Portable Coilgun

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***Abstract* — The Portable Coilgun is a coilgun that launches projectiles made of ferromagnetic material. This project has military, civilian, and scientific applications and uses. These include defense, electromagnetic rail travel, and magnetic field generation. The project goals include portability, high velocity projectiles, and accuracy. These goals are achieved through the utilization of the concepts of magnetic fields, electronic circuitry, and microcontroller programming.**

***Index Terms* — Coils, Projectiles, Guns, Electromagnetic fields, Microcontrollers,**

I. Introduction

The Portable Coilgun is a handheld coilgun that is capable of accelerating ferromagnetic projectiles to high velocities. The project features a boost converter, capacitor bank, custom firing circuit, custom printed circuit board (PCB), velocity sensors, an LCD, and voltage sensors. The Portable Coilgun was chosen because it provided design and implementation challenges for both Electrical and Computer engineering disciplines. The Portable Coilgun also required knowledge of power electronics, electromagnetic field theory, software development, computer programming, and embedded systems. This project provided challenges to each group member that required direct application of knowledge gained through each group member's engineering coursework. This project also provided each group member with a foundation of experience in group work and working on a team to complete a project, which can be directly applied to a chosen career path.

The Portable Coilgun operates off of a 12V rechargeable battery pack. The battery is connected to a boost converter circuit, which steps up the voltage to a high voltage level. This high voltage is used to charge the capacitor bank that is mounted on the coilgun. The capacitor bank is then discharge through a firing circuit with the use of a silicon-controlled rectifier (SCR). The acceleration of the project is due to the current pulse of the discharge of the capacitor bank. A voltage sensor circuit in the PCB is used to determine the voltage across the capacitor bank and print it on the LCD. The velocity of the projectile is measured using a sensor mounted on the barrel and calculated and printed to the LCD using the PCB.

II. Coilgun

A. Coil

The coil was designed based on the energy calculations computed to meet the velocity requirements for our project. The coil was not designed based on the magnetic field because the coil's time constant and inductance have a greater impact on performance than the generated magnetic field. The coil was designed to meet the parameters that we achieved in simulation of the coil. These parameters were based on the size of the copper conductor used to fabricate the coil.

Enameled copper magnet wire was chosen to fabricate the coil because of its physical properties. One of those properties was insulation because of the enamel, which allowed for a much tighter wound coil and a more concentrated generated magnetic field. Another important property of the conductor used was conductor size. This was chosen to maximize heat dissipation based on the heat generated by current pulse of the discharging of the capacitor bank. The dimensions are designed to result in an inductance that results in the desired time constant.

The coil's inner diameter is determined by the outer diameter of the barrel and the outer diameter is designed to be three times larger than the inner diameter. This is done to maximize the magnetization of the projectile. The coil length is designed and calculated using equation (1). The calculations are then compared with the assumed acceleration distance used to perform the force calculations. Simulations shown in Fig. 1 and 2 were then performed to verify the design of the coil. The coil was fabricated by hand winding it using a jig to match the design dimensions of 14 mm, 42 mm and 52 mm for the inner and outer diameters as well as the length respectfully.

$$L = \frac{0.8(NA)^2}{6I + 9O + 10l} \qquad (1)$$

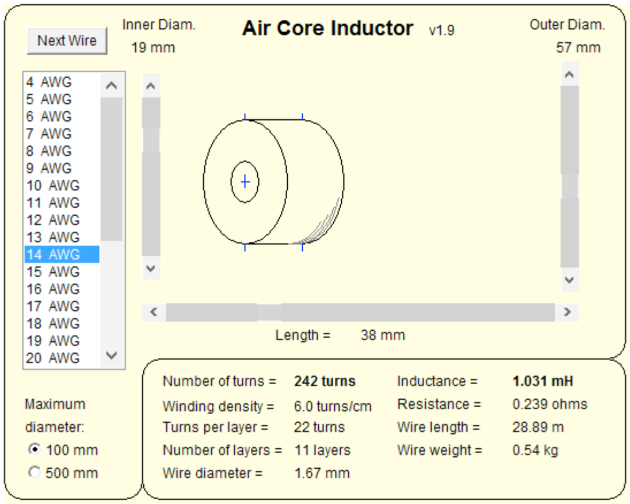

Figure 1 Inductor simulation to verify coil calculations (permission from Barry Hansen)

Figure 2 RLC Simulation showing Current Pulse (Reprinted with permission from Barry Hansen)

The chosen material of the coil was copper magnet wire with an enamel coating. The enamel coating insulates the wire so that there are no shorts in the coil windings. This also allows for a much tighter wound coil, which in turn creates a much more concentrated and dense magnetic field. The next parameter that was taken into account when choosing the magnet wire's gauge was the ability to handle current and heat dissipation. 14 AWG magnet wire was chosen for this coilgun's design because it can handle the amperage that will be flowing through it and it would not get too hot to the point that it melts. Heat dissipation was not as big of a factor to take into account because the coilgun was designed to fire only single shots at a time. This allows the coil time to dissipate heat while the capacitor bank is charging up for a second shot.

B. *Projectile*

A coilgun functions by generating a magnetic field that causes the projectile to accelerate to a desired velocity. For this reason, the projectile that is used must be ferromagnetic. Table 2 below shows the ferromagnetic materials that can be used based on their magnetic properties. For this project, we chose a steel rod because of its properties and low cost. Since this project was designed with portability in mind, it was important that the weight of the coilgun was kept as low as possible. Therefore, the projectile's diameter and length needed to be taken into consideration.

Material	Relative Permeability (μ_r)
Cobalt	250
Nickel	600
Cold Rolled Steel	2,000
Iron (99.8% Pure)	5,000
Iron (99.96% Pure)	280,000

Table 1 Magnetic Property of Materials

The projectile was machined from a two foot long steel rod. The two foot long steel rod was cut into 1/2 the length of the coil. The coil wound was one and one-half inches long. Therefore, we cut the steel rod into ¾ of an inch pieces to be used as projectiles for the coilgun. This was an optimum length based on the mass of the projectile and the magnetic field that will be produced within the ferromagnetic projectile.

C. *Field Generation*

For a coilgun to work, a magnetic field must be generated to accelerate a projectile. The magnetic field is what provided the accelerating force on the projectile. Designing a coil can become a very complex process that requires various complex calculations when a projectile is introduced into the system. This project used a different approach. An approach that focused on the energy and force required to produced the desired acceleration and velocity of the projectile. This was achieved with the use of equations (2) – (5). These calculations were performed assuming a desired muzzle velocity of 100 feet per second and an acceleration distance of 1 inch, which is half the length of the coil. This is done to prevent any pull back effect on the projectile by the coil. Another consideration assumed was an efficiency factor of 5 percent.

$$t_a = \frac{2da}{\Delta v} \quad (2)$$

$$F = \frac{(m * v)}{t_a} \quad (3)$$

$$KE = .05 * PE \quad (4)$$

$$\frac{1}{2}mv^2 = .05(\frac{1}{2}CV^2) \quad (5)$$

Using equations (6) – (8) the coil's inductance and time constant were calculated. These calculations were made based on the requirements for the energy design.

$$I = C\frac{dV}{dt} \quad (6)$$

$$L = \frac{(2PE)}{I^2} \quad (7)$$

$$\tau = \pi\sqrt{LC} \quad (8)$$

Variable	Value	Units
Kinetic Energy	40.824	J
Potential Energy	816.84	J
Force	1071.24	N
Time Constant	6.36	msec
Coil Current	732	A
Coil Inductance	1.031	mH

Table 2 Results of energy and force calculations

D. Barrel

For this coilgun, a barrel made out of PVC was chosen. PVC was chosen because of its non-ferromagnetic properties. It is important to have a non-ferromagnetic material because it will not affect the magnetic field or be affected by it. PVC will eliminate the need for additional design to eliminate eddy currents and therefore simplify the overall design. A one half-inch PVC pipe diameter was chosen over an aluminum barrel because it fit in our coil design and provided enough rigidity to stabilize our coil and overall gun.

The barrel's inner diameter was chosen to closely match the projectile diameter while still allowing it to pass through the barrel with little friction. The walls of the PVC create an air gap between the coil and the projectile, which generates a magnetic field. The smaller the gap between the coil and the projectile, the more efficient the energy transfer will be between the magnetic field and the projectile acceleration. The barrel was cut to 16 inches to allow enough space to integrate all components and for the velocity detection sensors.

E. Frame

Due to the design of a portable coil gun, an appropriate frame must be designed in order to hold the necessary components for the gun. The frame must be light for the user, but at the same time sturdy enough to handle the weight of these components. It also must be able to open from the outside in case we have to make any adjustments and must be reasonably able to be sealed. Aesthetics are an optional requirement, but help out in selling the product as a gun.

The first approach with designing this gun frame is to look at projects that have designed guns. Many coil guns previously buy a toy gun and design their gun around fitting it in its frame. However, this project is doing the opposite. The circuits are being designed first and the frame will be built around the gun. This is because of the uncertainty of the dimensions for each possible component. If the gun is able to fire first, that is all that matters. The frame can and should be built around a product that works.

For this project, Nerf's Air Warriors: Air Max - Tyrant was used as our initial frame for the gun. There are many benefits of using a premade plastic gun as a base frame. For one, the design is already premade. Also, the Nerf gun seems stable enough to hold the necessary components. The gun's trigger is a separate piece that slides in smoothly with the frame so we can implement a way to use it. However, there are a couple of downsides with this gun.

The main issue is that this gun is not large enough to fit what needs to be fit in order to work. The barrel of the coil gun has a radius of 2.5 inches. This is barely enough for it to fit if we can saw off specific parts of the inside of the gun. The bigger issue lies in the fact that a capacitor that has a height of 5 inches and a radius of 3. This makes the gun too thin and too small to hold the capacitor. Therefore, instead of using the Nerf gun, a frame would be designed while using that as a base line.

The final product will ideally be a 3d printed gun. For prototyping however, it was decided that using a 3d printed gun would not be the best solution for various reasons. This is because with the various components still being designed, if the proposed frame was printed, there is a high likelihood that adjustments would have to be made. Even if the measurements are correct, even a small error could result in having to reprint the gun. If the gun has to be reprinted, this would mean larger more time and money wasted.

Therefore, a frame that could be adjusted and changed on the spot would serve as an ideal prototype gun frame. For this project, it was decided that Knex would be used. Using these building pieces allows for quick adjustments and a visual schematic of what the final product would look like. From there, measurements would be taken from this prototype, and then recreated using a 3d designer tool such as Autocad. From there, there are companies around Orlando that should be able to print based off of the 3d file created.

Using the recently installed laser cutter at UCF, a wooden based gun frame was made. Since the frame had the job of holding the capacitors, and the barrel with the appropriate electronics, only two encasings would need to be made. Essentially, two wooden boxes, one that was 3.5x3.5x21inches to hold the two Phillips 6300 microfarads capacitors, and one that was 3x3x14 inches to hold the barrel and all the appropriate wirings, would be created.

However, the task is not as simple as cutting out six rectangles for each box and gluing it all together. The box had to be designed so that the edges would interlock with each other, making it a box that naturally holds together, while any form of glue that is used would simply help reinforce those edges. These parameters made drawing the schematics in SolidWorks a little bit easier since it would all be 2d schematics. Conveniently, a wooden box schematics generator called makercase.com was found that creates the file to be used on the laser cutter when the user enters in specific dimensions. There was another option called t-edge locking, but the normal edge locking boxes was chosen in order to save time.

The result of this turns out to be two stable boxes made from ¼ inch thick wood with the box serving as the capacitor container fits nicely in the user's hand. Modifications to the box will be made such as drilling holes through it to connect the capacitor to the rest of the system, adding a trigger in the end of the frame, and possibly adding a grip for easier use.

F. Velocity Detection

To accurately asses the coilgun's performance we will need the MCU to calculate the velocity of our the projectile exiting the barrel. To calculate velocity we will need distance and time. We will use two IR break beam sensor. The break beam sensor contains a transmitter and a receiver. It triggers an interrupt when it detects something pass in front of it. From there we will begin a timer on the MCU and continue the timer until the second IR break beam detects the projectile. From there we will know the distance between the two IR break beam sensor so we will have time to calculate velocity. The velocity will be displayed on the LCD display for the user.

IV. System Interface

The system interface of this coilgun project consists of the feedback and monitoring of the system for the user. This includes the control of the voltmeter and velocity detectors and also the control of what is printed on the LCD. The microcontroller implemented was printed on a PCB to fulfill the PCB design requirement of the project and will be used to implement the programs that will provide real time feedback of the system to the user of the coilgun.

A. Microcontroller

The microcontroller used is the ATmega328P-PU by Atmel. It is a low cost microcontroller that the Arduino Uno comes equipped with. It is relatively easy to program with and fulfills all our project needs. To fulfill the need to read the voltage from our capacitors the microcontroller will need fast ADC inputs for the volt meter, digital lines for the velocity detector, and the ability to output that data to the LCD Display. The MCU's ADC module has 10-bit resolution with +/- 2LSB accuracy. MCU also contains 13 Digital lines which is greater then the 6 digital lines our LCD Display requires and 2 digital lines our IR break beam sensors require.

B. PCB

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 respected ground planes. We also have two different power supplies on the ATmeag328P-PU one Vcc for analog supply and another Vcc for digital supply. We use an LC network to reduce the noise from the digital power signals.

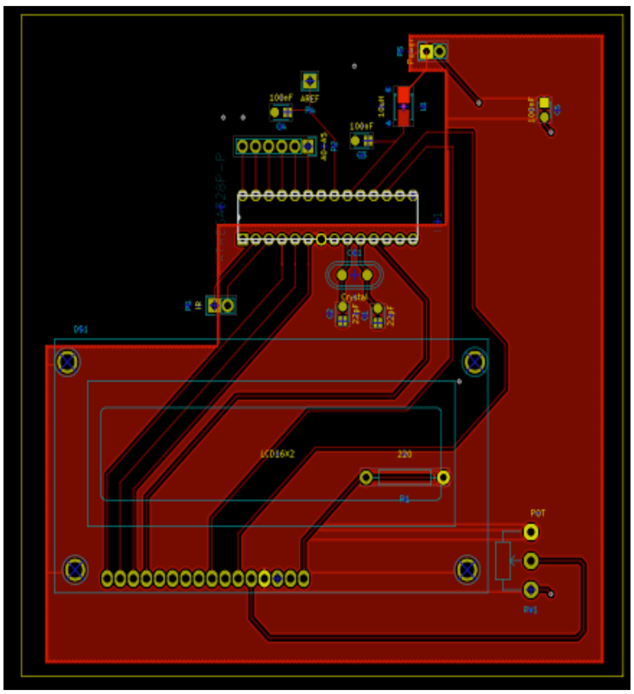

Figure 3 Front Copper Layer

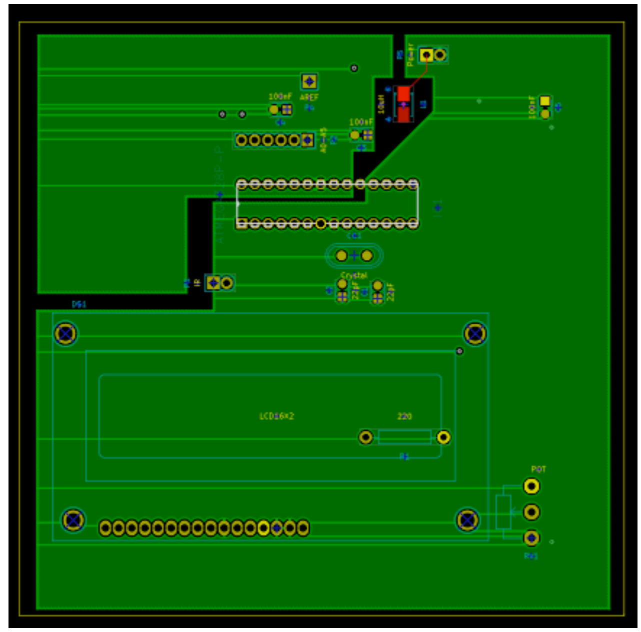

Figure 4 Back Copper Layer

C. Software

Arduino comes equipped with its own IDE, which uses C/C++. We will use the LiquidCrystal library to to help control our LCD display. By including the library header <LiquidCrystal.h> and initializing the library with the 6 digital pins we are using to output data. From there we can use the function print from the liquid crystal library to output data to the LCD. To read the voltage of the capacitors we will use the Analog Read() function built in the Arduino library. The function requires an argument for which pin we want to read. Because we are reading such a high voltage we will use a voltage divider, which we will account for in the code.

Next, we must calculate velocity using our two IR break sensors. Using two digital inputs to read the break sensor, when the first input detects the projectile we fire an interrupt. This interrupt will start a timer. We use the Timer library, which utilizes the 16 bit hardware timer the ATmega328p uses. Once the second IR break sensor fires an interrupt we can stop the timer. Using a fixed distance between the break sensors we can calculate velocity and output it to the display. Essentially there are two tasks, one that reads voltage and another that calculates velocity. We decided not to check the digital input of the first IR break sensor until the trigger is pulled and stop the voltmeter. This will solve issues of concurrency we may face by attempting both at the same time.

D. Volt Meter

The voltmeter will provide the user with real time data on the voltage of the capacitors. We will use the Atmel ATmega328P MCU to input that voltage and output it to a 16x2 HD44780 LCD display. Because of the high voltage capacitors and the MCU's ability to only read an input voltage of Vcc +5Vdc we will need a voltage divider before the MCU reads it. We will be using 1 of the 10-bit ADC channels that the ATmega328P MCU comes with to read the voltage. The MCU will begin reading when the charging circuit begins and ends when the trigger is fired. There will be an alert on the LCD Display when the capacitors are full and ready to shoot.

V. Power Supply

A. Battery

The power supply chosen for this project was the tenergy 12V 2000mAh nickel metal hydride battery pack. This battery was chosen for its ability to handle heat and higher temperatures. We need the battery to be able to supply a constant voltage to the charging circuit in order for the charging circuit to step up the voltage to charge the capacitor bank. This battery was also chosen for its ability to be recharged quickly and its overall lifetime. We chose this battery because it has a very high rating on overall lifetime and is able to be discharged and recharged several times before needing to be replaced. This battery has a very fast recharge time and does not need to be recharged often unless it is used consistently for several hours.

A second power supply will be needed to power the PCB that will implement all of the user interface and real time data output. This can be accomplished by using a 9.6V tenergy nickel metal hydride battery that will then be stepped down using a buck converter to maintain efficiency. This battery was chosen for its ability to recharge and maintain a stable voltage for the buck converter to use to step down the voltage and power the PCB implemented microcontroller. This battery also has very high heat tolerance and can be recharged quickly with a long overall lifetime.

B. Buck converter

A buck converter is a device that steps down voltage to a certain desired value and maintains that value. The buck converter also regulates the voltage that is stepped down at a certain value to maintain constant and reliable voltage at the output of the device. The buck converter plays a critical role in the powering of the PCB because it supplies a constant 5V source for the PCB to run off of. This supply needs to be maintained at 5V in order to insure that the PCB does not lose power.

If the PCB loses power, the real time user feedback interface would lose power and a critical feedback data source would be lost to the user. Therefore, the type of buck converter selected was very critical. The project implements a buck converter that has the ability to step down and regulate a voltage of 9.6V to 5V efficiently and reliably. This was chosen because the battery we chose to power the PCB was a 9.6V tenergy rechargeable battery pack.

VI. Charging circuit

The charging circuit is a key component in the design of the overall coilgun because this will step up the voltage to be used to charge the capacitor bank and will be directly converted to energy to be used. This energy that will be generated will be used to accelerate the projectile to the velocity design specifications of this coilgun project.

A. Boost Converter

The boost converter was initially designed by the group to meet the design specifications goals. The boost converter designed was very costly and would need to be implemented on a PCB or protoboard and soldered on. The group deemed this extra cost to be an inefficient use of project funds and would cause a drastic overage in the budget. Therefore, a boost converter was purchased and implemented in the coilgun final design. The SMAKN high voltage variable output boost converter was purchased because it meet the output and input voltage requirements for our design. The input voltage can be adjusted to 12V and the output can be adjusted to 390V, which was implemented perfectly to charge our capacitor bank.

B. Charging Circuit

The charging circuit of this project's coilgun is critical to the overall success of the gun. The coilgun was designed with the ability to charge up to full voltage at a relatively quick rate. The boost converter plays the key role in the speed and success of the charging of the capacitor bank of the coilgun. The boost converter steps up the 12V from tenergy rechargeable battery pack. The boost converter also regulates the output voltage to maintain a stable voltage on the output of the charging circuit. This output can also be varied using a potentiometer on the boost converter circuit. The goal set out to meet with the speed of the overall full charge of the capacitor bank was less than 20 seconds. Upon testing, the charging circuit will charge the capacitor bank to almost a full charge in around 25 to 30 seconds. This test data was satisfactory for the group based on the requirements we set out to meet.

VI. CAPACITORS

There are many options to consider when choosing a capacitor for any specific project. Options including size, cost, material, maximum voltage rating, capacitance, polarization, leakage current, tolerance, and many more. Knowing which specification will impact your project the most is imperative to maximizing efficiencies and minimizing footprint and cost.

A. Type

The Type of capacitor to choose is very important since large amounts of energy will be discharged in a very short period of time. The coilgun uses polarized aluminum electrolytic capacitors. Electrolytic capacitors were chosen because of the large range of capacitance values from 1 microfarad to even 2 farads. Also, electrolytic capacitors can have a maximum voltage rating from 50 volts to 500 volts. There are a few downsides with using electrolytic capacitors, the first being the size. Aluminum electrolytic capacitors are large and are quiet heavy. They also suffer from having large quantities of leakage current.

B. Specifications

For the coil gun, the specifications that were considered include maximum voltage rating, capacitance, leakage current, and cost. The coilgun uses aluminum electrolytic capacitor with a maximum voltage rating of 400 volts. The capacitance of each capacitor is 6300 microfarads with a tolerance of plus or minus twenty percent. Although twenty percent is fairly large range, choosing precision capacitors for this capacitance range is can be immensely expensive. In the worst-case scenario, more capacitors can be added to the coil gun, in parallel, to add more capacitance if needed. The coilgun implements two capacitors in parallel for the capacitor bank of the gun. Adding two capacitors in parallel effectively doubles the total capacitance of the capacitor bank, while keeping the overall voltage across the capacitors the same.

VII. DISCHARGING CIRCUIT

A. SCR

The capacitor bank is being discharge 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 and the total discharge time is blank.

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 manor then it will negatively charge the capacitors and because the capacitors are polarized, if they are negatively charge too long they can explode.

B. Firing Circuit

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.

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.

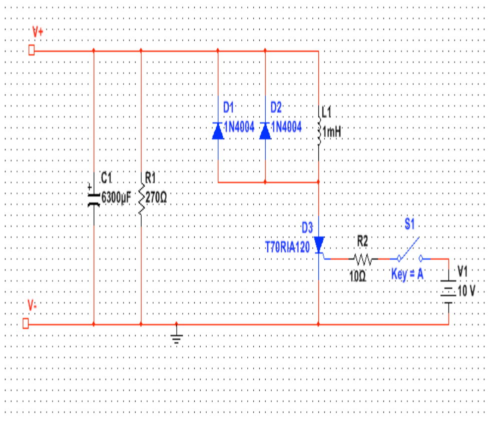

Figure 5 Firing Circuit

VIII. CONCLUSION

The design and development of the Portable Coilgun gave great insight to the concepts involved in the engineering process. We have come into contact with many issues throughout research, design, and assembly stages of the project that were efficiently solved thanks to teamwork and research. We look forward to taking the new found knowledge and skills that we have gained from working on this project and carrying it over into our future careers as engineers. We also look forward to future senior design groups and individuals to improve on the design that we have created.

ACKNOWLEDGMENT

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THE ENGINEERS

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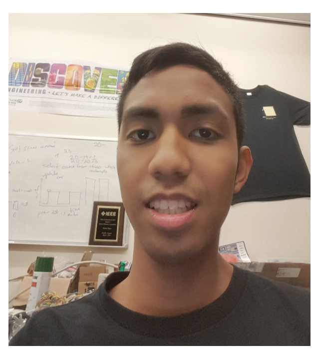

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