by imposing a magnetic field in the opposite direction. Once the material is brought back to zero magnetization and the domains are reoriented, it takes more energy to return to turn them back again. This causes the ferromagnetic material to have a property that resembles a memory. Certain Compositions of ferromagnetic materials can retain a magnetization from an external field indefinitely and can then be considered as permanent magnets. The hysteresis loop can be seen in **figure 3.10** below.

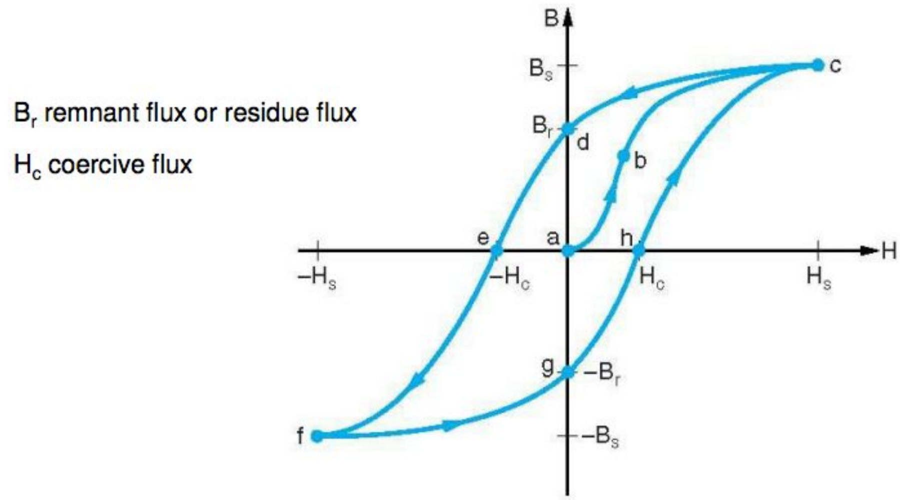


Figure 3.10
Hysteresis Loop (obtained permission from Dr. Elashab)

Therefore, the use of a ferromagnetic projectile in the design of our coilgun is crucial. A material with a higher permeability will allow the magnetic field to influence it more and resulting in creating a higher force. The friction between the projectile and the barrel itself also has to be taking into consideration to minimize energy losses. This can be seen from the above stated information. Without the use of a ferromagnetic material, the projectile will not be affected to the fullest extent by the magnetic field created by the current running through the coils. This will be discussed further in the paper.

Due to a change in magnetic flux, caused by the acceleration of the projectile, the projectile will actually induce eddy currents. This can be seen by Faraday's law and Lenz's law.

Faraday's law states that any change in the magnetic environment of a coil of wire will cause a voltage or electromagnetic field to be induced in the coil. The change can be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, or rotating the coil relative to the magnet.

Lenz's law states that when an electromagnetic field is generated by a change in magnetic flux according to Faraday's law, the polarity of the induced electromagnetic field is such that it produces a current whose magnetic field opposes the change that produces it. The induced magnetic field inside any loop of wire always acts to keep the magnetic flux in the loop constant. If the magnetic field is increasing, the induced field acts in opposition to it. If the magnetic field is decreasing, the induced field acts in the direction of the applied field to try to keep it constant.

According to Lenz's law, an eddy current creates a magnetic field that opposes the magnetic field that created it, and thus eddy currents react back on the source of the magnetic field. Eddy currents can be a source of energy loss in alternating current inductors, transformers, electric motors, generators, and other AC machinery. Eddy currents can also generate a lot of heat in the objects they are created in.

This can lead to issues inside the coils and is something we will have to take into account when we are calculating our forces and currents. Heat can lead to a change in resistivity of the copper wires. As the temperature of the coils change, the dimensions of the copper wires will change as it expands or contracts. With these expansions and contractions, comes the changes in resistivity. A conductor will tend to increase resistivity as the temperature of the conductor increases. Therefore, we have to take into account the possibility that our copper coils might have an increase in resistivity if the eddy currents can generate enough heat to affect the temperature of the copper coils. The eddy current will create a magnetic field that will oppose original magnetic field inside the coils. This opposing magnetic field will create a drag force on the projectile slowing it down over the course of its time inside the barrel. Therefore the projectile must be designed in a way to minimize the eddy currents. (citation for eddy currents)

The reasons stated are why we chose to go with an iron number 2 phillips bit as our ferromagnetic projectile. We deliberated as a group and discussed making our own bits to serve as a ferromagnetic projectile, but we came to the conclusion that the making of our own bits would be inefficient and time consuming. Therefore, we decided to go out and purchase the iron number 2 phillips bits to use as our ferromagnetic projectile. This bit will be affected the most by the magnetic field that will be created inside the coils and that is another reason we chose to go with this bit.

3.2.3.1 Magnetic Field

A coil gun can be implemented using two different methods. The two different methods differ in the way that the magnetic field accelerates the projectile that is being used.

One method that can be implemented in the design of a coil gun is the reluctance method. The reluctance method uses the properties of the ferromagnetic projectile to generate an electromagnetic force that accelerates the projectile by using attraction. The ferromagnetic projectile is essentially pulled through the coils by the magnetic fields that are created through the coils when an electric current is run through the coils.

The second method that can be implemented in the design of a coil gun is the induction method. The induction method requires the use of a non-ferromagnetic projectile. This method uses repulsive forces of eddy currents that are generated in the projectile by the magnetic fields created through the coils to accelerate the non-ferromagnetic projectile through the coils.

The design method that we chose for our project is the reluctance method. We chose this design method for our coil gun because we are using a ferromagnetic projectile and it is a more efficient way to design a coil gun. This is due to the fact that the magnetic field creates the force used to accelerate the ferromagnetic projectile through the coils. Research will show that a common thought for increasing the ferromagnetic projectile's acceleration and speed is to build bigger coils for the projectile to go through. However, increasing the size of the coils can often reduce the coil gun's efficiency and performance. The magnetic flux and the density of the coils is one of the least important factors to consider in designing the coil gun to be efficient and powerful. The most important factor of the design of the coil gun is the projectile.

As a group, we chose to go with a ferromagnetic projectile because it will be affected the most by a magnetic field. This choice is what led us to further design schemes. The coil gun needs to be design to optimize the acceleration of the ferromagnetic projectile. The number of turns in each coil need to be accounted for and the coil parameter need to be calculated precisely to ensure the coil gun performs effectively and efficiently with high power. The coil gun needs to be designed to ensure that power to each set of coils is perfectly timed to be switched off once the tip of the ferromagnetic projectile reaches the midpoint of each consecutive coil.

This can be implemented with an infrared sensor placed at the end of each consecutive coil. The infrared sensors will break when the tip of the projectile reaches the middle of each coil. The microcontroller will be programmed to control the flow of current to each coil and will be programmed to switch off the power to each consecutive coil as the projectile reaches the middle of each coil. This will ensure that the projectile is getting the maximum amount of acceleration from the electromagnetic force that will be created by the magnetic fields. This will also limit any pull back on the projectile from a counter force in the opposite direction. This process is illustrated in **figure 3.11** below.

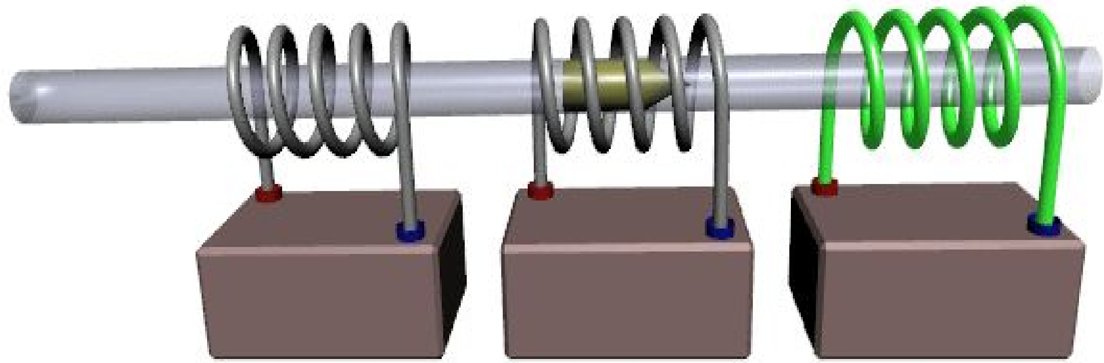


Figure 3.11
(Public Domain)

The muzzle velocity and acceleration of the projectile can also be improved by increasing the amount of coils that we use for the coil gun. With an increase in the amount of coils we use in our design, an increase in the effect of timing issues arises. This is a factor that we need to take into consideration when we are designing our coilgun. The current running through each coil needs to be timed correctly to achieve the maximum of acceleration from the the magnetic field that will be generated in each coil. The effect of each additional coil will produce a diminishing return for each added. This causes each additional coil that is added to contribute less of an effect on the muzzle velocity of the coil gun and the projectile. This can be attributed to the fact that as we add each additional coil, the amount of time that the projectile spends in each coil decreases.

In turn, this lessens the amount of time that each magnetic force is acting upon the projectile as it travels through each consecutive coil. The magnetic field creates magnetic poles on the projectile ends and this causes an internal magnetic field in the projectile that opposes the external magnetic field created by the current running through the coils.

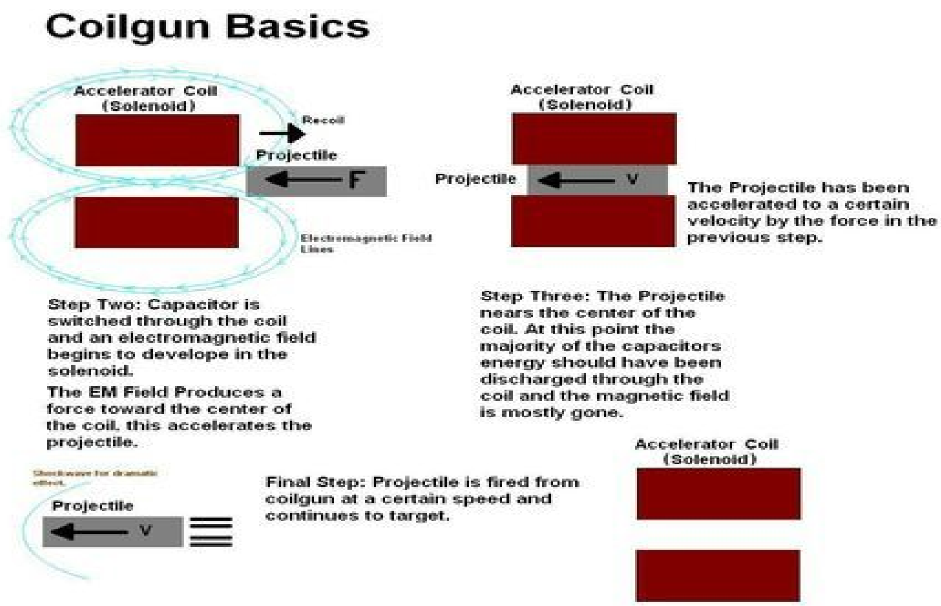


Figure (3.12)
(Public domain)

The field that is created inside the projectile is considered a demagnetizing field. The strength of the demagnetizing field is directly related to the size and shape of the projectile. A projectile that has a length much greater than its diameter will not experience as great of a demagnetizing force. This type of projectile can be seen in **figure 3.14**. A projectile that had a diameter much greater than its length will experience a much larger demagnetizing force. This type of projectile can be seen in **figure 3.13**. The force that is acting on the projectile can be seen by the **equation 3.2**. In **equation 3.2**, I is the current, N is the amount of turns in the coil, and dphi/dt is the flux linkage which is the change in flux density with respect to the displacement of the projectile. The straightforward way to increase or decrease the force acting on the projectile is to increase or decrease the current and/or the number of turns of the coil.

Another way to increase or decrease the force acting on the projectile is to increase or decrease the flux linkage which is not as easily done. The flux linkage can be changed increased by adding some external iron around each of the coils or changing the projectile and optimizing it to a projectile with a higher saturation flux density. Implementing these changes into our design will cause the time constant for the coils to be changed and it will also change the inductance of the entire system.

$$F = 1/2\, NI\, (d\phi/dx) \quad \textbf{(3.2)}$$

Figure 3.13
(Public Domain)

Figure 3.14
(Public Domain)

3.2.4 External Iron

In considering our design for the coil gun, putting external iron around each of the coils to improve the magnetization of the projectile and improve the efficiency of the transfer of energy throughout the coil gun. Adding the external iron to the outside of the coils improves magnetic flux of each of the coils and the system overall. This is due to the fact that the external iron's magnetization is added and it directs the flux lines created to the center of the coil and thus the projectile. This effect can be seen in **figure 3.15**. This effect causes the projectile to accelerate even more due to the forces acting on it. External iron around the coils can also cause the reluctance of the system to decrease, which in turn causes the magnetic flux within the coils to increase. The external iron around the coil eliminates the air around the coil and replaces it with iron. This is what causes the reluctance to be reduced because air has a higher reluctance than iron does because of the inverse relationship between reluctance and relative permeability.

You can model the magnetic circuit representation that is described above similarly to how you would model an electric circuit using Ampere's circuital law and Ohm's law. This can be done by converting current to magnetic flux(B), voltage to magnetomotive force(mmf), and resistance to reluctance(R). This is represented in **equation 3.3**.

$$\mathbf{B = mmf / R} \qquad \mathbf{3.3}$$

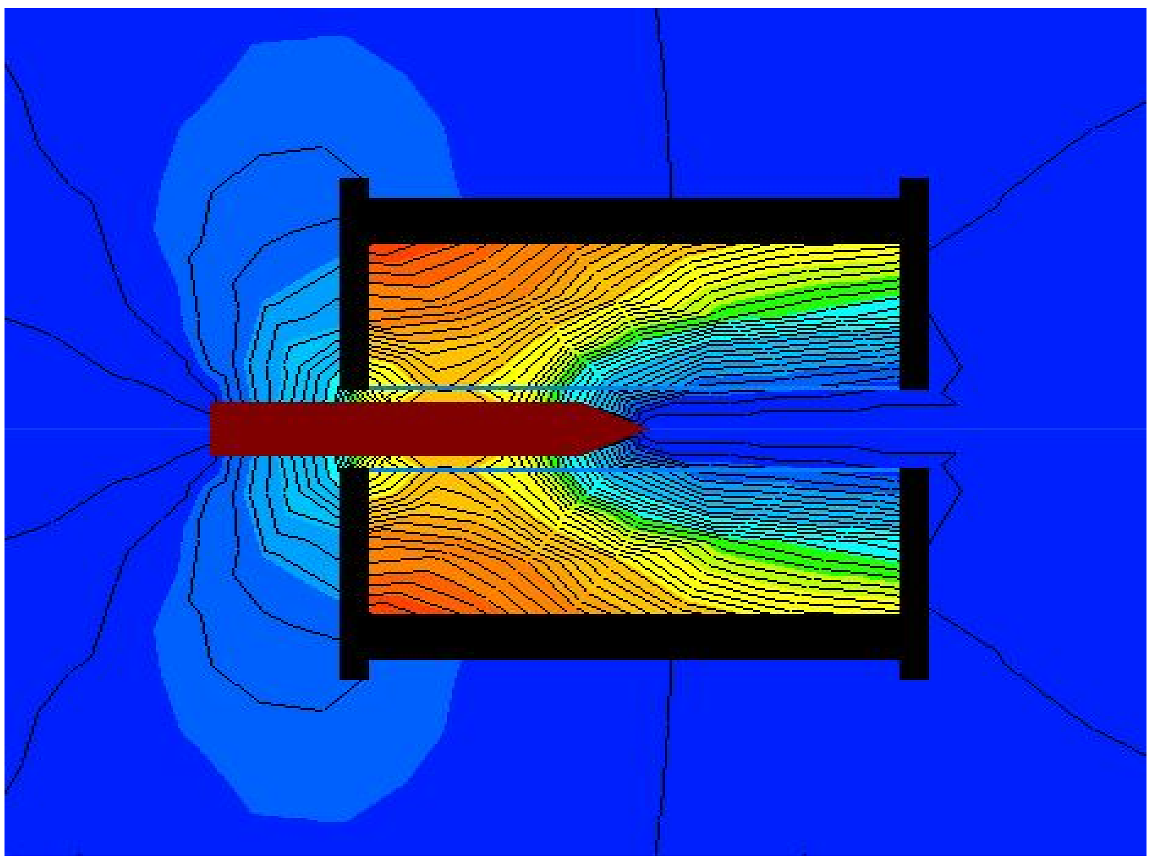


Figure 3.15
(Obtained Permission from Barry Hansen)

Implementing the external iron around the cores is something that will be very useful in our design and can be accomplished relatively easily. One way to implement this into our design would be to use an iron pipe that goes around all of the coils. This pipe would have to be chosen to closely eliminate as much of the air gap between the coils and the pipe itself. This will minimize the reluctance of the system because the air gap between the coils and the external iron will be very small. The coil's diameter and the pipe's will have to be carefully decided in the design process in order to ensure the air gap is as small as possible.

The external iron does have its disadvantages though. One disadvantage is that the added external iron will increase the weight of the overall coil gun and could affect one of our design parameters, which was portability. This is something we must strongly consider as a group and make sure the added effects of the external iron outweigh the effects of the added weight. Another disadvantage of the external iron being added to the outside of the coils is the effect it will have on heat dissipation around the coils.

This could prove to be an issue in the final design because we have to take into account the temperature of the coils and the system as a whole. This design will have to be heavily considered and another form of heat dissipation will have to be found if the heat in the coils becomes too great and the system's overall heat becomes too much.

3.2.4.1 Heat Dissipation

One of the issues we are going to have to take into consideration when designing the coils on the coilgun is the heat dissipation. The coils require an extensive amount of power and with that power comes heat. The coils are made of copper and copper has an internal resistivity that is very low. Therefore, copper acts as a very good conductor. However, the internal resistivity with current running through the coils will generate heat in the coils.

This can prove to be an issue if this begins to heat the system as a whole. It can damage components and cause short circuiting if the temperature reaches a level that is not able to be sustained by the circuit. The way the members of the group decided to design the coil gun was to dump all of the power into the coils for one shot, but we also would like to design it in such a way that it would be possible to have multiple firing modes for the coil gun.

One of the main issues with heat dissipation is the heating of the coils could cause them to melt and when the coils melt, they could cause a short circuit. This short circuit happens when the turns of the coil come together and touch. If the circuit shorts, the entire coil gun will cease to work and all of the energy we have stored in the capacitors will be discharged and wasted.

Another issue we could have with heat dissipation is the change in resistivity of the coils. Temperature greatly affects the resistivity of electrical components in a circuit. According to Mcgraw-hill, the failure rate of electrical components exponentially increase with increases of temperature According to www.learnabout-electronics.org, Conductors like copper will tend to have their resistivity increase with an increase in temperature. This happens in conductors because the dimensions of the conductor will tend to expand or contract based on the temperature changes that are being applied to the conductor. This can be seen by **equation 3.4**. Unlike conductors, insulators tend to decrease their resistance with an increase in temperature. The electrical resistivity of copper at different temperatures Kelvin can be seen in figure **3.16**

$$R=R0[1+alpha(T-T0) \qquad (3.2.1.5)$$

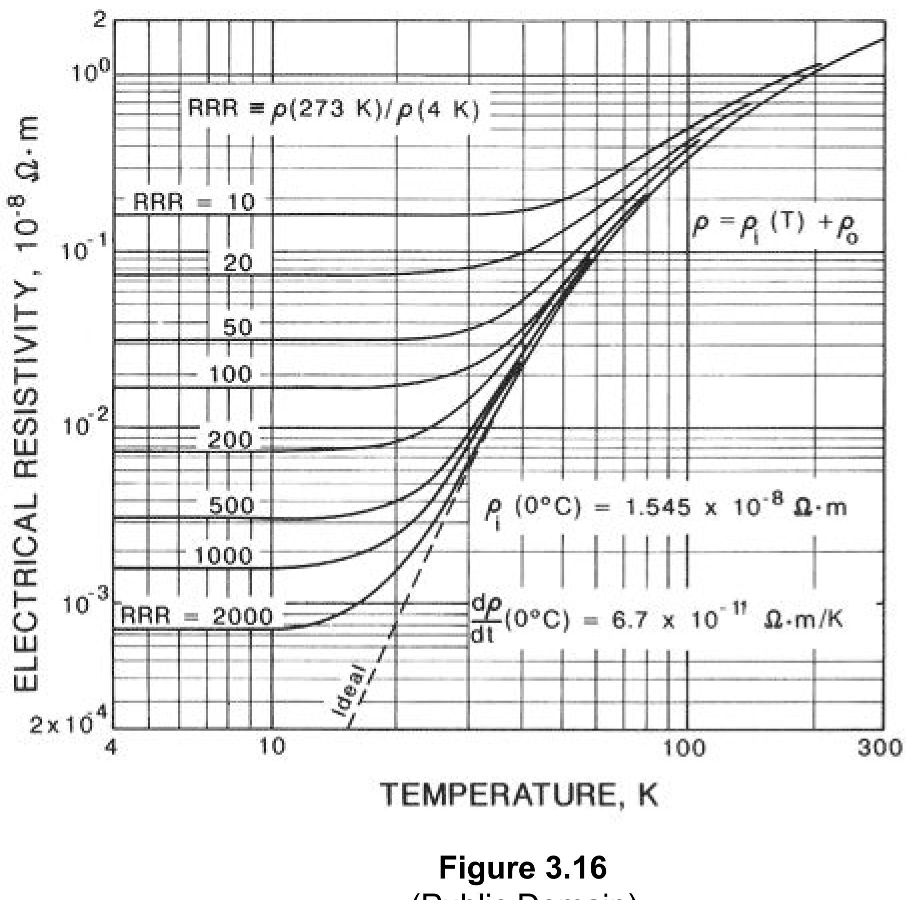


Figure 3.16
(Public Domain)

The group contemplated several ways to address the heat dissipation in the coil gun as a whole, specifically the coils. Some of the options we considered were surrounding the coil in nonconductive oil or gas, applying forced air cooling, or using heat sinks. Nonconductive oil or gas surround the coils and pull the heat away from the coils and they reduce the heat of the coils in that way. This is not the most viable option because then the group run into sealing issues. Sealing issues would cause a big problem if the non conductive oil or gas began to leak because it would reduce the heat dissipation. However, this method is the most effective way to cool electrical components in a system. This method is used in power systems grids to cool large electrical equipment such as transformers, breakers, transmission lines underground, and generators.

Another option we have for dissipating heat in the coils would be forced air cooling. According to the article on Thermal management, forced air cooling is an effective way to cool electronic devices. Forced air cooling forces air over the electrical components and uses heat transfer to pull the heat away and ultimately cool the electrical components. This is effective because of the transfer of heat. The continuous replacement of air at a cooler temperature than the electrical component forces the heat to transfer to the air and then that air is pushed away from the electrical components. Forced air cooling can be applied using a fans as those are the most common form of forced air cooling.

The final option we took into consideration for heat dissipation of the coils and the system as a whole was heat sinks. According to an article on Thermal Management, heat sinks are the most common ways to cool electrical components in electronic devices. Heat sinks use a metal object brought into contact with an electical components hot surface to pull heat away from the electrical component and ultimately cool the electrical component. According to wikipedia.org/wiki/Thermal_management, heat sinks usually consist of a metal structure with one or more flat surfaces to ensure a good thernal contact with each surface of the electrical components that are going to be needed to be cooled, and an array of fins or combs protrude from the metal structure to make contact with the air around the electrical components. These fins or combs create a greater amount of surface area with the air and therefore increase the rate of heat dissipation of the electrical components of the system. Heat sinks would be a very efficient method for cooling the electrical components of the coil gun, but they are very hard to implement due to the cylindrical shape of all coils.

3.2.5 Battery Charger

The problem with coil guns as we have discovered from previous chapters is that they are extremely power inefficient. After about fifteen shots, the batteries run out of voltage and have to be replaced. Therefore, in order to test our batteries, we would have to either buy several packs of batteries or buy a battery charger in order to recharge the batteries.

Now assuming that we use rechargeable batteries, there are a few things that we would have to consider:

cost - given our estimated budget of $400, we want to make sure that we are still able to design the gun while making it relatively cheap
time - a long recharge time would result in having to wait a long periods of time to setup and test our gun, we hope to find something that can charge these batteries at a relatively fast time
recharge efficiency - battery charges in general are not able to recharge batteries up to 100%. There is a natural inefficiency when working with rechargeable batteries.

When looking for a battery charger, we found different options. The first product we found is the Tenergy TN162 8-Bay Smart Battery Charger. Sold online from all-battery.com for $34.08 dollars, it claims to have over-heat, over-current, short-circuit and reverse polarity protection features. There are LED modes to indicate when the batteries are fully charged. It also claims that the recharge times are about 1.8 to 6 hours depending on the kind of batter and current used. An image of the Tenergy TN162 8-Bay Smart Battery Charger can be seen in **figure 3.17** below.

Figure 3.17: TN162 8-Bay Smart Battery Charger
(Public Domain)

The price seems all right, but the charge times seem to be pretty long for our purposes. Of course, if we are doing initial testing during our development phase, one hour may suffice since our preparation time for the next set of shots will be longer, but as we refine our gun, we hope to be able to shoot a fair amount of bullets, and be able to reload using the same batteries within a short period of time. For this purpose, we feel that this may not be the most appropriate. On top of this, we have no information on the charging efficiency of this product.

The second product we found is the Duracell 15 Minute Charger. Claiming to be Duracell's fastest charger, it is able to charge four AA batteries in fifteen minutes.

With a price of $55.00, it seems to be a good option that fits our criteria. In terms of efficiency, it claims to be able to charge the battery up to 80%. An image of the Duracell 15 Minute Charger can be seen in **figure 18** below:

Figure 18: Duracell 15 Minute Charger
(Public Domain)

The price is significantly higher than the first one, which implies that in order for it to be worth it, the increase in performance must be equally significant. It's convenient to know that we should only expect about 85% of the battery's initial capacity since charging efficiency is something we have to take note of. However, it runs the downside that it implies the charger only works with Duracell rechargeable batteries, limiting our battery selection. We will consider this as an option should we choose Duracell batteries.

The last product we found is the La Crosse Technology BC-700 Alpha Power Battery Charger. We found this product interesting because it showed up in the Top Ten Reviews for battery chargers as the number one product, earning a rating of 10/10. The charging time is as fast as 70 minutes, and provides an LCD screen to display the status of the batteries such as if it's rechargeable or not, and how much the batteries are charged. The product is able to charge up four batteries at a time and priced on Amazon for $35.11 (as of December 2015). An image of the La Crosse Technology BC-700 Alpha Power Battery Charger can be seen in **figure 19** below:

Figure 19: La Cross Technology BC-700 Alpha Power Battery Charger
(Public Domain)

Though this product has a longer charge time than we were hoping, it is at a fairly low price and is considered one of the best online. It seems to allow only NiCd and NiMH batteries, but reviews has shown it is a reliable product.
Overall, we feel like using La Crosse Technology BC-700 Alpha Power Battery Charger would be the best option to go for. In the end, it seems to be based on the type of battery we use, since that will play a heavy role in what battery chargers we will be able to use. We plan on using one of the batteries the specifications allow, and feel that overall, it would be worth it to buy a few sets of batteries and a charger versus buying several packs of batteries and draining them all.

3.2.6 Battery

Coil guns from previous projects all require a source of power. The most common power source in these types of projects is the battery. Depending on the design of the coil gun the battery would be connected to a charging circuit or the battery will independently be the power supply to the coils. Connecting the batteries to the charging circuit would allow the us to step up the voltage from something in the range of four to ten volts to four hundred volts. Charging the capacitor bank to around four hundred volts will allow to push as much current as possible through the coils. The batteries will have to be rechargeable due to the nature of the amount charge the capacitors are going to require and constantly inserting brand new batteries is not an efficient process.

Nickel-cadmium cells have been used successfully for over 60 years in a wide range of consumer products today, including power tools, digital cameras, and radios. Nickel-Cadmium batteries use nickel hydroxide as the cathode, cadmium as a the anode, and potassium-hydroxide as the electrolyte. The main advantage of a nickel-cadmium its ability to charge and discharge at a high rate and is relatively inexpensive. If a capacitor bank based design is implemented the high discharge rate of the battery would allow us to be able to charge and then fire the coil gun very quickly.

Unfortunately the nickel-cadmium battery suffers from the memory effect.The memory effect is when a battery loses some of it maximum charge storage due to not completely discharging every time before recharging. To ensure that the memory effect doesn’t have lasting effects on the battery, it must be completely discharged at least once a month. A way to bypass this effect is by using a charger that has a discharge circuit built in. Therefore, every time the battery is set to charge it is discharged completely before commencing to charge. **Figure 3.20**, shown below, shows the inner makings of a nickel-cadmium battery.

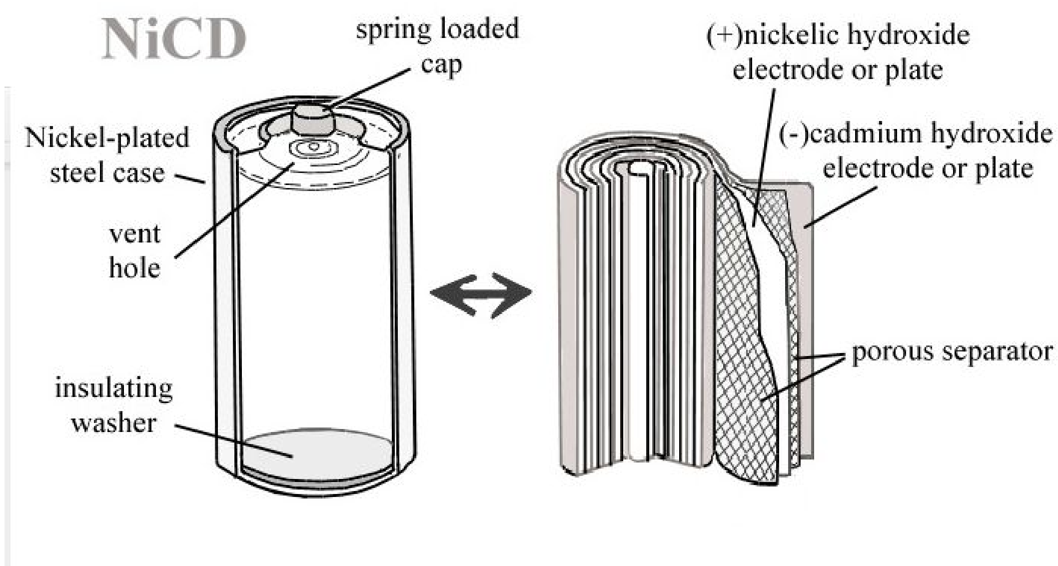


Figure 3.20: Nickel-Cadmium Cells
(Public Domain)

Nickel-metal-hydride batteries have been around since 1986 and features a similar technology to the nickel-cadmium batteries. The only difference in the chemistry comes from the anode being a hydrogen absorbing negative electrode.

They were commonly used in electronics until lithium cells took over the market but are still commonly used as car batteries. Being made of a similar composition to Nickel-cadmium cells, nickel-metal-hydride batteries have a high discharge rate but not as fast as the nickel-cadmium batteries. Nickel-metal-hydride batteries have high energy density, meaning that it would supply more power per kilogram.

If implemented into the design it would allow the weapon to be lighter than one that would nickel-cadmium but not lighter than one with lithium ion. These batteries can be almost entirely discharged repeatedly and last for more than three thousand cycles. They can be stored for months at a time either charged or discharged without have detrimental effects on the battery over time. This useful since most people who own a gun do not use it every day and store their weapons in a secure location. Therefore, one could do the samething with a coil gun. unfortunately because nickel-metal-hydride batteries are similar to nickel-cadmium they also can be effected by the memory loss effect and also have to be fully discharged at least once a month. This kind of battery also faces a high self discharge. Self discharge is when the chemical reaction within the battery reduces the charge stored inside itself without being connected. **Figure 3.21**, shown below, is an illustration of the internal components of a nickel-metal-hydride cell.

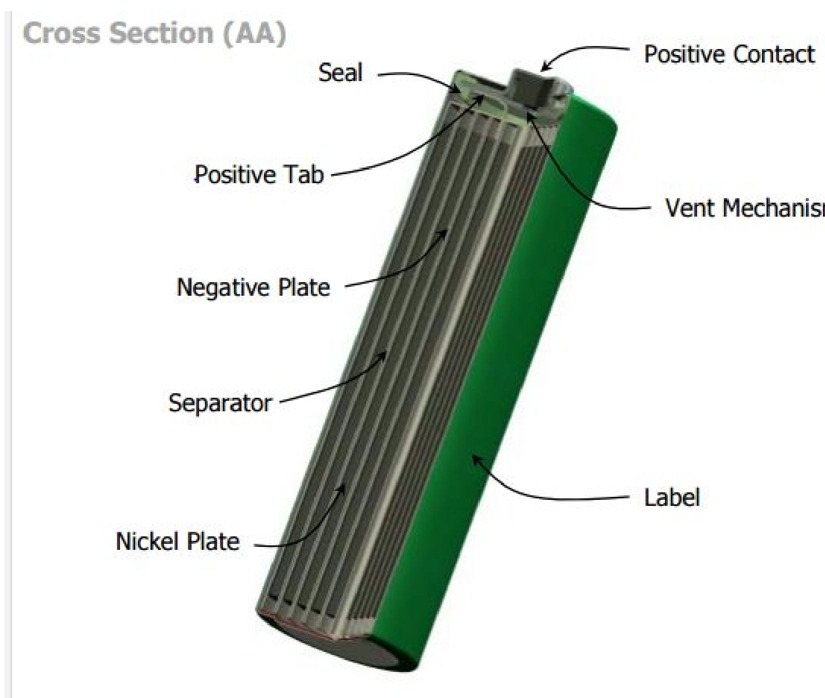


Figure 3.21: Nickel-Metal-Hydride Battery Cell
(From Energizer Data Sheet)

Lithium based batteries have been around since about the 1970s but the first safely rechargeable one was introduced into the commercial market in 1991 by Sony. Lithium ion batteries are made of Lithium cobalt oxide(positive electrode), carbon (negative electrode), and a gel polymer electrolyte. Lithium ion batteries today are being used for a wide variety of applications, ranging from portable communication devices to powering electric vehicles. Lithium ion batteries have an even greater energy density than nickel-metal-hydride batteries and they are not susceptible to the memory effect. Therefore, the are lighter than other two batteries and don't have to be discharged constantly discharged every month.

On the other hand, lithium-ion batteries are very sensitive batteries and only have a life of about two to three years. Lithium-ion batteries have to be connected with a protecting circuit to make sure it is not being overcharged, deeply discharged, being supplied to much current, nor being drained of too much current. Lithium ion batteries are the most expensive batteries of the three options that are being considered.[15][38][39][40]

3.2.7 Capacitors

Capacitors today come in a variety of options, each having their own advantages and disadvantages. There are many characteristics that have to be taken into consideration when choosing the right capacitors for the coil gun. Things to consider include the capacitor's capacitance, voltage rating,tolerance, and how much leakage it produces.

The first thing characteristic that will be considered is voltage rating. For the coil gun, capacitors with a high voltage rating will be considered be to achieve the maximum amount energy supplied the coils that is possible. The ideal range for the capacitor's voltage rating will be somewhere from three hundred to five hundred volts. Due to the fact that the gun's power supply is coming from a pack of rechargeable batteries, the voltage will have to be stepped up through the use of a transformer. This range of voltage rating is chosen because the energy that is stored in the capacitor is squarely proportional to the voltage across the capacitor.

It should be noted that charging the capacitors above their rated voltage will cause damage to the capacitors and could potentially render them useless. the maximum voltage rating is not an indicator of voltage the capacitors should be charged to, but just the maximum voltage that the capacitors can withstand during regular use. Therefore, it would be idea to choose a capacitor that has a higher voltage rating than what the capacitors are going to be chosen to be charged at.

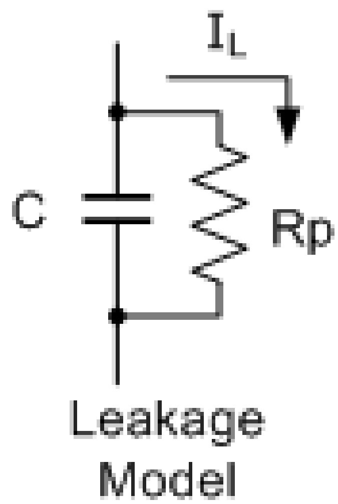


Figure 3.22: Leakage Model of a Capacitor
(Obtained permission from Electronic Tutorial)

The second characteristic to consider is the amount of leakage current the capacitor produces. Leakage current is the small amount of current that comes out of the capacitor due to the dielectric material inside of the capacitor not being a perfect insulator and the strong electric fields acting on the created by the charges inside. In **figure 3.22**, above, leakage model of a capacitor is shown. In smaller capacitors, the leakage current is in the order of nanoamps. But electrolytic capacitors have very high leakage current, in the range of five to twenty microamps per microfarad, and it increases as the temperature of the capacitor increases. **Figure 3.23** shows the leakage current of an electrolytic capacitor and how quickly the capacitor leaks current.

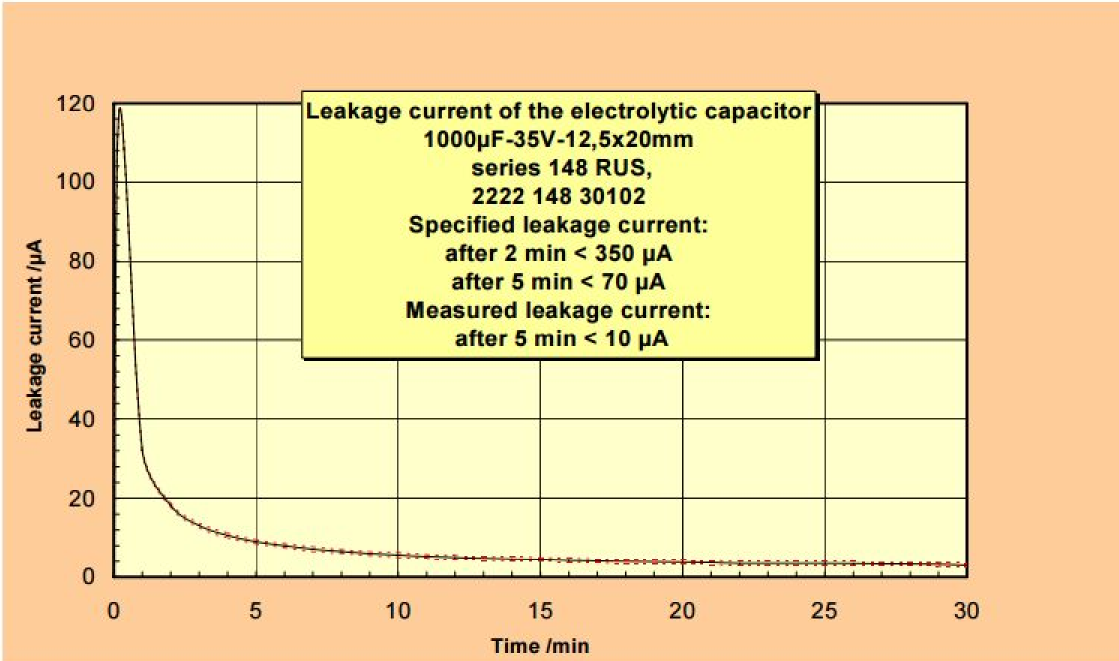


Figure 3.23
(Waiting for permission from Tandarin Batteries)

Tolerance is another important characteristic to consider because the capacitance value of a capacitor can vary depending on the tolerance, much like a resistor. The rating is in the order of picofarads when the capacitors nominal value is less than one hundred picofarads but for larger capacitors the value varies by a certain percentage. For instance if a four thousand microfarad capacitor is chosen to be implemented in the final design and it has a tolerance of plus-minus twenty percent that means that the capacitance of the capacitor could range anywhere between thirty two hundred microfarads to forty eight hundred microfarads. That is a huge difference that must be taken into consideration because that affects the amount of energy that is going to be stored inside the capacitors. If not enough energy is supplying the coils then it will translate to a slower projectile but it too much energy is being applied then the projectile will go much faster but then heat will become an issue.

As mentioned before, there are designs the do not rely on the capacitors due the implement the use of capacitors and only rely on the batteries to power the the coils. These designs tend to be slightly more efficient than ones that use capacitors because most of the times all the energy from the capacitors is being dumped into the coils without any regulation.

The reasoning behind designing a gun without capacitors is in order to create a gun with a useful rate of fire. With a higher rate of fire, more capacitors would be needed and each capacitor would be charging at different times. This idea was from *ourbadscience.com*. His counter-intuitive design argues that you can have a lower voltage from the batteries. The idea is that it would give a slow current rise in the coils creating a weird timing of the coils, and turning off each coil once the projectile passes through. The advantage he argues is that the coils will be only powering up for a short period of time, contrary to most known coil guns. Also, this induced-style design would mean induced current would not be an issue, and because all the coils act as one coil, the timing will not have to be perfect for the gun to work.

However, based on our current plans, we will be using the capacitor design, one for each coil. Though there are a lot of efficiency issues that may arise, we feel that this be the safest route to go. If we run into design issues or see possibilities of improvements to the gun, we will look into creating a gun without any capacitors. For now we plan to use two 4000 microfarad capacitors in order to provide power to the coils. The capacitors we plan on using can be found on Ebay for $10.99 each, shown here below in **figure 3.24.** [16][41]

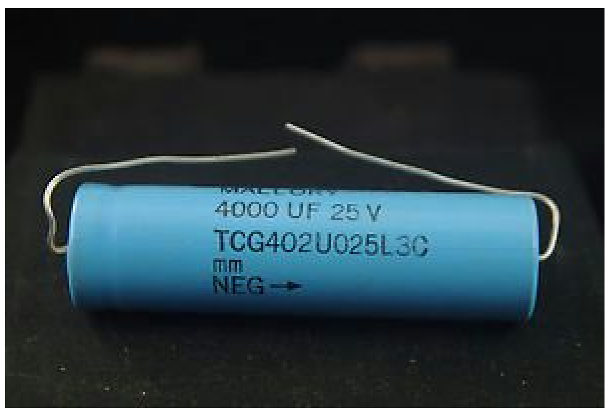


Figure 3.24: One Mallory 4000 uf 25 Vdc Electrolytic Capacitor
(Public Domain)

3.2.8 Coils

The coils will be used in order to accelerate the projectile from the body to exiting the barrel of the gun. The coils will be made out of copper wire wound a specific number of times. This can also be referred to as a solenoid and has the same properties as a solenoid. The reason for this is due to the fact that copper wire has a high conductivity. Another way of saying that is that it has a low resistivity and therefore will easily conduct a current if a potential is applied across the wires. The electrical resistivity of copper wire is 16.78 nΩ•m at 20 °C. When an electric current is run through a coil, a magnetic field is created through the coil. This can be seen from the Biot-Savart Law, which states that a magnetic field is generated by a steady electric current running through a coil.

Ampere's law is another way to relate current and magnetic field. Although, Ampere's law is a more general way to relate the current and the magnetic field. Ampere's law can be used to calculate the magnetic field for any case where there is a steady current through a closed loop. The coil and Ampere's law is illustrated in **Figure 3.25.**

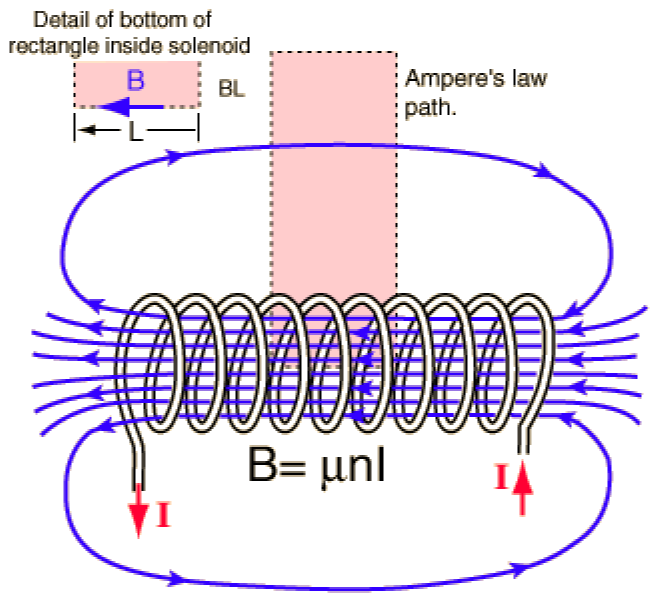


Figure 3.25 (Public Domain)

From our research, the traditional methods hold to have a specific number of coils, based on how long you want the barrel to be. When you turn on the first coil, the moment the projectile passes through, you turn on the next one and turn off the current one at the same time. This poses a problem, because with each additional coil we add, it increases the odds of failure.

Therefore, we proposed turn all the coils on at the same time and turn each coil off as the projectile passes through each of the coils. We will have infrared sensors in between each of the coils to send a signal to turn off the current to the specific coil that the projectile just passes through. We believe this will be the most effective way to accelerate the ferromagnetic projectile through the coils and ultimately through the barrel of the gun and to a target down range. This specific design will allow for a maximum amount of magnetic flux and force to be exerted on the ferromagnetic projectile. Therefore, we will program the microcontroller to read the signals from the infrared sensors attached in between each of the coils.

The microcontroller will interpret the signals from the infrared sensors and then turn off the current being sent through the coil that the ferromagnetic projectile passes through. This will help prevent the magnetic fields generated in each coil from affecting the ferromagnetic projectile after it has already passed through each consecutive coil. This is due to the fact that once the current has stopped being sent through the coil, the magnetic field will disappear. Therefore, nothing will be affecting the ferromagnetic projectile besides the magnetic field in the coil that the ferromagnetic projectile is passing through.

Eddy currents also known as Foucault currents will be induced by the magnetic field within the coil. As seen by Faraday’s law of induction, when a magnetic field changes in a conductor, circular currents are induced in the conductor. Eddy currents flow in closed loops perpendicular to the magnetic field. The magnitude of the current in a given loop is proportional to the strength of the magnetic field, the area of the loop, and the rate of change of flux, and inversely proportional to the resistivity of the material.

According to Lenz’s Law, eddy currents create a magnetic field that opposes the magnetic field that created it. This means that the eddy current reacts back onto the source of the magnetic field. Therefore, eddy currents act as a source of energy loss and can act as a heating source which can cause many issues within the coils. These issues can include overheating of the coils, which can affect the equipment around the coils as well. This means we will try to prevent the effects of eddy currents by turning the coils off as the projectile passes through them. Eddy currents can be seen in the illustration in **figure 3.26** below.

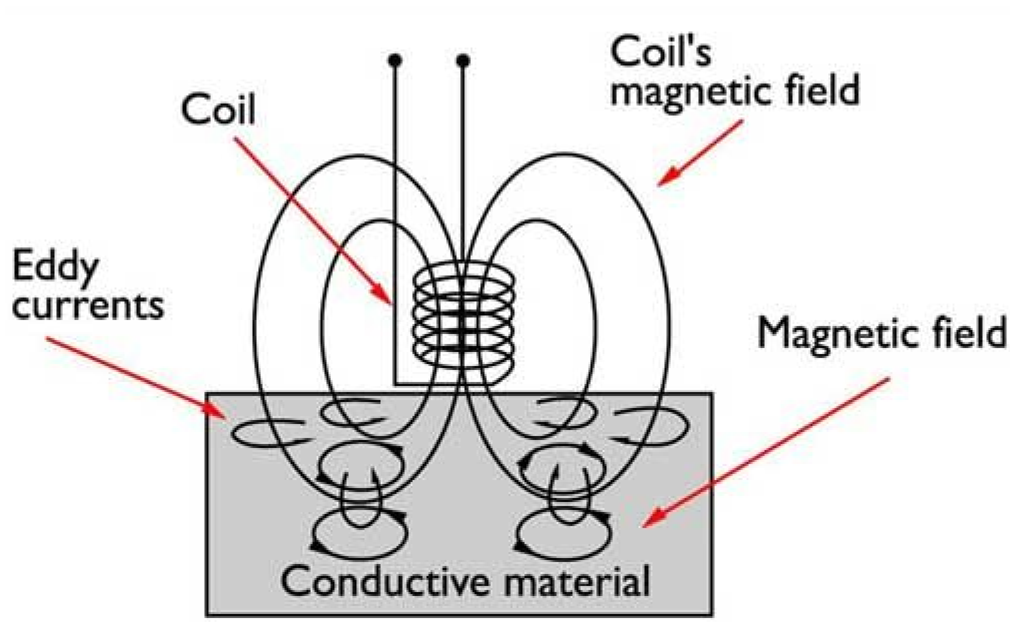


Figure 3.26
(Public Domain)

3.2.9 Timing circuit

The timing circuit is a tool which allows to turn a component on for a certain amount of time. In the case of our coilgun, the idea would be to implement a timing circuit on both the trigger and the capacitors of the coils. Upon trigger pull, the timing circuit would send a signal to charge the capacitors in order to activate the coils, and after a certain time, it would turn on the current coil, and turn on the next coil until the projectile leaves the barrel of the gun. (refer to 6.2.2 to see the full logic layout)

In this case, the basic circuit diagram we would be using would be a 555 timer IC in monostable mode. This is the best-suited mode as it functions as a “one-shot” pulse generator. The diagram of a basic timing circuit is shown in figure X below.

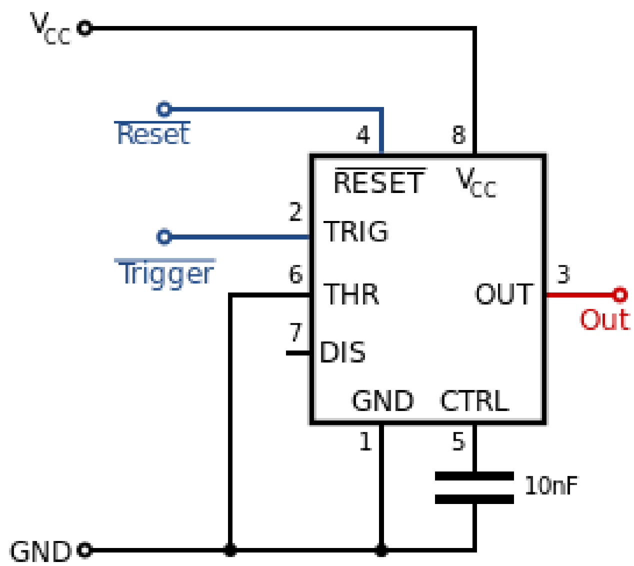


Figure 3.26: Basic Timing Circuit
(Public Domain)

This seems like a good idea in theory, but in our design, we plan to implement sensors at the end of each coil in order to determine when to turn on or off each coil. Because of this, if is very unlikely that a timing circuit will be necessary to implement.

We discuss the idea of using a timing circuit on the off chance implementation of the sensors prove to fail. However, we wish to not rely on time for when a coil should be turned on or off as inconsistencies of when the projectile reaches a certain point at a certain time may occur.

3.2.10 Infrared sensors

For the coilgun, the coils must be turned on and off precisely at the right time. There are two ways to get this done, one would be to hard-code the timing so that after a certain amount of milliseconds, the coil turns off and the next one turns on. However, this would be an unreliable method due to the fact that anything can happen and turning on/off the coil at a very specific time every single time would result in failure. (For example, the projectile doesn't reach the next coil in time, charging the next capacitor is a split-second too late).

Therefore, in order to ensure better timing of the coils, it is best to use a sensor. The idea would be that at the end of each coil, there would be a sensor waiting to detect the projectile. While the sensor is able to "see" the projectile, the next coil would stay on until the sensor is no longer able to sense the projectile.

From what we have gathered online, there are two (subject to change) possibilities for the sensors. Using mouser.com as our store to look up the sensors, we have found the OPB621 by TT Electronics and the EE-SX198 by Omron.

The specs and image of the OPB621 are as follows in Figure **3.27** and **Figure 3.28**

Ordering Information					
Part Number	**LED Peak Wavelength**	**Sensor**	**Slot Width / Depth**	**Aperture Emitter / Sensor**	**Lead Length / Spacing**
OPB610	890 nm	Rbe Transistor	0.150" / 0.240"	0.06" / 0.06"	0.100" / 0.275"
OPB611		Diode			
OPB620		Rbe Transistor	0.190" / 0.285"		0.100" / 0.320"
OPB621		Diode			

Figure 3.26 - OPB621 Specs

Figure 3.27 - OPB621 Sensor

The OPB621 is an interesting sensor to look into because the PIN photodiode has a low t_r/t_f ratio, ideally making the reaction of the sensor to be extremely fast. It also claims that sensitivity to ambient radiation is minimized.On the other hand, the EE-SX sensors have the following characteristics shown in figure **3.28** and **3.29**:

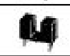
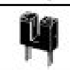
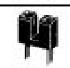
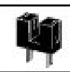
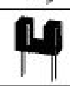
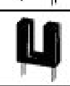
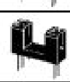
Appearance	Sensing method	Slot width	Slot depth	Sensing object	Output configuration	Weight	Part number
	Transmissive	2 mm	4.5 mm	Opaque, 0.5 x 1.5 mm min.	Phototransistor	Approx. 0.2 g	**EE-SX1018**
		2.8 mm	4.4 mm				**EE-SX1025**
		3 mm	7.5 mm	Opaque, 0.5 x 2 mm min.		Approx. 0.6 g	**EE-SX198**
							**EE-SX199**
		3.4 mm	7.2 mm	Opaque, 0.5 x 2.1 mm min.			**EE-SX1071**
		5 mm	8.2 mm	Opaque, 0.5 x 2.2 mm min.			**EE-SX1041**
		5 mm	12 mm	Opaque, 0.5 x 2 mm min.		Approx. 0.8 g	**EE-SX1042**
		8 mm	8.2 mm	Opaque, 0.5 x 2.2 mm min.		Approx. 0.6 g	**EE-SX1070**

Figure 3.28 - EE-SX Sensors Specs

Item		Symbol	EE-SX1018/1025/1041/1042/1070/1071		EE-SX198/199	
			Value	Condition	Value	Condition
Emitter	Forward voltage	V_F	1.2 V typ. 1.5 V max.	I_F = 30 mA	1.2 V typ. 1.4 V max.	I_F = 20 mA
	Reverse current	I_R	0.01 µA typ. 10 µA max.	V_R = 4 V	0.01 µA typ. 10 µA max.	V_R = 4 V
	Peak emission wavelength	$\lambda p(L)$	940 nm typ.	I_F = 20 mA	940 nm typ.	I_F = 20 mA
Detector	Dark current	I_D	2 nA typ. 200 nA max.	V_{CE} = 10 V 0/x	2 nA typ. 200 nA max.	V_{CE} = 10 V 0/x
	Peak spectral sensitivity wavelength	$\lambda p(P)$	850 nm typ.	V_{CE} = 10 V	850 nm typ.	V_{CE} = 10 V
Combination	Light current (collector current)	I_L	0.5 mA min. 14 mA max.	I_F = 20 mA V_{CE} = 10 V	0.5 mA min. 14 mA max.	I_F = 20 mA V_{CE} = 5 V
	Collector-emitter saturated voltage	V_{CE} (sat)	0.1 V typ. 0.4 V max.	I_F = 20 mA I_L = 0.1 mA	0.1 V typ. 0.4 V max.	I_F = 40 mA I_L = 0.5 mA
	Rising time (See Note.)	tr	4 µs typ.	V_{CC} = 5 V R_L = 100 Ω I_L = 5 mA	4 µs typ.	V_{CC} = 5 V R_L = 100 Ω I_L = 5 mA
	Falling time (See Note.)	tf	4 µs typ.		4 µs typ.	

Figure 3.29 - EE-SX Sensor Specs (con't)

With its output configuration being a phototransistor, it appears that the rising and falling times of these sensors are approximately 4 microseconds.

There are many factors to consider when choosing which sensors to use in our project. The important part is the reaction time. Since the projectile is moving at a fast rate, we will only have a small period of time to properly process the data and power up the capacitors and coils accordingly. Overall, we considered both series for the sensors because from researching past coilguns, those were the ones that were used so we know for a fact that they can be considered reliable.

The biggest factor that it will be for us overall is cost. Our design plan holds to have about four to eight sensors throughout the barrel, with plans to either position them at the end of each coil or the midpoints. Since the objective of this project is to be able to design a gun that is performance reliable and low-cost to make, we feel that for now, the OPB621 Optek sensors should be the sensors to use.

Despite our decision, because we are in the planning stages of this project, we shall look into other sensors and possibly reevaluate our initial decision with this component.

3.2.11 Microcontroller

The microcontroller’s job consist of two big tasks: powering the coils, outputting data to the user. Powering the Coils is a time intensive task is our number priority when it comes to choosing our microcontroller. It is a task that cannot fail and must meet timing requirements. Outputting data to the user is a bunch of little tasks that will help with the overall user experience of the coilgun. It will take in analog data and digital data and outputting it to a LCD display on the coilgun. When it comes to choosing a microcontroller there are many variables to consider. These variables include hardware, software architecture, memory needs, power constraints, and development environment.

When it comes to software architecture and instruction set ARM is one of the more popular options out of this list and it's one of the first ones be decided to check out. Its popular stems from the fact that lots of microcontrollers use ARM architecture. They are known for their low power but also how good their performance is based on the low power. Also the ARM architecture uses the newer RISC architectures giving it nice performance boost. Because we so many popular microcontrollers that use the ARM architecture we decided to choose it. Once again we were faced with range of options in the ARM architecture family. There are 4 popular families in the ARM architecture: ARM Cortex-M, ARM Cortex-R, ARM Cortex-A 32 bit, ARM Cortex-A 64 bit. The ARM Cortex-M maintains a microcontroller profile while the other three families are catered for high-performance application profiles. Because we only have a few tasks the ARM Cortex-M seems much more suited for the coilgun.

Next we had to decide the specific chip we wanted in the ARM Cortex-M family. There are 6 different ARM Cortex-M chips ranging from the ARM Cortex-M0, ARM Cortex-M0+, ARM Cortex-M1, ARM Cortex-M3, ARM Cortex-M4, ARM Cortex-M7. We immediately cut out the ARM Cortex-M7 because we didn't need something with that high of performance and required a lot of power.

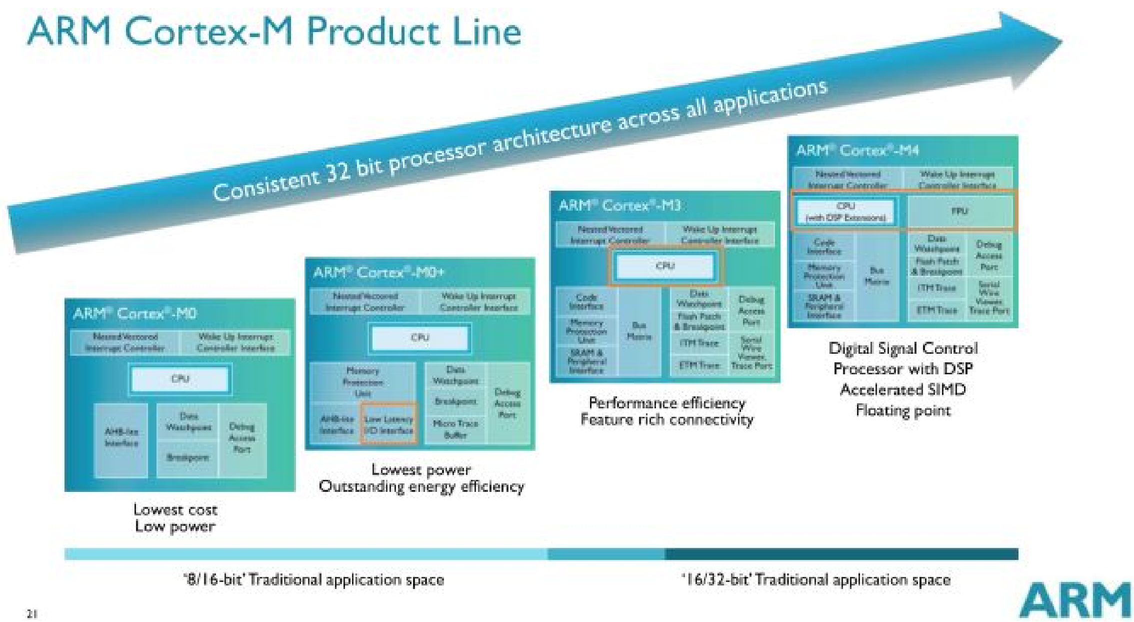


Figure 3.29
(ARM website)

We decided to go with ARM Cortex-M3 because it had a balance of our needs and quite frankly we didn't think one thing stood out to us as a mandatory need. Each ARM Cortex-M architecture had the capability to accomplish our goals

Now that we decided what processor architecture we will be using we now need to choose the actual microcontroller. We had to choose from alot different microcontroller but the four big brand named microcontrollers are STM, Arduino, TI, and SiLabs.

	Pros	**Cons**

STM32L1 Series	• Up to 512 KB Flash Memory • Built-in LCD Display • Price $10	• 24 MHz clock
Arduino Due	• Open Source • 16 ADC 12-bit converter • Arduino IDE • Easy to understand documentation • Up to 512 KB Flash Memory • 84 MHz clock • Arduino Shields	• Price $50
TI Hercules TMS470M	• Up to 640 KB Flash Memory • 80 MHz clock • 1 ADC 10-bit converter	• IAR IDE • Expensive • Requires separate Debugger
SiLabs EFM32 Gecko MCU	• Price $30 • Built-in LCD and buttons	• 32 MHz clock • Up to 128KB Flash Memory

Table 3.1 Microcontroller Pros and Cons
(Data from Datasheets)

From earlier we had 4 big options to choosing the microcontroller, the first being hardware. We really needed a microcontroller that analog lines help with all the analog data we are reading for the LCD display. It isn't a necessity but it has a nice option to have instead having to buy ADC converters. We also need a sufficient amount of communication specifically with I2C or SPI. Because we do have this LCD display we will have many sensors and a LCD Display to connect through. This a must because we cannot add more lines of communication after we a buy a board. Our absolute minimum is 5 I2C lines or 5 SPI lines. Another hardware need was our clock choice, thankfully ARM already comes with higher clock frequencies but there are several things to consider when choosing a clock. We must consider accuracy, cost, power consumption, and environmental requirements. The obvious two that will be important for us our accuracy and environmental requirements. The clock speed of the microcontrollers relates to how fast the microcontroller can execute a command. A huge plus because powering up the coils is a very time sensitive task. Environmental requirements will be another important variable considering the amount of heat the coilgun may ensue. As you can see the Arduino Due sports the highest clock frequency from

Figure X. Next important component is memory which we will consider two types Flash and SRAM memory. Flash memory is what holds program code so we would like a microcontroller that has a sufficient amount of flash memory just in case we have big libraries or decide to add more things in the future. All the boards in Figure X hold sufficient amount of memory except the SiLabs EFM32 Gecko MCU which for that reason we will not be using that microcontroller. SRAM is a temporary data storage for the microcontroller but SRAM has its limitation. So we did not factor in the size of the SRAM in our decision when choosing the microcontroller. In general when it comes to microcontrollers Development environment is another factor in choosing a microcontroller. We are not professional embedded developers so choosing a microcontroller that has a friendly IDE and compiler is big when it comes to actual development. The one microcontroller that stood out to us on that aspect was the Arduino Due. Arduino is an open source platform with lots of online resources to learn and test our source code. On top of that because it is open source there are many libraries out there from us to choose from if we decide that the Arduino Codebase does not provide us with something we may need. Arduino IDE is also another aspect that we took into consideration. We played around with and immediately was able to do lots of work right out of the box. For that reason the Arduino Due became our top choice but we still on some more factors. We are on a limited budget so cost was another factor we took into consideration. All of the remaining boards are in a budget but because TI and STM are not open sourced there may be extra charge for licenses and IDE which was a huge minus in our eyes. TI does come with a free version of their IDE CCS but it limits the size of our code which could be a huge burden when it comes to external libraries. STM does have some free options but when it comes to microcontroller we would prefer to use an IDE that is supported by that company and we can use right out of the box. So other minor components but still play a role in our decision is power, DMA controller, and size. These are minor components because we know all 4 of these microcontroller meet our criteria, it's a matter of tradeoff in which of these components we would lean on more.

We finally decided to go with the Arduino Due. It had all the necessities we needed from power, performance, and memory but was open source, tons of third party libraries and easy to read documentation. The Arduino Due can be seen in **figure 3.30**

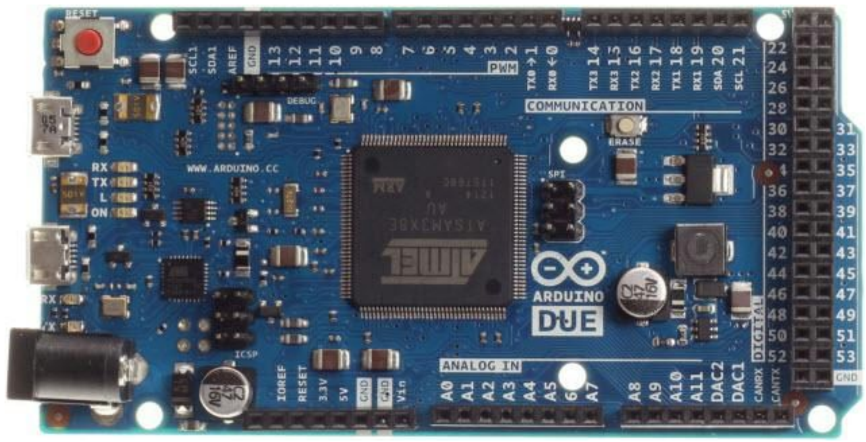


figure 3.30 - Arduino Microcontroller
(Arduino Due Datasheet)

When we implemented the project we downgraded to the Arduino Uno microcontroller. Since we decided to use a single stage coilgun it would be overkill to use the Arduino Due. The Arduino Uno uses the ATmega328P microcontroller which is an 8 bit Atmel MCU. It has 10-bit ADC resolution and less GPIO lines.

3.2.14 LCD display

Because we choose to use an Arduino board it makes much more sense to use an LCD Display that is easily compatible with Arduino. Arduino has a ton of third party hardware that are easily connected and ready to go called Arduino Shields. We decided to look for some LCD display Arduino Shields.

One important aspect in choosing our LCD Display was memory footprint. We want to leave as much memory as possible for real time-tasks. Second we needed something small because portability of the coil gun is an important feature. Third is a ready to go library. Fourth is a low power. From researching we saw that Adafruit has a great selection of LCD Arduino Shields with library that is ready to go on the Arduino Due board.We also have the ability to implement many different screens because the LCD Display comes equipped with 4 GPIO buttons. Giving us the ability to add more features in the future.

Figure 3.31 LCD Display Module
(Adafruit LCD Datasheet)

We have also explored the opportunity of using TFT Displays with the Arduino Due. They are a very popular option with lots of resources online and can possibly enhance the user experience with the coilgun. TFT Display is a form of LCD displays that uses Thin-Film transistor which drastically improves the quality of the screen.[44] They come in a much bigger size so this may get in the way of the coilgun housing but it is a viable option if we can make it work. The option we choose is a 3.2inch TFT LCD display that comes with a shield for the arduino due.

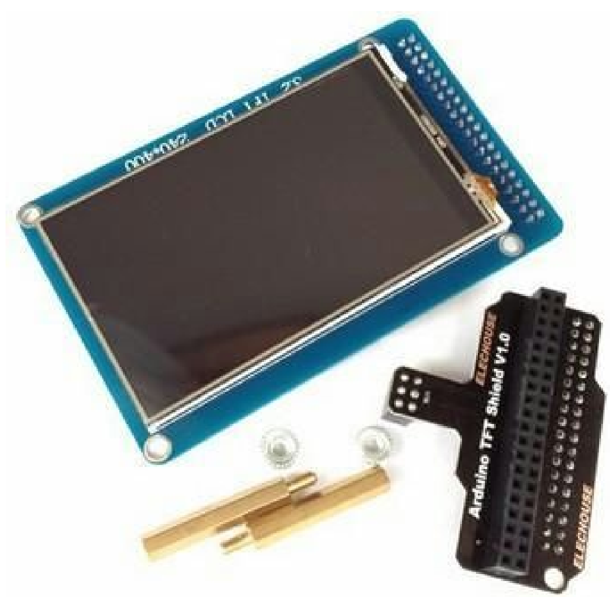


Figure 3.32 TFT LCD Display
(Datasheet)

As you can see the TFT LCD Display is much more pleasing to the eyes. A drawback is the TFT LCD Display uses a touch controller but because the screen is so small a stylus is used to maneuver around. We won't be able to test this feature until we have the TFT LCD Display in hand but it is another drawback to the TFT LCD Display. The TFT LCD Display does support lower power consumption and uses I2C communication so not much would have to change in the software design.

We implemented the basic 16x2 LCD HD44780 display. It was simple in terms of wiring which became an issue in making the coilgun portable. It only requires 4 data lines and 2 additional lines from MCU to LCD.

3.2.15 Temperature Sensors

We will use temperature sensors throughout the coilgun as fail safe and monitoring system. Because we are working with a high voltage system heat as become a topic discussion and we discussed its potential hardware damage in Heat Dissipation section. What we haven't discussed is the potential for software damage and what limits we must obtain to maintain accurate data. First is to put a sensor before the microcontroller reads in the capacitance for the volt meter. This way we can monitor the temperature and correct it the data coming in if the temperature is too high. This sensor will be used as a failsafe, if the barrel gets too hot it could actually melt so capturing that before it happens and shutting the coils off could help save a massive amount of damage being caused and in general would make it much more safer. Since we are anticipating a large amount of heat, we must pick a temperature sensor that can operate. And because we have no idea what the heat will actually be could be without testing. We have to make some assumptions. The first temperature sensor is called the TMP36 sensor by Analog Devices. It operates from 2.7 to 5.5 Volts and can measure temperature up to 150 degrees celsius.[33] One reason why decided to go with this sensor is it has a built in shutdown operation. When the shutdown operation is triggered the sensor drops its current to a non-operational number.

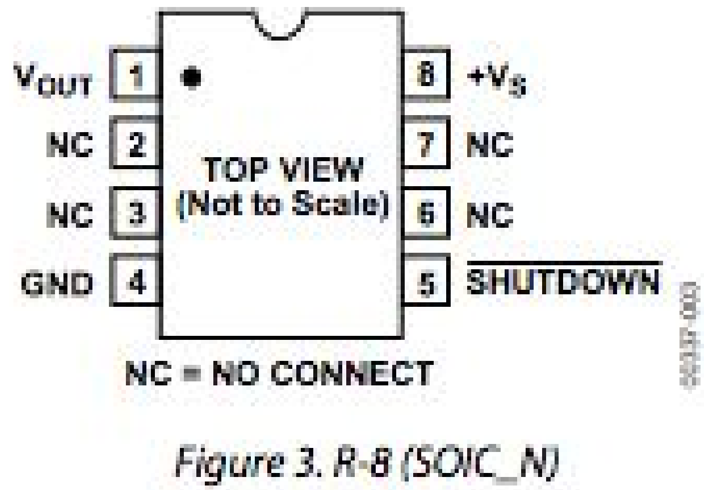


Figure 3.32: pin layout of sensor
(TMP36 Datasheet)

The Temperature sensor can also be set up as “Microprocessor interrupt generator.” This means you can set a certain celsius threshold that would generate an interrupt. This will come in handy for our objective of creating an fail safety for too much heat. Because heat is a slowly moving quantity measures are taken to ensure a hysteresis.The Interrupt Generator circuit was given in the datasheet and we will use it as a starting point in our design

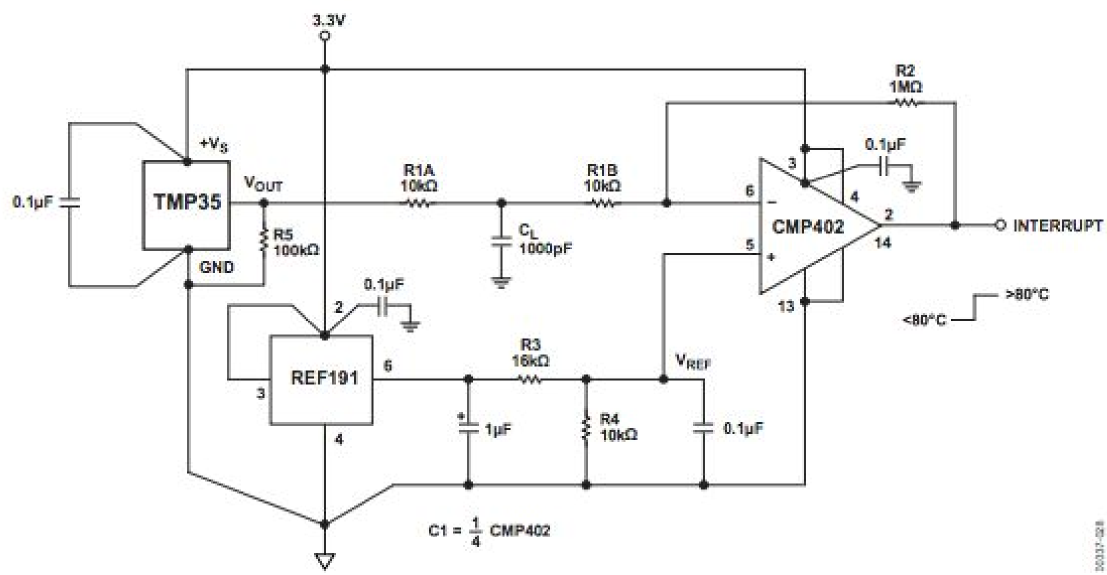


Figure 3.33: Interrupt Generator
(TMP36 Datasheet)

$$V_{HYS} = \left(\frac{R1}{R2}\right)\left(V_{LOGIC\ SWING,\ CMP402}\right)$$

Figure 3.34:Hysteresis formula
(TMP36 Datasheet)

REF191 in the **Figure 3.33** represents a 2V precision voltage reference and CMP402 represents an analog comparator which will help with the hysteresis also. [33]

We also explored the opportunity to use a Digital Temperature Sensor which have built in ADC conversion for our microcontroller to operate. The ADT7420 from Analog Devices is the component we choose for the Digital Temperature Sensor. It operates at a high performance between -20 Celsius and 105 Celsius of +-.25 Celsius but can operate between -40 Celsius and 150 Celsius. It also has a 16 bit ADC to monitor and digitize the temperature to 0.0078 Celsius.[34] It also uses I2C communication to communicate with our microcontroller so our software design would not shift if we went with the analog sensor or digital sensor.

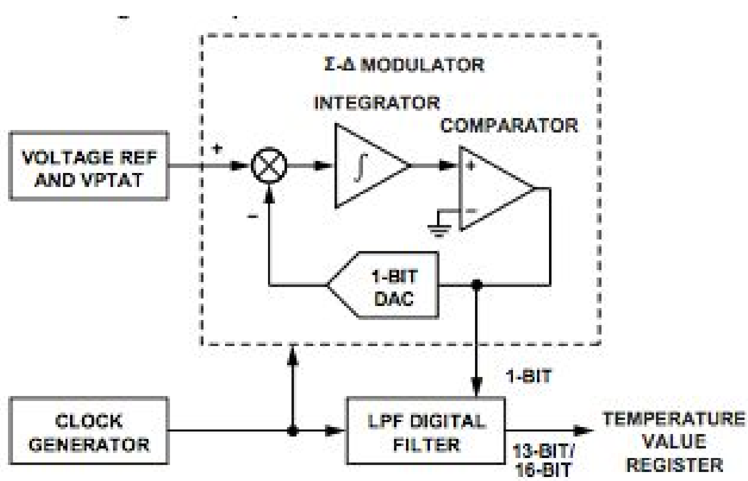


Figure 3.35 Digital Temperature Sensor
(ADT7420 Datasheet)

We can see in **Figure 3.35** that the Digital Temperature Sensor simply outputs a Register to which our Microcontroller can read in real time.One big benefit of the Digital Temperautre Sensor is it contains an interrupt mode just like our Analog Temperature Sensor. When the temperature reaches a certain threshold which we will conduct in testing it will fire an interrupt to which our microcontroller can handle that interrupt. For that reason we decided to go with the Digital Temperature Sensor ADT 7420.

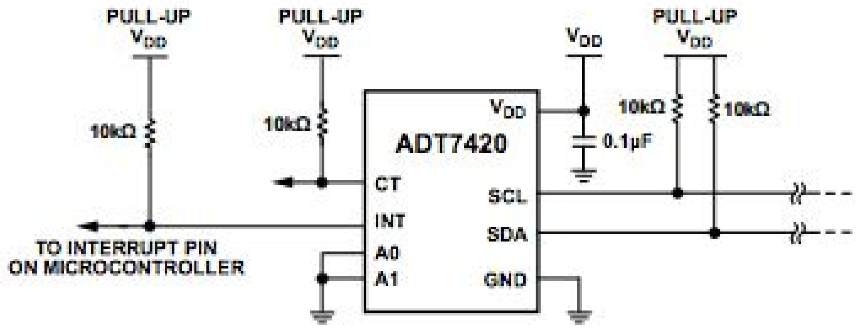


Figure 3.36 Interrupt Lines
(ADT7420 Datasheet)

3.2.14 Power Conversions

3.2.14.1 DC/AC Conversion

The Power source for this project is several DC batteries. The DC voltage is going to need to be converted to an AC signal in order to step up the voltage high enough to achieve the amount of power and current we want to run through each of the coils and possibly charge the capacitors at a fast rate and to its maximum rated voltage. This is going to be achieved through the design of a DC to AC converter or the use of one from the market. DC stands for direct current and it has a unidirectional flow of electric charge. Direct current is seen in things such as batteries, photovoltaic cells, and Dynamos. According to the website wikipedia.org/wiki/Direct_current, direct current can flow through a conductor such as a wire, but can also flow through semiconductors, insulators, and even has the ability to flow through a vacuum in the form of electron or ion beams. Direct current is different from Alternating current (AC) in that the current flows in a constant one direction, whereas alternating current will move in two directions constantly switching and flowing.

Direct current can be acquired from alternating current through the use of a rectifier which only allows current to flow in one direction. A few common rectifiers are full wave, bridge, and half wave rectifiers. Full wave rectifiers convert both of the alternating cycles of the alternating current and are used mostly in the power systems applications. Full Wave rectifiers have the ability to convert the alternating cycles to either all positive or all negative.

For our coil gun design, the capacitors are polarized a certain way a charging them with the opposite polarity can cause damage to them and even cause the possibility of an explosion or a catastrophic failure if the voltage is high enough. Therefore, in our design it would be best to make sure the current can only flow in one direction when the capacitors are being charged. Full wave rectifier circuits are comprised of diodes and these diodes have an operating voltage that they are rated for. The advantage of full wave rectifiers is that they have a center tap design that eliminates any voltage drop that is required to operate each of the diodes. This full wave rectifier has an advantage because the polarity of the input does not matter. Either way, the output voltage polarity will be the same. A full wave rectifier can be seen in the **figure 3.37** below.

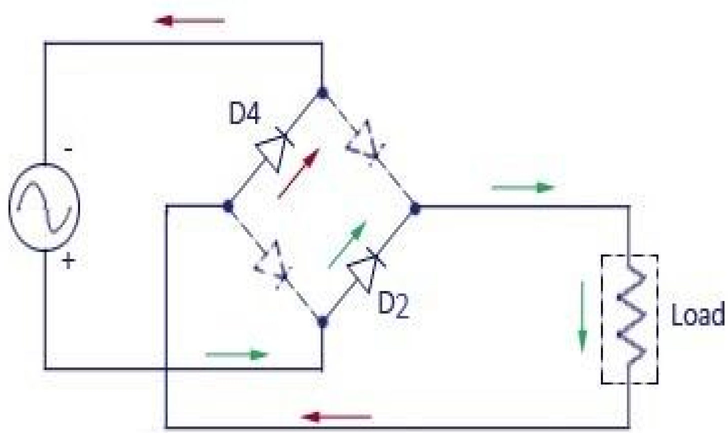


Figure 3.37
(Received permission from Electronic Tutorial)

Half wave rectifiers are another form of rectifier. These rectifiers only convert half of the alternating cycles, so it does not use part of the alternating signal and is in turn a waste of energy from the power source. A half wave rectifier can be seen in the figure **3.38** below.

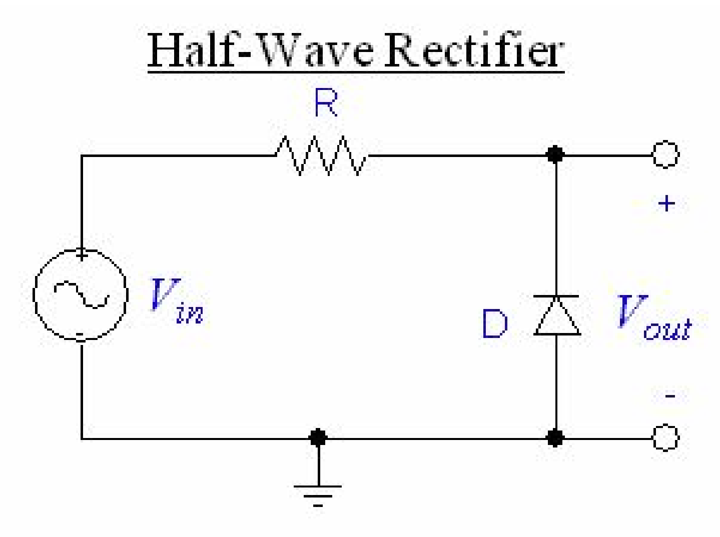


Figure 3.38
(Received permission from Electronic Tutorial)

The final common rectifier is the bridge rectifier. The full wave bridge rectifier produces the same output waveform as the full wave rectifier. The advantage of a full wave bridge rectifier is that it does not have a center tap transformer and is therefore smaller and less expensive than the full wave rectifier. The full wave bridge rectifier is a single phase rectifier that uses four diodes connected in a closed loop bride configuration. The full wave bridge rectifier can be seen in **figure 3.39** below.

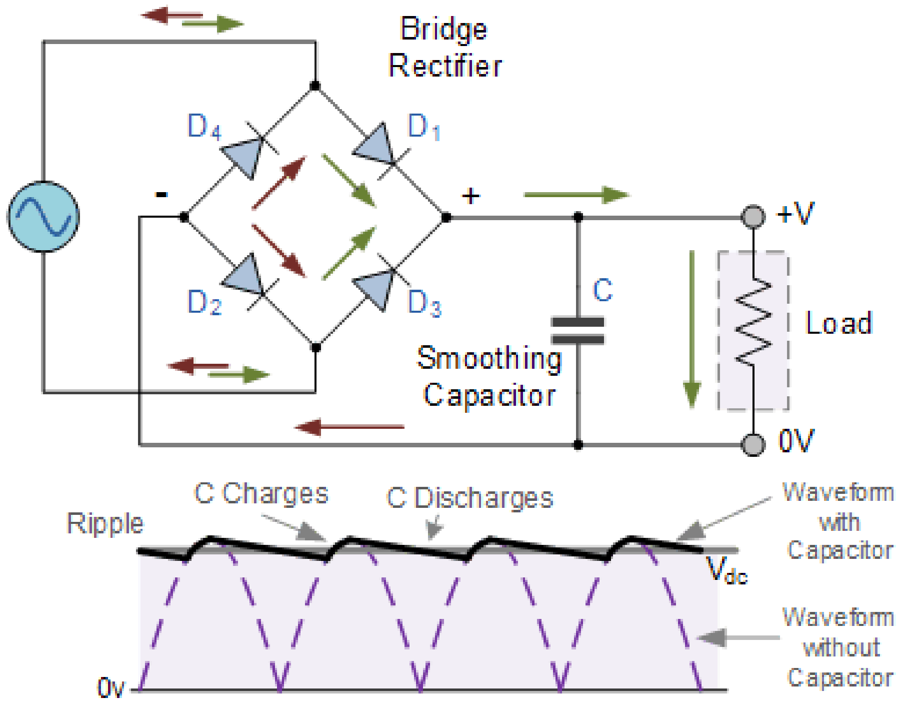


Figure 3.39
(Received permission from Electronic Tutorial)

The DC current is what the group decided on to use to charge the capacitor bank. This is due to the fact that frequency is a factor that needs to be taken into consideration for the selected power source. The most common frequency used in the United States is 60 Hertz sinusoidal. A 60 Hertz power source would be 60 cycles per second and it would represent a direct current source. The use of an alternating current source to charge the capacitor bank is not going to be a feasible option to charge the capacitor bank. Alternating current will produce a ripple voltage even after being rectified by a full wave bridge rectifier. This means that the signal is going to be distorted and bumpy due to the ripple voltage.

According to wikipedia.org/wiki/Ripple, ripple voltage is a residual periodic variation of the direct current output from an alternating current power source. This effect can be attributed to the incomplete suppression of the alternating waveform within the power source. The ripple voltage effect can be seen in **figure 3.40**. The reason direct current should be used is because it is more efficient and effective to charge the capacitors using a constant voltage without the ripple effect.

There are methods that can be used to reduce the ripple voltage you receive from using an alternating current source. Some common methods to reduce the ripple voltage are to use a filter by connecting a capacitor and resistor in parallel with the full wave bridge rectifier. This is a very effective way to manage the ripple voltage easily and inexpensively. However, the ripple voltage can still vary in slight amounts. This could prove to be an issue when considering the way we are going to power the microcontroller. The voltage supplied to the microcontroller must remain above a certain level or the microcontroller could possibly turn off and/or operate incorrectly. This is crucial to the success of our coil gun because the microcontroller is controlling a majority of the components on the coil gun. Therefore, in order for our coil gun to be successful it is essential that we generate a smooth and steady supply of power throughout the coil gun.

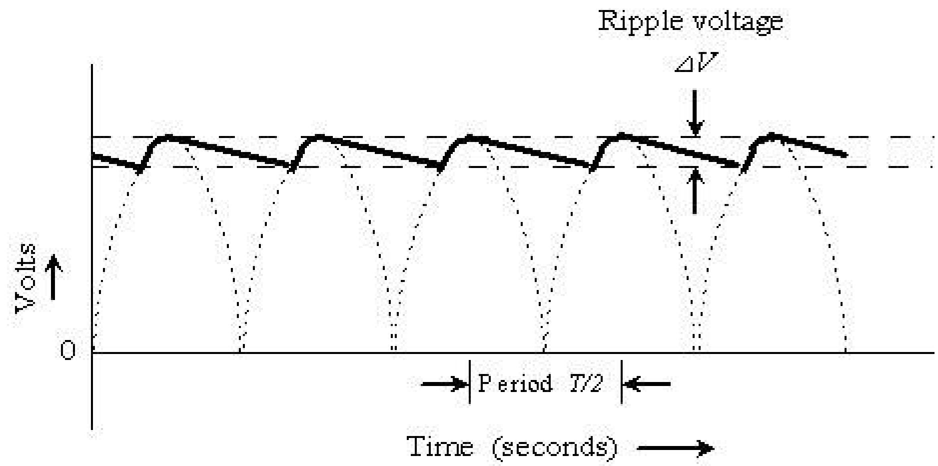


Figure 3.40
(Received permission from Electronic Tutorial)

The group explored various ways to contain and decrease the ripple voltage to make sure a constant and steady supply of power was created throughout the coil gun. The most common ripple definition is the small residual periodic variation of direct current output from a power supply that was derived from an alternating current input source. The ripple that occurs is attributed to the incomplete suppression of the alternating current source waveform in the power supply. Another form of the ripple effect is the frequency domain ripple. This ripple arises in some filters and other signal processing networks. This periodic variation or ripple is a variation in the insertion loss of the network against increasing frequency. In this case, ripple is also an unwanted effect because its existence is a compromise between the amount of ripple and the design parameters.

Ripple voltage is usually expressed as a peak-to-peak value. This is because peak-to-peak is easier to measure on an oscilloscope and it is also simpler to calculate theoretically. Filter circuits are designed to reduce the ripple and are known as smoothing circuits. Smoothing circuits can be in the simplest form just a reservoir capacitor or smoothing capacitor placed at the direct current output of the rectifier. There is still an alternating current ripple voltage component at the power supply frequency for a half-wave rectifier, twice that for full-wave rectifiers, because the voltage is not completely smoothed. However, there is a tradeoff because the capacitor takes up space and costs more.

The advantage of having a larger capacitor is that a larger capacitor will reduce the ripple a greater amount, but it will be more expensive than a smaller capacitor and take up more space than a smaller capacitor would. The larger capacitor also creates higher peak currents in the transformer's secondary windings and in the power supply that feeds the larger capacitor. To create the most efficient way to limit ripple to a specific value the capacitor must be a certain size that is proportional to the load current and inversely proportional to the supply frequency and the number of output peaks of the rectifier per input cycle. This capacitor can be seen in **figure 3.41.**

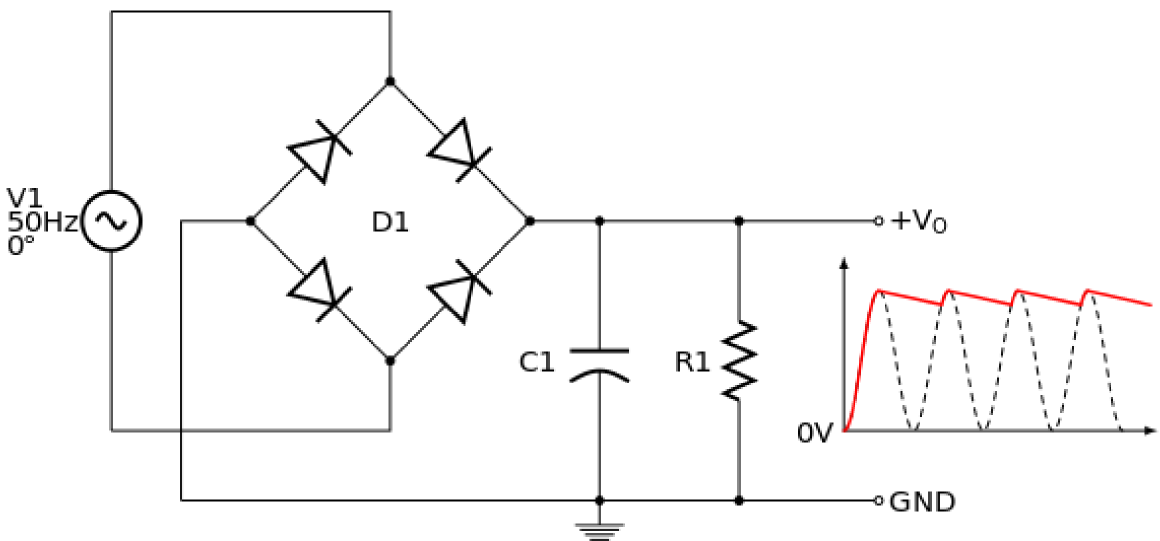


Figure 3.41
(Public Domain)

3.2.14.2 Step-up Transformer

In power systems, transformers are used at many steps in the process or transmitting and distributing power to customers. Transformers are used to either step-up voltage or step-down voltage from an alternating voltage source. Transformers are seen commonly at power plants, transmission and distribution substations, and areas where power is distributed. The transformers at power plants are used to step the voltage up to a higher voltage to be transmitted long distances. This is to ensure that there is not a significant enough loss of power due to transmission distances. Transformers has different rating and voltages and can have several different variations of windings that accomplish different things. The transformers used in power systems are large scale transformers and would not be practical to apply to our coil gun. Therefore, we will be utilizing a small transformer to implement the step-up and step-down voltage changes we wish to apply to our circuits.

After doing research and going through some calculations, the group can to the conclusion that a 4 to 1 ratio transformer would be suitable to achieve the voltage output we require. The transformer is a device that transfers electrical energy between two or more circuits through electromagnetic induction. A transformer is composed a primary winding and a secondary winding. The varying current on the primary winding creates a varying magnetic flux in the core and a varying magnetic field on the secondary winding of the transformer. The varying magnetic field on the secondary winding induces a varying electromotive force or voltage in the secondary winding of the transformer and this is attributed to the electromagnetic induction. Therefore, our turn ratio is equal to 4 which creates a step-up transformer. When the turns ratio is greater than 1, a step-up transformer is created, and when the turns ratio is less than 1, a step-down transformer is created. We want to create a step-up transformer, so our primary windings must be fewer than our secondary windings to achieve a step-up transformer.

The equation that governs the ratio for the voltage transformer that happens inside a transformer is seen in **equation 3.4.** The 4 to 1 ratio with a power rating around 450 VA would allow a voltage of around 400 volts and one amp of current to flow from through the output of the transformer. A step-up transformer can be seen in **figure 3.42**.

$$\textbf{Voltage transformation ratio} = N_s/N_p \qquad (3.4)$$

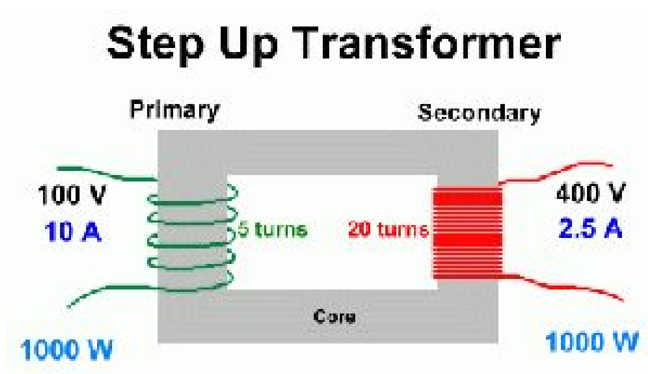


Figure 3.42

The advantage of using a transformer is the that the frequency of the input does not need to be considered. If we were to use a DC to DC step up, the switching frequency would be important in the implementation. The disadvantage of using a transformer is that they take up space and that may cause a problem with the design goal of creating a portable coil gun. This is due to the fact that the transformer is going add weight to the coil gun and have to be integrated into the design of the gun, which is going to take up space. Therefore, using a transformer that is too big will not be able to be integrated into our design. However, the transformer that is we could use for the design of our coil gun project is not very heavy and should not take up space. We would need to use a single phase transformer if we were going to use one in the design of our coil gun.

Our coil gun design will have the heaviest component being the capacitor bank, which will need to be considered when we distribute the weight of the gun to achieve the portability goal of our design. For this reason, the group decided that the use of a single phase step-up transformer might not be the most efficient way to increase the voltage throughout the coil gun. As a group, we researched alternative methods for increasing the output voltage. These researched methods will be covered in the next section of the paper.

3.2.14.3 DC Step-up

The group explored several methods that had potential to be used to charge the capacitor bank. We explored methods that would use direct current instead of alternating current. This is due to the fact that we would have to step up the alternating current and then convert it to DC current to be used to charge the capacitor bank. One way we can stay with the use of just direct current to charge the capacitor bank is by using voltage regulators. The use of regulators has become increasingly more feasible because of the decrease in cost and the effectiveness of the regulators. Regulators allow direct current to produce a large output voltage while also still fitting in a small space. One of the reasons we identified transformers as having a disadvantage was due to the fact that they can become bulky. Transformers can take up space and increase the overall weight of the coil gun and that goes against our goal of portability. Therefore, a more feasible option for the design of our coil gun is to use a step-up regulator.

A step-up regulator can be used to step up direct current. Another name for step-up regulators is a boost converter. A boost converter is a direct current to direct current converter that converts a small input voltage into a larger output voltage. Inside the boost converter is a capacitor or inductor as a storage element, a diode that creates current pulses at higher voltages, and a switch. The boost converter can be powered from any direct current power sources, such as batteries, rectifiers, and solar panels. The output current, with the use of a boost converter, is lower the the source current, but the output voltage is higher. When you close the switch on a boost converter, the current in the inductor increase varying with time and based on the time constant for the inductor and a magnetic field will be created. When you open the switch, current will decrease because the impedance will be higher and the magnetic field that will be created in the inductor when the switch was closed will be destroyed to maintain a current towards the load on the converter. The polarity of the inductor will then be reversed and the two sources will be in series creating a higher voltage with which to charge the capacitor through the diode in the converter. An example of a boost converter can be seen in **figure 3.43**

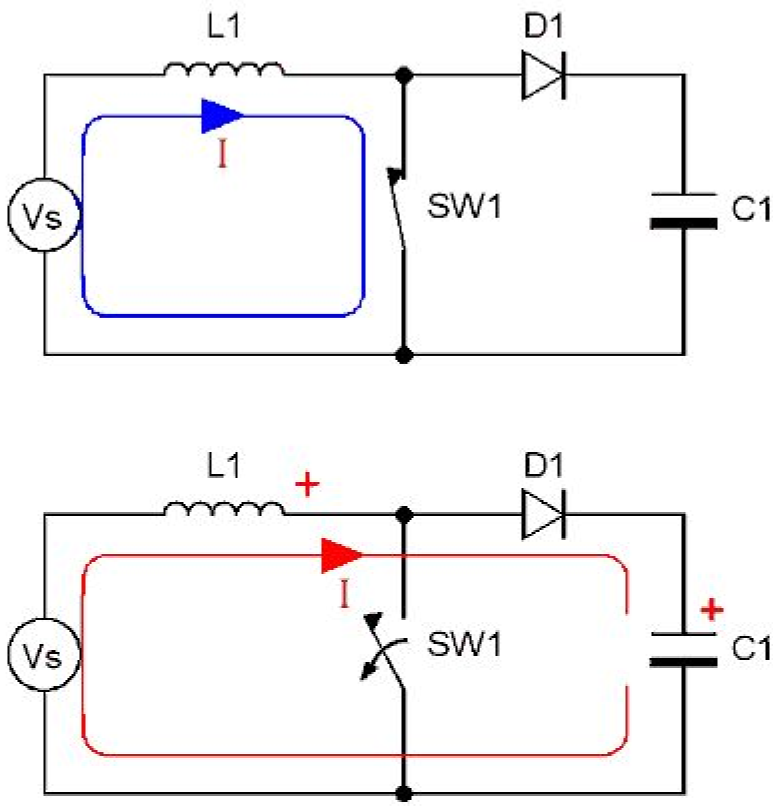


Figure 3.43
(Public Domain)

Boost converters consist of two different states, one when the switch is closed, and one when the switch is open. When the switch is closed, the circuit is in the on-state, which increases the inductor current. When the switch is open, the circuit is in the off-state, the inductor current goes through the diode and into the capacitor and the load. The energy is transferred from the energy accumulated during the on-state. When a boost converter is continuously operated, the current through the inductor is never zero and the overall change in the current is zero. Since power must be conserved in this circuit, if the output voltage is 10 times higher than the input voltage, the output current is 10 lower than the input current. Boost converter circuits sometimes require the use of a filter circuit to be added to the output to reduce the ripple voltage. This means that the use of a microcontroller to control the switching of the circuit and ensure that the circuit is switching efficiently and effectively.

3.2.14.4 Separate Battery

Another option we needed to consider as a group in the design of our coil gun is how to power other components of our gun that do not require high voltage. The microcontroller requires a low voltage power supply and that is not going to be able to be powered by the batteries we are using to charge the capacitors and power the coils. This is due to the fact that we will have to step the voltage up to be used to charge the capacitors and power the coils to fire the projectile. If we wish to use the same power source we would need to step the voltage back down with a direct current step down converter. This is known as a buck converter when it is direct current to direct current being stepped down.

A buck converter can be used because the voltage at the output is smaller than the voltage at the input of the circuit, while the current at the output is greater than the current at the input. The current in the buck converter circuit is controlled by two switches and a diode and transistor. The off-state is when the switch is open in the circuit. In the off-state, current in the circuit is zero. When the switch is closed, the circuit is in the on-state. In the on-state, the current will increase and the inductor will produce an opposing voltage across itself in response to the current change. The voltage drop counteracts the voltage of the source and reduces the net voltage across the load. The converter can operate in a continuous mode if the current through the inductor never falls to zero. A buck converter circuit can be seen in **figure 3.44.**

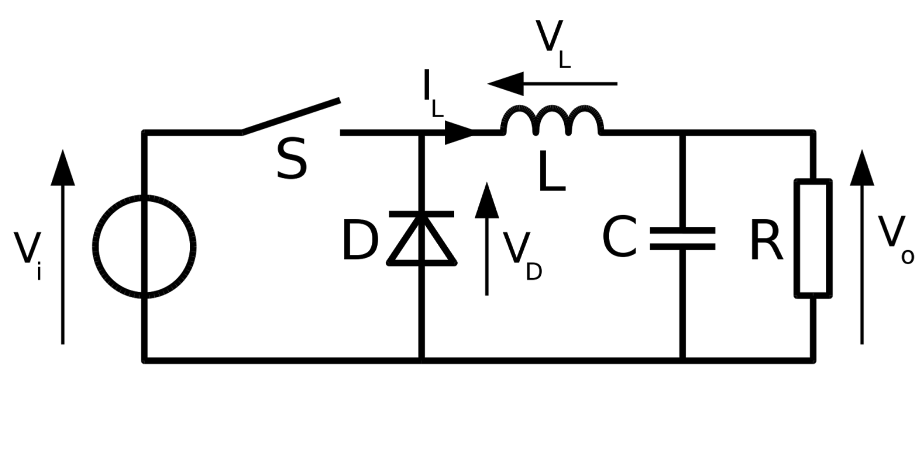


Figure 3.44

Another method to reduce the voltage of a direct current power supply is to use a linear regulator. Linear regulators are a system used to maintain a steady voltage. The regulator has a resistance that varies according to the load that is applied to the circuit and it results in a constant output voltage. Linear regulators contain a zener diode and a series resistor. Linear regulators are commonly integrated into an integrated circuit nowadays due to the fact that they are used commonly in many electronic devices. However, linear regulators can be inefficient. This is due the fact that the transistor in the circuit acts like a resistor, since it wastes electrical energy by converting it to heat to dissipate it. Therefore, the group can to the decision not to use the linear regulator as a way to step the voltage down.

A third method we researched is the step-down transformer. A step-down transformer can be used to set down high voltage alternating current to a lower voltage. The turns ratio of a transformer is determined by the primary and secondary windings around the core of the transformer. When the turns ratio is greater than 1, a step-up transformer is created, and when the turns ratio is less than 1, a step-down transformer is created. If we want to create a step-up transformer, our primary windings must be greater than our secondary windings to achieve a step-down transformer. However, due to the size of the transformer and the amount of space the step-up transformer would take up it is not feasible to use a step-up transformer in the design of our coil gun. There is one last method for powering the microcontroller that the group has researched and considered in the design. A step-down transformer can be seen in **figure 3.45**

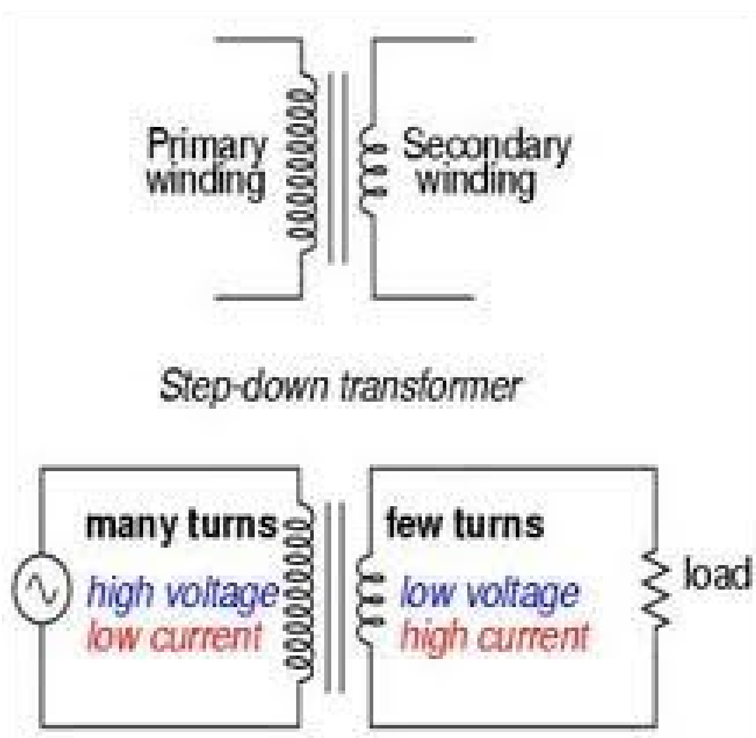


Figure 3.45

(Public Domain)

The final method the group researched and considered while designing the coil gun was the option of another direct current power source. The direct current power source we would use would be another battery to power the lower voltage equipment of the coil gun. The battery would be connected to a charging circuit or the battery will independently be the power supply to the low voltage components of the coil gun. The battery will have to be rechargeable due to the amount of charge that will be used by the low voltage components and that there might only be one battery being used to power the low voltage components. The low voltage components are going to require constant power and constantly inserting brand new batteries is not an efficient process. The low voltage components such as the microcontroller cannot afford to lose power. If the microcontroller loses power, it could damage the software and end up damaging the gun if the microcontroller fails because it is controlling several of the high power components of the coil gun. Therefore, we will need an efficient and reliable battery that is able to be recharged with ease to insure that the low voltage. This will be covered in more detail in the next section.

3.2.14.5 Powering Microcontroller

We will need to convert the AC voltage back to DC for the volt meter. Conveniently our microcontroller, Arduino Due, has 12 built-in lines but can only measure ground to 3.3V. This will require us to step down the AC voltage with the options listed above before its get read by the analog inputs or we can jeopardize damaging the board. Another important point to make is sampling speed of the analog inputs. Because we want to output voltage to the LCD display in real time. The 84 MHz the Arduino Due holds seems sufficient enough for our needs and in section X.x.X of the software design we will discuss how to speed up the sampling data. We want to maintain a backup ADC converter just in case the Arduino Due analog lines do now perform up to our needs. Our backup ADC converter will be the TI ADS1110. It is a 16-bit ADC converter which would give us even more of an accurate reading. It uses I2C bus for communication which is a good option for us since we have an abundance of available I2C data (SDC) and clock (SCL) lines. This can be seen in **figure 3.46**.

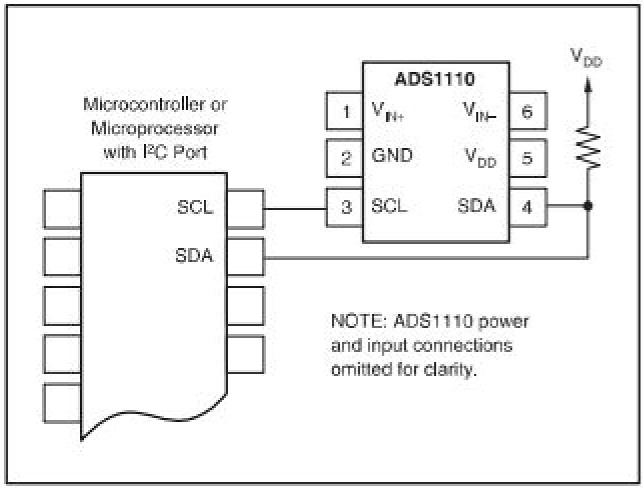


Figure 3.46
(ADS1110 Datasheet)

The minimum and max analog input voltages are 2.7-5.5 which gives us a little bit more range than with the built in ADC lines on the Arduino Due. We also cannot harness the onboard clock of the Arduino Due because the ADS1110 features its own on board clock oscillator.

4. Standards

In order to have quality assurance for our project, a list of standards must be mentioned. The purpose of this is to ensure a set of formality and regulations that we are taking when designing any component of the coil gun. With that in mind, here are the list of standards we feel will be relevant to our project.

4.1 IEEE Standards

Shown here are a list of IEEE Standards that we feel our project would fall under. Due to the fact that there is a large cost way outside our budget in buying these standards, we are simply going to acknowledge them and get as much information as we can

- 1726-2013 - IEEE Guide for the Functional Specification of Fixed-Series Capacitor Banks for Transmission System Applications
- 295-1969 - Electronics Power Transformers
- 9945-2009 - Information technology Portable Operating Systems Interface (POSIX) Base Specifications, Issue 7
- 1500-2005 - IEEE Standard Testability Method got Embedded Core-based Integrated Circuits

- 855-1990 - IEEE Standard for Microprocessor Operating System Interfaces (MOSI)

5 Design Constraints

5.1 Introduction

In order to make a gun practical on the field, it has to have certain properties. It has to be safe to use, accurate, portable, and be able to fire enough times to have an impact in a real life combat scenario. Also, by definition of creating the coil gun, there are several properties we must implement. With this in mind, there are several constraints that we have on ourselves for this project:

- the gun must operate solely on electricity.
- the use of magnetism should be the only way to accelerate the projectile / bullet.
- a microcontroller must be implemented in order to direct which coils to turn on or off.
- a display of the power should be implemented in order to judge how much voltage the battery has left.
- the gun must be relatively lightweight, meaning that a person who is wielding it must have enough mobility to run with it with ease.
- the gun must have accuracy that is inversely proportional to its rate of fire. This means that if our rate of fire is low, the gun should compensate by having a high hit-rate and vise-versa

We are very well aware about the limitations of a coil gun. For our research, we have seen that the gun must operate on direct current power source that can be carried or worn by the user of the coil gun. Therefore, we must design a power source that is portable and comprised of only direct current power usage. In order to do that, we are going to use direct current battery sources.

Another design constraint that must be met is the ferromagnetic projectile must be accelerated with the use of the magnetic fields generated inside each coil. In order to do that, we will optimize the coil's magnetic field production and use of power. We will also be using infrared sensors to monitor the motion of the ferromagnetic projectile as it accelerates through each coil. The infrared sensors will be connected to a microcontroller which will turn the coils off to maximize the magnetic acceleration of the ferromagnetic projectile as it accelerates through each consecutive coil.

The third design constraint that must be met for the coil gun project is the use of a microcontroller to control the electrical components of the gun and the infrared sensors. The microcontroller will be utilize and integrated into several components of the coil gun. One of the most crucial tasks of the microcontroller is to control the infrared sensors to turn the power to each consecutive coil off and on and measure the muzzle velocity of the projectile.

The fourth design constraint that must be met for the coil gun project is the implementation of the LCD display to monitor the voltage of the capacitors as they are being charged. The LCD will be controlled by the microcontroller and will monitor the voltage of the capacitors as they are being charged. The LCD display will display the voltage of the capacitors as the power supply we use is powering the capacitors to a full charge. Once the full charge on the capacitors has been reached, the power supply will stop charging the capacitors and the LCD will display the total voltage which should be the maximum design voltage.

The fifth design constraint that must be met for the coil gun project is the ability to carry the coil gun with ease. This falls into our design goal of portability of the coil gun to give the user the ability to move with ease and aim and fire the coil gun with ease. In order to meet this design constraint, we must design our coil gun in order to minimize the amount of weight that is being put into it. This means designing parts that are lightweight and thinking of different ways to design circuits to minimize the amount of components. This also means that we need to make sure the weight of the gun is distributed correctly in order to allow the user to aim and move around freely with the coil gun. Therefore, the placement of all the components of the coil gun will be designed to minimize the effects of the weight by distributing it in a way that is easy to manipulate by the user.

The final design constraint that must be met for the coil gun project is an accuracy rate that is inversely proportional to the rate of fire. In order to optimize the accuracy, the group has designed the coil gun to fire one ferromagnetic projectile at a time. Therefore, we must use all of the charge stored in the capacitors at one time to accelerate the ferromagnetic projectile at the fastest muzzle velocity. This means that the accuracy of the coil gun ideally will be very accurate and precise in order to compensate for the one shot dump of all the charge stored in the capacitors. The other option the group explored was to have a multiple firing mode. In this mode, we could decrease accuracy to allow for a greater firing rate. We would ideally still like to maintain as much accuracy as possible for our coil gun. Therefore, we will be focusing on a design that allows for the maximization of accuracy of the user when they fire the coil gun.

5.2 Budget

The objective of this project is to design a relatively low-cost coilgun. Based on the parts we’ve decided to use, the budget comes as follows: (adjust as needed)

Part	Cost ($)	Description
4xBattery	$24.00 x 4	12V, 2000mAh, 20C NiMH Battery
2xCapacitors	$15.00 x 4	3900uF Electrolytic Capacitors (400V max)
4x molded plastic sheets	$7.00 x 4	Sheet plastic
4x molded plastic pipe	$5.00 x 4	Plastic pipe/tube for barrel and body
4x copper wire windings	$15.00 x 4	Copper wire for coils
Miscellaneous	$40.00 x 1	Wiring equipment (wires, small capacitors, diodes, resistors)
1x Microcontroller	$40.00 x 1	Microcontroller
1x ADC converter	$15.00 x 1	Converter
1x LCD display	$15.00 x 1	LCD display for voltage
1x battery charger	$30.00 x 1	Charger for batteries
1x Multimeter	$20.00 x 1	Multimeter for voltage and current readings
Total Cost ($)	$424.00	Estimated budget total

The estimation for all these parts will come up to around $600 dollars. However, with Boeing's funding of $450 dollars, this will drastically reduce the cost for us to design the gun and to look at more higher end options.

6. Design Details

6.1 Projectile

The primary goal of a coil gun is to shoot out a projectile that was sitting inside its barrel using electromagnetic theory. The effectiveness of the coils and the gun depends on the type of material the projectile is composed of and the dimensions of the projectile. Looking at previous design the guns were all rated to have less than ten percent efficiency.

6.1.1 Magnetic Properties of the Projectile

In order to accelerate a projectile using an induced electromagnetic field, the projectile has to be constructed out of a ferrous material. This is so that the induced magnetic field can have an effect and apply a force onto the projectile. A hysteresis loop for a given material shows the relationship between the magnetic field strength acting on object and magnetization of an object. While looking at the hysteresis loop, it is evident that there isn't a linear relationship between the magnetic field strength and the magnetization of the object and that there are diminishing returns after a certain magnetic field strength. In order to create the most efficient design, a projectile that has a higher magnetic permeability will be chosen. Common ferromagnetic materials include nickel,cobalt, and iron. To determine which material will be best the availability, cost, and the materials malleability will also have to be taken into consideration with magnetic properties. **Table 6-1** shows the relative permeability of the materials just listed. By taking into consideration the amount energy that would be used to accelerate the projectile to the target muzzle velocity we can determine the strength of the magnetic field that would be required for a specific type of material that would allow for the most efficient transfer of energy. That taken into consideration, a steel rod will be used to forge the material to the desired dimension. A steel rod is being used because it's very easy to find either online or at a local hardware store and due to its inexpensive price.

Material	Relative Permeability (μ_r)
Cobalt	250
Nickel	600
Cold Rolled Steel	2,000
Iron (99.8% pure)	5000
Iron (99.96% pure)	280000

Table 6.1 Permeability of Ferromagnetic Materials

6.1.2 Projectile Dimensions

The size and shape of the projectile can have the same effect on the efficiency of the entire coil gun as the material that was chosen. It is was found by Barry Hansen that having a projectile that is exactly seventy-five percent of the length of the coil provide maximum efficiency when talking about energy transfer. By looking at the **figure 6.1**, projectiles below ten millimeters are incredibly inefficient and that there can be a range of lengths that could be approximated to have maximum efficiency. Therefore, a convenient length for the projectile can be chosen as long as it’s between twenty-five to seventy-five percent of the coil length. The projectile chosen will be cut from the steel rod to be a quarter inch in diameter and three quarters of an inch in length.

Since the projectile will be made out of a steel rod, which is smooth, eddy currents will a challenge to the efficiency of the design. eddy currents generate a magnetic field that opposes the one that is created by the coils. This will slow down the projectile while traveling. One way to ensure that eddy currents do not have an effect on the projectile would be to add slots into the side of the projectile. This will have to be tested. If the difference in the muzzle velocity between a projectile that had slots cut out and one that fully intact is negligible then a solid projectile will be used in the final product.

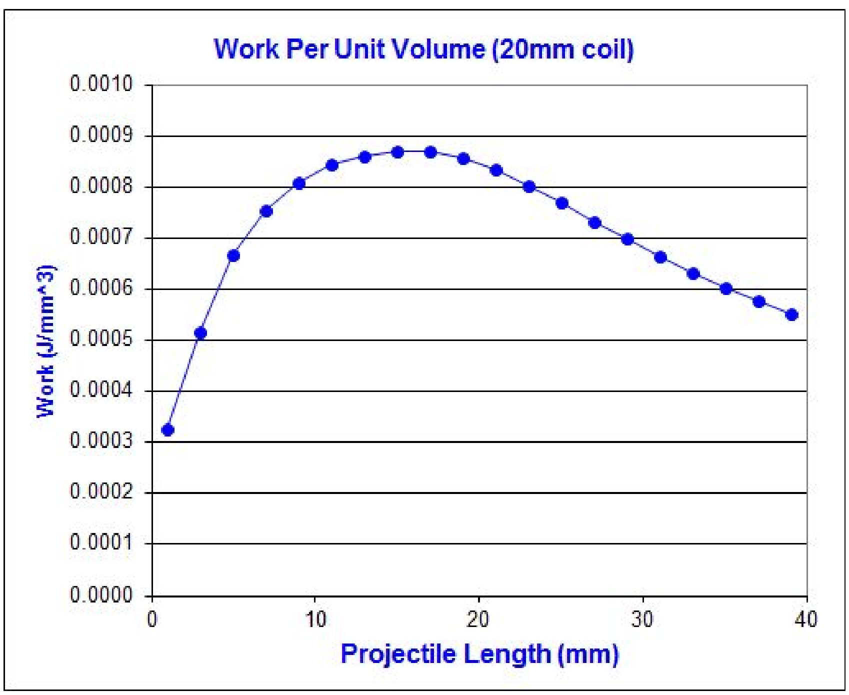


Figure 6.1: Work Density Required to Move Projectile

6.2 Barrel

When comparing to a barrel from a traditional firearm and a barrel for a coil gun there are many differences in the design logic of a barrel. The first thing that is different is that in a coil gun the barrel creates an air gap, but that barrel must be made out of a non ferrous material so it does not get influenced by the magnetic field created by the coils. This function is not needed in a traditional firearm. The air gap allows the projectile to freely move throughout the length of the barrel. If there was no barrel that projectile would more than likely stick to one of the coil and fail to exit the coil gun. Another issue with using a barrel that is made out of a non ferrous metal is that the coils will be getting hot due to the high amount of current that is going to be passing through. If the barrel is made out of metal the barrel could also heat up and possibly compromise the safety of the coil gun and the user.

Another difference between a barrel in a traditional firearm and one from a coil gun is that the length affects the projectile flight in different ways. In a traditional firearm the length of the barrel has an influence over the accuracy and the muzzle velocity. This is due to the gasses that are released when firing a traditional firearm.While in the case of a coil gun the length the barrel only changes how many more coils can fit onto the entire coil gun. Therefore, the barrel length is only a factor when deciding how many coils can fit or in the case of just one coil along the entire length of the barrel it will just affect the length of coil.

Since the main goal of this project is making a powerful coil gun but making sure that the coil gun is still something that can be handheld for an extended period of time. Using a PVC pipe as the barrel will ensure that the barrel is light weight unlike a coil gun with a metal barrel.

6.2.1 Rifling

In a traditional firearm, the rifling of the barrel is one of the most important factors that contributes to the accuracy of the overall weapon. Rifling is process of carving out helical grooves into the inside of the barrel. The purpose of rifling is to give the projectile that is being fired spin. This spin will allow the projectile to fly in a smooth parabolic shape if there is no other force to disrupt it. Firearms that are constructed without rifling suffer from a great loss in accuracy due to when the projectile comes out of the barrel the projectile will begin to tumble in the air.

$$Twist = \frac{(CD^2)}{L} \times \sqrt{\frac{SG}{10.9}} \quad \textbf{6.1}$$

Where:

- C = 150 for muzzle velocities lower than 2,800 feet per second or 180 in cases where the muzzle velocity is greater than 2,800 feet per second
- D = the projectile's diameter in inches
- L = length of the projectile in inches
- SG = specific gravity of the projectile

Equation 6.1,shown above, is Greenhill's formula for twist. Greenhill's formula calculates what the twist ratio of the barrel should be for the given projectile that is to be fired through the barrel.

As mentioned before, a barrel can be riffled using different techniques. The three most commonly used methods are button forged, hammer forged, and cut rifling. Cut forging is the most practical option to be considered for this project currently. While cut rifling is done by hand and each groove must be done individually over the course of repeatedly passing the cutting tool through the length of the barrel, the other two methods required specific machinery. Rifling by hand should not be a huge challenge because the barrel was chosen to be made out of PVC pipe which should be easier to handle than one that was made out of metal. The biggest disadvantage in choosing this method is that it will be time consuming.[42]

6.3 Energy Characteristics

In order to created a magnetic field, a current must be passed through a coil. To determine the strength of the field that is required, the final muzzle speed of the projectile must be chosen so that it is possible to determine the amount of energy that must be supplied to the coils. The coil gun that we plan on design will try to bring the most amount of power to the coils while making sure that it is still light weight. The capacitor bank is where the energy that will be sent out to the coils is stored. The capacitor bank will be the largest, in terms of volume, and heaviest component of the entire coil gun. There will be a tradeoff in terms of energy stored versus the weight and size of the coil gun. Another important consideration to take is the firing mode of the coil gun. Again due to the face one of the main goals is maximum power output, the capacitors are going to transfer as much energy as possible to capacitors one time, therefore currently the coil gun is only designed to have only one firing mode, semi-automatic. The design is specified to have a projectile that ways around 5 grams and the muzzle velocity to be 300 feet per second, 91.44 meters per second. The projectile's acceleration period is calculated using an acceleration distance which will be the length of four and a half coils. This is because each coil will turn off when the projectile reaches the midpoint of the coil to minimize inefficiencies when flying through the barrel. Each coil will be designed to be an inch in length, 0.0254 meters. Therefore, the projectile will be accelerated over a distance or 8, or .2032 meters. Manipulating and combining **equations 6.2** and **6.3** yields **equations 6.4** which allows for the calculation of the time the projectile spends accelerating, which is also how long the magnetic field exist inside the coil.

$$v = at_a \quad \textbf{(6.2)}$$

$$d_a = (1/2)at^2 \quad \textbf{(6.3)}$$

$$t_a = (2d_a) / v \quad \textbf{(6.4)}$$

Now since acceleration time as just found in 6-4, it is now possible to find how much the projectile will be accelerated by the magnetic field by using **equation 6.5**.

$$a = v / t_a \quad \textbf{(6.5)}$$

$$F = ma \quad \textbf{(6.6)}$$

$$E = F d_a \quad \textbf{(6.7)}$$

After finding the acceleration, the force can be easily calculated by using **equation 6.6**. With the mass of the projectile being around 5 grams. Once the force is found, the energy required to accelerate projectile can be founds simply as shown in **equation 6.7**. **Equating 6.8**, is the kinetic energy of the projectile.

$$KE = (1/2)mv^2 \quad \textbf{(6-8)}$$

$$PE = (1/2)CV^2 \quad \textbf{(6.9)}$$

$$KE = e(PE) \quad \textbf{(6.10)}$$

$$I = C(dv/dt) \quad \textbf{(6.11)}$$

The whole process of the coil gun is to take the potential energy from the capacitors, **equation 6.9**, to power the coils, once the coils are powered that energy is then used to create a magnetic field and then final converted to kinetic energy in the form of the projectile moving at a velocity, **equation 6.8**. Unfortunately coils guns have been extremely inefficient for many years. From looking at previous projects it will be assumed that it will be around two percent efficient in converting from one form of energy to the other. thus giving us **equation 6.10**, where *e* is the efficiency of the energy transfer. **Equation 6.11** shown above, gives the relationship between the current voltage relationship of a capacitor.c

$$L = (2PE)/I^2 \quad \textbf{(6.12)}$$

$$\tau = \pi\sqrt{LC} \quad \textbf{(6.13)}$$

Equation 6-12 gives use the inductance based on the amount of energy stored in the capacitor and the current supplied to the coils. While **equation 6-13** allows for the calculation of the coils time constant based on the inductance and the capacitance of the coils and the capacitors respectively. All the values calculated are in **table 6-2**.

Since it is currently only designed for a semi-automatic fire mode, all the capacitors included within the capacitor bank will be supplying the coils with energy. Later one if there is enough time or interest within the group, an automatic fire mode may be added in later but then the capacitors would have to be split up into two different groups. One set of capacitors will be utilized in the semi-automatic firing mode and the other set to automatic fire mode. This is done to simplify the design but the calculations for the automatic fire mode will have to be recalculated to take into consideration the slight decreases in voltage every time a projectile is shot and the induced magnetic fields of potentially have more one projectile in the barrel at a given time.

Description	**Variable**	**Value**	**Unit**
Acceleration time	t_a	6.67	msec
Projectile's Acceleration	a	4,572	m/sec^2
Force	F	1071.24	N
Energy	E	40.824	J
Kinetic Energy	KE	40.824	J
Potential Energy w/ 2% Efficiency	PE	816.84	J
Capacitance - 2 x 3900 µf	C	12.5	mf

Voltage	V	345.12	V
Coil Current	I	749	A
Coil Inductance	L	1.031	mH
LC Time Constant	τ	11.6	msec

Table 6.2

6.4 Coils

The coils have to be designed in a way to ensure that they can create the maximum magnetic field. To determine the parameters of the coils, the equations from www.netdenizen.com were used to find the relationship between the magnetic field and the demmensions of the coil. The equations are modeled to find the magnetic field in a solenoid in a direction that is parallel to the axis of the solenoid.

$$B = \frac{x_2 \mu_0 I N}{2(r_2 - r_1)} * ln\left(\frac{\sqrt{r_2^2 + x_2^2} + r_2}{\sqrt{r_1^2 + x_2^2} + r_1}\right) - \frac{x_1 \mu_0 I N}{2(r_2 - r_1)} * ln\left(\frac{\sqrt{r_2^2 + x_1^2} + r_2}{\sqrt{r_1^2 + x_1^2} + r_1}\right) \qquad \textbf{(6.14)}$$

$$B = \frac{\mu_0 i N}{2(r_2 - r_1)} ln\left(\frac{\sqrt{r_2^2 + (\frac{l}{2})^2} + r_2}{\sqrt{r_1^2 + (\frac{l}{2})^2} + r_1}\right) \qquad \textbf{(6.15)}$$

Where:

- μ_0 = the permeability constant
- i = current in the wire, in Amperes
- N = number of turns of wire per unit length
- r_1 = the inner radius of the coil, in meters
- r_2 = the outer radius of the coil, in meters
- l = the length of the coils

Equation 6.14 is the equation for the general case, but since it has been researched that the projectile experiences the maximum strength of the magnetic field at the center of the coil. Therefore, allowing **equation 6.14** to be able to be simplified to **equation 6.15**. **Figure 6.2** is the visualization of **equation 6.14**.

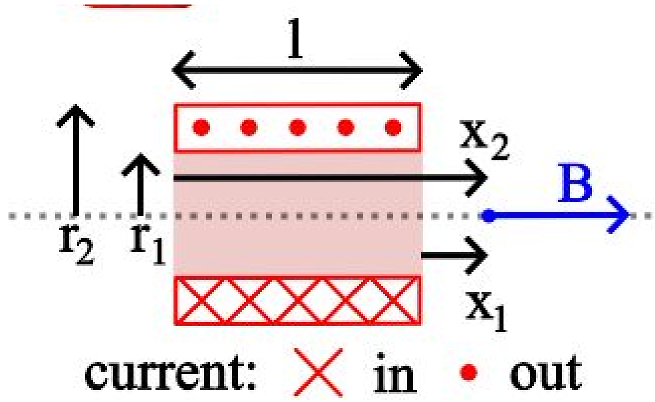


Figure 6.2: Illustration of equation 4.14 from netdenizen.com
(Received permission from Eric Dennison)

The equations above initially seemed helpful for figuring out the dimensions of the coils, but in reality turned out to be a headache because of the interaction with projectile and the additional magnetic field the projectile will induce. Therefore is was concluded that the magnetic field's strength is not as an important factor when compared to the coil's LC time constant. So it was conclude that the equations above would be better suited to compare the results from a different design methodology to ensure the accuracy of calculations. To design the coil, the equations and calculations that were found in section 6.3 will be used.

6.4.1 Dimensions

There are only three dimension that must be taken into consideration when designing the coils. The inner radius, the outer radius, and the length of the coils.

6.4.1.1 Diameters

The first thing about the coil that has to be taken into consideration is what is going inside of the coil. The projectile and the barrel both have to be able to fit within the coil. Therefore, the inner radius will be decided by size the barrel. The outer diameter of the barrel is nineteen millimeters. So the inside radius of the coil will all be nineteen millimeters. If the coils were to be any wider that would create an air gap which would lower the magnetization of the projectile. By making the coil be the exact size needed to snuggly fit the barrel, it allows for the manufacturing process of the coils much simpler. This is because a portion of PVC pipe that will not be used to construct the barrel could be used as a guide to create the coils. Thus allowing us to minimize any inefficiencies and differences between the coils.

Since there isn't anything that is going to be limiting the outer diameter of the radius, the outer radius has to be chosen in such a way that it would maximize the magnetization of the projectile while staying within reason to the inductance value of .510 millihenries calculated in 6.3 Energy Characteristics. Also using some more equations that were found from www.netdenizen.com that magnetic field can be optimized by find the ratios of alpha and beta. **Equation 6.16** calculates alpha which is the ratio between the inner and the outer ratio. While **equation 6.17** is one over two times the inner radius. The magnetization of the projectile will be maximum at a given power input when alpha is equal to three and beta is equal to two.

$$\alpha = r_2/r_1 \qquad \textbf{(6.16)}$$

$$\beta = 1/(2r_1) \qquad \textbf{(6.17)}$$

Due to the fact that the inner radius is set by the barrel and the projectile, the beta cannot be optimized. Therefore that only leave us with alpha and since the inner radius is going to be set at nineteen millimeters. As mentioned before to achieve maximum magnetic field the ratio alpha has to equal three, and because the inner radius is ten millimeters that leaves the outer radius to me thirty millimeters.

6.4.1.2 Coil Length

The length of the coil was assumed before in 6.3 Energy characteristics to be one inch (25.4 millimeters). This length was chosen earlier because that would be the length that the projectile will be accelerated through to achieve the chosen muzzle velocity. Those calculations resulted in giving us the inductance value of .510h millihenries. Since the inner and outer radius are already optimized at values of ten millimeters and thirty millimeters respectively. Using the calculated coil inductance and **equation 6.18** it is possible to determine the length of the coil. This value will value will be compared with the value that was chosen in the earlier section.[43]

$$L = \frac{.8(NA)^2}{6A+9B+10C} \qquad \textbf{(6-18)}$$

Where:

- N= the number of turns
- A= the average radius of the coil
- B= length of the coil
- C=the coil thickness

6.4.2 Conductor

The conductor to be chosen as the coil will be considered base on the functionality of the coil fabrication, current carrying capacity, and any type of heat loss and dissipation. Any type of conducting material can be chosen to create a magnetic field but the wire that is most commonly used in application of electromagnetism is magnet wire. Magnet wire is wire the consists of aluminium or copper conductor with a thin layer of insulation. This type of wire is commonly used in transformers, motors, and speakers. Magnet wire allows for more turns per unit length which will increase the magnetic flux density that will be created. The size of the conductor will give a better idea of the maximum current the coil will be able to hand and how much heat dissipates during use.

6.4.2.1 Type of Conductor

Magnet wire has a few differences when compared to a traditional conductor. Magnet wire is heated and then cooled down slowly and also wrapped in a different kind of insulation. This allows for the magnet wire to be coated in a thinner insulator while maintaining its temperature rating and insulation breakdown voltages. The process of heating up and then allowing for the wire to be cooled down very slowly is called annealing. The annealing process is used to remove any defects within the structure of the material, which in returns improves the ductility of the wire. Using a conductor that has a higher ductility allows for a tightly wound coil. Making a tightly wound coil allows for more turns per unit length which improves the magnetic flux density created by the coil. Therefore, by increasing the magnetic flux density that the coils can create that would increase the efficiency of the overall system. Also have a magnet wire conductor would allow for easier fabrication of the coils.

There are two types of magnet wire. There is magnet wire that is made out of copper and then the other is made aluminium. Magnet wire that is made from aluminium is softer because aluminium is a softer material than copper. That allows for a much easier fabrication of coils. That is the only advantage that aluminium magnet wire has over its copper counterpart. This is because aluminium has a higher resistivity, is less ductile than copper, and has a lower melting point.

Copper has a much lower resistivity meaning that there will be less losses and produce less heat when a large current is applied to it. Also since aluminium is one and half times larger in copper for the same application it would take up more space. Thus, a coil constructed with aluminium copper would have less turns per unit space and could potentially create an awkward shape around the barrel making is less portable. Finally due to its lower melting temperature, aluminium copper wire would potentially not be able to withstand the amount of current need to create a magnetic field with the strength required to accelerate the projectile to our set specification. Aluminium magnet wire is traditionally used in large electromagnetic machines and copper magnet wire is typically better suited for small designs. Due to the many reasons stated above, copper magnet wire will be used to create the coils.

6.4.2.2 Insulation

The insulation of the magnet wire provides a tough layer to prevent any type of shorting in any application. Since the coils are going to be wrapped in a fashion to ensure the optimal number of turns and it is important to make sure that the coils do not get shorted. If the a coil becomes shorted the mean it will not create a magnetic field and therefore the projectile will not be accelerated while passing through. The advantage of magnet wire is that it's insulation layer is thinner without having to sacrifice temperature and voltage ratings. Magnet wire is identified by it's NEMA rating, which rates the insulation by its thermal capacity. **Table 6.2** shows the thermal classes of magnet wire by their temperature rating and insulating materials.

Thermal Class	**Insulating Material**
105° C	Polyvinyl, Acetal-Phenolic, Polyurethane/Polyamide/Polyvinyl Acetate
130° C	Polyurethane/Polyamide
155° C	Polyurethane, Polyurethane/Polyamide, Glass Fibers
180° C	Polyurethane, Polyamide, Modified Polyester-Imide, Modified Polyester-Imide/Polyamide, Polyester/Polyamide Imide/Bond Coat
200° C	Polyester/Polyamide Imide, Glass Fibers
220° C	Polyester, Polyester/Polyamide Imide, Aromatic Polyamide Paper
240° C	Aromatic Polyimide

Table 6.2 - Magnet Wire Insulation Ratings

Different insulation materials allow for different applications of of magnet wire. The type of insulation for magnet wire is chosen based on temperature rating, flexibility, chemical resistance, heat shock, abrasion resistance, moisture resistance, and many other factors depending on the wire's application within a system. In this project, flexibility and temperature rating are the two key factors that must be decided upon. Flexibility is important because as stated before the coils are going to be designed in a way to maximize the magnetic field. The flexibility has direct effect on how easy it will be to shape the coils to specified dimensions.

Temperature rating will be important for the prolong use of the coil gun and safety of the person operating the coil gun. A temperature rating of about 180° C will be chosen because the coils should not reach a temperature of 180° C and it will bring costs down. A copper magnet wire made with a insulator that is constructed out of polyurethane will be implemented because they are usually used in other applications that calls for the fabrication of coils, offer a high thermal resistance, decently flexible to allow for tightly wound coils, and abrasion resistance.

6.4.2.3 Conductor Size

Because the current flow through the coil will only be passing through the conductor for a few milliseconds, the standard current ratings for conductors can not be applied to this design. To overcome this issue, the Onderdonk equation, **equation 6.19** ,will be used to determine the size of our conductor. The Onderdonk equation is typically used to determine the size of the wire used in fuses and will determine that time it takes a conductor to melt base on the current applied, surrounding temperature, and size of the conductor.

$$S = \left(\frac{A}{I}\right)^2 \times log_{10}\left(\frac{T_m - T_a}{234 + T_a} + 1\right) \div 33 \quad \textbf{(6.19)}$$

Where:

- S: duration of current flow in seconds
- A: the wires cross-sectional area in circular mils
- I: current in Amperes
- T_m: the melting point of the conductor in ° C
- T_a: the ambient temperature in ° C

Matlab will now be used to calculate the conductor's melting time by taking in input for the wire size, applied current, and the ambient temperature. Since the coil gun will be portable the ambient temperature will change depending on if someone wants to fire this at a range of if they would like to fire the coil gun outside. Since ambient temperature can very so much the design will be made with the thought that the coil gun's main application are going to be outside. The average temperature of a summer day in florida is about ninety degrees Fahrenheit (around thirty two degrees Celsius) and this is the number that will inputted into the Onderdonk equation. **Table 6.3**, shown below, displays the results of the Onderdonk equation showing the melting time, wire size, and ambient temperature.

Conductor Size	**Applied Current (A)**	**Melting Time (s)**	**Time Derated 20% (s)**
8 AWG	964 A	6.1743 s	4.9349 s
10 AWG	964 A	2.4421s	1.9537 s
12 AWG	964 A	0.9659 s	0.7727 s
14 AWG	964 A	0.3820 s	0.3056 s
16 AWG	964 A	0.1511 s	0.1209 s
18 AWG	964 A	0.0598 s	0.0478 s
20 AWG	964 A	0.0236 s	0.0189 s

Table 6.3: Results from Onderdonk Equation

6.4.3 Coil Simulations

6.4.3.1 Inductor Simulator

Using the inductor simulator, created by coil gun enthusiast Barry Hansen, will be able to cross reference any calculations that have performed. The inductor simulator is Java applet that anyone can have access to at www.coilgun.info. The inductor simulator works by having a user input all the various parameters of the coils they would like to design or have already designed and then the simulator will tell the user the number turns, inductance of the coil, resistance, and total length of the wire. Having not previously found the number of turns per unit length, the inductor simulator actually calculated that value and helped out by giving the total length of the wire to be used. **Figure 6.3** is the inductor simulator on www.coilgun.info with the designed parameters of the coil gun.

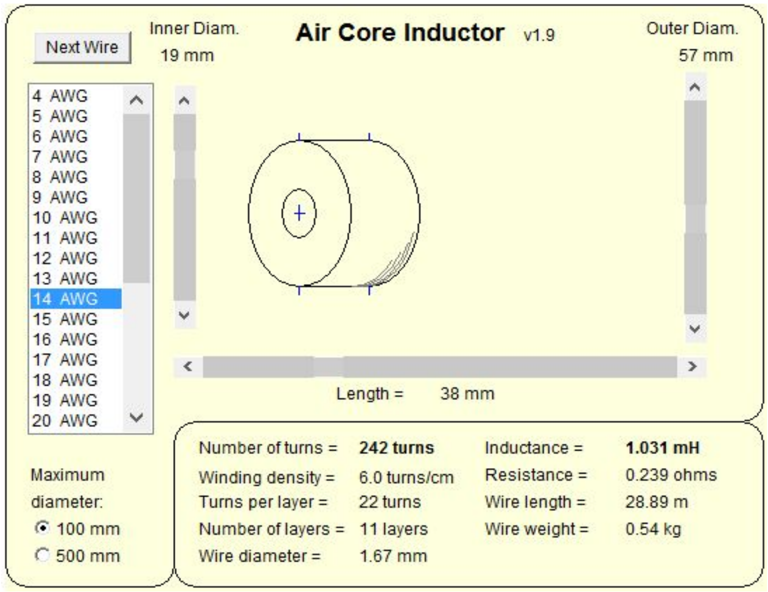


Figure 6.3: Inductor Simulation

6.4.3.2 RLC Simulator

The RLC simulation is also another Java applet made by Barry Hansen, also available at www.coilgun.info, that can calculate the peak current and the duration of the current pulse of a system. The coil's resistance values are taken from the inductor simulation done in section 6.4.3.1 and then the values for the capacitance and voltage are entered from the values calculated in section 6.3. **Figure 6.4** is the RLC simulator Java applet on the www.coilgun.info displaying the current pulse of the system.

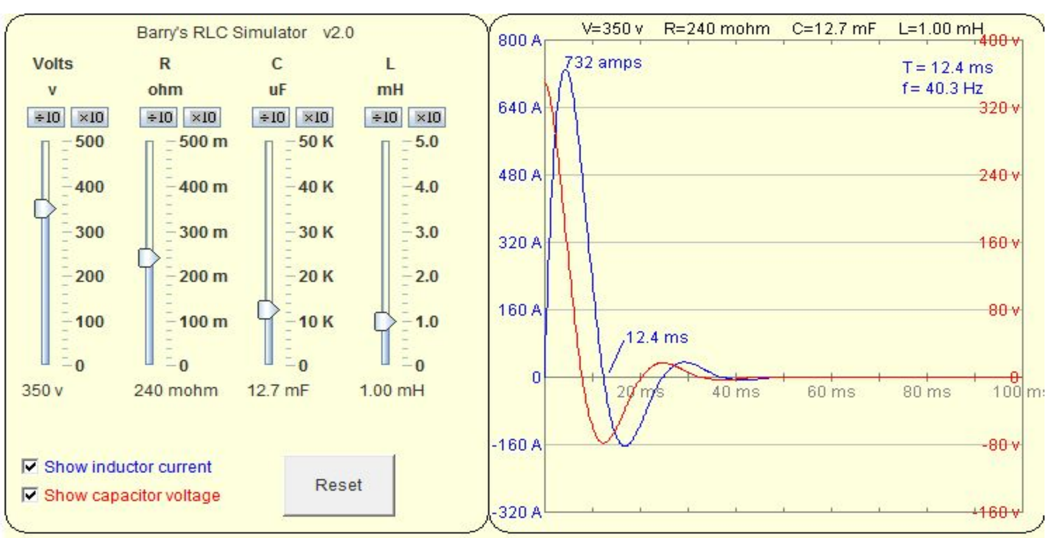


Figure 6.4: RLC Simulation

Table 6.4 is all of the dimensions of the coils to be designed. Then the value for inductance, wire resistance, and the total length will be compared between the inductor simulation and the matlab programs. **Table 6.5** is display the values that were taking from the RLC simulator and then compare them with numbers the were calculated in 6.3 Energy Characteristics,

Description	**Variable**	**Value**	**Units**
Coil Parameters			
Inner Diameter	r_i	19	mm
Outer Diameter	r_o	57	mm
Length	l	38	mm
Wire Size	d_w	14	AWG
Results		**Matlab**	**Simulation**
Inductance	L	1.031 mH	1.026 mH
Resistance	R	0.239 Ω	.255 Ω
Total Length	l_{wire}	28.8 m	29.1 m

Table 6.4: Coil Properties

Description	**Variable**	**Values**	**Units**
Energy Calculations			
Current Pulse	I	749	Amps
Pulse Duration	t_a	11.6	ms
RLC Simulator			
Current Pulse	I	732	Amps
Pulse Duration	t_a	12.4	ms

Table 6.5: Current Pulse Properties

6.5 Magnetic Field

The magnetic field that exists in a coil gun during the firing of the projectile is very difficult to calculate due to the relationship between the coil and projectile as it moves through the coil. Finite Element Magnetics or FEM models are a good tool for modeling the magnetic field of the coil gun. QuickField offers a student version of their FEM software, this software does have limitations on the complexity of the systems being modeled, but will be useful in illustrating and understand how the magnetic field in the coil changes depending on the position of the projectile.

A Matlab function was created using **equations 6.14** and **6.15** to examine the magnetic flux density of this particular design. The function allows the ability to change the coil parameters, current pulse and point at which the flux density will be measure. This code can only be used to understand the flux density of the air core, the coil itself is not able to incorporate the effects of the projectile. Table 6-6 Contains the results of the matlab function for the designed coil at the midpoint and the an assumed firing position in the front of the coil, of 8 millimeters.

Description	Variable	Value	Units
Magnetic Flux at Midpoint	B	0.0410	T
Magnetic Flux at Firing Position	B	0.0666	T

Table 6.6: Magnetic Flux of Coil Without Projectile

The QuickField FEM modeling programs was used to model the magnetic field and flux density of the designed coil incorporating the steel projectile. The model can be created using the top cross-section of the coil and projectile due to the symmetry of the system. **Figure 6.5** through **6.7** show how the magnetic field of the coil changes as the projectile passes through the coil. The created FEM model of the coil gun was then used to determine the magnetic flux density in the coil and projectile. **Figure 6.8** shows the strength of the flux density concentrated in the projectile. This figure illustrates the importance of current pulse duration since the majority of the magnetic flux is concentrated in the projectile.

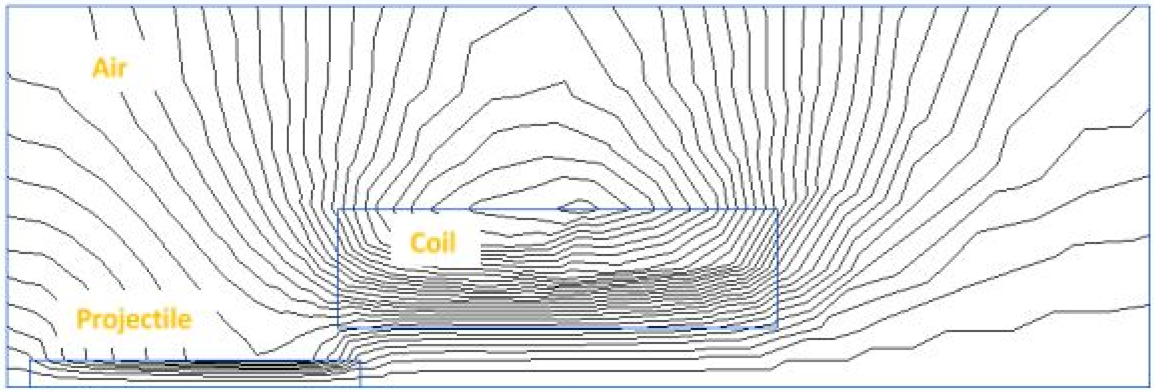


Figure 6.5: Magnetic Field with Before Firing Projectile

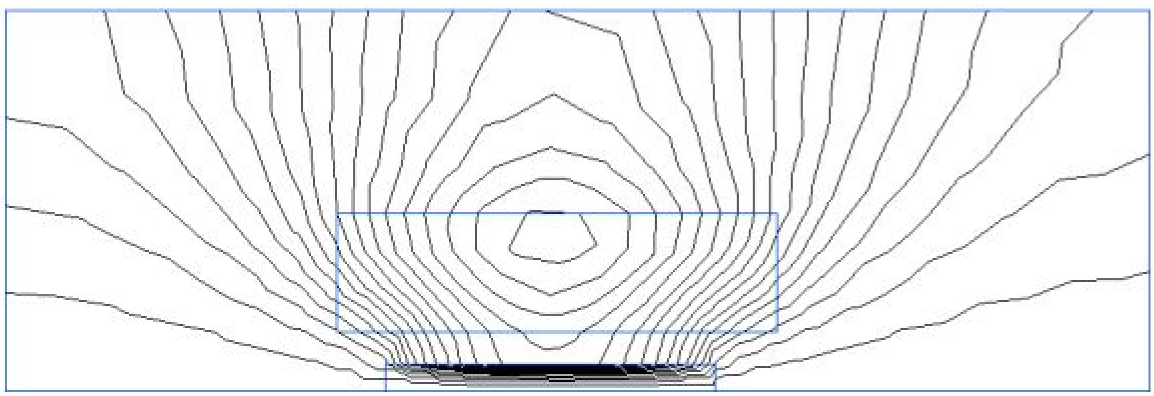


Figure 6.6: Magnetic Field with Projectile at Center

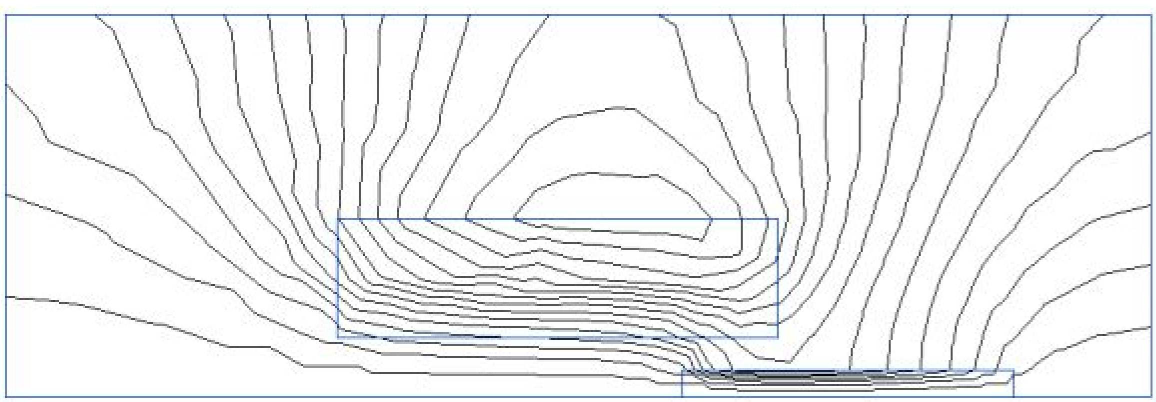


Figure 6.7: Magnetic Field with Projectile Leaving Coil

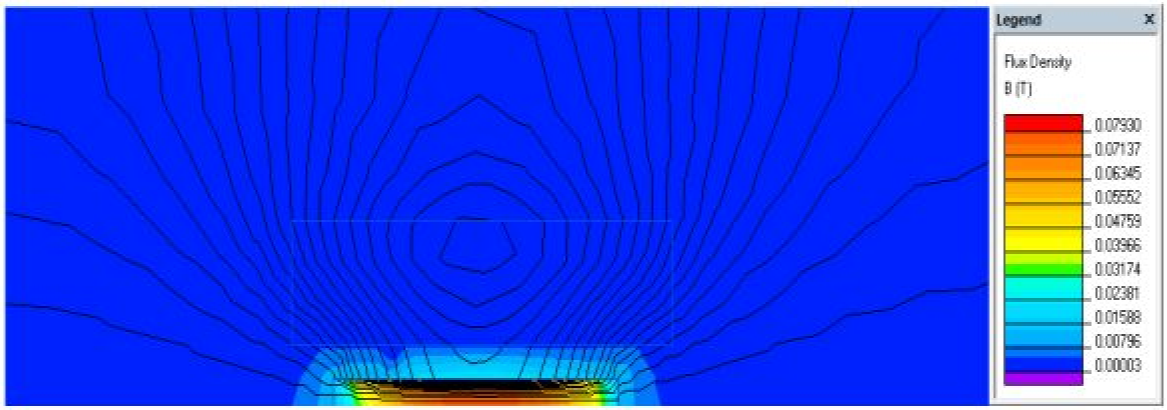


Figure 6.8: Magnetic Flux Density in Coil Gun

6.6 Heat Dissipation

The heat generated by the current pulse through the coil is the factor most affecting the ability to fire projectiles consecutively in the design of the coil. Since the current pulse is very short with a coil gun it can be assume that no natural cooling of the coil takes place during the pulse duration. Since the coil gun is going to be operating in a semi-automatic firing mode there will be no need to worry about passing too much current within a short amount of time causing the coils to melt. The change in temperature will be measured when testing the coils. If there is need to cool down the coils it will be implemented into the design. For right now, there will be a sensor placed to measure the temperature of the coils to ensure that the user doesn't not melt the coils.

Temperature increase in the coil is due to the heat losses in the conductor. The amount of energy lost due to the heat of the coils, in jules, can be calculated with equation 6-x using the current pulse, and resistance of the coil and the acceleration time. There is an issue with trying to calculate the heat loss of a conductor because as the temperature of the conductor increases so will the resistance of the conductor to increase as well. The temperature rise is based on the ratio of resistances and the temperature coefficient of copper α_c, which is 0.393 percent per degree Celsius. **Equation 6.20** can be used to determine the temperature rise by measuring the coil's change in resistance due to the current pulse.

Table 6.7, shown below, contains the results of the coil's heat losses after firing, the potential energy of the system and the percent of energy that is lost due to heat, which is calculated by **equation 6.21**. By looking at the results from **equation 6.22** it is quite simple to see the reasons why coil guns are so inefficient. Most of the energy that is going to be stored in the capacitors is going to be lost as heat in the process of powering the coil. This shows how important it is to optimize the coils and magnetic field created by the coils. Since most of the energy is going to be lost as heat it would be important to make sure that the remaining energy would be efficiently used to accelerate the projectile.

$$E_j = I^2 R t_a \quad \textbf{(6.20)}$$

$$\Delta T = \frac{\frac{R_2}{R_1} - 1}{\alpha_c} \quad \textbf{(6.21)}$$

$$\%_{loss} = \left(1 - \frac{PE - E_J}{PE}\right) \times 100$$

(6.22) **(6.22)**

Description	Variable	Value	Units
Heat Loss	E_j	440.61	J
Potential Energy of System	PE	464.515	J
Energy Loss Due to Heat	$\%_{loss}$	94.854	%

Table 6.7: Heat Losses in Coil

6.7 Charging Circuit

The common theme throughout the hardware design is to get as much power through the coils as efficiently possible. In order to do that the capacitors must be charged to power the coils. To charge the capacitors Eirik Taylor's CFPR Capacitor charger will be used as our charging circuit. **Figure 6.9** is an illustration of the charging circuit. The circuit's input is 12 V while it can charge up to 380 to 450 V. This charging circuit has been tested to charge a capacitor bank of 3.29mF to 430V in 6.3 seconds. Proving that it is very fast and very efficient.[37]

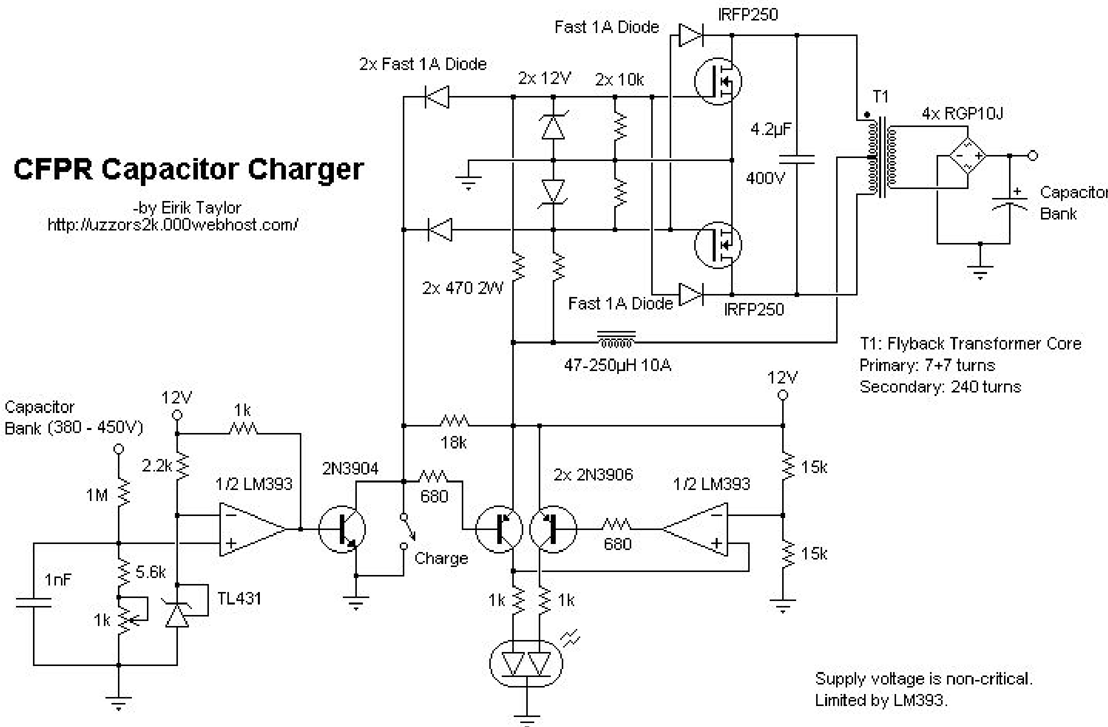


Figure 6.9: CFPR Capacitor Charger.
(Public Domain)

Figure 6.9 is the capacitor charging circuit that was initially set out to be designed and put onto a PCB. Unfortunately due to cost of creating a PCB with a surface mounted transformer, somewhere along $80 to have the PCB created, the CFPR Capacitor Charger was not implemented into the final design of the gun. The CFPR Capacitor Charge was replaced by the The SMAKN High Voltage Boost Converter. The SMAKN High Voltage Boost Converter, shown in **figure 6.10**, takes a range eight to thirty-two volts and steps it to a variable output of forty-five to three-hundred-ninety volts. The SMAKN High Voltage Boost Converter has a maximum output current of 200 mA and can charge the capacitors to three-hundred Volts, our firing voltage, in less than 25 seconds.

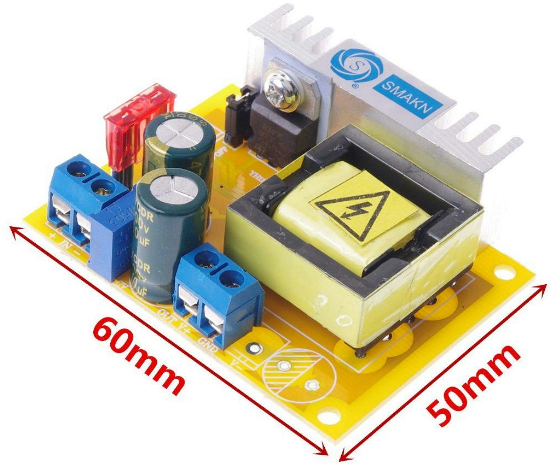


Figure 6.10: SMARKN High Voltage Boost Converter
(Public Domain)

6.8 Firing Circuit

The capacitor bank is being discharged through the coil once fired. The switch that is being used to control the current flow is an SCR, silicon controlled rectifier. We chose the VS-T70RIA120 SCR for the project. That specific SCR was chosen because it can handle a maximum peak non-repetitive surge current of 1.74 kA.
Allowing us to have room to test quick changes to design in the form of power. The SCR gate requires approximately 120 milliamps and is controlled by the trigger on the gun. The typical turn-on time for the SCR is just underneath one microsecond. While the SCR allows for the high current switching, the SCR does not close after the gate current has been turned on. So once an SCR is on it will remain on until the voltage across the capacitor is depleted. This means that the SCR does not close in time to stop the inductive kick back created by the current flow through the coil. If this Inductive kickback is not dissipated in a safe manner then it will negatively charge the capacitors and because the capacitors are polarized, if they are negatively charge too long they can explode.

In order to prevent that from happening, a set of diodes will be placed in parallel with the coil allowing for the inductive kickback to dissipate safely through the coil. This inductive kickback is also known as back EMF. This can be very disruptive to the circuit and can cause an induced magnetic field in parts of the circuit or coilgun that would cause very many issues with the overall performance. This back EMF can also be very damaging to the components of the coilgun. Those include the Charging circuit, boost converter, capacitor bank, coil, and diodes that are placed for protection against this. The circuit for the firing circuit is shown below in **Figure 6.11**. This firing circuit provides a reliable and capable way to discharge the capacitors overall charge and effectively apply this voltage across the coil. This voltage will create the current pulse of close to 800A across the coil that the SCR will have to be able to handle. This circuit also allows the user to determine when the projectile will be fired by applying current to the gate with the use of the trigger of the gun. This applied current will then turn on the SCR and allow the voltage from the capacitor bank to create a current pulse across the coil and generate a magnetic field to accelerate the ferromagnetic projectile.

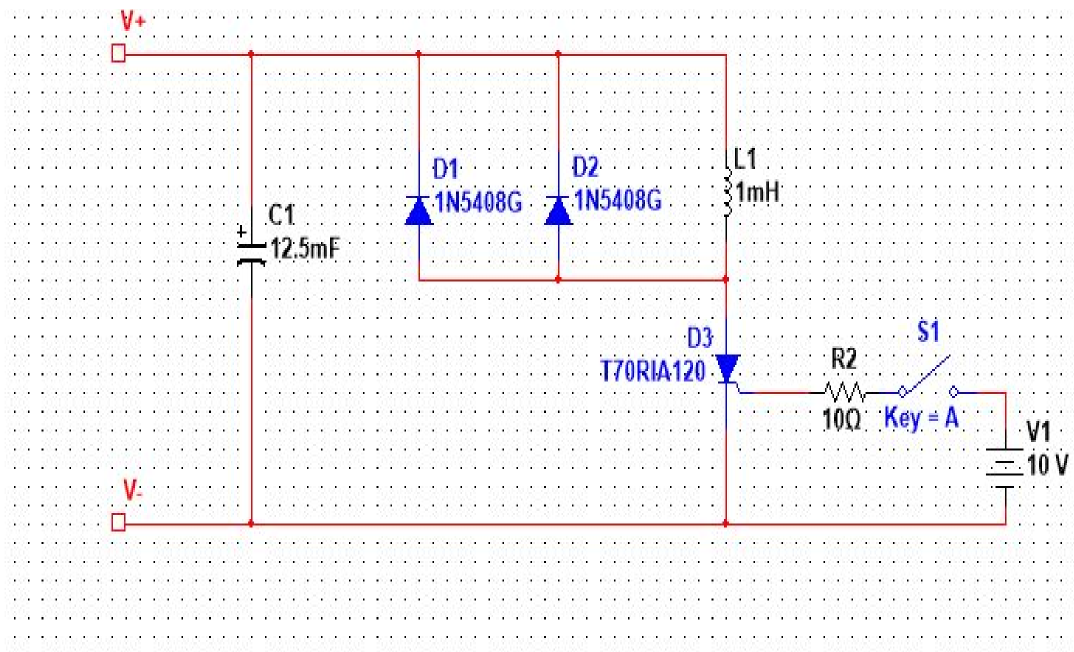


Figure 6.11: Firing Circuit

6.9 Power

There are three different areas in the coil gun that need to be powered independently in order to make sure all parts are working correctly. That is the SMARKN High Voltage Boost Converter, the trigger, and the Microcontroller. As mentioned above, the SMARKN High Voltage Boost Converter has a variable input of eight to thirty-two volts. When testing, we found out that if we connected a battery that had a voltage less than twelve volts the boost converter would takes a very long time to charge the capacitors and would just stall. When using a battery that is over twelve volts the SMARKN boost converter charges our capacitors in the time frame that would meet our project's design specifications. Because of the observation made above we chose to use a the Tenergy 12 V battery. The trigger will be controlling the SCR and the flow of current through the coil and will be powered by a sole battery. The gate trigger current of the Mouser T70RIA120 SCR is a minimum 100μA. In order to meet the minimum requirement we used a 10 ohm resistor and a 9.6 V, actually measured to 10.31

V when fully charged. **Figure 6.x** shows the batteries that were used within the project.

Figure 6.12: Tenergy 12 V and 9.6 V Batteries
(Public Domain)

Finally, the last thing that needs to be powered is the microcontroller. Trying to make due with just the 12 V and 9.6 V batteries that were already purchased we would need to use a voltage regulator to power the microcontroller safely. The Arduino Uno can only take 5 V as a power supply. To achieve that we used an LM7805CT linear regulator to step our 9.6 V input from the battery to a nice and safe 5 V as show in Figure 6.xx below.

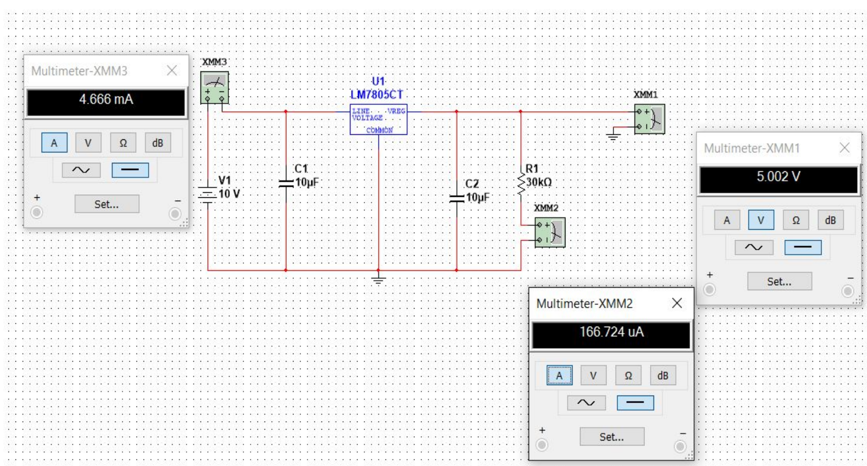


Figure 6.13: Simulation of Linear Voltage Regulator Using LM7805CT

6.10 Software Design

6.10.1 Responsibilities of Microcontroller

The Microcontroller will have many responsibilities. These responsibilities include determining the power of each coil and determining when the capacitors are full while displaying that on the LCD display . Determining the power of each coil will be an extremely time intensive task for the microcontroller and may require multiple threads happening at the same time. We have explored the opportunity to use an RTOS(Real Time Operating System) to handle all these task in a safe manner. The LCD display will be presenting the user when the capacitors are ready to shoot but also not allowing the trigger to begin powering of the coil until the capacitors are full.

6.10.2 Choosing Our Programming Language (C++ vs Java)

There are two languages that most electrical and computer engineers are familiar with, Java and C / C++. However, up to this point, there has not been really much of a difference between the two languages. Both are object-oriented languages (referring to C++, not C) and the syntax is almost exact from an entry-level programmer perspective is nearly identical. Other than how they import libraries (#include <libraryfile.h> for C and import libraryfile for Java), and C's use of a header file as a schematic for a classes variables and functions, there doesn't seem to be much of a difference.

What is the difference between the two, and why is it so important to think about which one to use? The reason why we have to consider the language that is going to be used here is because it may have different effects on the system. Both have the ability to port code onto an embedded platform, but how it performs will make all the difference in which ones we end up using.

First off, the major differences between the two types of programming languages is it's purpose and usability. C++ was designed for systems and applications programming, while Java is a general purpose language, with overall portability. This means that Java code can be transferred from Windows to Linux to Mac without much trouble. C++ on the other hand holds some problems because there are some Windows specific libraries that Linux may not be able to catch. However, this issue can be solved since C++ has the ability to do conditional compile (#ifdef and #ifndef) statements in order to make the code adapt to whatever operating system it is on.

Another noticeable difference between Java and C++ is how both languages deal with memory. Unlike C++, Java does not support pointers. The reason for this being is that Java is considered "memory-free", meaning that it handles allocating memory for data types and freeing unused memory types automatically (called garbage collecting). C++ on the other hand, requires the programmer to tell the computer to allocate and free memory as necessary. There are also no checks to ensure that C++ won't suffer through a memory dump, making it slightly harder than Java to deal with memory.

There are other smaller syntax differences between C++ and Java, such as Java having a String type object while C++ has Strings in the form of character arrays. Java doesn't support type conversions unless it's guaranteed and safe, boolean statements in C++ are evaluated to either a 1 or a 0 while in Java, it has it's own separate type with the possible values being true or false and C++ has destructors while Java doesn't support it. The extensive list is all found in Professor's Baldwin's *Similarities and Differences Between Java and C++*.

The language of choice we will be using for this project will be C++. Through evaluating the pros and cons of each language, we feel this is the best route to go with. The reason being is that it appears that porting C++ onto an embedded system is easier than with Java. However, from a performance standpoint, this is the more logical option.

The requirement that C++ makes the user deal with memory allocation manually allows us to control what the microcontroller is using what and when. This helps us improve performance especially when execution of the coils will be very time heavy (as we will discover in the programming process). Also, the FreeRTOS IDE to program on the Arudino uses C++. We will be provided with has some example C++ code with libraries for us to import, making it more reasonable for us to choose C++ over Java.

6.10.3 Arduino Codebase

There are two programming languages embedded engineers must work with, C and C++. The main difference is in the paradigms of the languages, C is a functional paradigm and C++ has multiple paradigms including functional and object-orientated. Most hardware and libraries uses C still because it has always been the standard in the hardware, it wasn't till too recently that embedded engineers started using C++ to wrap all firmware in objects/classes. The requirement that C++ makes the user deal with memory allocation manually allows us to control what the microcontroller is using what and when. This helps us improve performance especially when execution of the coils will be very time heavy (as we will discover in the programming process)

Arduino comes fully equipped with an IDE ready to go which uses C++. Our RTOS(Real Time Operating Systems) was developed in C. We do have other options like VIPER which is a development suite for Arduino boards including our Arduino Due. VIPER allows us to code in Python. But their are extra complications with C and Python and the job would be much easier using C++. We will be using many other debugging tools with our IDE. Embiro is a real time visual programming environment. This will be great tool when it comes to testing the interrupts and data from sensors.

We are faced with an important implementation decision when it comes to running multiple tasks. In the embedded world we have two options: Real time Operating System or Finite State Machine. Finite State Machine partitions task depending on resources and represents each task as individual state machines. [13]Most Finite State Machines are written in C and our possible in the Arduino IDE. Arduino also comes equipped with a Finite State Machine library. The overall IDE that we plan to use looks like the following below in figure **6.9**.

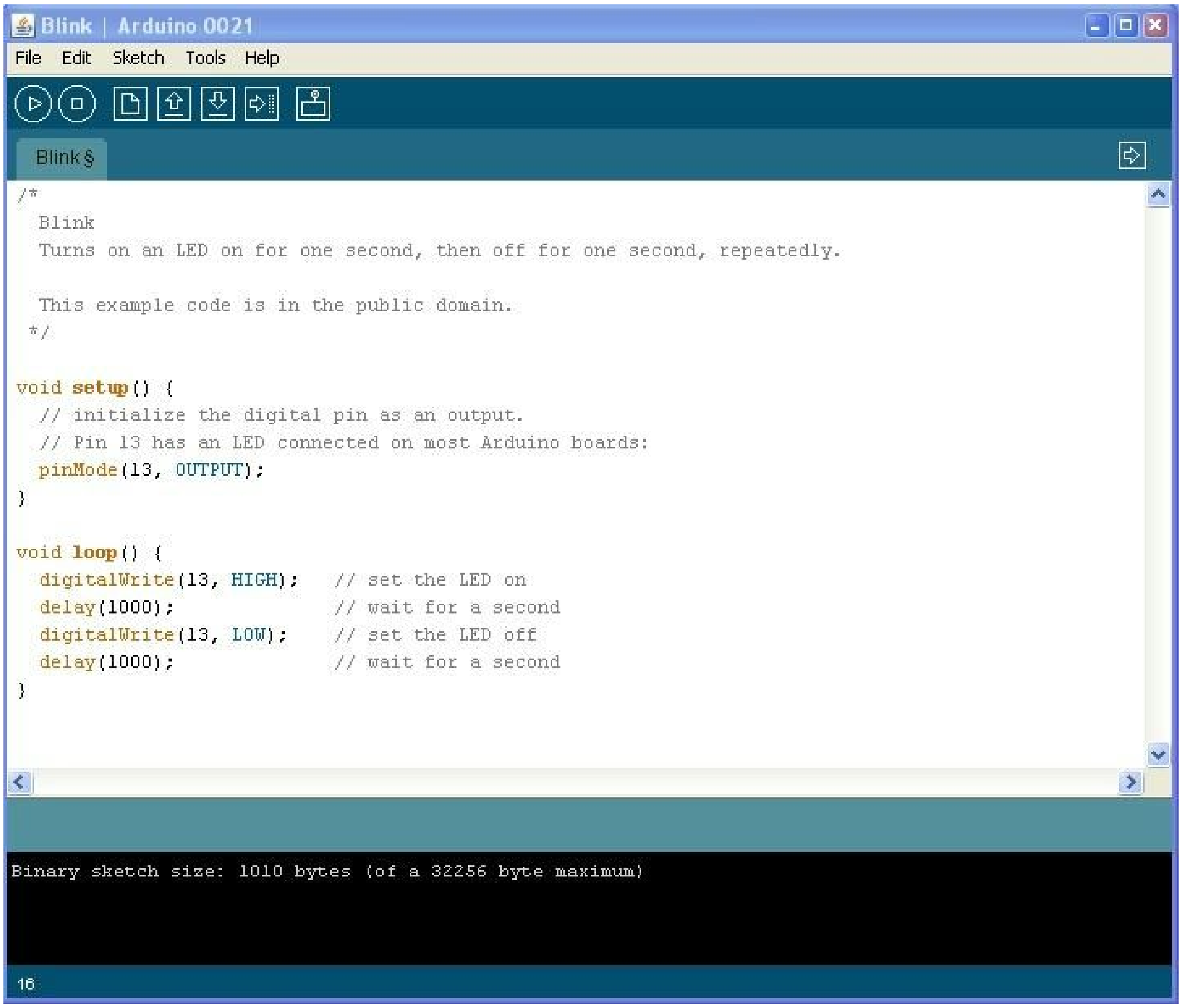


Figure 6.9 - Arduino IDE

The Real Time Operating System divides each task and is controller by the Real Time Operating System scheduler. The Scheduler could be fixed or dynamic giving us the ability to suspend and start task whenever we need to.[13] We first explored the Arduino Interrupt library and Scheduler library but were worried that these libraries don't provide fast execution and management of many time intensive task. So if we decide to go with a Real Time Operating System we need to search for a library that will port to our arduino board easily and not use lots of memory.

	Pros	Cons
Finite State Machine	● better performance (no context switching) ● predicable behavior ● easier implementation ● built in library from Arduino	● higher power consumption
Real Time Operating System	● reusable code ● hard and soft real time ● scalable ● tolerant of hardware change ● lower power consumption	● extra time to set up RTOS ● memory intensive ● extra complications with tasks

Table 6.8: Finite State Machine vs Real Time Operating System

We decided to go with the Real time Operating System. One of the main reasons was the ability to have hard and soft real time. The ability to act fast when it came to powering the coil is a top priority for us and we are not certain we could accomplish that with a Finite State Machine. Hard real time is in a timing situation the deadline has to be reached and Soft real time is in the event that some data can be missed or deadlines missed. These real time approaches seems fit for our task considering that this is a weapon and time of the projectile going through the barrel must be very exact or the whole system will fail. We will be using the hard real time for powering our coils.

Another big aspect was that real time operating systems are tolerable of hardware change, so in the event that we have to change our microcontroller whether its for memory reason,size, and clock speed we actually have the option too. The real time operating system is isolated from the hardware, it is very unlikely that this would happen but it's good to have that option.

Another reason is power consumption will come very handy considering one of the main objectives of this project is portability. The Microcontroller only needs a supply voltage of 3.3V which is good for the portability access. But it means power consumption must be considered and monitored. Because the real time operating system gives us the ability to put the microcontroller in lower power mode when it's in its idle task. It will greatly reduce the power consumption of the microcontroller versus it always be in the state machine.

We did not use an RTOS because we went with a Single-stage coilgun that uses a firing circuit and not the MCU to power each coil.

6.10.4 Coil Programming Options

Option 1: Time - One method of programing the coils to turn on and off is by telling the microcontroller to wait a certain number of milliseconds before activating the next coil. By doing this, the coils would be timed exactly the same way after each trigger pull. The benefit of doing this is that if the calculations are done perfectly, we would not have to implement the sensors on the gun.

Therefore, the code outline will look something like this: turn on coil one, when the projectile passes through coil one, turn off coil one, turn on coil two.

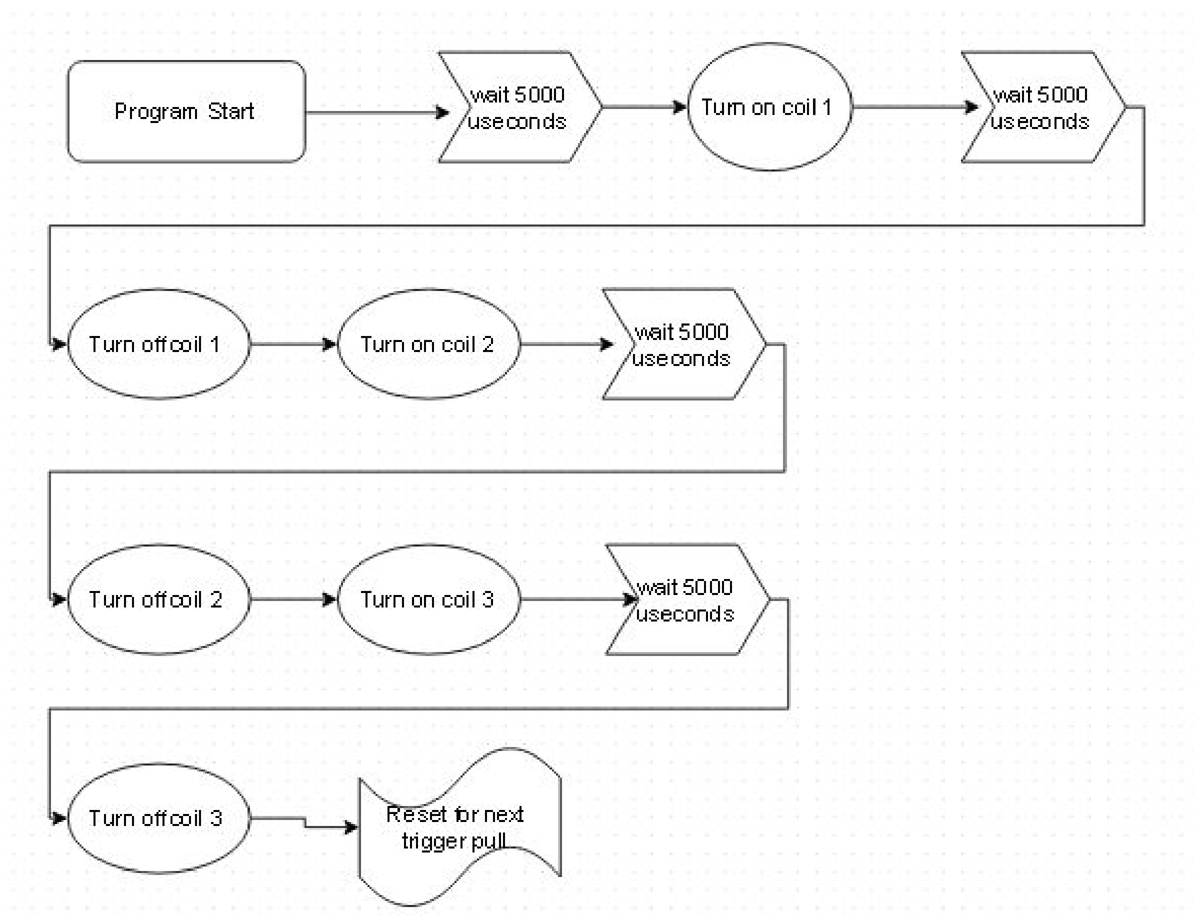


Figure 6.10

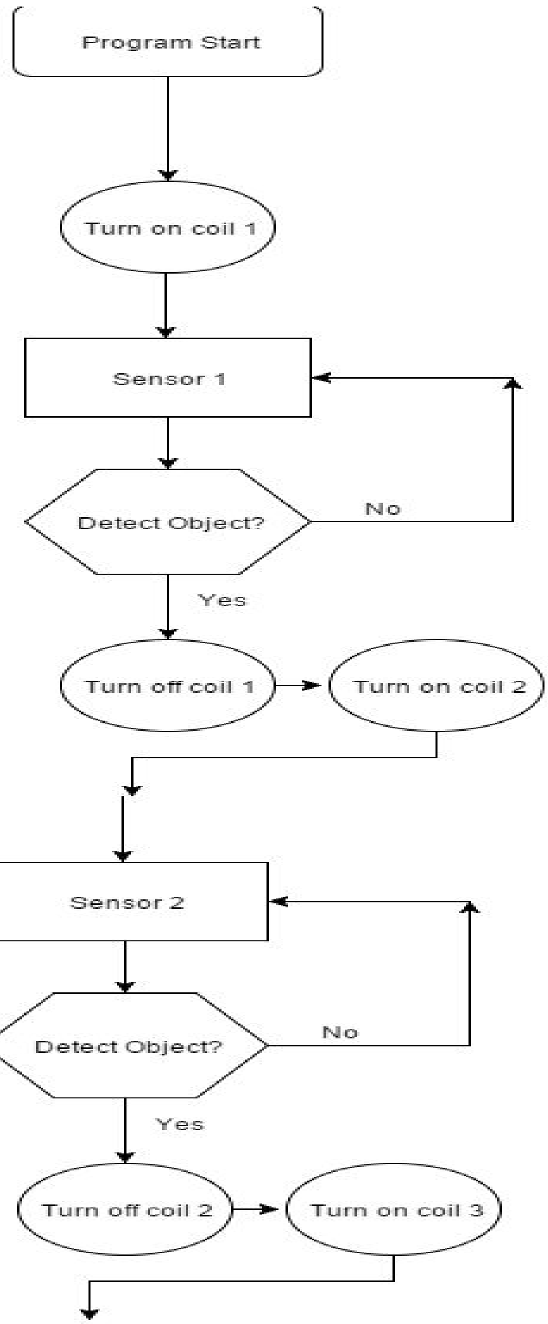
The problem is that finding a time that works for every single shot is near impossible considering all the fluctuations happening with circuits and capacitors. This method would yield a low success rate. Also, notice how this kind of linear coding calls to turn off one coil and then turn on the next. This implies that there will be a delay between the two functions, meaning that the coil may not turn on in time.

Another thing to note is the fact that we are assuming after a certain amount of microseconds after each iteration. However, because we are accelerating a projectile through each coil, the time it takes to travel from one coil to the next will decrease. Therefore, if we were to choose using a timer for the coils, we would have to have extremely precise calculations for each step. Because we are in the planning stages of this project, we chose an arbitrary amount of time for design purposes.

Option 2: Sensors - Theoretically, the previous would work, but the reliance on using a timer to accelerate the projectile into the next coil may lead to a low success rate. Also, the time it takes for the microcontroller to execute each line plays a role because if the time to turn off the previous coil and turn on the next coil is too long, it could result in the projectile not making it to the next coil. However, because our design would implement sensors, we can adjust our code to make it not reliant on time, and rather when the object passes a specific point.

Since we are making this reliant heavily on the sensor, we are relying on the reaction time between the sensor detecting the object, the sensor then sending a signal through to the microcontroller and then the microcontroller doing the proper procedures to turn on the next coil.

Modifying the previous code from above, it would look something like this shown in figure **6.11** on the next page.



Program Start
Turn on coil 1
Sensor 1
Detect Object?
No
Yes
Turn off coil 1
Turn on coil 2
Sensor 2
Detect Object?
No
Yes
Turn off coil 2
Turn on coil 3

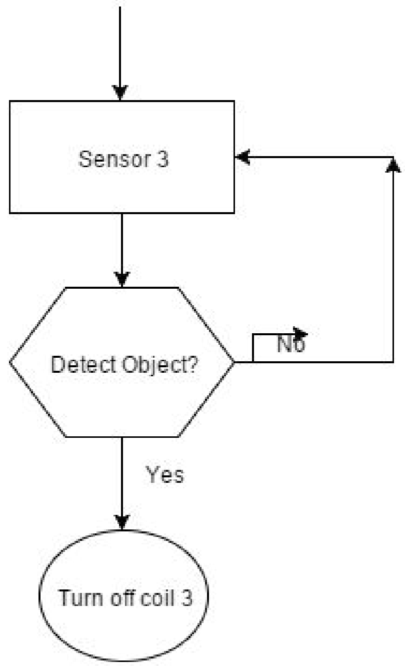


Figure 6.11:

This kind of code has a short side to it, when the sensor detects the projectile, it has to turn on the coil and turn off the coil almost in the next instant. This makes the code very dependent on the reaction time of the sensors, and turns the problem from a software issue to a hardware issue.

Option 3: Sensors and Time - Before we explain the thought process behind this method for the coils, it’s best to do a recap of the downsides of the first two methods. If we have no sensors at all, and we rely solely on our accurate calculations in order to determine when a coil should be turned on or off, we run into the problem that maybe the projectile intending to come through the barrel at a certain time came a split second slower.

Despite perfect calculations, unforeseen factors can affect the speed of the projectile at certain points. Maybe the charging of the capacitor got slightly delayed or maybe the next projectile that gets loaded in is slightly different from the one before and thus changes our calculations. Either way, it can result on turning on the coils at the wrong times. On the other hand, if we rely on the sensors to determine when we should turn on or off the coils. We then rely on the time it takes for the sensor to send a signal to the microcontroller, then the time it takes for the microcontroller to perform the necessary operations to turn on and off the appropriate coils.

If the reaction time is too long, then the projectile will stay stuck in the coil who's sensor it just passed through because instead of accelerating the projectile out, the coil will instead begin to attract it.

Therefore, in order to circumvent both scenarios, the idea would be to use a mixture of the two methods mentioned above. We would still implement the sensors in order to signal at what point the projectile is at, but we would also use time in order to calculate the velocity and acceleration of the projectile. The thought process would go as follows (flowchart shown in **figure 6.11)**

1. Fire projectile
2. Each sensor pass, calculate speed of the projectile
3. Turn on coils based on speed
4. Repeat step 2 until projectile exits the barrel
5. Turn off all the coils (safety measure)

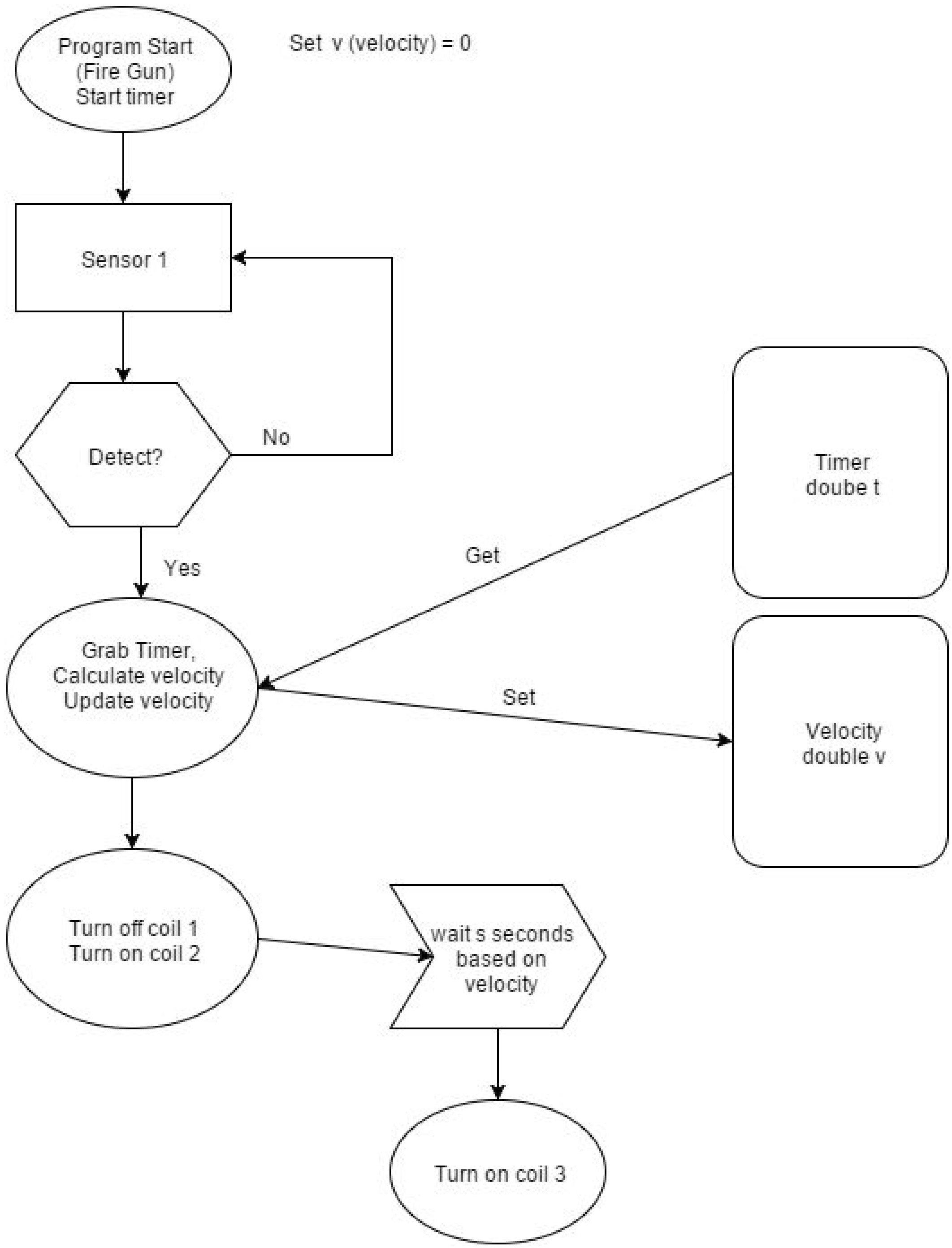


Figure 6.12

Final Decision (Sensors vs Time) - After weighing the pros/cons and also using past coilgun projects as a reference we will choose to go with the sensors. The reason behind it is because it feels like it will be more consistent than solely using time, but at the same time, easier to test and implement than using both sensors and timing. The code for using the sensors is straightforward, and the sensor may be fast enough to where we don't have to compensate for the possible lag.

However, if we feel that our sensors response to microcontroller and back to the coils is too slow and achieves enough errors in the testing process. Then we shall proceed with using the hybrid option of implementing sensors and timing into our code.

6.10.5 Powering the Coils

Powering the coils will begin when the capacitors are full and the user presses the trigger. The programmer end of the coil faces the huge problem of timing. When we turn off and on each coil can potentially affect if the projectile will come out of the gun or stay stuck in there.

There are two main methods of turning on and off the coils. From there, we will use sensors and timers to determine when to turn on or off the coils.

The first method is by turning all the coils on, and one by one, turning off each coil. This is a feasible method because if at time = 0 seconds, if all coils are turned on, then they will all be accelerating the projectile. When the projectile passes the midpoint of the coil or the sensor, we would turn off that specific coil until the projectile exits the barrel.

There are many advantages to designing this from a programming perspective. For one, because we turn all of them on and then off one by one, this makes programming this a lot easier since it will be a straight-forward task. However, this style creates a design issue on the hardware end. Because of the fact that we are turning all the coils on at once rather than one by one, we will be using a lot of power in order to get the job done. This can prove to be a power inefficient gun should we design it in this manner.

The other problem we see happening is that the coils that are on from a large distance away from the projectile (more than one coil's length) will not be as effective at accelerating the projectile as the coils that are closer to the projectile. This adds even more to the fact that we are wasting energy that could be allocated to more efficient means.

The second way of dealing with the system of coils is to only turn on the coils we need. The first coil must be turned on in order for the projectile to go through it. Immediately after the projectile gets past the first coil, that coil must turn off and the next coil must turn on. If the coil stays on too long after the projectile passes through, the projectile will start to go backwards.

Likewise, if next coil doesn't turn on in time, the projectile will not move at all. If we intend on doing a 'burst' mode, where one trigger pull will fire 3-shots back to back, the timing must be that much more precise. Timing will become everything for this project. If we time the coils right, how the projectile passes through the barrel should look like this:

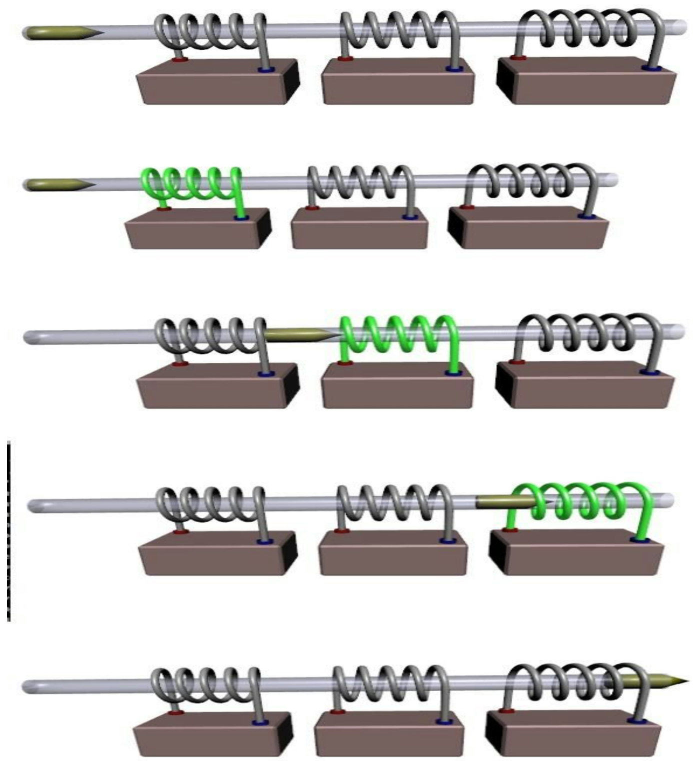


Figure 6.13: Powering of Coil [45]

There are many potential downsides to structuring our software in this style. Versus the "turn on all coils then turn off one-by-one method", this will be more difficult to program because of the fact that we have to time the coils perfectly. If there is a period where none of the coils are on, then the coil will no longer be accelerating. This makes this more programming intensive than the initial style.

On the other hand, it does make powering the coils more efficient. We will be wasting less energy to turn on each coil on then off one at a time versus turning on all the coils at once. Because of this, we feel that it is better to program the microcontroller to interact with the coils in this fashion.

For the upcoming sections relating to programming, we will discuss the possible methods that we will use in order to time the coils correctly, write out our logic reasoning for why this is a possible solution, and appropriate pseudo-code and UML diagrams to properly support the code. We will discuss the pros and cons of each solution and our likelihood of implementing it when we create the coil gun in the spring. Note that in our flowcharts, diagrams and pseudocode, we are creating a three-coil system gun.

However, we have researched guns that reach as many as twenty-three coils. We feel that because more coils means the same code iterated over and over, we feel that for our plans, coding and drawing out a three-coil system gun will be sufficient on paper.

Threads and parallel programming is a powerful tool because it allows us to be able to execute multiple tasks at once. The Arduino library has a built in multi threading but it is very limited. Because we are not performing a lot of task we believe we will be using a RTOS to handle multiple threads in a safer way. We begin to look around for options that were open source because of the budget we were presented with. We discovered the FreeRTOS when looking for popular kernels on the ARM-Cortex M3. It gives us the ability to run multiple threads or tasks, mutexes, semaphores and software timers.

Having multiple event synchronization allows us to do all kinds of testing with our programming to see what implementation runs best. From some research on the FreeRTOS we saw that it is known to have very small memory footprint, low overhead, and very fast execution. But memory was something we had to consider and very important in our process. The Arduino Due has 96KB SRAM and from some researching we discovered that the scheduler uses 236 bytes and cost 64 bytes for each task. That gives us plenty of wiggle room. [46]

RTOS scheduler controls what task to run and when to suspend that task. RTOS scheduler uses priority to handle multi task scheduling. A low number in the scheduler means a low priority and high numbers means a higher priority. If the priorities are the same then a round robin is implemented between those task so one task does not hog all the resources.[9] Sensor must be read on a very strict schedule or we will have timing issues with the readings. We will create a very high priority task in reading the sensor data. We have multiple sensors so creating a task for each sensor data is possible because each sensor will be read through its own analog line.

Picking the priorities for each sensor will be finalized after some actual testing. Our initial approach is for each task to have the same priority. The Scheduler will undergo a round robin in this case where CPU time will be shared among the task. The amount of CPU time will be determined by the engineer and will be determined and adjusted during testing. The round robin will allow each task to read the sensor data and determine if the coil needs to be powered.

When a sensor detects the projectile an interrupt will be triggered to power the coil. Also when an interrupt is caused by the trigger then we can start the round robin of task that reads sensor data. Interrupts have their own set of priorities depending on what we set them as. The priorities are also subject to change based on testing. At this point we have the basic outline of how the powering of coils is.

FreeRTOS comes up event synchronization task that help ensure safety between all these tasks and interrupts. We will be using a semaphore which is a features of RTOS. A Semaphore is simply a variable that is used to control multiple process. When the semaphore is not available the task the task is simply blocked and waiting for that interrupt to be triggered. When the interrupt is triggered we signal the semaphore and unblocks the task. We envision this process to happen uniquely with each task. When the interrupt associated with the task is signaled then we begin powering the coil that corresponds with that task. We envision the same process with the trigger interrupt. Visual explanation of this process is in **Figure 6.14.**

We see the wide range of abilities we have to control our coilgun with the microcontroller. FreeRTOS has created a ready to go library for the Arduino Due making it easy for us to make all the function calls we need to create a task, create interrupts, and creating a semaphore.

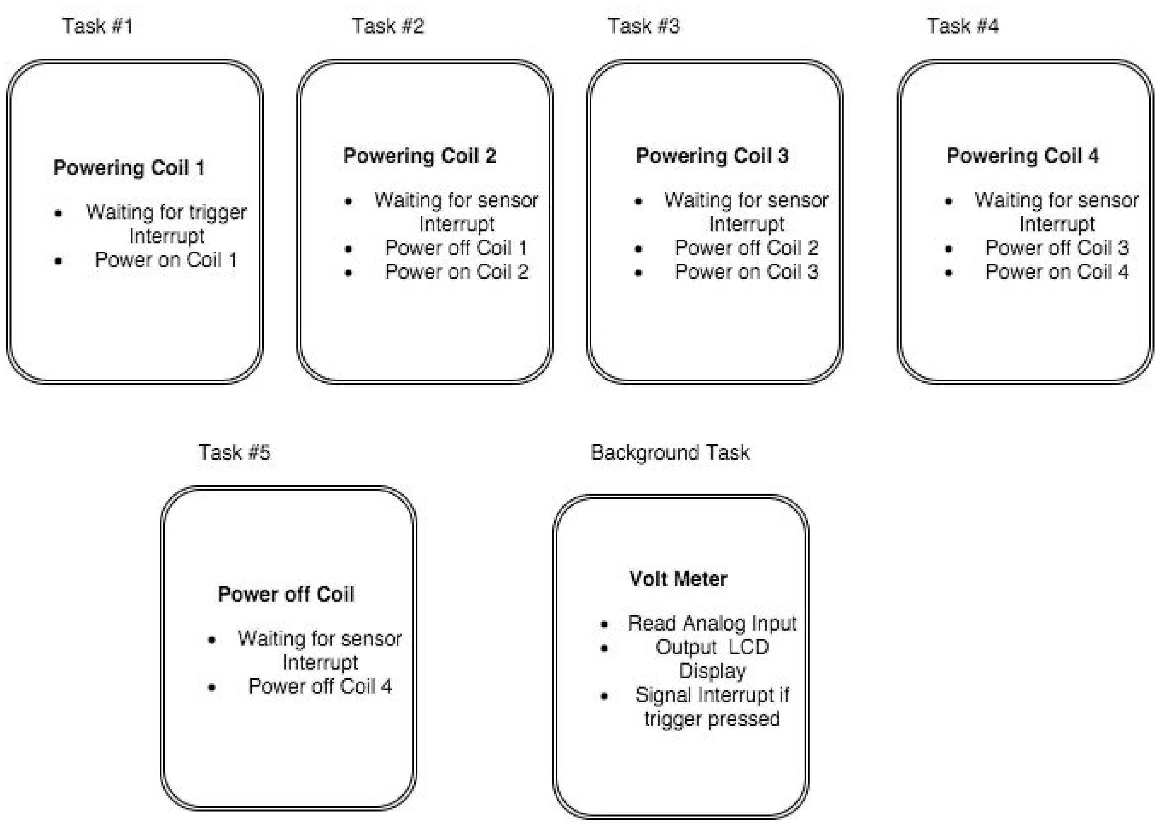


Figure 6.14: Tasks

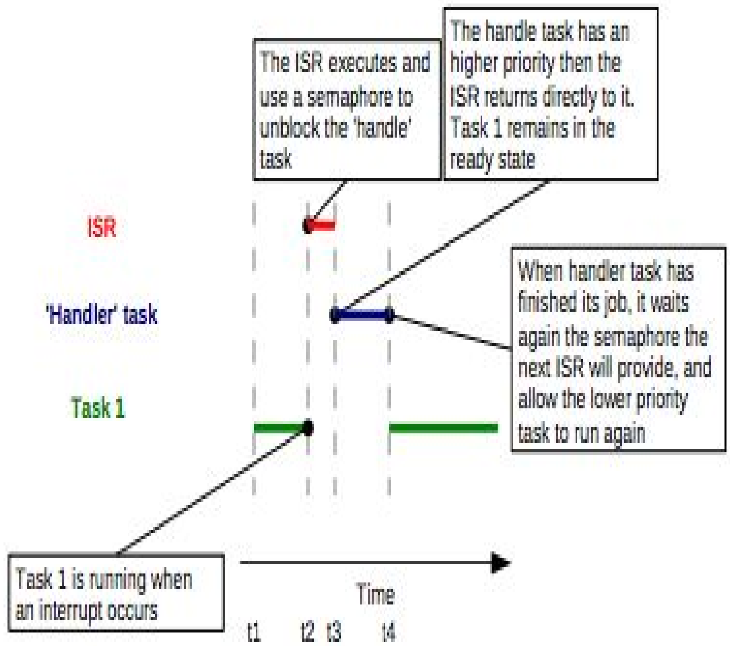


Figure 6.15: Semaphores
(FreeRTOS Datasheet)

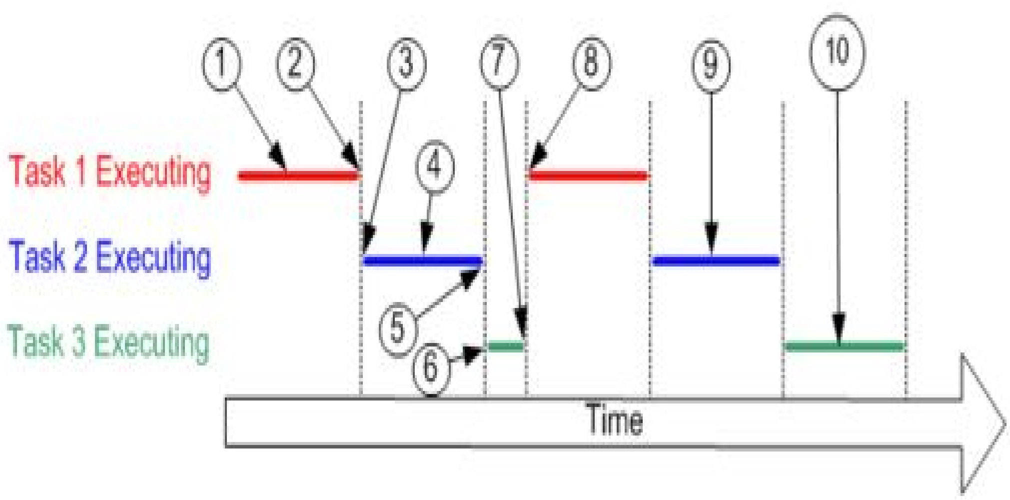


Figure 6.16: Priority
(FreeRTOS Datasheet)

6.10.6 AC/DC Conversion for Microcontroller

The arduino due has a built in ADC converter. Giving us the ability to read in the analog data from Capacitor/Battery without using extra hardware. We will have 16 12-bit ADC inputs giving us a wide range of data we can output to our LCD Display. We will be utilizing one of the lines to read in the capacitors and 4 other lines for the 4 sensors we will be using for each coil. Because we are using the built-in Arduino ADC converter we can use its built in calls.

- analogReadResolution()
- analogRead()

[46]
Speed of the analog reads are important seeing that sensor data will be coming through 4 lines. From some research we see that the analogRead() seems to be the faster of the two. It reads at about 40uS per sample at a 1MHz clock which is impressive but has the possibility of speeding that up. First adjustment is made to the register ADC Mode Register by changing its default value to 2 we can speed up that sample rate to 3.97 uS which 10x improvement. The next adjustment is the FREERUN flag which puts the ADC into continuous mode. This improves the sample rate to 3.12 uS. Third adjustment is to increase resolution to 12 which makes a minor improvement of 3.11 uS sample rate but still an improvement. [47]

Final adjustment is to not allow the ADC to disable itself after every conversion because we want data in real time there is no need for this. This improves the sample rate to 1.79uS giving us 20x improvement from our original 40uS per sample. This just goes to show by researching and digging around we have the ability to push the onboard ADC to must better accuracy and sample rate. This gives us the ability to make 526000 samples per second at 10kHz and 50kHz shown below:[47]

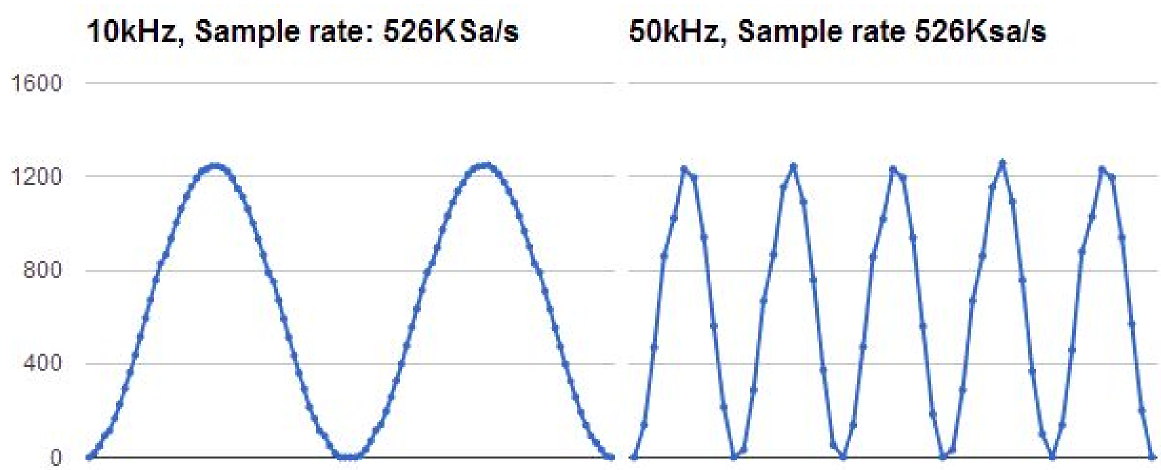


Figure 6.17: Sampling Rate[47]

One drawback in the onboard ADC reading is noise and accuracy. We cannot simply just read a sample we have to take into account that there will be errors in the measurement. On top of that the ADC also has non-linearity, which means physical imperfections will occur and we must take this into account in our software design. The goal to achieve an accurate reading for the Arduino Due analog inputs is a ½ LSB. LSB is 1 count of the ADC which represents analog quantity equal to one half of the analog resolution.[47] The analog resolution for the Arduino Due is twelve bits as stated before but because of noise we actually only have ten bits for the resolution. Since we have six error sources we will still see about three LSB with the ½ LSB goal which is a serious drawback when it comes to accuracy.

On top of that because there is a drastic temperature change in the coil gun that could cause even more error. This is called temperature drift and we can use erikson's law to measure temperature drift. With our temperature sensor we can monitor this. We need to find a way to correct some of these errors or our reading will be not be accurate enough to use. One technique to use is calibration. Gain and offset can be usually calibrated out using simple linear correction.

TI ADS1110 features a much high resolution and accuracy then the onboard Arduino Due ADC converter which is why we choose it as a backup. One reason the accuracy on the ADS1110 is better than the Arduino Due is the ADS1110 self-calibrates. We trade-off the amount of samples we get per second but that tradeoff will only give the user less samples to the LCD display causing a slight delay to when the capacitors are full. This is a tradeoff that we can afford but accuracy is something we cannot afford to lose. So if we feel as if the Arduino Due accuracy is too far off we can substitute the ADS1110 as our ADC converter since we know that its reading will be accurate.

The Self-calibration system in the ADS1110 operates continuously and cannot be adjusted by the user. As you can see the in figure X.X.X the LSB of the at a PGM = 8 which is the ADS1110 highest form of sample rate holds a 60% of LSB which is still higher than our desired ½ LSB but if we drop the sample rate then we can achieve the LSB we desire.[48] Total error of the ADS1110 shown in the error ranges from .2 - .6 mV depending on our sample rate PGA which is much better than the Arduino Due total error.[48] Which proves that with a little software design we can achieve more accurate readings then the Arduino Due ADC which makes it a sufficient backup.

ADS1110 communicates with the Arduino Due through I2C**.** It acts as a slave device at all times allowing the Arduino Due to read and write data as it pleases.

The communication between act as any two devices that communicate through I2C. Master Devices(Due) issues a start command meaning its wants to communicate with the Slave Device (ADS1110). An address is then sent to the slave so it knows if the master wants to read or write. Then a byte, whether it is an address to read from or data to write, is transferred and the slave returns an acknowledge that it received that byte.

6.10.7 Temperature Sensors

The process of communicating with the Temperature sensors and Microcontroller is very similar to that of the ADC converter ADS1110. It will be using I2C communication and we will be only reading data from it since we will always be monitoring the temperature of the sensor the chip must be awake. We will implement the sensor in the barrel as a high priority because if temperature gets too high we need to turn off the whole system. The second sensor near the microcontroller that monitors the heat coming through the ADC converter will simply monitor the temperature and output it to the LCD display. When the temperature gets too high we will warn the user that the data on the voltmeter may be wrong while we let the microcontroller correctly adjust all the data

6.10.8 Volt Meter

The goal is to present the user when the capacitors are full. We will need analog input from the capacitor to check the status at real time. This task is also a gateway into powering the coil because the user can only fire the gun if the capacitors are full

There can be different ways in which we prevent the trigger from setting off the projectile when the capacitors are not in full power. One way, is to stay within this task until the capacitors are full and at that time allow the the interrupt to run to begin the RTOS scheduler. The upside is that it would be more software-end than hardware end.

Another way to ensure safety is to have some form of hardware that acts as a lock, like the safety lock on a gun. The advantage with this way is that we would not have to rely on synchronization as much as there would be a physical lock to prevent us from pulling the trigger. The challenger here versus putting locks in the code is that this would be more tasking on the hardware end.

Adafruit provides a library for the arduino due, the library was written in C which will allow us to use the LCD Shield by simply calling the functions they have created:

- begin()

- print()
- setCursor
- setBackLight()

[8]
Easy to use library gives us the ability to implement the screen with very little code. We will be outputting the capacitor status, each analog line of the sensors, and velocity of the projectile through the barrel. We only have 16x2 LCD display but the LCD display comes with GPIO buttons that will allow us to switch between the screens. We have about 20 SDA/SCL lines for I2C and so far we only have the possibility of the alternative ADC converter using one of those lines so the possibility of implementing buttons through I2C communication is very possible and memory is the only thing that could hold us back.

One of the reason we choose this LCD display is only uses 2 I2C pins less than the initial 5-6 I2C pins we assumed we would need. Each screen will hold one of the previous options. These GPIO buttons use I2C communication. Button1 will share the capacitance status, Button 2 will show real time data of each sensor, and Button 3 will show performance including velocity of the projectile from another sensor. The buttons will fire low priority interrupt to adjust the screen to another performance metric and each of these screen will become tasks in our RTOS design.

We will be communicating with the LCD display just as we are communicating with the ADS1110 ADC converter. With the LCD display acting as a slave device to the Arduino Due. We will operate at the fastest I2C data rate because we want data to be presented at real time. The communication between the will be writing data to the LCD display and reading the inputs of the GPIO buttons. We have the opportunity to utilize some of the object orientated paradigm of C++ since we have multiple buttons that react pretty similar only differing in what task they choose. We can create a base class GPIOInterrupt and create a derived class for each GPIO button. This is valuable because it will make adding new buttons and getting rid of new buttons much easier and will be much more friendly to our memory then just creating 4 multiple GPIO interrupts with a function programming paradigm.

7 Testing

7.1 Project Testing

Ideally, this gun will be able to accelerate a projectile outward at a high speed. In order to be able to test this, we need a fairly open environment in case anything goes wrong. We propose to have a controlled area with no one within a 30 feet radius in front of the coil gun for safety purposes. (We’ve seen coilguns where the projectile successfully fired from the gun, but couldn’t find the projectile due to its random path). Luckily, around the University of Central Florida, there's a lot of nature trails and woods that very few people walk through, making it the ideal open environment to test our gun.

The testing will come in (3 stages): testing if the gun works, testing its range and accuracy and testing its burst-mode.

Stage 1: This is the initial stage in order to prove that our gun works overall. The test will be fairly simple as we will simply fire the gun at a target 5 feet away. If we can see the projectile come out, then we have at base value a working gun.

Stage 2: This stage will be to test one of our reach goals and to see the limits of our working gun. This involves placing a target away from our gun at increments of 5 feet each time, hoping that with each placement, we hit our target. The goal hopefully will be that our gun can hit a target at least 50 feet(?) away.

Stage 3: The burst-mode stage is another reach-goal of ours in order to try to compete against actual guns. We want to be able to design a gun similar to an assault rifle, accurate at midrange and able to fire fast. Our reach-goal design is to be able to incorporate burst-mode, so we will only be testing to see if the gun fires three projectiles with one trigger pull. We are aware that the quick rate of fire will result in a kickback, which will result in a massive decrease in accuracy. However, we are only concerned only about the fire-rate for this test.

To be able to test the accuracy of the gun between all stages of the testing when we present the project to the professor, we will be using a standard shooting range target. Academy Sports + Outdoors has a website that provides a range of different types of targets to use. The one shown below in **figure 7.1** sells in packs of ten for $3.99.

Figure 7.1 - Shooting Target

As stated before, the objective is to be able to design a fairly accurate, reasonably distanced gun for a low cost. That being said, none of the team members for this project would consider themselves as professional shooters. On top of that, the wind can deviate the path of the shot, though the odds of that happening are very unlikely.

Therefore, we propose to test accuracy with the user firing from prone position. The four types of shooting positions with a rifle is prone, sitting, kneeling and standing. Prone position is when the person is shooting when his entire body, head first is on the ground. It is a common position for snipers to shoot from since it allows the shooter to stay extremely still. An image of a person in this position is shown in **figure 7.2** below. Shooting from prone position is best because that position provides the most accuracy. Also, we will be putting the human-figure shooting target at ground level.

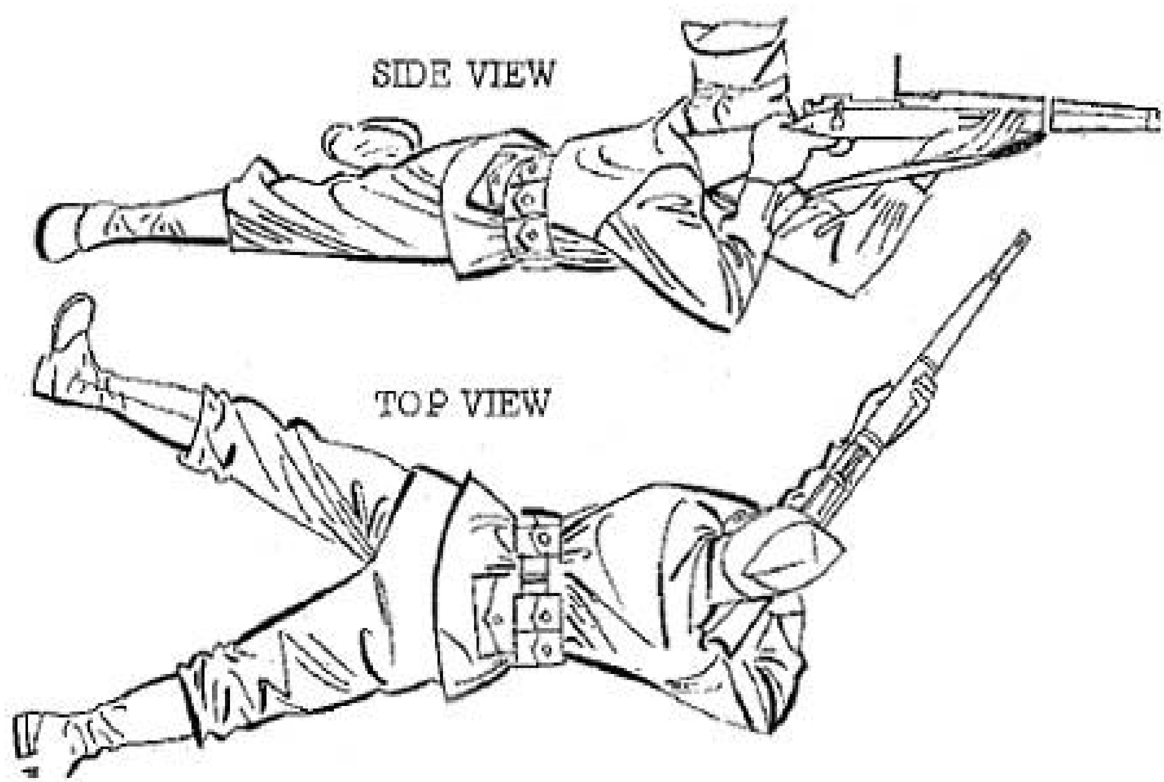


Figure 7.2 - Illustration of Prone Position
(Taken From Reddit.com)

However, we also propose to test the gun by buying or developing a stand specifically for the gun and attaching a cheap laser sight on the end of the barrel to see where the bullet should ideally hit. The height of the stand should be based upon the height of how we plan on setting up the target. If we plan to use the frame that holds the capacitors as the point where we attach the stand to, and assuming that the target's center is 9 inches high (according to academy.com dimensions of the target is 12 inches in width and 18 inches in height), the stand should be at the height where the center of the target is minus about four to five inches. This is because our planned height of the frame for the capacitor is about four inches (as explained in the section of frames).

7.1.1 Creating the Stand

As mentioned before, because of the lack of shooting experience from all four team members, there is a good chance we will miss, even if the gun performs perfectly. Therefore, we wish to attach the gun onto a tripod to ensure the accuracy of the gun.

Guns designed for accuracy such as sniper rifles have always had the option to have a tripod attachment on it. In the case of heavy machine guns (HMGS) which have practically no accuracy, the tripod takes away the burden from the user of carrying something heavy. It also helps control the burst for the HMG. An example of a tripod attachment taken from Ebay can be shown in **figure 7.3** below .

Figure 7.3 - Hammers Telescopic Shooting Tripod

However, since buying tripods are expensive and adds a cost to a budget that is already fairly constrained, we have to build a tripod or use a tripod that is in our possession. Luckily for us, one of our members possess a tripod that is meant to hold up a speaker. An image of this stand is in **figure 7.4** below

Figure 7.4 - Proposed Tripod to be Used

Most tripods are designed to be able to secure tightly the gun in order to provide stability. In the case of ours, we plan to do little design to fasten the gun onto the tripod. At best, we plan to use some sort of strap onto the top of tripod. The reasoning behind not having the most secure tripod is because the coilgun naturally has no recoil on it. As mentioned before, since it's using electromagnetism instead of gunpowder to accelerate a bullet, there should be little to no kickback from the gun.

7.1.2 Laser Sight

Though the laser sight is an unplanned attachment on the gun, for testing purposes it is necessary. If the purpose of the tripod is to provide general stability when aiming and shooting the gun, the laser sight's purpose is to show where the projectile should land. Laser sights is a common attachment on military rifles and guns due to the fact that they provide another boost of accuracy on the gun. The only downside for on-field use is that the enemy can see the laser sights as well.

For our coilgun, we do not plan on hooking up the laser sight to the microcontroller as another feature to the gun. Instead, the plan is to buy a toy laser sight that turns on and off with the push of a button and tape it onto the end of the barrel.

Buying a laser attachment is actually pretty cheap and we will be using those that are typically placed on airsoft guns. The one we found on Ebay is called Swiss Arms Airsoft Optics Accessory Kit for $13.99. Displayed below in **figure 7.5** it comes with not only a laser sight but a red dot reflex sight that could also be used on the gun to allow us to experiment with other ways of testing out our product.

Figure 7.5 - Swiss Arms Airsoft Optics Kit (shown from Ebay)

7.2 Hardware Testing

Each component of the coil plays a vital role in the success of the gun. In order to ensure functionality of each component, we must test it out before we implement it into our gun.

Testing the microcontroller hardware will involve testing whether we program it with the programming port, communication lines with other devices (I2C,SPI,UART), clock frequency, and accuracy of analog line/digital lines. Testing hardware when it comes to microcontroller is a much more accurate representation then checking with the software. The best way to test the clock frequency and make sure we are getting peak performance is to use a oscilloscope. Typically you see an output in **Figure 7.6** that sine wave to represent that the clock is running.

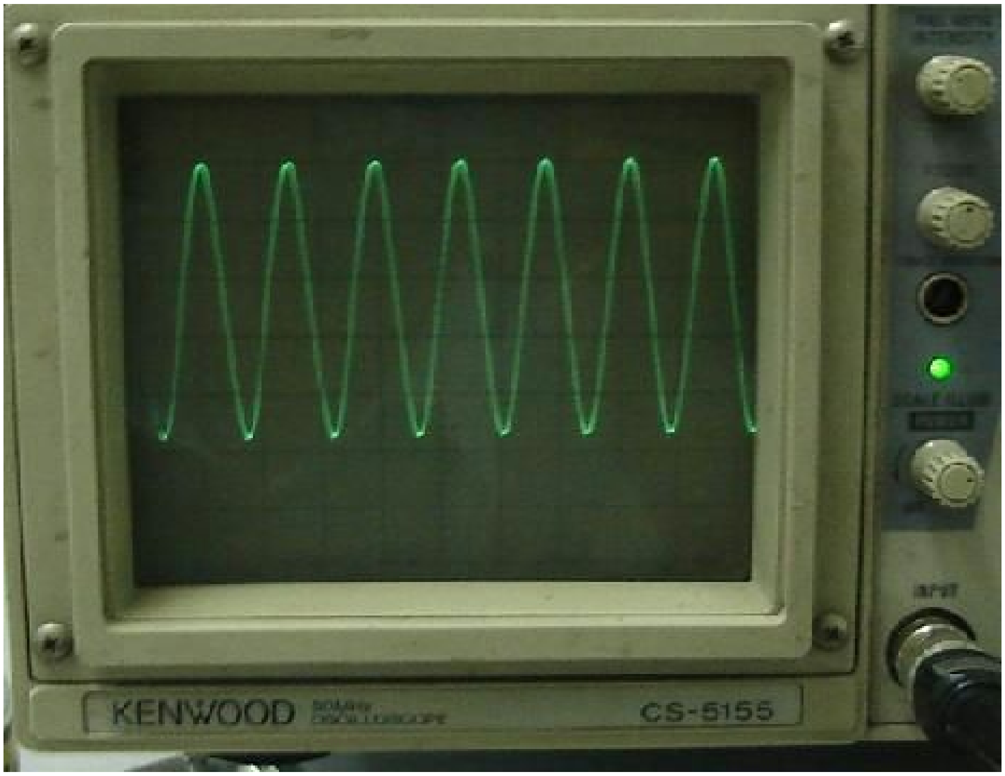


Figure 7.6: Crystal Output[49]

Next we can use a meter to test the actual frequency of the clock. The last option to the test the clock frequency is to use what is called a crystal checker. It is simply turns an led on if the clock is running. To test whether the communication lines are working we can use a logic analyzers. Logic analyzer will read the data across the I2C lines and from there we can double check that the data being passed through is correct data our software is seeing. We can see in **figure 7.7** what the data would be like for the data line and clock line of the I2C.

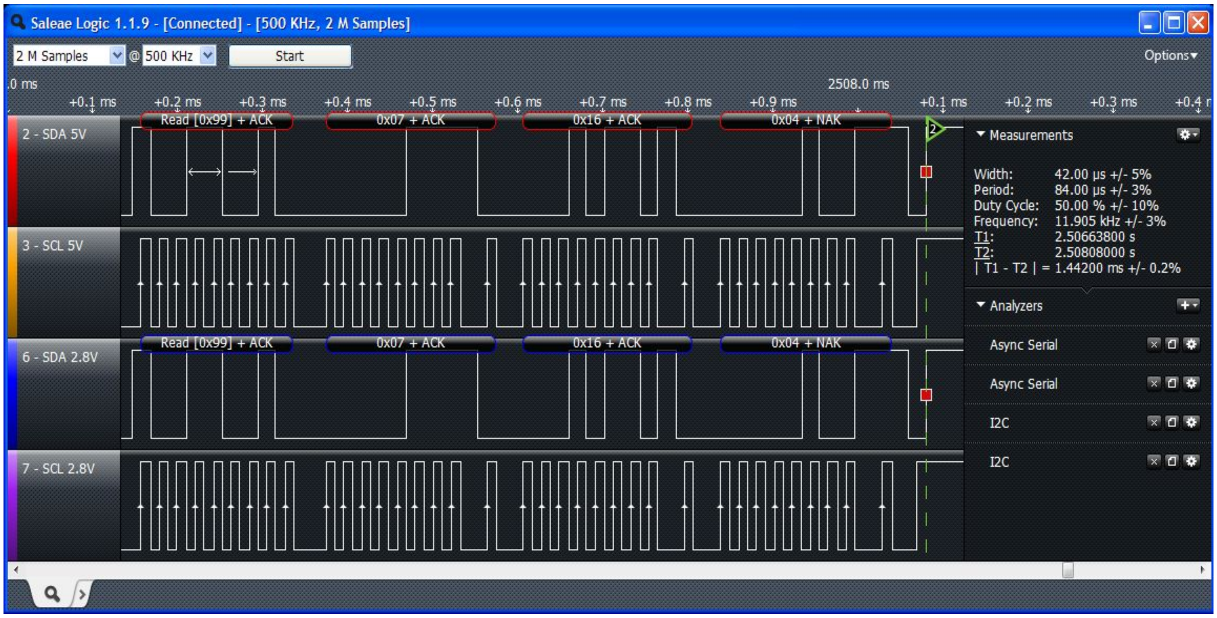


Figure 7.7: Example Logic Analyzer I2C (Reference 49)

On top of that to test the Interrupts and GPIO buttons we can use a meter to see if the test point turns on when we push a button or when the Interrupt is generated. Next we want to test the accuracy of our analog lines and digital lines. The first is to use a voltage reference we can probe that line to see the voltage we are getting in our software is the voltage we are getting on our voltmeter.

7.3 Software Testing

To guarantee that the coil gun will work, the software will prove to be equally as important as testing all the components of the gun. There are many aspects of the software that we will be testing in separate stages.

Because we are currently in the planning stages of developing the coil gun, we will be mainly be basing our results off the outputs the IDE we use to develop the code give us. After we feel that the code performs as expected, we will port it onto the Arduino board, and use basic LED lights to see if the right voltages are being outputted at the right times. Ideally we will be writing up all possible codes for our gun and testing each of them and implementing what we feel to be the best solution to our design.

7.3.1 Testing Software Design 1 : Using Time

A recap of this design: the idea for this is that upon the trigger being pulled, it turns on immediately the first coil, then a few milliseconds later, the coil after until finally the projectile exits the barrel. Since the idea of this design is to do everything based on precise calculations, we will simply run print statements at each of the coils and at what time the command is issued. Basing our flow chart from above, the testing plan for this solution would look something like this:

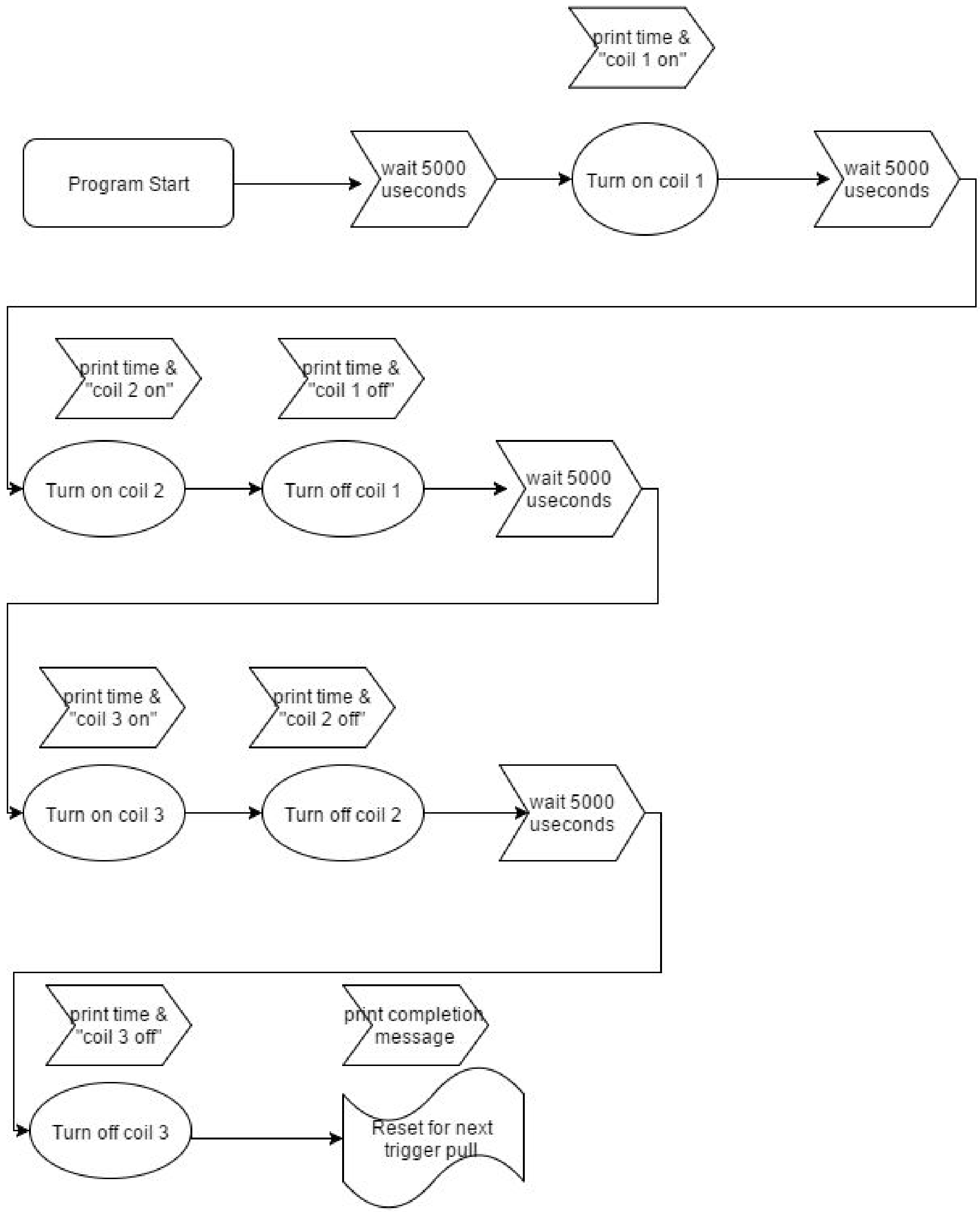


Figure 7.8

By having print statements at each process, we can begin to simulate on the computer when certain coils will be turned on and when. If done perfectly, the output should show very little delay between how the “wait 5000 useconds” step to the “turn/on coil” step.

However, even if testing on the IDE shows these results, it may not show the actual delay on the Arduino microcontroller. This is why we would use LED lights to at the desired ports to simulate the coils properly being turned on. If the code works as expected, there should feel like there is no delay between lighting up each of the lights to the human eye.

Once we feel that this code is functioning properly, the next step would be to implement the coils instead. By this step, we are assuming that the trigger circuit, coils, and capacitors functions as expected by our calculations. If possible, we will use a clear barrel, or a small wooden slot so we can see the projectile pass through each of the coils. If the code work as expected, the projectile will immediately accelerate out of our test barrel. We will also have a video camera running to record our experiments in order to help us tweak the code to time the coils better.

7.3.2 Testing Software Design 2: Powering Coils

While we build the coils and build all the analog circuits, we need a way of testing our RTOS design before the gun is ready. To replicate the coils we will use the LEDS as stated in the last test but set up four LEDs in series just like the coils. Instead of using sensors we will use buttons for each led which replicates each sensor for each coil. When the button is triggered an interrupt should fire according to our design of the tasks. The interrupt will call the Interrupt Service Handle which will power up the LED. This is very similar goal of the coils so if we can achieve success through this test then we can be much more confident in transferring this design to the coils. We will also be able to output this data to the LCD display to also ensure that data is being outputted to display in real time. We also be able to adjust priorities of the task and the priorities of the interrupt so we can have idea of what priorities will accomplish our goal of powering coils.

7.2.3 Testing Software Design 3: ADC conversion

Speed of data and accuracy will be the most important part of AC/DC conversion. So really our test comes down to driving an AC voltage and seeing how fast that conversion rate is. We will begin our testing by applying a small voltage somewhere between 2.5-4.4 We will adjust voltage to test the accuracy and see if the arduino due ADC converter can output accurate readings. This testing must be done early on because it the readings not accurate we will need to reconfigure our ADC converter to use the ADS1110. We will need an oscilloscope to how much bits the Arduino Due ADC actually contains, gain and offset accuracy, what kind of calculations we would need to do in the software design to correct the error, and can we produce the sample rate we believe we can achieve. Specifically we will measure Resolution, Offset error, Gain Error, Resolution Noise, Effective Number of bits, Overvoltage Recovery, and Signal-Noise ratio. These measurements will help with our initial tests to see which ADC converter covers our needs. Once we have achieved that we will enter the next step of testing for the ADC conversion and that's heat. Heat has the potential to cause error in our reading and with the temperature sensor we will be able to monitor the heat throughout different trials. This will allow us to make the correct adjustments to our software design dynamically. Which is important because heat is not a fixed variable, it will fluctuate based on the many variables we have in this high power system. We will also test the ADS1110 side by side with the Arduino Due to measure accuracy versus each other. The ADS1110 will be hooked up through I2C and will run through the same testing we will be doing with the Arduino Due ADC converter.

7.2.4 Testing Software Design 4: Using Timing and Sensors to Calculate Speed

As a recap of the software, instead of immediately turning on the next coil and turning off the current coil, we would estimate the velocity of the projectile and use that to time when to turn on the next coils. The reason behind that is in case the time it takes for the projectile to travel between the sensor and the coil is so fast, we have to already be telling the sensors from the microcontroller to turn on the coil before it even reaches the sensor. It also helps that the ideal time between turning on the first coil and the second coil and the time between the second coil and the third coil is a lot shorter.

Assuming that the sensors still work, (testing for hardware in later sections) the plan of action is to hook up the sensors to the microcontroller and the microcontroller to the computer. Since the software will be designed to wait on a trigger pull when we begin running it, we will simply pass an object by the first sensor, wait a definite amount of seconds, then pass the same object through the second answer. With it being hooked to the computer with the IDE, we would be taking advantage of the print statements. Since the distances between the sensors and the coils should be the same, we could use that to our advantage to estimate the output velocity of the software. For example, for our hypothetical test, if it took two seconds to pass from the first sensor to the second sensor, and the distance is about an inch (since it’s traveling through the coil), we should expect a velocity of 0.75 inches / second. Of course, we’re aware that in the actual testing phase of the gun, the projectile will travel many degrees faster than the numbers we are using, but again, we just want to confirm that the velocity is outputting the correct results.

7.2.5 Testing Software Design 5: Using Temperature Sensor Interrupts

We will do multiple types of testing for the temperature sensor. Because we are using a digital temperature sensor we are going to hook up the sensor first to the microcontroller and make sure that the sensor is communicating over I2C with the microcontroller. We can test that by reading registers and writing registers to see if I2C communication is correct. Next we will test the Interrupt line by hooking it up to a digital line on our microcontroller and applying voltage of between 2.7-5.5 the interrupt should be flipped at a certain point. We can also update the threshold of the interrupt to see how the temperature sensor truly behaves and making sure the interrupt line goes back down after we have dealt with the interrupt. Because the temperature sensor primary use is high temperature fail safe, it will be very hard to test it at high temperatures until we are truly done with our coilgun. But because this is a major operation to our system we won't have to worry too much about the temperature sensors being of high accuracy.

8.0 Administrative Tasks

Because this is a long-term semester project, we wish to complete this project weeks before the presentation day which is around May. Therefore, we will design a system and tasks in order to create a schedule that allows us to finish around the second week of April.

8.1 Schedule / Tasking

Our proposed schedule will hopefully allow us to finish our project two weeks prior to our deadline
January
week 1-2 - Due to the fact much of the fall semester was planning out parts and theoretically hashing out numbers for our design, we plan to go through our calculations thoroughly to make sure our numbers match up to the projectile velocity we desire and that the components needed to create those velocities match that of the components that we plan on buying. We should also be ordering the components as well

week 3-4: Design schematics on software using Matlab and Multisim. We desire to have a simulation functional and working, that way we have something to base our physical design off of in the future.

February
week 1-2 - Test all components that we intend to use, computer engineers should test the capability of the Arduino microcontroller. We want to make sure every product that we ordered works as properly, the microcontroller especially. We need to ensure that the IDE on the computer communicates perfectly with the microcontroller since it’s an extremely important part of the coilgun.

week 3-4: Produce first prototype of the gun, hook up microcontroller, sensors, capacitors, batteries etc. (no frame) Without the frame in tact, we want to make sure the main parts of the gun works perfectly. It also allows us for testing purposes where in the barrel the projectile gets stuck (if it does get suck) and allows the programmers to tweak the timing of the coils to suit the needs of the gun.

March
week 1-2: two tasks: Testing the prototype and building the frame. While testing the gun’s functionality naked (without the frame), we are able to physically see what’s wrong with the gun inside. At the same time, it allows us to modify our frame design since now we can measure the gun’s dimensions and build our frame to be based off it.

week 3-4: Test coilgun with frame built, this should be the easiest part of the development stage for this project. Assuming that the initial testing in the previous stage went well, this should take no more than a day or two. The two week period is a buffer in case we get delayed for any reason.

April
week 1-2: Final touches plus calibration, test for accuracy, range and shooting capability on a standard shooting target. We want to make sure that anything that could possibly go wrong with the coil gun doesn’t go wrong. We will also be using the tripod and attaching the laser sight at the end of the barrel. Ideally these last two weeks will be used solely to optimize the accuracy, velocity, and distance of the gun.

9 Conclusion

From designing this gun, we hope to achieve a portable gun that is able to fire a projectile using electricity and magnetism. Using the wide range of skills we have learned during our electrical and computer engineering we can achieve with this coilgun. Not only that we believe the coilgun can help us apply all the skills we have learned in college to build something quite incredible.

Some of the coursework that will help us with this project will be Electrical Networks, Networks & Systems, Electronics 1, Electronics 2, Electric Machinery, Computer Science 1, Computer Science 2, Digital Signal Processing, Thermo Fluids, Dynamics, Electromagnetic fields, Analog & Digital Communication, Embedded Systems, and Digital Signal Processing. By the end of this project, we hope to be able to reinforce and apply the following skills obtained from our studies:

- embedded programming
- multi-thread programming
- real time operating systems
- high voltage system design
- complex circuit design
- design/build portable proeduct
- integration of electromagnetism with circuitry

On a long term scale, we hope that our design could prove to be applicable in the future when military research dives further down the area of coilguns and railguns. Though we are well aware that until we improve the quality of batteries, it will be awhile before coilguns can take off, we hope that we can push the boundaries of the coilgun design. Because it runs off of electricity and not gunpowder, there are naturally many benefits in a battle scenario. There’s no kickback meaning the user would have more consistent shots and it’s quieter compared to traditional military guns, making it useful for semi-covert scenarios. Figure **9.1** is a picture of the General Atomics Blitzer System, developed by Boeing, which became the inspiration of our desire to create a coil gun for Senior Design

Figure 9.1 General Atomics Blitzer System (public domain)

10 Acknowledgements

We would like to thank Boeing for giving us financial support to design this gun. Their help relaxed our budget on this project. Boeing is a well-known aerospace engineering company that specializes in creating new aircrafts in our industry. They helped donate a contribution of four hundred dollars to our project and we are very much grateful for this opportunity that they have provided us with. We provide utmost assurance that with their contribution, we will optimize the quality of this senior design project and the overall gun.

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Appendix B- Permissions

Site | Theory | Coilguns | Levitators | Projects | Ham Radio — Sitemap

About This Site

Topics: **About**

Barry's Coilgun Designs

1. Home
2. Whats New
3. Overview
4. Site Map
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7. Twitter
8. Disclaimers
9. Copyright
10. Privacy Policy
11. Terms of Use
12. About Barry
13. Links

Copyright

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Permission to Use Pictures from Your Website

ED Eric Dennison <ericd@netdenizen.com>
To: Ian Fuentes; admin@netdenizen.com;

Reply all | Wed 12/9/2015 5:45 PM

Hi Ian,

You have my permission to use the image. Thank you for asking!

-Eric

Eric Dennison
Hanover, NH

IF Ian Fuentes
Hello, My name is Ian Fuentes and I'm an Electrical Engineering student from the University of Central Florida. I am currently working on a senior design project and would like to ask for your pe... Wed 12/9/2015 2:28 PM

Permission to use Pictures from Your Website

IF Ian Fuentes
To: info@tadiranbatteries.de;

Reply all | Wed 12/9/2015 2:18 PM

Hello,

My name is Ian Fuentes and I'm an Electrical Engineering student from the University of Central Florida. I am currently working on senior design project and wanted to requested permission to use the graph showing the leakage current of electrolytic capacitors from http://www.tadiranbatteries.de/pdf/applications/leakage-current-properties-of-modern-electrolytic-capacitors.pdf .

Leakage current properties of modern electrolytic capacitors
Original article published in German by Jens Both, BC Components, 31.08.2001 Power saver Leakage current properties of modern electrolytic capacitors
Read more...

Thank you,
Ian Fuentes

Permission to Print Pictures from Your Website

IF

Ian Fuentes

To: jason.murray@deltaveng.com;

Reply all

Wed 12/9/2015 1:32 PM

Hello,

My name is Ian Fuentes and I'm an Electrical Engineering student from the University of Central Florida. I am currently working on senior design project and wanted to requested permission to use some of the photos that you have on your site, www.deltaveng.com.

Thank you,
Ian Fuentes

Delta-V Engineering

Delta-V Engineering is about making concepts from science fiction become reality. This website details my major projects and explains the processes I followed to ...

Read more...

Barry Hansen <barry@coilgun.info> Today at 2:25 PM

To Daniel

You have my permission to reproduce this image, and any other information you find useful.
Please reference your source in the usual way for your project, nothing special is needed for my sake.
I would be grateful for a copy of your paper after irs complete to help further my education, but it's not required.
Best regards,
Barry Hansen
Seattle, WA
On Dec 9, 2015 10:36 AM, "Daniel" <daniel_bears@yahoo.com> wrote:

> Good Afternoon,
>
> I am an Electrical Engineering Major at the University of Central Florida. I am currently doing a senior design project for my university and I am writing you to ask for permission to reference the photo showing the magnetic field line due to external iron around a coil. The picture is pasted below. Please let me know if this is ok as soon as you can.
>
> Thank you,
> Daniel Bears

RE: Permission

ET Electronics Tutorials <webmaster@electronics-tutorials.ws>
To: Daniel Bears;

Inbox

Hello Daniel,

Firstly, thank you for you email and for asking in advance to use some of my tutorial images as part of your design project. Most people would have just copied them regardless.

As you have kindly asked I would have no objection to you using some of my images as part of your engineering design project, free of charge.

However, I must ask that you correctly reference my tutorials, images and site: www.electronics-tutorials.ws accordingly within your presentations.

Good luck with your course.

Kind regards.
Wayne Storr
webmaster@electronics-tutorials.ws

Appendix C- Matlab

```
function [d_w] = wire_d(AWG)

d_w = .127*92^((36-AWG)/39);

function [B] = B_entry(d1,d2,I,N,x1,x2);
r1 = d1/2*.001;
r2 = d2/2*.001;
x1 = x1*.001;
x2 = x2*.001;
mu = 4*pi*10^-7;
num1 = sqrt(r2^2+x1^2)+r2;
den1 = sqrt(r1^2+x1^2)+r1;
num2 = sqrt(r2^2+x2^2)+r2;
den2 = sqrt(r1^2+x2^2)+r1;
ln_func1 = log(num1/den1)/log(exp(1));
ln_func2 = log(num2/den2)/log(exp(1));
B1 = ((x1*mu*I*N)/(2*(r2-r1)))*ln_func1;
B2 = ((x2*mu*I*N)/(2*(r2-r1)))*ln_func2;
B = B2 - B1;


function [B_m] = B_midpoint(AWG,d1,d2,I,N,l)
% Magnetic Flux Density at front of air filled coil
% B=((mu*j*l)/2)*ln(((r2^2+(l/2)^2)^.5+r2)/((r1^2+(l/2)^2)^.5+r1)
% l is length of coil, r1 and r2 are coil diameters
```

```
% mu for copper is 4*pi*10^-7
d_w = wire_d(AWG);
r1 = d1/2*.001;
r2 = d2/2*.001;
l = l*.001;
mu = 4*pi*10^-7;
A = N*pi*(d_w/2*.001)^2;
j = I/A;
num = sqrt(r2^2+(l/2)^2)+r2;
den = sqrt(r1^2+(l/2)^2)+r1;
ln_func = log(num/den)/log(exp(1));
B_m = (mu*j*l)/2*ln_func;

function [S,S_20] = Onderdonk(AWG,I,deg)
Tm = 1084;
Ta = (deg-32)*5/9;
A = (5*92^((36-AWG)/39))^2;
S = (A/I)^2*log10((Tm - Ta)/(234 + Ta) + 1 )/33;
S_20 = S*.8;

function [L] = inductance(AWG,d1,d2,l)
r1 = d1/2;
r2 = d2/2;
d_w = wire_d(AWG);
N_per_layer = floor(l/d_w);
layers = floor((r2-r1)/d_w);
N = N_per_layer*layers;
B = N_per_layer*d_w*.039;
A = ((r2-r1)/2 + r1)*.039;
C = (d2-d1)*.039;
L = (0.8*(N*A)^2)/(6*A + 9*B + 10*C)*10^-3;
F = pi/4;
rho = 1.68*10^-8; % for copper
n = 0;
c = 0;
l_wire = 0;
while n ~= layers;
 r_layer = ((r1 + d_w/2) + n*d_w)*.001;
 c = 2*pi*r_layer;
 l_layer = c*N_per_layer;
 l_wire = (l_wire + l_layer);
 n = n + 1;
end
l_wire
A = pi*(d_w/2*.001)^2;
R_wire = (rho*l_wire)/A
```