

Ferromagnetic Material Launcher

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Abstract — The ferromagnetic material launcher is a coilgun that launches magnetically permeable material. This technology has both military and scientific applications such as defense, space launches, train travel, etc. This project uses principles of magnetic fields, electric circuitry, computer programming, and mobile application software in order to achieve the project goals; these being the FML capable of high velocity projectiles, smooth turret movement, and portability.

Index Terms — Automatic control, Bluetooth, Coils, Guns, Projectiles

I. INTRODUCTION

The Ferromagnetic Material Launcher (FML) is a turret mounted coil gun controlled by an android mobile device. This project features high and low power transformers, a coil gun, capacitor bank, custom printed circuit board (PCB), Wi-Fi camera, and turret. The FML was chosen because it offered challenges in both electrical and computer engineering concepts. The project was chosen because it required knowledge in electromagnetic forces, power systems, embedded systems, computer architecture, and software development. Not only did this project challenge the group to apply concepts learned throughout their engineering coursework, providing a foundation for future projects with the knowledge and experience gained.

The FML functions using an Android application as the user interface running off of a cell phone. The application communicates with the coil gun through a Bluetooth module connected to the PCB. In order to control the coil gun position, servo motors have been attached to mounting brackets to allow movement in the direction defined by the operator. The movement is dictated by signals sent by the built in accelerometers inside the mobile device. The mobile device also controls the firing of the coil gun. The mobile application receives a live video feed from a camera allowing the user to see from the viewpoint of the barrel. These features allowed for the gun to be completely wireless. The acceleration of the projectile is achieved through discharging a current pulse through a coil. In order to achieve the energy required, a 120 volt source is stepped up to 480 V to charge a bank of capacitors using a relay and then discharged across the

coil using an SCR. The velocity of the projectile will be measured using an optical speed trap and the result will be displayed using the Android application.

III. COILGUN

A. Projectile

For a coilgun the projectile's force of acceleration is generated by the coil's magnetic field and for that reason the projectile must be ferromagnetic. Table 1 below gives different options that are available to be used for this project and based on the properties shown in the table as well as the availability and low cost a steel rod was chosen to fabricate the projectile. Another concern with the projectile design is the diameter and length in which to make the projectile. Since this project was also going to implement a turret for user interaction the overall size and weight of the coilgun needed to be kept at a minimum. An 8 millimeter steel rod was chosen to fabricate the projectile and cut at a length of 1.25 inches giving it a weight of about 12 grams. The projectiles were fabricated by cutting the steel rod to the designed length and filing any edges smooth to minimize friction and drag as the projectile accelerates along the barrel. The decision not to make a more complex projectile was due to the fact that it was outside the scope of this project. Assumptions were made that eliminating the buildup of eddy currents in the projectile as well as creating an aerodynamic shape were not worth the additional work and would not have much effect on the muzzle velocity.

Material	Relative Permiability (μ_r)	Saturation Flux Density (tesla)
Cold Rolled Steel	2,000	2.10
Nickel	600	0.64
Iron (99.8% Pure)	5,000	2.15
Mo/Ni Superalloy	1,000,000	0.80

Table 1 Magnetic properties of material choices for projectile.

B. Barrel

For this type of accelerator the barrel has special design considerations in that it must be constructed from a non-ferromagnetic material such as plastic, glass, paper or brass in order to provide the air gap between the coil and projectile that is necessary to generate the accelerating force. A quarter-inch PVC pipe was chosen over brass for the barrel because it provides the required physical properties and strength without the need for additional fabrication to eliminate eddy currents that would buildup in a brass barrel and is much easier to fabricate and modify. The barrel's inner diameter was chosen to match the projectile diameter while still allowing it to slide along the barrel. The thin wall thickness of the PVC barrel creates the air gap and the smaller the gap greater the efficiency of the energy transfer. The barrel was cut to a length of 18 inches to provide adequate space to integrate all components, then modified by drilling holes for the velocity detection components and notched along the top to allow for the loading of the projectile.

C. Field Generation

The generated magnetic field provides the accelerating force of the coilgun, but designing the coil based on a field strength proved very difficult due to the complexity caused by introducing a projectile into the coil design. Therefore, the design was conducted by determining the required forces and energy. Using equations (1) – (4) the energy source required to achieve the muzzle velocity was calculated assuming a 2 percent efficiency factor. These calculations were performed assuming a desired muzzle velocity of 120 feet per second and an acceleration distance of 1 inch, which is half the length of the coil in order to eliminate any pull back effect on the projectile.

$$t_a = \frac{2d_a}{v} \quad (1)$$

$$F = (m \cdot v)/t_a \quad (2)$$

$$KE = .02 \cdot PE \quad (3)$$

$$\frac{1}{2}mv^2 = .02 \cdot (\frac{1}{2}CV^2) \quad (4)$$

Then using the results for the design of the energy source the specifications for the coil's inductance and time constant were calculated using equations (5) – (7).

$$I = C \frac{dV}{dt} \quad (5)$$

$$L = (2 \cdot PE)/I^2 \quad (6)$$

$$\tau = \pi\sqrt{L \cdot C} \quad (7)$$

Variable	Value	Units
Force	158.04	N
Kinetic Energy	4.01	J
Potential Energy	200.7	J
Coil Current	865.6	A
Coil Inductance	0.536	mH
Time Constant	1.70	Msec

Table 2 Results of force and energy calculations.

D. Coil

The design of the coil was based on the energy calculations and not the generated magnetic field because the coil's inductance and time constant have a greater impact on the resulting performance. The coil was designed in order to achieve the calculated inductance and to be able to handle the current flow through the conductor. The ability to meet these parameters determined by the size and type of conductor that is used to fabricate the coil. Copper magnet wire was chosen to fabricate the coil due to its physical properties, the most important of which is the insulation which allows for a much tighter wound coil and denser magnetic field. Next the conductor size was chosen in order to best dissipate the heat generated by the current flow and would best handle continuous firing of the coilgun assuming that there is no cooling between shots. The Onderdonk equation shown below, (8), was used to determine the amount of time it will take a conductor of a specified size to melt, based on the amount of current applied and ambient temperature. These results, which is shown in table 3, along with considering the size and weight of the coil 14 AWG copper magnet wire was chosen..

$$S = \left(\frac{A}{I}\right)^2 \times \log_{10} \left(\frac{T_m - T_a}{(234 + T_a)} + 1\right) \div 33 \quad (8)$$

Size AWG	Current (A)	Melting Time (sec)	Shots
12	865.6	1.215	714
14	865.6	0.480	282
16	865.6	0.190	111
18	865.6	0.075	44
20	865.6	0.030	17

Table 3 Results of Onderdonk equation for conductor melting time and number of possible shots for continuous firing.

The dimensions are designed to result in an inductance that results in the desired time constant. The coil's inner diameter is established by the outer diameter of the barrel

and the outer diameter is designed to be 3 times the inner to maximize the magnetization of the projectile. The coil length is designed using equation (9) and 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.

$$L = \frac{0.8(NA)^2}{6A+9B+10C} \quad (9)$$

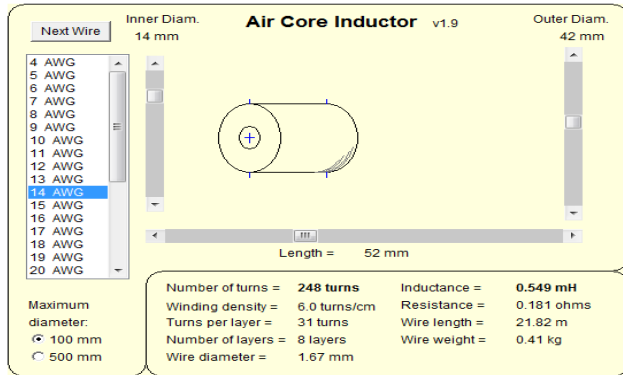


Fig. 1 Inductor Simulator to verify coil calculations and assumptions. (Reprinted with permission from Barry Hansen).



Fig. 2 RLC Simulator showing current pulse. (Reprinted with permission from Barry Hansen).

E. Velocity Detection

The electronic circuit shown in Fig 3 was designed to measure the velocity of the projectile. The circuit consists of 2 sets of IR LEDs and phototransistors to detect the position of the projectile as it accelerates along the barrel. The voltage drop across the phototransistor changes as the projectile blocks the IR LED this voltage is compared to a

reference voltage using comparators. The comparator output goes high when the projectile is detected and goes low otherwise, this output signal is sent to the microprocessor which calculates the velocity and the measured velocity is then displayed on the App.

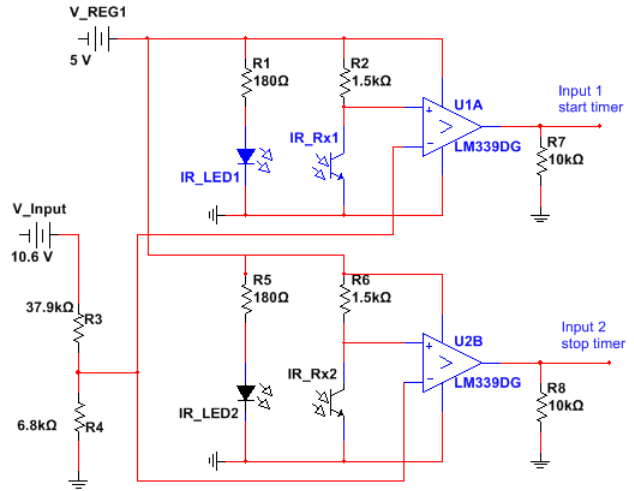


Fig. 3 Velocity detection circuit.

F. Coilgun Frame

The frame of the coilgun is constructed using acrylic sheets secured to square acrylic blocks to create the shape of the frame and provide strength. The acrylic allows the frame to be easily modified to integrate and mount the coilgun to the turret. The design of the frame allows for the routing of all necessary wiring and the mounting of components, such as the camera and projectile magazine. Fig. 4 is the design of the coilgun frame.

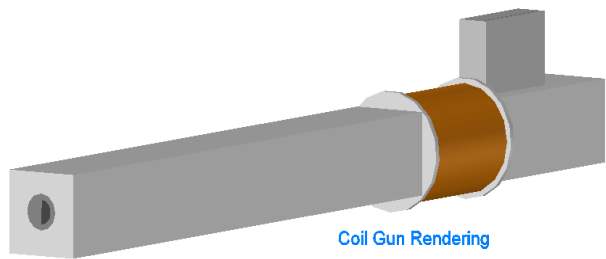


Fig. 4 Rendering of the coilgun frame.

IV. TURRET

The turret subsystem of the project provides a dynamic feature to the coil gun project. The turret gives the operator the ability to remotely control the aim of the coil gun. This provides for unique benefits such as the ability for the operator to change the object they are targeting or

continue to target an object as it moves. The remote operation allows the coil gun to change positions without having a person physically repositioning the system. This provides for convenience of use, greater adaptability in repositioning, and most importantly safety. The final design consists of two major components, the servo motors and mounting brackets.

A. Mounting Hardware

The mounting hardware is made up of two separate brackets that are affixed to each other to give movement on two axes. The first is a cylindrical part which is mounted on the bottom and allows for the panning movement. It provides 120 degree coverage on the horizontal plane. The part chosen to meet the needs of this component is the DDP 155 Base Pan. The second mounting part has an under slung cradle design and is attached directly on top of the DDP 155 Base Pan. It allows for the tilting movement and the coverage in the vertical plane will be limited to 45 degrees to meet project specifications. The part chosen to meet the needs of this component is the DDT 540 Direct Drive Tilt. The pan and tilt parts are both made out of ABS plastic, have aluminum standoffs, and use ball bearings. These features provide smooth movement and rigidity to the platform. Each part accommodates a separate standard size servo motor manufactured by Futaba or Hitec.

B. Servo Motors

The other major component in the turret system is the servo motor. Two individual servo motors are used, one for panning and one for tilting. The model chosen to meet the needs of the system is the Hitec HS-5585 MH. This servo motor can be operated at 6.0 volts or 7.4 volts. For this project they will operate at 7.4 volts to fulfill the torque needed. At this voltage the servo has a torque rating of 236 ounces per inch. The HS-5585 MH has ball bearings and heavy-duty metal gears to further support the sturdiness and smooth motion of the turret system. This is a standard size servo motor and it fits well with the pan and tilt brackets chosen for the turret. The key component to control the movement of the turret is the closed-loop control that is used by these DC servo motors. The motors receive a pulse width modulated signal for control of their position. The pulse width will be determined by the microcontroller based off the operator's input for the desired position. The microcontroller will use a time period of 20 milliseconds to send a pulse to the servo motor. The width of the pulse determines what angle the servo will rotate towards. For each servo a 1.5 millisecond pulse width is used for the neutral position. On the pan servo, decreasing the pulse width rotates the turret left,

counter clockwise, and increasing the pulse width rotates the turret right, clockwise. On the tilt servo, decreasing the pulse width tilts the turret up and increasing the pulse width tilts the turret down.

V. SYSTEM CONTROL

A. Microcontroller

The microcontroller implemented on the system control board is the ATmega328-PU manufactured by Atmel. It is a simple, low powered, low cost microcontroller which met all the needs of the project without having a lot of extra features and capabilities that went unused. It has 23 I/O pins which are sufficient in number for the communication lines needed by each of the peripherals in the project. The pins were used for velocity detection, Bluetooth communication, charging of the capacitors, firing the coil gun, and controlling the servo motors. The microcontroller has 32 Kbytes of flash memory which allowed for programming and reprogramming of system functions. This microcontroller has the unique advantage of being the same microcontroller implemented on the Arduino Uno which was the developmental board used extensively for development and testing of the project.

B. Software

One advantage of using the ATmega328-PU as the microcontroller for the project is its compatibility with the Arduino software programming environment. This integrated development platform was used for writing, testing, and debugging the functions used to operate the project. The Arduino IDE supports the C++ language which was used as the programming language for the project. The programming contained several functions that were each designed to perform a specific task. At the core of the microcontroller programming is the main function. This function runs as an infinite loop upon start up until the microcontroller is powered off. At each iteration of the loop the main function communicates with the operator's mobile device and executes the command received. Additional functions are called and used for tasks such as the charging of the capacitors, firing of the coil, and measuring the velocity of the projectiles. The programming also takes advantage of Arduino's built in servo library to simplify the pulse width modulation needed for precise control of the motors. It also simplified controlling multiple servo motors from a single device.

C. PCB

The project's system control has a custom PCB, seen in figure 5, as its base which was developed using Cadsoft's Eagle design software. Each component on the PCB is

used to accomplish a specific task of the project as required by the project specifications. The components were added to the PCB using a combination of surface mounted components and through-hole components. Through-hole offered an advantage in the testing and prototype stages as it was easier to make adjustments and replace parts as needed. Surface mount was also used because it offered the advantage of being more space efficient. With it a higher component density and a better layout were achieved. The physical layout of the components on the board was designed to allow easy access for the peripheral interfaces such as the GPIO connectors and the power supply.

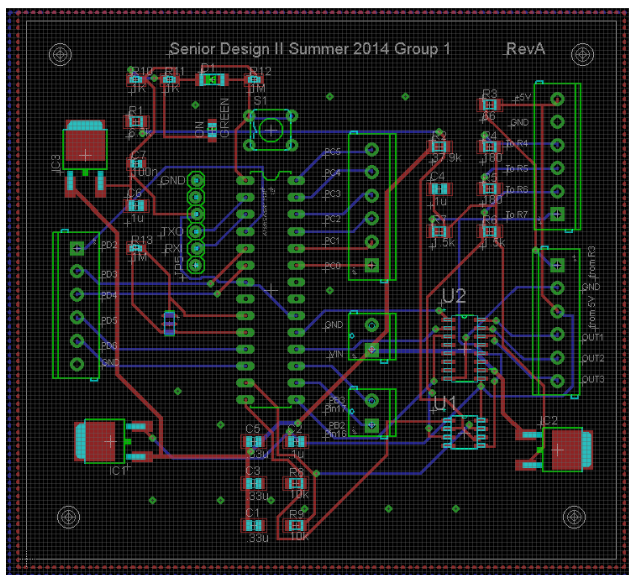


Fig. 5 PCB board layout using Eagle.

VI. BLUETOOTH

A key component of the project is the wireless communication capability from the microcontroller to the mobile device. A wireless connection in conjunction with a mobile device was chosen over a wired connection for better flexibility and mobility of the operator. The mobile device uses the wireless connection to control movement of the turret along with the charging and firing mechanism on the coil gun. Bluetooth was implemented as the means of wireless communication because the connections were easy to set up with minimal configuration necessary. The transmission range provided for class 2 Bluetooth is approximately 10 meters which is sufficient to operate the automated coil gun and turret from a safe distance. The HC-05 Bluetooth module was chosen for the project. It provided easy configuration of baud rate, stop bit, parity bit, device name, and passkey. This module also provided

a simple interface with the microcontroller only needing to connect the RX and TX pins of the Bluetooth module to the TX and RX pins of the ATmega 328-PU. The HC-05 also runs on 5 volts which is the same as the rest of the components on the PCB.

VII. DEVELOPMENT PLATFORM

There were many different platforms that could have been chosen with respect to how the device could be controlled. With each design consideration there were two main aspects to be considered before choosing our final design. These aspects included power, and ease of use. In the final design Android OS was chosen for many different reasons shown below.

A. Power

The first aspect looked at and the most important was the power of the system. Power includes the length of time this device would need for testing and use, data output, and complexity of the application itself. As the coil gun did not require large amounts of data or a complex application to control it these two specifications could be overlooked. On the other hand the length of time for testing of this would require a few hours of testing to achieve the desired results.

B. Ease of Use

With the testing of a potentially dangerous device with such large voltage the ability to control this device in many different environments with relatively easy setup was important. During the course of development for this project rigorous testing would be done some of which had to be done in open areas in case of malfunctions. This required the control application to be able to be used anywhere hours on end. Another important part that was looked at was accessibility. As many of the group members would be testing parts of the project on their own time the ability to be able to test this project individually was important. To accommodate this the android platform was chosen as all the group members had access to this platform.

VIII. CONTROL APPLICATION

The control application had many individual parts to be considered. Some of the most important features were security, response, and accuracy. All of these features were necessary for the proper development of a control application.

A. Security

In order to protect the device and others security was very important to the overall device. Improper control of the device could potentially fry the internals of the device or worse injure another person. To avoid this password protection was implemented at the start of the application. Although the pairing of the Bluetooth provided initial security a secondary precaution was implemented. This password was stored as a HashMapped value on the PCB which was sent via Bluetooth transmission.

B. Response

The movement of this device was controlled through the built in accelerometers of the Android device, and because of this response was crucial. If the movement was to be fluid the response of the application to the set thresholds needed to be as quick as possible. In order to achieve this, advanced features were limited in order to allow priority of this control. The timely response of this control allowed for an overall more desired outcome.

C. Accuracy

Along with the response of the device accurate movement was important. If the charge time or the movement of the device was off the entire application would fail to provide an enjoyable user experience. This accuracy was achieved through real time response from the PCB and the Control application. For each millisecond the accelerometers met or exceeded the threshold the turret position responds accordingly. This allowed the user to have a feeling of full control.

IX. USER INTERFACE

There were two main interfaces for the user to view which included the login screen and control screen. These two interfaces would be seen in their order respectively. The interface needed to be simple yet appealing to the user. The importance of the interface was not to be overflowing with graphical content, but instead easy to understand controls.

A. Login Screen

Since this application was not developed for users with different needs. A single login field of just a password would suffice. This allowed for a very simple layout requiring minimal design and programming.

B. Control Screen

The control screen required three main components. These components include the video view, accelerometers current output, and the buttons to control the firing of the

coil itself. The buttons and accelerometers read the users input and transmitted this information using simple Bluetooth wireless communication. The part of the control app that was the most intensive was the live video feed. This feed not only needed to work but also required it to receive this video in real time in order to provide the user with useful feedback.

X. CAPACITORS

Capacitors vary in many different aspects. Features to consider include size, material, max voltage rating, capacitance, polarization, cost, leakage current, tolerance, etc. Understanding what specifications to choose from for each project is crucial to maximize energy output, or more generally utilize the correct capacitor and minimize cost.

A. Type

Material type is important to consider when discharging large energy amounts. This application uses polarized aluminum electrolyte capacitors because of the large range of capacitance values available ranging from one to 47000 microfarads. In addition, these capacitors typically have max voltage ratings up to 500 volts or more.

B. Specifications

The exact specifications of the max voltage rating, capacitance, leakage current, and cost were considered. This project uses electrolytic capacitors with a max voltage rating of 450 volts, which is acceptable for the 400 volts that they will be charged to. The capacitance on each capacitor is 1800 microfarads with a tolerance of 20 percent. Although this is a large tolerance range, precision capacitors within this capacitance range become more expensive. In addition, if the aggregate capacitance is low, more capacitors can be added to make up for the drop, negating the needs for more precise tolerance.

XI. Power Supply

The power supply chosen for this project was the common residential 120 volt, 60 Hertz source. The use of this source is also reliable and readily available through any outlet. The use of this source limits the range of operation; however an extension cord can be used to allow further distance. Batteries have no limit in range, however were not considered since they would need to be recharged. In addition, a larger surge current was achievable use a rapidly discharging capacitor bank.

A. Transformers

The capacitor bank is being charged to 400 volts. In order to achieve this for the 120 volt AC source, a

transformer was used to step up the voltage. Transformers have the advantage of allowing higher current flow with a higher transformer power rating. This allows the capacitor bank to be charged quickly. The transformer used has a one kVA rating allowing roughly two amps of current to charge the capacitor bank at 480 volts after rectification.

A second transformer is used to step down the 120 volts AC source to roughly 10.3 volts for the low power components. The power rating on the smaller transformer is 72 watts, which allows for approximately 7 amps of current to be supplied.

B. AC to DC Conversion

Since the power source is an alternating current source, rectification is needed to charge the capacitors with direct current. In addition, the power source for all other components (i.e. microcontroller, LEDs, servos, etc.) needs to be powered with DC. Two full wave bridge rectifiers with ratings of 1000 volts and 50 amps were used for both the high voltage charging circuit and the low voltage power supply to the microcontroller, printed circuit board, LEDs, and servos. A summary of the power ratings each component is shown in table 4.

Component	Voltage(V)	Current(A)	Power (W)
Servo 1	7.4 V	2.0 stall	14.8W max
Servo 2	7.4 V	2.0 stall	14.8W max
microcontroller	9 V	400 mA	3.6 W
LEDs	5 V	100 mA	0.5 W
Capacitor Bank	480 V	2 A	960 W

Table 4 Summary of power ratings for each major component.

XII. CHARGING AND DISCHARGING CIRCUIT

A. Charging Circuit

The charging circuit is triggered after firing using control signal from the microcontroller. The charge time is controlled by a timed relay to allow the capacitor bank to be charged to 400 volts in approximately six seconds. Figure 6 shows the measured charge time with an oscilloscope. A voltage divider was used to scale the voltage measured with an appropriate ration for the oscilloscope to handle.

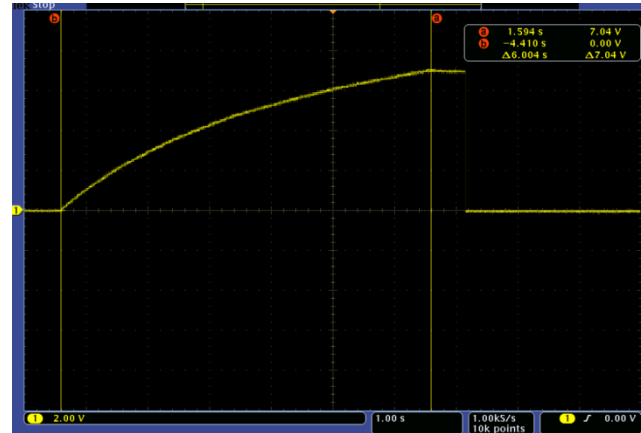


Fig. 6 Charging time for capacitor bank measured at 6 seconds.

B. Discharge Circuit

The capacitor bank is being discharged through the coil once fired. The switch used to control this is an SCR with a 1.67 kA max forward current rating. The use of the SCR allows the microcontroller to switch the high current flow using a much smaller switching current. The control line for the SCR requires approximately 100 mA and is controlled by the firing button from the mobile app. The switching time for the SCR is one microsecond and the total discharge time is approximately 3.7 milliseconds. An oscilloscope reading of the discharge time is shown in Figure 7.

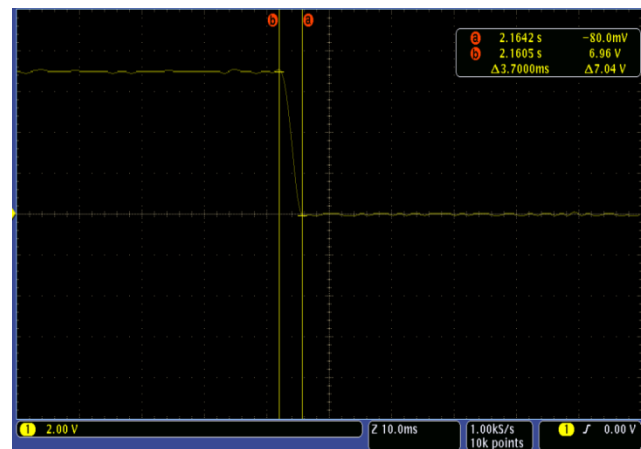


Fig. 7 Coil gun discharge time measured at 3.7 ms.

While the SCR allows for the high current switching, the SCR did not close in time to stop the inductive kick back from the current flow in the coil. The solution was to put a diode in parallel with the coil in order to allow the current to circulate through the coil until it dissipates. This prevented the inductive kickback that negatively charged

the capacitors; an important issue since the capacitor bank is polarized. The circuit for the charging and discharging circuit is shown in Figure 7.

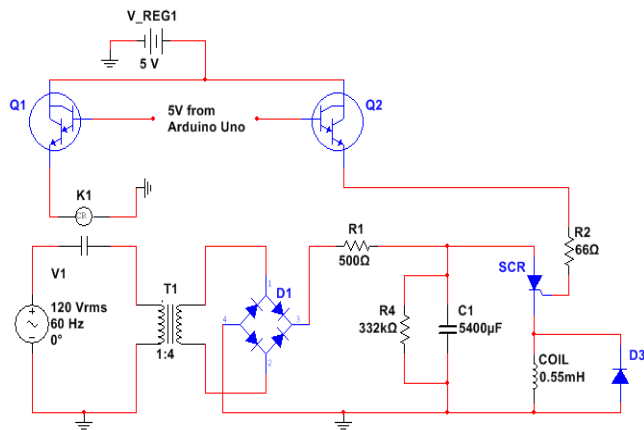


Fig. 7 Overview of charging and firing circuit.

XIII CONCLUSION

In conclusion, the Ferromagnetic Material Launcher was a project that greatly improved our understanding of concepts involved in the engineering process. Throughout the project we encountered many obstacles and problems in the researching, designing, prototyping, and testing stages. We were able to adapt and overcome these obstacles through research and collaboration during the entire duration of the project. The processes we went through gave us a final product with features that include: a coil gun, servo controlled turret mount, wireless communication, live video feed, and PCB design.

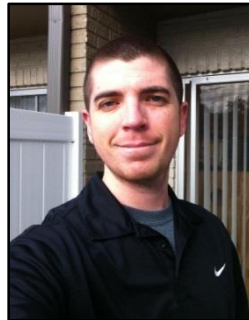
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The Engineers



Austin Akey joined the Air Force ROTC his sophomore year at UCF and will commission into the United States Air Force (USAF) as a 2d Lt when he completes his Bachelor of Science in Computer Engineering (BSPE) in August 2014. After graduation, Austin will relocate to Texas to begin work with the USAF. There, he will begin training to become a Remotely Piloted Aircraft Pilot and continue pursuing his passion for national defense.



Joshua Sanchez joined the Navy NUPOC Program his junior year at UCF and will commission into the United States Navy (USN) when he completes his Bachelor of Science in Electrical Engineering (BSEE) in August 2014. He will relocate to Rhode Island and then North Carolina to train to become a nuclear propulsion officer and eventually roam underwater in a submarine.



Donald Freeman is a senior graduating in August 2014 with a Bachelor's degree in Electrical Engineering. He has experience as an industrial electrician prior to pursuing his education and completed a summer internship with Duke Energy at the Brunswick Nuclear Power Station. Plans after graduation include taking some time off and then pursuing work as an engineer within the power generation or manufacturing field.



Brett Oden is a computer engineering student graduating in the summer of 2014. Williams's goals are to acquire a job in the local Orlando area with a software company. His specializations are in algorithmic processes and testing.