Magnetic Accelerator Cannon

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1.0 Executive Summary

The development of projectile launchers with chemically propelled projectiles reached a plateau more than seventy years ago. Since then only marginal improvements have been made. Most of those improvements that have been made come from the aerodynamic and kinematic improvement to projectiles. The idea for electrically propelled projectiles has mostly been in fiction throughout society and in some R&D facilities. Our project, The Magnetic Accelerator Cannon also known as the MAC, has the potential to bring the state of projectile launch to a whole new level.

As mentioned, the idea of using electromagnetic fields to accelerate projectiles is not particularly new, but with electrical energy storage capabilities evolving every year, a practical product with rivaling capabilities that exceed its chemical-based counterparts is in the near horizon. This project's purpose is to showcase the capability of current electromagnetic launch technology and to demonstrate the many advantages that this method of launch has over chemical-based ones. This includes, but is not limited to, the ability for the user to dynamically alter the projectile's energy to different levels in a user-friendly way.

The magnetic accelerator cannon can be easily be implemented into our society today. The new technology available now allows for a much cheaper alternative than a magnetic launcher 15 years ago. The MAC takes advantage of the latest technology while still being adaptable to older technology that is still being used today. The cannon is able to charge off of any standard wall plug allowing it to be a versatile and flexible solution for many different situations.

The MAC can achieve near silence in firing a projectile. This quality can be utilized in many applications which would require silence to be a priority. Hunting can be one of those industries which can be utilized. The military industry would also be another facet that can be exploited with the use of a silent projectile launcher.

Another positive military use is the ability to implement the cannon with no change to the existing supply chain. The MAC can be adapted to be powered by most vehicles, which allows the MAC to be an easy complement to a military arsenal. Less weight and resources are needed by the MAC to launch projectiles compared to other conventional weaponry. The magnetic accelerator cannon is going to be an enormous task to build, but when done it will change the way weapons and projectile launching is viewed.

Each of the project members brings a unique set of interests and knowledge, including electromagnetic fields, microelectronics, power systems and embedded systems. This project will both engage and cultivate those skills. Figure 1 depicts the initial top level system block diagram for the Magnetic Accelerator Cannon. The project documentation which follows will go into depth into how the MAC will be the foundation for the next generation of launch technology systems.

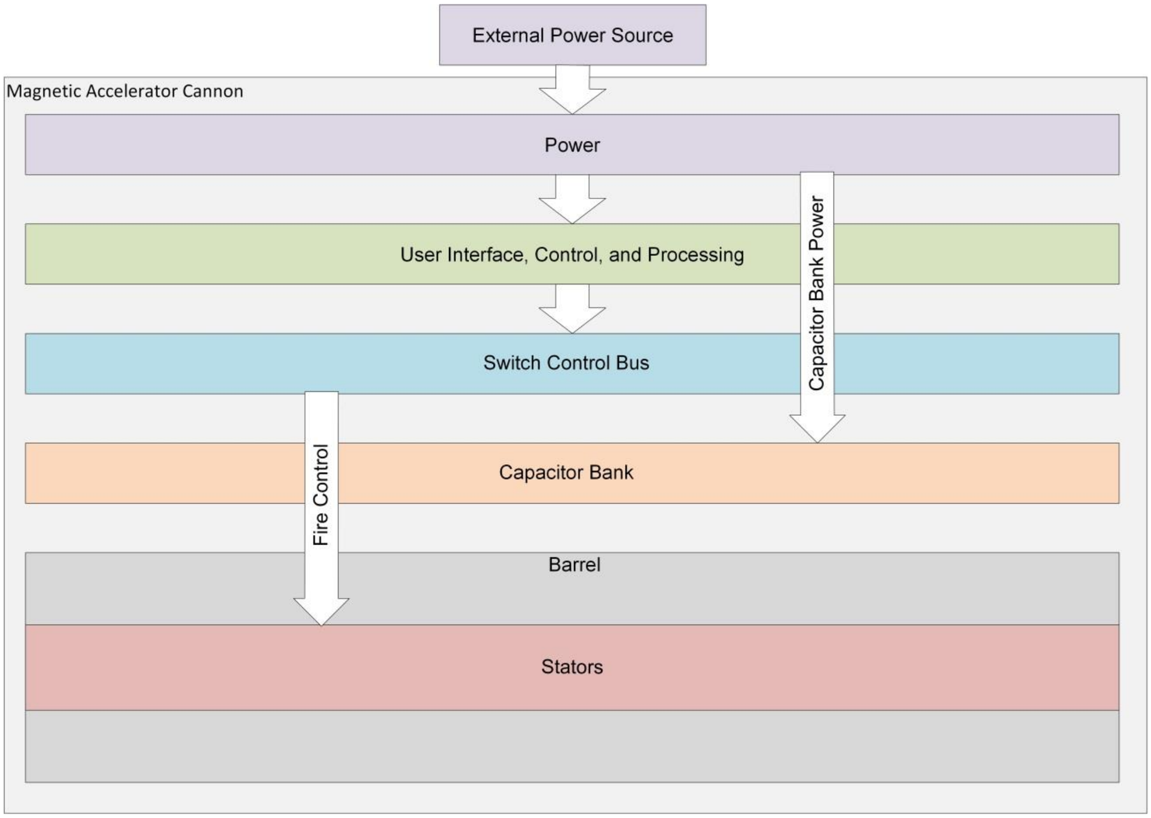


Figure 1 M.A.C System Block Diagram

2.0 Project Description

2.1 Project Motivation and Goals

The main motivation of this project is to create a device that not only showcases current technology and pushes the boundaries of contemporary designs, but also enrich the participants by applying the knowledge from an undergraduate Electrical and Computer Engineering education into the design of an original machine. The goal is to create a device that is safe, powerful, fast, easy to use and flexible. In addition to these objectives, emphasis will be placed on cleanness of design so that the final device has the appearance of a production commercial product.

2.2 Objectives

The final device will accelerate a metallic projectile using electromagnetic fields packaged in a visually appealing and easy to use design. Most importantly it will be safer and less hazardous than chemical-based launcher residuals. Also, unlike its chemical-based counterparts, there won't be a need for extensive cleaning to remove residue from chemical propellant. The MAC has no moving parts or burning powder, and it does not mechanically degrade even after repeated use. It will also be powerful by efficiently converting stored electrical energy into kinetic energy.

A user interface will provide a list of eight modes to choose from, representing different muzzle energies for the projectile. The interface will also display the range to the target. The provided distance will also be used by the built in controller to automatically calculate the targeting adjustments needed to accurately deliver the projectile. In addition, the interface will inform the user of the remaining shots available based on the remaining stored energy. Being able to modulate the amount of energy released allows for many different launching options. These options can range from multiple, low energy, non-lethal shots to one or two highly-lethal, maximum energy shots. The objectives for projectiles and relative number of shots can be seen in the *Table 1*.

Table 1 Projectile Objectives

Number of rounds	Ammunition Equivalent
1 x	7.62 x 51 mm NATO
3 x	5.56 x 45 mm NATO
9 x	9 mm Parabellum
33 x	Bean bag

A built-in power supply will allow the user to interface to a standard wall outlet to charge the device in a short amount of time. The design will be built so that the user can charge the cannon off of their vehicle's electrical system with ease. Energy storage is crucial due to the large amount which is needed to launch. A capacitor bank will store the energy from the power supply until it is applied to the stators for firing. The built-in energy storage will allow for multiple shots at low to medium power. Listed in *Table 2* are the seconds needed to charge the capacitor banks to fire the specified round. According to preliminary calculations, charging the capacitor bank will approximately take 30 seconds.

Table 2 Capacitor Charging Objectives

Ammunition Equivalent	Time to charge
5.56 X 45 mm NATO	~6.2 s
7.62 X 51 mm NATO	~3.16 s
9mm Parabellum	1.02 s
Bean bag	0.29 s

The launcher will utilize an auto-loading mechanism to load a projectile from a hopper into the magnetic barrel for launching. An auto-loading mechanism allows for multiple shots in rapid succession.

The preceding objectives for the project will be achieved with close accuracy, but as all projects go there will be unforeseen barriers and issue that could prevent the final design from having the full arsenal of objectives. Time and budgeting can limit the final objectives and can be mitigated by scaling down the objectives for the MAC.

User Operation

- i) User turns on power supply to charge capacitors
- ii) After capacitors are charged, user selects the output mode
  - (1) If "Velocity" is selected, the user chooses one of eight different energies for the projectile
  - (2) If "Target" is selected, the user chooses one of eight different energies for the target
- iii) The user acquires the target using the built in targeting reticule
- iv) The user pushes the firing button to launch the projectile to the target with the specified energy chosen in the previous menus

Method of Operation

Choosing the number of stages on the user interface will determine the number of coils to be used when firing. The original plan was as follows: If "Target" mode is selected, the controller calculates the muzzle energy and switch timing needed to deliver the projectile towards the pointed target at the specified target energy. The calculated timing is then provided to the firing subroutine for launch. In "Energy" mode, the kinetic energy specified by a user is sent to the control system to calculate the switch timing needed to achieve the muzzle energy requirements.

The timing subroutine will determine the time needed to ensure the necessary magnetic flux gradient provided by the current passing through the stator to achieve the desired power output. It will also use the linear position of the projectile, which is provided by sensors between each stator, to determine when to switch each stator on and off in order to translate the projectile down the barrel using magnetic forces. The essential current provided to the stators will be produced by short circuiting the capacitor banks installed in the firing mechanism. The magnetic accelerator cannon will be able to quickly charge and fire multiple shots rapidly, all while being relatively silent.

2.3 Project Requirements and Specifications

- 1 meter barrel
- 14 mm projectile diameter
- <52 g projectile mass
- <5 cm projectile length
- Multiple capacitors
- 400 m/s maximum muzzle velocity
- Multiple Stages

3.0 Research

Research was performed on the concepts of electromagnetics and electrical components to determine the correct methods of approach for the MAC.

3.1 Existing Similar Projects and Products

There have been many previous designs and concepts which knowledge and lessons could be learned from. Many of the past projects and research have studied various aspects of the electromagnetic launcher. The following references will provide the knowledge and methods needed to solve the complex problems which are encountered when designing a coilgun.

3.1.1 The Methodology for Selecting an Electromagnetic Gun System

In May of 1992 a graduate thesis was published by Captain Karl E. Reinhart of the U.S. Army describing methods to select electromagnetic launcher systems, EML, for the military. The thesis is a complete framework for designing and selecting EMLs. Basic concepts of electromagnetic theory are covered including the applications in which these concepts could be applied. Many concepts from this thesis will be utilized in the design and implementation of the MAC. The following will outline the major concepts and lessons learned from the thesis for use in this project.

Conservation of energy is a very important concept in the development of electromagnetic launch systems. The typical launch system uses expendable chemical energy converted into kinetic energy to achieve the goals of the system. On the other hand electromagnetic systems utilize recoverable electrical energy converted into kinetic energy to achieve the goals of the system. The use of electric energy reduces the need for costly chemical materials. The chemical method has to take into account the losses incurred by thermal energy, and friction in the barrel in chemical systems.

The thesis discusses two different electrical launch systems; the railgun and the coilgun. Each has its positives and negatives. For the purpose of this project the coilgun description and design process was analyzed to learn lessons and concepts. As in most electrical systems the main propulsion forces are due to magnetic fields which are created by stator coils. The principle force in a coilgun is dependent on the current in the stator, the current induced in the armature (projectile), and the mutual inductance between the stator and armature [5].

Mutual inductance is based on the distances between coils. Therefore, the position of the projectile and the currents induced determine the amount of force which the projectile experiences. The thesis uses “Inductance Calculations” by Frederick W. Grover to solve for the mutual inductances between coils using the current filament method. This method and book is described in the following sections and is a primary driving method to solve for the force between filaments of the stators and projectile.

The investigation into mutual inductance in the thesis shows that the mutual inductance between stator and armature peaks when the stator coil and projectile radius are near equal [5]. This is an important design concept in which the coils can be sized to reach maximum coupling when they are near the size of the projectile being launched.

It was determined that when currents run in one direction in the stator a current is induced in the opposite direction in the projectile creating a propulsive force in the direction in which the projectile is being launched. It was theorized that an efficient coilgun can operate in combinations of repulsive and attractive forces to efficiently propel a projectile down the length of a coilgun [5].

It was stressed in the thesis that heat and stress consideration should be taken into account in the design of a coilgun. The magnetic forces that can be experienced in the stator stages and projectile need to be kept to safe limits or taken into account to get good efficient operation of a coilgun. The calculation of these considerations is a difficult task and is usually left to computer simulations to be solved as discovered in the thesis [5].

The thesis discusses many different energy storage options to be used for coilguns. It was found that approximately 30% efficiency can be achieved between energy storage to coil excitation. Batteries, capacitors, frequency generators, and other generators were investigated to determine the most efficient source to be used in the gun. For the purposes of this project the primary focus was done on the capacitor investigation of the thesis. Capacitors can hold a lot of energy and have been proven to be ideal components for pulsed power applications and this project.

Switching for a coil gun is a very important area of design which cannot be ignored. The switches must make contact, transfer large amounts of current, and be able to withstand the large voltages crated when breaking a line of current in the kA range. The coilgun will have large voltages and currents which will need specialized switching. Closing switches, opening switches and buswork are investigated in the thesis and provide great insight to the types of switches that will be needed in order to complete the project.

The thesis describes the methodology recommended to properly design an EML. The methodology uses a mission profile to set initial requirements of the system. For the use of this project this methodology was used as a reference. The length of the barrel was determined and then the projectile dimensions were determined. With these initial requirements the design of critical components can be determined. The velocity, timing, kinetic energy of the projectile, muzzle velocity, and other important variables are determined using simple equations of motion under constant acceleration.

Using the mission profile and initial requirements the thesis solves the differential equations that would be needed to model the coilgun and the electromagnetic and kinematic properties which are experienced in the gun. The following equation (*1*) is listed in the thesis and is the basis to keeping the force in the coilgun as constant as possible.

$$\mathrm{F}(z,t) = \sum_{i=1}^{N} I_{ai}(z,t) I_{si}(z,t) \frac{\partial M_i(z)}{\partial z} \qquad (1)$$

Where, N = number of stators. The dimensions of the coils greatly determine major design considerations for the coilgun. A balance in bore diameter and projectile weight must be taken into account to be a realizable system [5]. The projectile is designed and the stators are also designed upon the parameters of the projectile.

As said before, it is most efficient to keep the projectile and the stator coil radii almost equal with very little air gap to increase efficiency and magnetic coupling in the coilgun. The mutual inductance gradient between coils was investigated in order to achieve close to constant acceleration in the coilgun barrel. In the thesis this was accomplished by varying the length of the stators and using the method described in “Inductance Calculations” by Grover. It was discovered that finding a length that is equal in each coil is preferred to achieve an almost constant mutual inductance gradient, which, according to the force formula above, would achieve acceleration close to being constant down the barrel [5] With stator lengths defined by the thesis, the timing for the accelerating projectile can be considered to determine the required inductance, and capacitance values needed in each stator.

The final steps in the design process of a coilgun, as described in the thesis, is to determine the switches and required wiring needed to connect all circuit elements. The power supply and energy storage options determine the required properties for the switches and wiring. The timing needed for each circuit is taken into account along with the voltage and current limits which will be achieved. From these values the switches can then be selected for proper integration into the coilgun. Low resistance and inductance is important in choosing the right wiring and switches [5]. The thesis report then recommends the system be simulated and optimized to meet realistic design of the coilgun. This thesis was utilized as a powerful tool in the analysis of the MAC Many useful equations were used from the reference along with the references the thesis also utilized.

3.1.2 Operational Requirements and Issues for Coilgun Electromagnetic Launchers

The Sandia National Laboratory has devoted the time to producing coilgun topologies for research and military uses. The lab, a subsidiary of the Lockheed Martin Company, has produced many coilgun types from large to small scales and in this report has documented the concepts and lessons learned from operation of these guns. The paper was used as a reference design criteria for the MAC

The research paper outlines coilgun operation. It describes the armature of the coilgun as a shorted coil. This significantly reduces computations needed to solve between projectile and coils. Since the projectile is a shorted coil it is modeled as a resistance in series with an inductor. It is mentioned that in order to solve for a solid projectile the circuit equivalent needs to be many parallel series inductor and resistance loops [8]. This representation takes into account the many current paths that can be induced in a solid material and how the mutual inductance between all current loops and the stator coils would need to be calculated. This concept would be used in the design and calculation for the projectile of the MAC

The paper also emphasizes on the importance of keeping current rise time close to the time it takes the armature to pass through each stator. Many design and geometry tradeoffs were discussed based on timing and stator properties which provided valuable insight into the design of the coils for the MAC. The paper investigated many different gun systems to evaluate performance. It was also used to validate their computer simulations made with their SLINGSHOT software as well as to show scalability to their design. [**8**]. Table 3 summarizes the parameters of the coilguns and projectiles tested.

Table 3 Coilguns Designed and Tested at Sandia National Laboratories © [January 2005] IEEE

Projectile		Coilgun		Maximum at Muzzle	
Diameter (mm)	Mass (g)	Length (m)	# Stages	Speed (m/s)	Energy (kJ)
25	10	0.44	10	317	0.5
131x112	*139*	2.3	14	1004	70
47	237	1.6	35	1000	119
140	5000	0.8	6	335	281

The average efficiency that was achieved in the coilgun designed was 30% without recovering the energy in the coils after one current cycle. With recovering the magnetic energy left over in the coils the efficiencies were brought up to an average of 65%. This analysis showed insight into the types of efficiencies that could be seen In the MAC

The topic on time switching was investigated by the lab as well. Performance profiles were developed for the coilguns built to determine switch and timing errors. The errors induced into the system were in the scale of micro-seconds. Errors at this scale provided a negligible effect on the performance in the low speed gun, 400m/s, and a small deviation from mean velocity in the high-speed gun, 2.5 km/s. This is an important find for the design of the MAC. Although timing has to be quite accurate, a deviation of a few micro-seconds can be acceptable. Orders of magnitude above micro-seconds cannot be tolerated in the design of the MAC

3.1.3 Analysis of Inductive Coilgun Performance based on Field Coupling Circuit Method

In the search for a solid method to solve for stator coil to projectile interactions this paper by Shoubao Liu, Jiangjun Ruan, Daochun Huang, and Zilin Wan from the School of Electrical Engineering at Wuhan University in Hubei, China provided insight to the current filament method that has been previously used in the preceding references. A basic understanding of the concept is covered to for properly model the circuit created by the stator to projectile interaction. The paper published in IEEE pulls upon previous work by Sandia National Laboratories to build and test their coilgun.

The paper also describes a new method, the composite grid method, to be used to confirm the current filament method and to model the flux density in the armature. This is a complex method to solve for the properties induced in the projectile by a stator. The composite grid method which is described is an insightful view on how the projectile behaves in the stator magnetic field, but due to its complexity the method is not used for MAC design criteria.

3.1.4 Inductance Calculations

The book “Inductance Calculations” by Frederick W. Grover was published in 1946 and is referenced in many of the papers that were compiled for research into the complex topic of coilguns. The book covers the many methods to solve for different inductance values. Two of the very useful and valuable parts of the book are the tables and formulas included. Many inductance calculations require complex mathematical methods such as elliptical integrals of the first, second, and third kind to solve. These calculations usually require the aid computer software to solve. This book uses solved tables to achieve quick and accurate results to inductor design problems. It has the most basic equations for all situations which arise with the use of inductors, or the construction of inductors.

The book is split up into two parts; inductance calculations for circuits of straight filaments, and coils and other circuits composed of circular elements. The second part of the text is most crucial to the design of the stator coils, and it is crucial in calculating the mutual inductance between different stator coils and between stator coils and projectile. The current filament method stated in the preceding texts primarily uses the concepts presented in this text to accomplish the calculations necessary for proper design of the coilgun.

The following will briefly cover the equations and concepts used from the text. There are many special cases for each concept and only what will be used for the design of the M.A.C is described below. One of the most important concepts is the design of single layer coils, which are utilized as the accelerators for the projectile in the MAC. The following equation is used to solve for single layer coil inductance. This equation is the general formula for inductance depending if you have pitch, *n,* given or number of turns, N, given.

$$L = 0.004\pi^2 a^2 b n^2 K \tag{2}$$

$$L = 0.002\pi^2 a \left(\frac{2a}{b}\right) N^2 K \tag{3}$$

Table 4 Variables used to determine the Inductance of a single layer coil

Variable	Description	Unit
L	Inductance	uH
a	Coil radius	cm
b	Coil length	cm
n	Winding density	Turns/cm
N	Number of turns	-

The K factor that is shown in (4) is found in a table presented in the book which takes the radius and the length ratio to find the correct value. Factors are a common occurrence in the text to eliminate the complex elliptical integrals into quick interpolation. K can be calculated directly using the series formula below.

$$\mathrm{K} = \frac{2\beta}{\pi}\left[\left(log_e\frac{4}{\beta} - \frac{1}{2}\right) + \frac{\beta^2}{8}\left(log_e\frac{4}{\beta} + \frac{1}{8}\right) - \frac{\beta^4}{64}\left(log_e\frac{4}{\beta} - \frac{2}{3}\right) + \frac{5\beta^6}{1024}\left(log_e\frac{4}{\beta} + \frac{1}{8}\right) - \cdots\right] \tag{4}$$

Where, $\beta = \frac{b}{2a}$. Three terms in the series work for β values up to 0.25. The preceding formulas (2),(3),(4) were used to determine the inductances that would be needed in the design of the MAC. Force applied to a filament by another filament is another topic which the text covers. The equation for force is mentioned above in (1), but does not cover how it is utilized properly.

The following formulas will describe the force on a filament by another. There are three different cases for this calculation and they will be summarized following the equations for force. There are three cases and In each case the currents in the solenoid and filament must be in the same directions to feel an attractive force, and opposite to feel a repulsive force.

$$\mathrm{F_o} = \mathrm{n_1}[\mathrm{m}(\mathrm{d_1}) - \mathrm{m}(\mathrm{d_2})] \tag{5}$$

$$\mathrm{F} = i_1 i_2 F_o\ dynes \tag{6}$$

The first case, shown in Figure 2, occurs when the filament is in the end plane of the solenoid. In this case d_1=0 and d_2 equals the length of the solenoid. Using these values for d_1 and d_2 the mutual inductance can be found from the equation for mutual inductance which is discussed below. The mutual inductance of two coaxial circles of radii *a* and *A* with a distance *x* between their planes is in abH (ab-henries). In this case $m(d1) = 0$ and is calculated for the method of coplanar filaments [9]. By analysis the force will be the largest at the end plane of the solenoid [9].

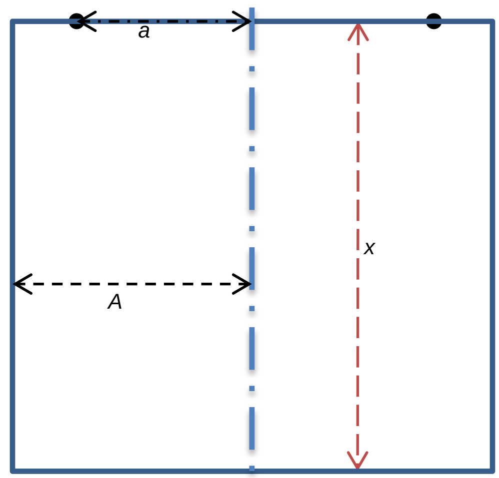


Figure 2 Coaxial Circular Filament at the End of the Solenoid; Case 1

The second case comes about when the circular filament is outside of the solenoid. The equation for force stays the same. There is a distance d_1 from the end plane of the solenoid and $d_2 = x + d_1$. Figure 3 below depicts this case. The larger d_1, the smaller the force between the filaments becomes.

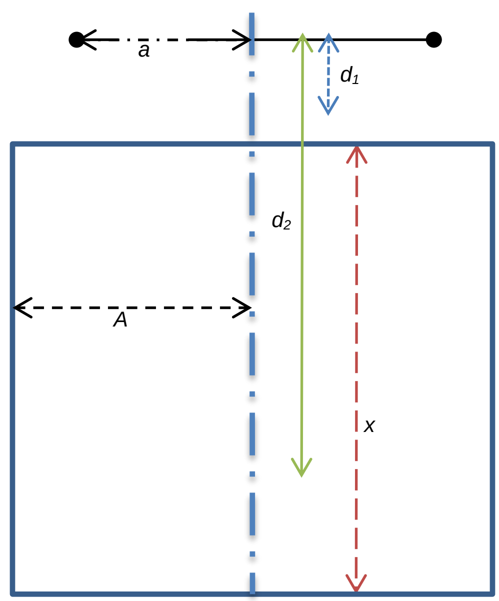


Figure 3 Filament outside the Solenoid; Case 2

The third case happens when the filament is inside the solenoid. In this case $x = d_1 + d_2$. The force equation stays the same and the mutual inductances are once again changed. Figure 4 below depicts the case. The closer d_1 gets to being equal to d_2 the force cancels out and becomes zero. At this point the filament is in the center of the solenoid.

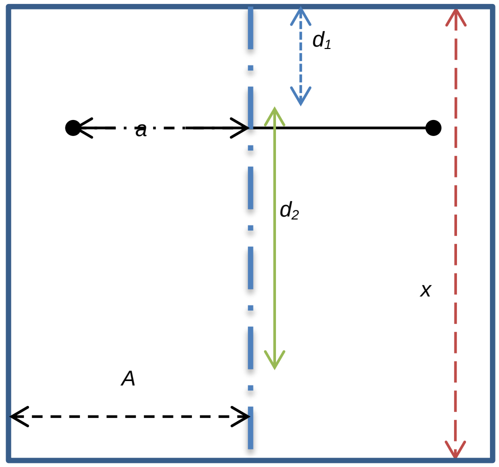


Figure 4 Filament inside the Solenoid; Case 3

In order to complete the above force equations the mutual inductance must be calculated. The following equation describes the mutual inductance for a between two filaments. The calculation relies on two parameters $\frac{a}{A}$ and $\frac{d}{A}$, where *d* is the distance between the filaments [**9**]. The mutual inductance formula based on the parameters stated is

$$\mathrm{M} = f\sqrt{Aa} = fA\sqrt{\frac{a}{A}}\,\mathrm{uH} \tag{7}$$

,where f is a function of the variable

$$k'^2 = \frac{(A-a)^2 + d^2}{(A+a)^2 + d^2} = \frac{\left(1-\frac{a}{A}\right)^2 + \frac{d^2}{A^2}}{\left(1+\frac{a}{A}\right)^2 + \frac{d^2}{A^2}} \tag{8}$$

The (8) is used to find the value of f. This works for almost all cases except when the filaments are very near ($k'^2 \leq 0.1$) or very far apart ($1 - k'^2 \leq 0.1$). For these cases other tables are calculated to find f from the variable k^2. The variable $k^2 = 1 - k'^2$.

Using the three cases depicted above with the calculation for mutual induction the current filament method can be understood more fully. As the projectile moves into the stator the above method is applied an N number of times. N equals to the number of filaments which are given to the projectile. As the projectile move in the coaxial direction the force is calculated for each filament. This method is used to determine the current needed to produce the forces which are necessary to accomplish the design goals of the MAC

3.1.5 Coilguns.info

The website coilguns.info is a renowned resource for building coilguns, referenced by almost every hobbyist's project and senior design groups. The webmaster, known as “Barry”, has designed and assembled five different coilguns with exhaustive accompanying documentation, including equations, measurements results and computer simulations of different components.

All the coilguns he’s designed are single stage, but much of the knowledge is useful for this design. The author also made helpful design tools, including an inductor simulator, and an RLC simulator. The inductor simulator was very helpful as an aid in understanding the physical dimensions of coils with different inductances. Early ideas about coil design could be quickly tested with this helpful tool. The RLC simulator was instrumental in helping increase the understanding of RLC circuits and how to properly simulate them.

3.1.6 UCF Senior Design (Spring ‘12) Nail Coil Gun

There have been two coil gun projects to recently come out of Electrical Engineering and Computer Science. The first project was from group 20 in Summer/Fall of 2012. They designed a “Nail Coil Gun.” This was a smaller design in comparison to the one being attempted. It was designed specifically for applications that require a standard nail gun, like roofing. It doesn’t appear to be a finished design and has a section labeled “Uncertainties.” Even though the design isn’t completed, they do have some interesting ideas of how to design a coil gun.

Their design was one foot in length and sized so it could be easily held in the hand. Assuming 50% efficiency per stage, they calculated a muzzle velocity of 200 m/s. Smaller 680uF capacitors were to be used in the design so they were able to be packaged into a handheld device. A similar oscillating circuit like the one used in this design is shown in Figure 5.

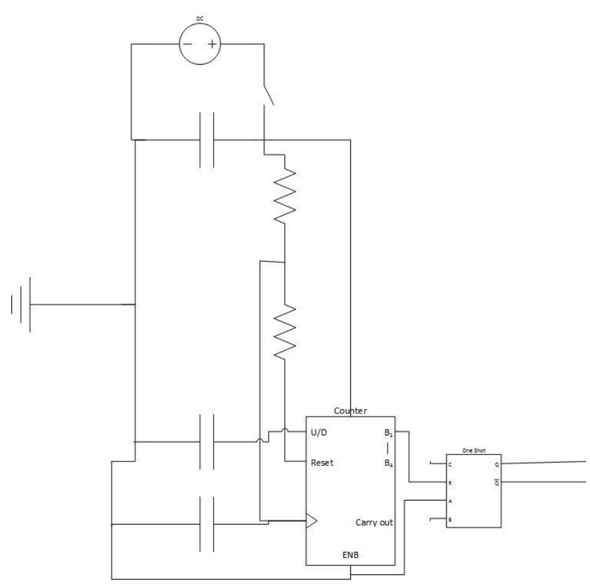


Figure 5 Oscillating Circuit

Infrared sensors were placed between the coils in the armature, such that they got tripped by the nail, triggering a discharge circuit and sending current from the capacitors to the coils. A similar circuit like the one used is shown Figure 6

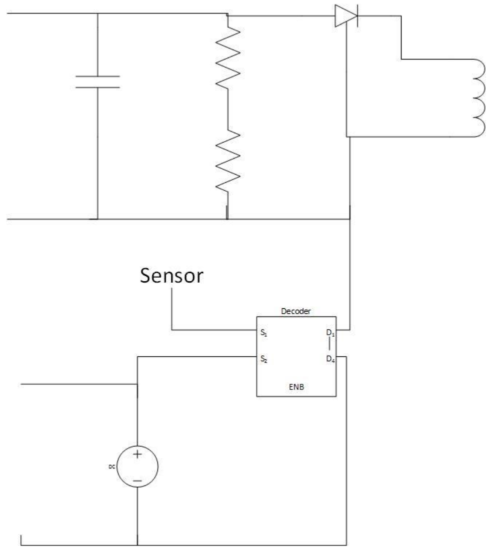


Figure 6 Discharge Circuit

The benefits of this design include a low maintenance device with no moving parts or powder residue as well as ease of use. An interesting idea that came out of this project is the use of an ATX power supply to supply the power needed for both the capacitor charging and powering the microcontrollers.

Originally they thought they could charge the capacitors off of lead acid batteries but found that they drained too quickly. To get the required voltage for the capacitors they chose, the transformers were going to be too large and expensive for the design. So instead they used a boost circuit to charge up to the 350 V requirements at a lower input voltage (12V-15V). A boost circuit similar to the one used can be seen here Figure 7.

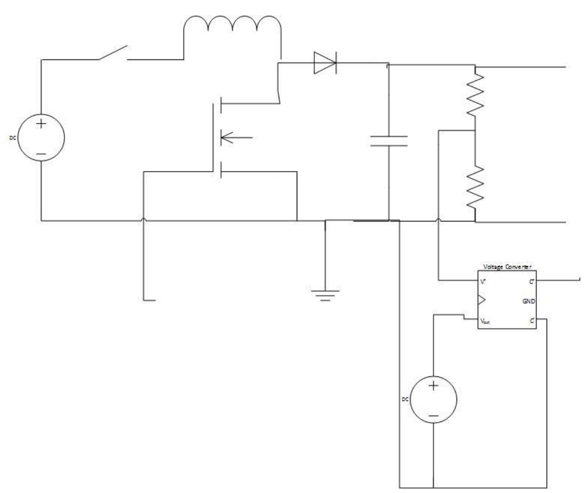


Figure 7 Boost Circuit

Another excellent idea is the use of bleed resistors. These were used to discharge the capacitors after use to make sure they don't have any residual charge. Residual charge can damage the capacitors if left for a long length of time. It can also be very dangerous to any person unaware of its charged state.

Coil inductance calculations were found using Barry's Coilgun Design website (Previous section 3.1.2 Coilguns.info). They chose their inductance to be 20uH. It was paired with a 680uF capacitor that could charge up to 350V. Two coils were used in the final design, soldered to the PCB board with the sensors, tube and other components. Lower costs and smaller projectile were the main design drivers for this build.

Plagued with voltage problems and burned PCBs, this design was flawed without required resistors for initial power on. By the last design, they found that more capacitors were needed for proper acceleration. Advanced design changes led to a faster charge time and added semi-automatic firing.

3.1.7 Coil Gun with Targeting System

The second project was from group 8 in Summer/Fall of 2010. They designed a "Coil Gun with Targeting System." They added an automated targeting system that could take parameters to find and track a target. The targeting system could be set to manual or automatic modes. In automatic firing mode, the coil gun could optically track a target and fire at it. Their thought behind the project was not for military or mounted vehicle applications, but more towards replacing a conventional firearm for recreational use. A muzzle velocity of 100 feet per second or approximately 31 meters per second was the set goal. Subsystems were created to break the project up into four sections: field generation, power, sensors/motion, and controls/software.

Initially, multiple solenoids were considered to create the field generation subsystem. A large current pulse of short duration through the coils is the means of creating an electromagnetic field used to accelerate the projectile. The field generation subsystem was used to transfer as much energy as possible from energy storage, capacitor bank or batteries, to the projectile. Multiple coils triggered with precision timing have advantages when trying to achieve high velocities. To program precision timing switches for a series of coils takes a lot of work. Because of this, one solenoid was used. This increased the ease of switch timing, but in turn increased the need for ultra-efficient energy transfer to the projectile. Being able to maximize force applied in the forward direction is crucial. To achieve this, the current pulse must be finished when the projectile is half way through the coil. If the current is still flowing through the coil after hitting the halfway point, the force generated by magnetic flux is in the opposite direction. This is called "suck back," and depending on the magnitude, decreases the muzzle velocity greatly.

Selecting the projectile to be launched was the next part of this project. Several shapes and materials were considered. Initially, a light mass, spherical shape was to be used. After researching different materials, it was found that the amount of force the magnetic field can apply on the projectile directly relates to the amount of ferromagnetic material in the projectile. Super alloy would be the best material to use as a projectile due to its high permeability, but couldn't be used due to its high price and availability. Iron and steel rods were the next choice of material. They used Barry Hansen's (coilgun.info) simulation for variation of projectile to coil ratio to determine that a projectile 75% the length of the coil yields maximum work. Iron dowels of various lengths ranging from 20 mm to 5 mm were tested to find an optimum projectile. Having a spherical projectile was scrapped in favor of a more rail like shape for maximum efficiency of energy transfer.

The barrel design for this project was interesting. When designing a barrel, several factors come into play. These include permeability, the ability for the magnetic field to penetrate the barrel, and coefficient of friction. Initially they wanted to use a brass barrel because of its durability, low coefficient of friction and its non-ferromagnetic properties. Considering safety and the metallic conduction properties, an insulator between the coils and barrel would have to be used. This would further the distance between the coils and projectile and reduce the amount of energy transferred to the projectile. Another variable to consider is induced eddy currents. Eddy currents are currents in a conductor that circulate and induce a magnetic field in the opposite direction to the original magnetic field. This further reduces the efficiency of energy transfer and is a big problem when efficiency is important to a good launch. To reduce the effect of eddy currents, slotting or notching of the barrel was going to be applied. Safety being a big component of this project, they decided on a non-conducting barrel. An eight mm inner diameter, polyvinyl chloride (PVC) pipe was selected for the barrel. The outside of the barrel diameter was 13 mm and was the inner diameter of the solenoid used. Barrel vibrations from the accelerating projectile were considered and a support structure was implemented to reduce these vibrations.

To increase a weapon's accuracy, rifling is implemented into the barrel to create a spin on the projectile. Rifling is the act of creating grooves throughout the inside of the barrel. These grooves force the projectile to spin while it's traveling down the barrel. A spinning projectile is much more stable and maximizes accuracy. The speed of rifling refers to its rotational speed or twist rate. This is calculated using variables including projectile shape, length and weight. Slower twist rates are used for short length, big diameter projectiles; while faster twist rates are used for longer length, smaller diameter projectiles. Keeping the rifling uniform throughout the barrel is important, so cutting all the groves in one motion is preferred. Buying a pre-rifled barrel is another, but expensive, option. Due to all of the variables and high cost of rifling, this was a part of the project that would be considered if time allowed for it.

Wire selection for the coils is also very important. A huge amount of current has to flow through the coils in a short period of time to create the magnetic flux used to accelerate the projectile. As current flows through the wire, some of the energy is dissipated as heat. If the heat doesn't dissipate fast enough, the wire can easily melt. If the wire around the solenoid melts then a system failure is bound to happen. Three wire gauge choices were considered for their project: 18, 16 and 14 AWG. A smaller wire gauge allows for more turns per coil and an increased magnetic field; while a bigger gauge allows for more current flow, less wire resistivity and faster heat dissipation. This translates into the ability to fire more shots rapidly. In their project, 16 gauge wire was selected for the solenoid. This variable hit a desired number of turns and heat dissipation. Magnetic wire was selected to be used in this design due to the enameled finish of the wire to limit short circuiting in the coils. A cooling device was considered for heat dissipation, but ended up not being needed due to the short time interval during the firing sequence. A great idea to come out of this project is the use of a bolt to wrap the wire for coil construction. The bolt diameter was the same as the barrel and had two nuts on each side used to force the wire close together. After each layer of wire is wrapped, they added a small drop of superglue to each side to hold the coil together. A handmade coil guide like the one used can be seen here in Figure 8. After enough time had passed for the glue to harden, the coil was removed and mounted to the barrel.

Figure 8 Hand Made Coil Guide

Picking a viable current source is a very important part of coilgun design. If the solenoid doesn't have enough current for firing then the proposed muzzle velocity will not be reached. Initially, an automotive battery was considered for their design. The biggest concern was the practicality of using a battery. The large charge time and bulky nature were some of the factors that led to scrapping the idea of using a battery. A capacitor bank was decided to be used as the current source. When picking the capacitors to use in the bank, several variables were taken into consideration. These include capacitors with low equivalent series resistance and low equivalent series inductance. Equivalent series inductance is only a factor if the inductance of the capacitor is greater than the inductor. Supercapacitors were not taken into consideration for this design because of the need for pulse generation. They had read that using supercapacitors for a pulse discharge could damage the supercapacitor. For a decent launch, 5 mF were needed for current pulse generation. Similar to our design, electrolytic capacitors were selected for their price and high capacitance relative to size. Keeping the polarity of the capacitors the same during firing is crucial. If the polarity of the capacitor is changed, the capacitor can be severely damaged. To circumvent this, they implemented flyback diodes into the design. The capacitor of choice was a Type CGS High-Cap Screw Terminal Aluminum Electrolytic Capacitor. This capacitor was a 350 Volt, 1000μF capacitor with an equivalent series resistance of 140 milliohms. In their design, five of these capacitors were to be used. They calculated that with the five capacitors, 225 joules would be accessible. A great idea that was implemented into their design was the use of a copper bus connecting the five capacitors in parallel. Because the capacitors have a screw termination, holes were drilled in the copper bus and fastened to the capacitors with screws.

An external enclosure to cover the barrel and coils was considered for this design. External iron around the armature could be used to reduce the reluctance of the coil. This would guide the flux into the central axis of the solenoid increasing efficiency of energy transfer to the projectile. For their design, a conventional iron pipe from a hardware store was to be used. After some research went into figuring out if this could be used, it was found that the advantages provided did not outweigh the detriments. The added weight was going to make work for the servo motors in charge of barrel positioning even tougher. To make matters worse, an enclosed armature means less heat dissipation and a longer cool down time. Eddy currents also come into play here, being detrimental to the overall energy transfer to the projectile. Using an iron shell to cover the armature ended up not making it into the final design.

Velocity detection is a necessity of coilgun design, due to many design constraints and the overall goal of a high muzzle velocity. In their project, there were several methods looked at for velocity detection, including: optical sensing, field sensing, mechanical contact and electrical contact. Electrical contact would implement a circuit at the end of the barrel. While the projectile moves down the armature, the circuit would complete and start a counter. Once the projectile breaks the circuit, the counter would stop. Major issues arise from using this method. Good contact with the projectile would be required for this to work correctly and this means slowing the projectile as it's launched. Mechanical contact is similar to electrical contact, with one major difference. Instead of the projectile completing a circuit, the projectile would hit and depress switches inside the armature starting a counter. The same issues emerge here as they did with the previous method: the projectile will ultimately decrease in velocity. The last two methods of velocity detection don't dampen the projectile's velocity while traveling through the barrel. Sensing coils at the end of the armature would be induced by the projectile traveling through it. This induction could be calculated and translated into a velocity. Compared to the induction sensing method, optical sensing has the ability to calculate velocity without slowing the projectile's speed in the barrel. The optical sensors would have to be placed inside the barrel to be able to see the projectile moving through it. Using optical sensors to calculate velocity is fairly simple. Two sensors are placed in the barrel a set distance from each other and measures the time it takes for the projectile to pass from the first to the second sensor. Using this measured time and the set distance between sensors, the velocity can be calculated. A light emitting diode will be used so that when the projectile passes through this part of the barrel, the projectile trips the sensor starting a counter. The counter stops when the projectile passes by the second sensor. For their project, an infrared spectrum optical sensor was chosen. The immediate benefit of using infrared is that visible light will not trigger the sensor. When the sensor was tripped, the signal was sent to a Programmable Integrated Circuit. They used a PIC16 as the counter and sent the output to an eight bit display. Their sensors were mounted three inches apart on the barrel, with the second sensor a half inch away from the end. An optical sensor circuit like the one shown in Figure 9 was used, and with this data, velocity can be calculated.

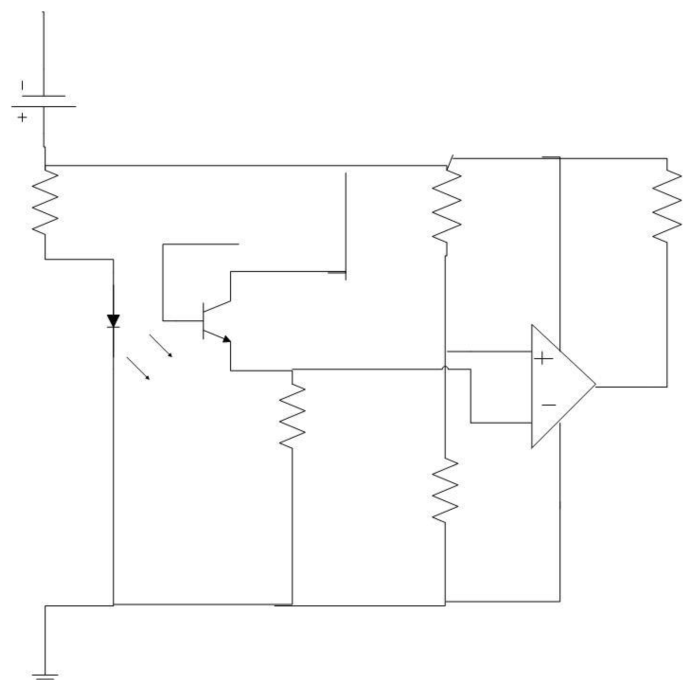


Figure 9 Optical Sensor Circuit

Heat dissipation is another important design parameter when it comes to building a coilgun. When running electrical systems with high current, heat is always an issue. The armature and the power supply will undoubtedly be the components most in need of heat dissipation. Reducing heat not only keeps the components from being ruined, but also increases efficiency. One of the methods for heat dissipation discussed in this project was the use of heat sinks. Heat sinks are used to transfer heat from one medium to another, either air or liquid. Liquid cooling is beyond the scope of this project because of price and practicality. Another great idea to come out of this project is the use of computer case fans. These fans are readily available and range in size, price, CFM (cubic feet per minute), and RPM. In their project, multiple fans and heat sinks were used to dissipate heat. They used capacitor coolers on their capacitor bank to help keep the capacitors at a good working temperature. For the circuitry, 80mm computer case fans were used. These fans not only delivered cool air to the circuits, but also expelled the hot air. Armature cooling was discussed for their project but a definitive design was not made. Leaving the armature somewhat exposed to open air while running fans over it and keeping the current pulse to a safe value are all ways to keep the solenoids at a safe working temperature.

Getting the current from the capacitors to the armature with the least amount of losses is a tough problem to solve. Without a proper switching system, the stored energy from the capacitors is lost and won't travel to the armature efficiently. Usually this can be done with any type of switch, but with high current high voltage situations, a special type of switch needs to be used. There are several different kinds of switches that could be used. Some that were considered in their project include: bipolar junction transistors, insulated gate BJT's, metal-oxide semiconductors, and silicon controlled rectifiers. All of these devices can withstand the high current used for this type of operation. The first device researched is the silicon controlled rectifier. A silicon controlled rectifier is composed of four layers of P and N type semiconductor materials. The rectifier is turned on and allows current to pass when it reaches the holding current value. Each rectifier has a different holding current and should be chosen according to the application. A major issue with a silicon controlled rectifier is that it will remain on as long as the current is larger than the holding current value. An upside to using one of these is its low cost for a high powered switch. A silicon controlled rectifier is pictured in Figure 10. Another type of switch that could be used for this application is a bipolar junction transistor. This type of transistor is an NPN type transistor. It can be used for switching when it is operating in saturation mode which can be achieved by supplying the base with a large current. The current supplied to the base allows for a larger current to travel from the collector to the emitter. Since the current supplied to the base has to be at least ten percent of the current traveling between the collector and emitter, using this would be highly inefficient. The configuration of a bipolar junction transistor can be seen in Figure 10.

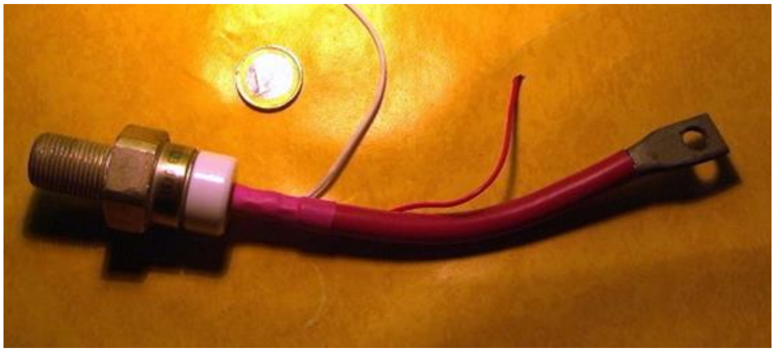


Figure 10 Silicon Controlled Rectifier, Reprinted with permission from Antonio Pedreira

A third type of switch that could be used for this project is a metal oxide semiconductor field effect transistor, or MOSFET. Using this type of switch in a coilgun design means adding a lot of extra circuitry to make sure no damage is done to the MOSFET. An example of a MOSFET can be seen here Figure 11 and 12.

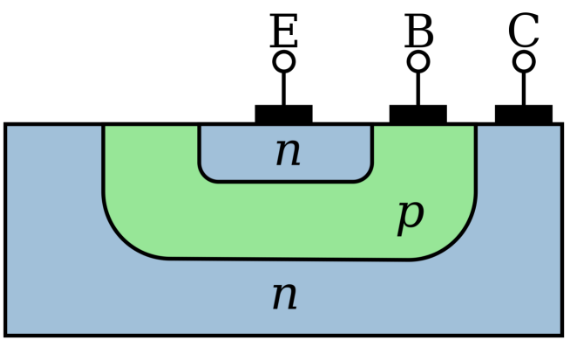


Figure 11 Bipolar Junction Transistor; Reproduced with permission to be used for any purpose without any conditions by the author; inductiveload.

A MOSFET isn't practical for this type of project because of its base properties interfering with the high amount of electromagnetic fields being produced.

The last type of switch considered for use in a coilgun design is an insulated gate bipolar transistor. These kinds of switches are known for large pulses when switching rapidly. Insulated gate bipolar transistors have the best characteristics from both bipolar junction transistors and metal oxide field effect transistors. An insulated gate bipolar transistor has three pins like a BJT, but one comes directly from a metal oxide field effect transistor. An insulated gate bipolar transistor can be seen here Figure 13. This makes a great switch because the gate is easily driven while allowing maximum current to flow from the collector to the emitter side. With all of these upsides it seems that it would make a great switch for any coilgun design that requires rapid switching.

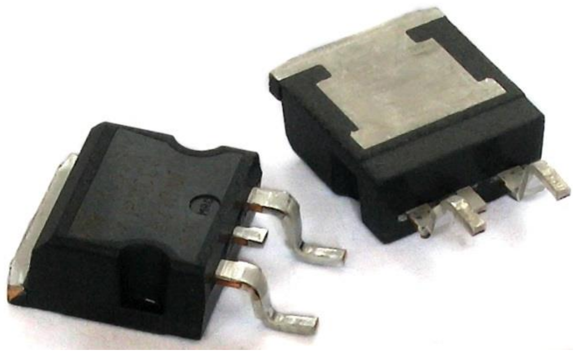


Figure 12 Power Metal Oxide Semiconductor Field Effect Transistor. Reprinted under permission of the GNU Free Documentation License and Creative Commons Attribution-Share Alike 3.0 Unported license.

Unfortunately, some drawbacks come with using an insulated gate bipolar transistor. Some of the drawbacks include high cost for high current ratings, a need for a gate driver, and possible voltage spikes when the device is turned off. For their project design, a silicon controlled rectifier was chosen. They chose one with the specifications of 100 amps and a holding current of 1400 amps. The biggest competition for this switching device was the insulated gate bipolar transistor. If it wasn't for the voltage spike problem with this device, it probably would have been used. Price also led this group to choose the silicon controlled rectifier for use as a switching device. They connected the rectifier between two parallel circuits, hooking the armature flyback diode circuit to the anode side and the capacitor bank to the cathode terminal. The gate terminal was supplied with a constant direct current.

Figure 13 Insulated Gate Bipolar Transistor. (Reprinted under permission of the GNU Free Documentation License and Creative Commons Attribution-Share Alike 3.0 Unported license)

It was recognized in this project the necessity of using bleed resistors. When the coilgun is put away and not in use, there should be no residual charge left in the capacitors. Launching alone shouldn't empty the capacitors fully, so another route has to be taken to drain them of charge completely. If residual charge remains in the capacitor bank, the capacitors can be easily damaged. Even worse is if an unsuspecting person get shocked with this much charge, it could lead to injury or death. A bleed resistor is a regular resistor placed in parallel to the capacitor bank. This way when the coilgun needs to be stored, the capacitors will drain fully. Choosing the correct value of the bleed resistor is very important because if it is too small, problems will arise with power dissipation heat. Using the calculated charge time, the bleed resistor value can be found. The time it takes the bleed resistor to drain the capacitor bank of charge is a hundred to a thousand times the charge time. The equation they used is given in (9):

$$\mathrm{R} = \frac{\mathrm{t}}{\mathrm{C}} \tag{9}$$

The R in the equation represents the calculated resistance value of the bleed resistor while the t represents the time it takes the bleed resistor to drain the capacitor bank of all its charge. Capacitance is represented by the C in the equation and is the value of capacitance of the bank as a whole. The time it takes to drain the capacitors of charge using the bleed resistor isn't all too important since it will only be used when the coilgun is stored. A 150 kohm resistor was used as a bleed resistor in their project even though calculations suggested a 100 kohm resistor.

In addition to researching flyback diodes for circuit and armature protection, damping resistors were considered. Both of these methods are for preventing suck back. This occurs when the projectile hasn't completely left the solenoid and experiences a force back in the opposite direction. Usually, this occurs when the switch timing is wrong and current is flowing when the projectile is more than half way through the solenoid. While a flyback diode prevents voltage spikes and damage to the armature, it also allows current to flow back to the coil. For this reason a damping resistor can be used to reduce the amount of current that can be transferred back to the armature. Using a damping resistor will make the circuit critically damped. If the circuit is critically damped then there is no need for a flyback diode. Whether or not the circuit is critically damped or under damped means choosing a damping resistor or flyback diode. If a damping resistor is used, it will be located in series with the armature. Seen here in equation (10) and (11) is what they used to calculate the value of the damping resistor.

$$R^2C^2 - 4LC = 0 \tag{10}$$

$$R = \sqrt{4L/C} \tag{11}$$

In this equation, C represents the capacitor bank capacitance, L represents the coil inductance, and R is the calculated resistance to keep the circuit critically damped. Looking at these equations, it is obvious that the calculated resistance value is primarily influenced by the overall capacitance. For their project, a damping resistor with a value of .583 ohms was selected.

Incorporated into their design was a digital voltmeter. This way, the voltage of the capacitor bank could be constantly monitored. Monitoring the voltage is a necessity of coilgun design because the capacitors can easily be damaged if the voltage goes over the designed maximum. This is also important to the capacitors' longevity. They placed the voltmeter in parallel with the capacitor bank to constantly monitor its charge. A thermometer was also integrated into their design. This is a very important factor when working with high power and high current: all of the connected components get hot. When some components get too hot they either become less efficient or stop working completely.

A coilgun's triggering system could be the difference between it working exceptionally or not working at all. There are several different ways to go about setting up a triggering system. Three of these discussed are an open loop triggering system, an optical triggering system and an induced voltage sensing system. In an open loop triggering system, trial and error are used to find the best timing. Timer circuits are used to send a pulse of current at a set time period. A more precise way to implement a triggering system is with optical triggering. Besides the benefit of more precise timing, the optical triggering system is largely unaffected by electromagnetic interference. The last way is induced voltage triggering. This method uses the induced voltage from the coil and projectile to trigger the circuit. Out of the three, this method is definitely the most complicated and requires the greatest amount of trial and error to find the most efficient trigger timing. In their project, an open loop triggering system was used due to its simplicity and its ability to be modified alongside other hardware changes.

The power system is one of the most important parts of coilgun design. If the coilgun doesn't have the required energy to launch a projectile, the rest of the design is useless. Capacitors have very recently reached a point in their technological life cycle where they can store massive amounts of charge easily. Getting the capacitors charged acceptable amount of time is a critical design challenge. Also, building a power supply to deal with this much voltage and current is another challenge. In this project, the group used one power supply to power all the electrical components as well as charge the capacitors. This includes current to power the switches, servo motors, charge the capacitors, and controls for automation of target acquisition plus firing. The basic layout of the power supply involved a step up transformer that upped the voltage and an AC to DC converter that allowed for capacitor charging. A few different charging methods were looked at for this design. These include using a standard ATX computer power supply, a car battery charger and conventional out-of-the-wall AC power. Using the first two methods were quickly dismissed because of the slow charging times and necessity for other circuit elements just to get them to work correctly. AC power being readily available, this seemed like the most viable option. The use of solar panels and cells were also discussed as a current source in order to make the coilgun portable. Because solar technology hasn't matured to the point of being a viable source for capacitor charging, this idea was quickly thrown out.

3.2 Relevant Technologies

Two existing technologies that are critical to the design being proposed are an AC to DC Power Supply and capacitor bank along with the microcontroller supply for the control.

3.2.1 AC to DC Power Supply

Outlets in the United States run 115-125 volt, 60 Hz, alternating current. Alternating current is a bidirectional sinusoidal power source, with voltage and current being out of phase. To charge the capacitor bank, the voltage must be stepped up, then converted to direct current. The voltage needs to be stepped up to allow for charging and matching the capacitor bank's voltage. Alternating current cannot be used to charge the capacitor bank directly since the capacitors will allow all alternating signals to pass right through. Direct current on the other hand is blocked by the capacitors and allows them to charge. The conversion process from alternating current to direct current will come from a simple diode circuit.

The easiest way to convert alternating current to direct current is the use of a rectifier. Rectification is the process in which AC is converted to DC. A rectifier is made up of one or more diodes in series with a resistor. There are three main types of rectification: half-wave, full-wave, and bridge rectification. The half wave rectifier is made up of a single silicon diode. This system is relatively cheap, but is suitable only for low demand operations. Voltage produced with this method is less than other rectifiers and limits efficiency of the power supply. Not only is the voltage much less, but some of the alternating current ripple makes it through the rectifier to the direct current side. This requires the use of voltage smoothing to make it compatible with most devices. The half wave rectifier only allows one half of each alternating current cycle to pass through. Essentially this means that half of the signal is blocked and voltage gets divided in half.

A full wave rectifier solves some of the problems that arise when using a half wave rectifier. If a center tapped secondary coil transformer is to be used, then two diodes are put into the circuit. The center-tapped secondary coil in the transformer produces two opposite phase outputs. Each of the outputs are rectified by means of half wave rectification; but because there are two sides, each diode conducts on alternate half cycles. Therefore the outputted voltage is double that of the equivalent half wave rectifier. This significantly increases the efficiency of power conversion to direct current. Another upside is the higher output frequency, which makes smoothing of surviving alternating current ripple much simpler. Even though this full wave rectifier design is much more efficient than half wave rectification, it requires an expensive center-tapped secondary coil transformer.

A bridge rectifier is the most advanced and is the most commonly used of the rectifiers. It uses four diodes arranged in a bridge circuit to allow for full rectification. This method of rectification doesn't require the use of a center-tapped transformer while also transmitting full power. Another advantage of bridge rectifiers are the need for diodes that only have to support half the reverse breakdown voltage compared to half and full wave rectification. A bridge rectifier will be used in our design to convert alternating current to direct current.

3.2.2 Capacitor Bank

For analysis purposes, a combination of capacitors can be considered a single capacitor for each stage. Three important characteristics must be considered and adjusted to obtain the best performance. The first is voltage. Since energy in a capacitor is "stored" in the electric field, the higher the voltage a capacitor can hold without the dielectric breaking down, the more energy the capacitor can store. Energy stored is geometrically proportional to voltage across the capacitor. Also, the current through a coil in an RLC circuit is linearly proportional to the capacitor's initial voltage. The second characteristic--capacitance--also contributes to the amount of energy stored in the capacitor, but only linearly. In an RLC circuit, the product of the capacitance and the inductance of the inductor that it is paired determines the circuit's frequency of oscillation. As the capacitance lowers and inductance stays constant, the frequency of oscillation increases. ESR, or equivalent series resistance, is a measure of the DC purely resistive characteristics of a real capacitor (not its impedance). A higher ESR means energy is converted into heat inside the capacitor and is therefore wasted. The magnitude of ESR directly affects the resistive exponent envelope (more on this in section 4.3.3.). In summary, the capacitor(s) have to be selected and arranged in a way where ESR is minimized. Also, capacitance and voltage have to be balanced in a manner where the proper frequency of oscillation is reached while at the same time not allowing the current doesn't get to the point where switching components become prohibitively expensive. These goals take priority. Only when they're met then can energy density maximization can be considered.

There are several tradeoffs between different arrangements of capacitors and the selection of the individual capacitors themselves in order to achieve the objectives mentioned above. The capacitors can be arranged in parallel, series or an arrangement of both. Adding more capacitors to a bank linearly increases the amount of stored energy by the same amount no matter if they are added in series on in parallel.

Where n is the number of capacitors connected in series and all capacitor units being arranged are identical:

$$V_{total} = V_{unit} * n \tag{12}$$

$$C_{total} = \frac{C_{unit}}{n} \tag{13}$$

$$ESR_{total} = ESR_{unit} * n \tag{14}$$

Decreasing the capacitance is desirable since it allows for a higher inductance coil to be used and thus allowing for the same energy to be stored in the coil with a lower current. However, lowering the inductance by connecting capacitors in series it comes at the 'cost' of higher voltage (up by integer multiples), which end up raising the current by the same amount previously lowered by allowing for a lower inductance. Thus any gains from a higher possible inductance are negated. Charging the series capacitor bank to a fraction of the maximum voltage can lower the peak current running through the inductor coil. However by doing so, potential energy storage is decreased and overall energy density is lowered. Stacking capacitors adds no advantage when the upper limit on current is rigid and the inductance of the coil is flexible (as is the case in this design). When this is true there is only an increase in ESR which further downgrades the performance of the circuit. Yet another disadvantage of connecting capacitors in series, stems from the real-world variations from the nominal values. Each unit will have capacitances that vary up to + or - 20% from the rated value. This can potentially create uneven voltages across the different units connected in series that if they exceed the rated voltage can damage and potentially destroy the capacitor. To account for this, a resistor must be connected in parallel with every capacitor unit to absorb any extra voltage applied to that "stage" in the capacitor bank.

The other way to connect multiple capacitors into a single bank is by connecting them in parallel. When connected in parallel, the capacitor bank will have the same voltage as the individual cells that compose it. The ESR is inversely proportional to the number of capacitors connected in parallel. The capacitance increases in direct proportion to the number of capacitors connected.

For parallel

$$\mathrm{V_{total}} = \mathrm{V_{unit}} \tag{15}$$

$$\mathrm{C_{total}} = \mathrm{C_{unit}} * \mathrm{n} \tag{16}$$

$$\mathrm{ESR_{total}} = \frac{\mathrm{ESR_{unit}}}{\mathrm{n}} \tag{17}$$

One of the advantages of this configuration is that the total energy of the bank can be increased by adding more capacitors without raising the voltage. As discussed previously, raising the voltage will effectively mean a higher, harder to manage current, so keeping the voltage the same is very desirable. Another advantage is that capacitors combined in parallel end up reducing the ESR, which increases reduces wasted energy and increases the efficiency of the overall system. Also, the resistive effects are spread out amongst more components allowing heat to be more effectively dissipated. Unlike the parallel arrangement the no resistors are needed to balance out variations between capacitors. One crippling disadvantage is that because of the increased capacitance of the aggregate capacitor, the inductance needs to be lower to keep the pulse time the same, thus making the current surge to unmanageable levels.

In addition to how the bank gets created from individual cells, there is also a choice between having a single large capacitor bank that is switched between each coil in series, versus each stage having its own capacitor(s) from which to draw power from. Having a single bank for all stages is advantageous because if it is paired with an inductor that allows that stage to have a underdamped response, less energy will be wasted overall and leftover energy gets charged back into the capacitor during the last half of the half-wave (second quarter wave). One disadvantage is that the capacitance becomes fixed across all stages, necessitating only the inductance to vary to create the right firing pulse time, which means very large current magnitude variations from first to last stage. Another disadvantage is that it usually means more capacitors are have to connected together to since there has to be enough energy for all of the stages in one bank. They will most optimally be connected in series to keep the bank’s capacitance down which in turn means a higher ESR. If the RLC is critically or over damped in any stage besides the last, then the banks entire energy will be expended and there will be none leftover for the next stage.

To choose the best arrangement and component, the desired attributes of the aggregate capacitors (the capacitor bank) must first be identified. Two critical objectives were first imposed on the capacitor bank design: high energy density, and fast peak current. After modeling and more research, it was determined that additional factors had to be taken into consideration. The interconnectedness of the capacitors and inductors necessitate both of them to be considered together in the design phase.

3.3 Strategic Components

In order for a coilgun system to function and meet the goals and objectives strategic components are necessary. The MAC system has six primary components and one support component. The strategic components include the capacitors, switches, coils, sensors, power supply, and a processor. The support component is the range finder to meet the objectives of the MAC. The following will describe the role each component plays in the system of the MAC

3.3.1 Energy Storage Components

The basic operation of a coilgun depends on the extremely short and powerful bursts of electrical energy. Most power supplies are unable to deliver such power. Thus, external electrical energy gathered from the power supply (3.3.5) must be “buffered” into the Energy Storage stage, where it can be pulsed at high power as needed. The exact type of components to use in this intermediary energy storage stage must first be determined. This stage must first and foremost be able to deliver high currents.

When a projectile passes through a coil, a minority of the energy of the magnetic field gets transferred into the kinetic energy of the projectile. The bulk of the applied energy remains in the magnetic field. The coil must be expeditiously demagnetized by terminating the current flow through it, lest the projectile be pulled back into the center of the coil from whence it came. the second feature that the intermediate energy storage must have is the ability to aid in the off switching of the coil.

Heavy batteries used in large boats and trucks are capable of delivering high currents in the kilo Amp range. These would be appropriate for this requirement. However they maintain voltages across their terminals close to their rating, making an energized coil stay “on” indefinitely in the time scale of a firing sequence.

To switch off a coil that was driven by a battery either/or a combination of two methods has to be used. The first method is to design the driver-coil circuit to rely exclusively on the dc resistivity of the coil to eventually dissipate all of the magnetic energy in a timely manner. The second is to break the very energy magnetic field in the coil with a high voltage switch which will waste all of the unused energy in the magnetic field.

The right capacitor or combination of capacitors can also provide the high current needed to power the coils. It also provides a better alternative to the “switching problem”. A capacitor and inductor in series create a harmonic circuit, where either a natural oscillation or a pulse is created, depending on the characteristics of the components used in the circuit. The capacitor and inductor values can be adjusted so that the pulse lasts the desired time. Switching can happen when the current in this natural oscillation reaches zero, or when the pulse dies down to an acceptable level naturally. Switching off with capacitors creating this type of response produces little to no losses. The energy stored in a capacitor is described by the expression:

$$\mathrm{E} = \frac{1}{2}\,\mathrm{CV}^2 \qquad (18)$$

Where, E is energy, C is capacitance and V is voltage.

Energy density was the primary objective when the capacitor bank was first conceived for this project. The initial specification called for a total of 40,000J of stored electrical energy. This was chosen since at the aspirational 50% capacitor-to-projectile efficiency, the projectile would have 20,000J of energy at the muzzle, making it comparable to similarly-sized chemical-accelerated projectiles. After some research the most cost-effective way to store this magnitude of energy in capacitors is through the use of ultracapacitors. The unusually high capacitance of this category of components made them seem like the ideal choice. In comparison to typical high-energy capacitors, usually in micro-Farad range, these ultra-capacitors, although at slightly lower voltages, had capacitances in the hundreds to thousands of Farads. In addition to the extremely high capacitances, they also typically have very low internal resistances. Two ultra-capacitor manufacturers were identified--Maxwell and Ioxus. After compiling their product offerings and subsequently analyzing and comparing them, the most energy per dollar composition was derived: Four 3000 Farad, 2.7 V Ioxus ultracapacitors [model number]. Using (18), this configuration could store up to 43740J--slightly above the desired energy. This capacitor bank possibility would be able to deliver up to 4000A of current at very low loads. This is a very attractive characteristic, since the according to (1) the force of the magnetic field on a ferromagnetic material is proportional to the current. Although this configuration did have several advantages, it has a very critical drawback discussed in section 4.3.2.

Because of the described drawback, the entire initial design parameters had to be reconsidered. Capacitors with capacitances in the range where the RLC pulses would last in the hundreds of microseconds, while keeping the currents at a manageable level did not have nearly the same energy density as the ultra-capacitors. A new acceleration profile was created with reduced target velocity and projectile mass in section 4.6.2.2.

3.3.1.1 Time to peak current

Since this is a multistage coilgun, the timing of switching each coil on in sequence is critical to the proper performance. As mentioned in 4.6.2.2, the total transit time of the projectile at maximum speed is about 5ms. As the projectile approaches the end of the barrel, it’s going so fast that it takes only about 80us to go from the center of the 24th (next to last) coil to the center of the 25th (last) coil. That means that most of the energy has to be transferred from the capacitor to the coil in the microsecond scale.

When a projectile is not present, the capacitor bank and a single stage of the coil gun can be expressed as a series RLC (Resistor, Inductor, Capacitor) circuit.

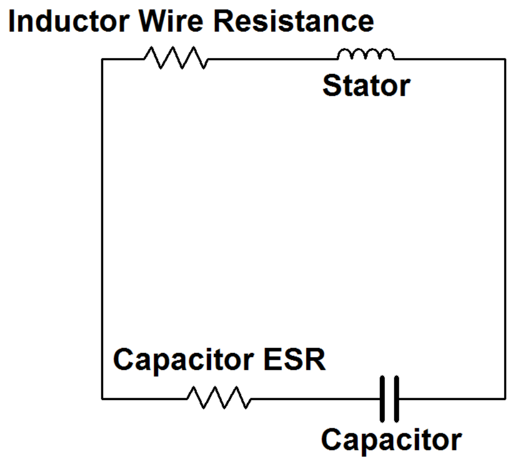


Figure 14 Basic RLC Circuit

The following differential equation expresses the behavior of the above circuit:

$$i''(t) + \left(\frac{R}{L}\right) i'(t) + \left(\frac{1}{LC}\right) * i(t) = 0 \tag{19}$$

With the solution for i(t) known:

$$i(t) = \frac{V_0}{\beta} * e^{-\alpha t} \sin(\beta * t) \tag{20}$$

Where, V_0 is the capacitor bank's maximum voltage; the initial condition when the capacitor is completely charged.

$$\beta = \sqrt{\left(\frac{1}{LC} - \frac{R^2}{4 * L^2}\right)} \tag{21}$$

$$\alpha = \frac{R}{2L} \tag{22}$$

The expression for the capacitor's voltage can also be found:

$$V_{c(t)} = V_0 e^{-\alpha t} V_{0e} \cos(\beta t) \tag{23}$$

The time for the current of this circuit to reach its peak must be acceptable. This "acceptable time" is the minimum time it takes a projectile to travel from the end of the previous coil to the beginning of the current coil. This time period must fit within the first half of one half cycle of equation $i(t)$. To verify if the selected capacitor can deliver its energy to the inductor in a timely manner, the expression for the half-cycle period must be identified:

$$\tau = \pi\sqrt{LC} \tag{24}$$

$$I_{peak} = V_0\sqrt{\frac{C}{L}} \tag{25}$$

The peak time can now be analyzed for the first capacitor bank chosen in section 4.3.1:

$$C = 750F$$
$$L = 1.367\,uH$$
$$R_{ESR} = 0.8m\Omega$$
$$R = .8m\Omega + 3.158m\Omega \cong 4m\Omega$$

Thus according to (24),

$$\tau = 3.22\,ms$$

This is almost 4000 times slower than the slowest travel firing period required. Lowering the inductance to compensate for the high capacitance in equation (24) introduces other challenges. To illustrate this, we solve equation (24) for inductance:

$$L = \left(\frac{\tau}{\pi}\right)\frac{2}{C}. \tag{26}$$

Then $\tau = 866\,us$ (the longest firing pulse) is substituted to find the inductance that would work with the target capacitance. This yields $L = 10.1\,nH$. Using (25) to find the peak current, $I_{peak} = 7.3MA$ (million Amps). First, constructing an inductor with such miniscule inductance would be outside the capability of even the most precise manufacturing processes. Not only that, but the titanic currents would never be able to happen because the resistive component would completely eclipse it. Clearly according to equation (26), almost all arrangements of ultracapacitors cannot deliver energy to an inductor in the short pulse of time required.

3.3.1.2 Stability

Different selections of Capacitors and Inductors throughout the system will produce responses with varying characteristics. These characteristics must be considered to arrive at the best design. A good way to categorize these different responses is from the perspective of “stability”.

The term zeta (ζ) indicates the stability of a circuit.

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{27}$$

If $\zeta > 1$, the RLC circuit is overdamped. If $\zeta < 1$, the circuit is underdamped. When $\zeta = 1$ (or very close), the circuit is critically damped. A time vs. current graph is shown in Figure 20 illustrating variations in ζ.

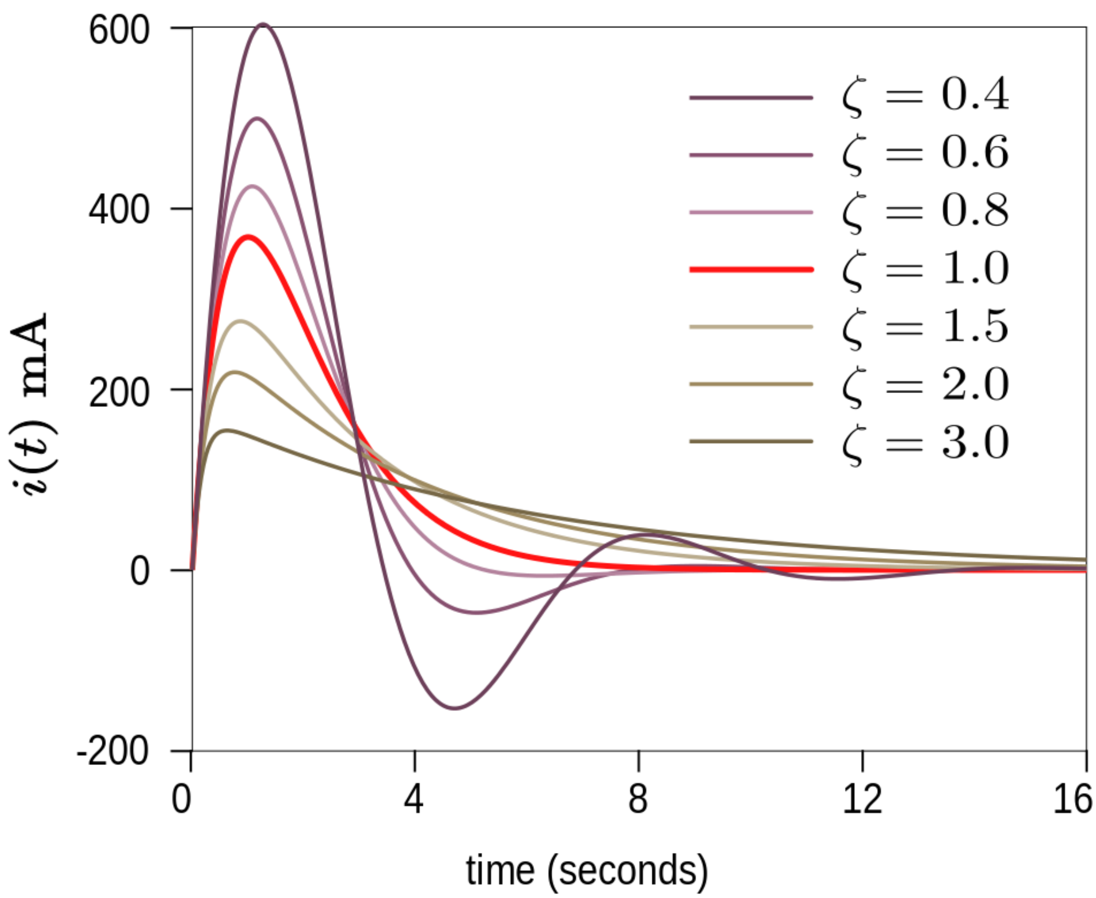


Figure 15 RLC Transient Plot. Reprinted with the permission from Spinningspark under the Creative Commons Attribution-ShareAlike 3.0 License. Attribution: Courtesy Spinningspark at Wikipedia

The RLC circuit can be designed to fall within the three aforementioned responses: overdamped underdamped and critically damped. Attributes of each as they relate to coilgun performance will be briefly discussed:

An RLC circuit with an overdamped behavior reaches its peak current the fastest. It also doesn’t produce oscillations which is very good if polarized capacitors are used in the storage bank. It does have some drawbacks however. The fast peak current only happens because the exponential component is such a dominant part that it dampens the peak current from the sinusoidal component. The resistive exponential envelope drowns out the sinusoidal rise before it has a chance to take effect. Because exponent represents resistive characteristic of RLC, much of the energy is wasted to heat. Also, the very high settling time can make switching off problematic as discussed in 3.3.1.1.

Critically damped circuit has a peak time that falls in between an overdamped circuit and an underdamped circuit. It settles to zero much faster than over damped and overdamped circuit. As a result, it reaches lower currents faster, which could make switching much easier. Like the overdamped circuit, it also does not oscillate, also making it suitable for use with polarized capacitors. The main disadvantage that it has is that it still about half of its energy wasted, as seen in the resistive α exponential envelope.

The underdamped circuit has the longest time to peak. This is compensated by the fact that it has the shortest pulse time. It does have oscillations that can be used to "save" leftover energy. Energy that isn't used get recharged into the capacitor with the reverse polarity of the initial charge. It is also the circuit that has the least amount of its energy wasted by resistive envelope. It is the easiest to switch since current reaches zero very quickly. It does hover become complicated to deal with polarized capacitors, since the falling current flows back into the capacitor in the opposite direction.

To aid in the selection and configuration of the capacitor bank, the critical value of C can be solved for when the inductance and the resistances are known. (27) is solved when $\zeta = 1$:

$$1 = \left(\frac{3.158 * 10^{-3}}{2}\right)\sqrt{C(1.367 * 10^{-6})}$$

Solving for C:

$$\mathrm{C} = \left(\frac{4\mathrm{L}}{\mathrm{R}}\right) \tag{28}$$

The circuit will be;

- Overdamped for any $C > (4L/R)$
- Underdamped when $C < (4L/R)$
- Critically damped when $C = (4L/R)$.

3.3.2 Switches

The switches that will trigger each coil to turn on must be able to handle high amounts of current and be able to respond to the switch on signal at extremely low latency. The device that was found to have all these characteristics is a thyristor, or a silicon controlled rectifier. They will be driven to turn on according to the calculations made by the firing algorithms in the controller (See section 6.1.2).

Having a coil energized for the right amount of time is critical to the efficient performance of a coilgun. As important as it is to activate a coil, it is equally as important to make sure that it no longer exerts a force on the projectile after it passes its center point. Doing so would cause work that is in the opposite direction of the desired motion. In addition to the control of the switching operations how an inductor can be forced to demagnetized needs to be explored.

A fundamental characteristic of an inductor is that it effectively opposes changes in current. This is demonstrated by the following equation describing the voltage across the two terminals of an inductor:

$$\mathrm{V} = \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} \qquad (29)$$

In order to stop the magnetic field, and in turn stop the attraction to the projectile, the coil needs to go to zero current in a very short time. To understand the magnitudes involved, the following ideal scenario is imagined:

As the projectile crosses the center of the last coil, it reaches maximum velocity of 400 m/s. If we want the entire switching process to occur before the projectile traverses 10% of the coil length (10% of $2.99 * 10^{-2}\, m = 2.99 * 10^{-3} m$), then it must happen in $t = (400\frac{m}{s})/(2.99 * 10^{-3}\, m) = 7.475\, \mu s$. If 90% of the peak current of a 4000A was flowing through the coil, 3600A would have remained. Thus, $di/dt = 3600A/7.475us$. According to (29), the voltage across the switch would be $V = 1.367 * 10^{-6} * [(4000)/(7.475 * 10^{-6})] = 731.5\, V$.

From an energy balance perspective, breaking the current of a magnetized coil converts all of the energy stored in the coil into waste heat. The inevitable arc due to the high potential burns all the energy through the insulators in dielectric breakdown and damages the switching components.

Thus, it can be concluded that the current pulses in each coil must be regulated in some other way besides opening the circuit on a fully magnetized inductor. This is done by tuning the inductor and capacitor values to create oscillations with half cycles the same length as the desired time to energize the coils (discussed in more detail in section 4.3.2). The critical advantage of approaching the design this way is that the tuned RLC oscillation naturally reaches 0 current exactly when it is desired for the pulse to end. At this point, rather than letting the circuit naturally rise to a negative current, it can easily be switched off (opened) without any of the problematic high voltages discussed earlier, since $di/dt = 0$ at this instant. Even more attractive, is the fact that there does not need to be any current measurement signal feedback to control or trigger the switching off event. A semiconductor device called a “Silicon Controlled Rectifier” also known as a Thyristor automatically switches off when the current going through it drops below its rated “holding current”. However, the timing for the “on” event transmitted to the SCR of each coil stage is part of a control loop discussed in section 6.1.2.

3.3.3 Coils

The coils, also called the stators, produce magnetic energy in the MAC barrel from the breach to the muzzle. Utilizing the magnetic energy, manifested as a magnetic field by a current passing through the coil as depicted in Figure 22, the coil interacts with a ferromagnetic material in the projectile and creates propulsive force with the induction of currents. This force, also called Lorentz force, is a basic concept for the use of coil guns. The coils are utilized with capacitors in the circuit to create an electromagnetic pulse which is converted into kinetic energy in the projectile. By using many coils aligned linearly, as shown in Figure 21, a magnetic pulse can be sent down the barrel of a coil gun to accelerate a ferromagnetic projectile.

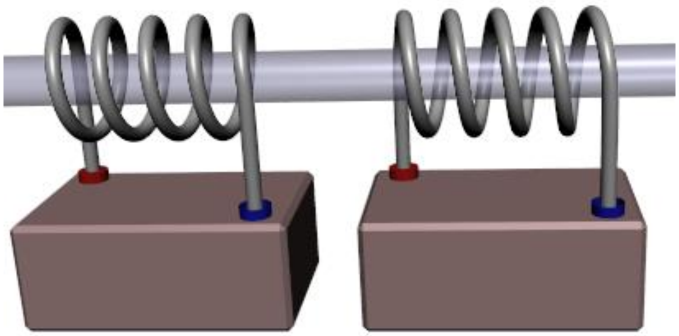


Figure 16 Coils Linearly Aligned to Form a Two Stage Coilgun. Reproduced with permission under the terms of the GNU Free Documentation License and under the Creative Commons Attribution-Share Alike 3.0

The geometry of the coils drives the magnetic properties of the barrel for the MAC. The geometry can be scaled to provide the necessary magnetic field and resulting kinetic energy with the introduction of a ferromagnetic material. The geometry of the coils can be changed by altering the turns per coil and the diameter of the coils. It is also possible to do multilayered coils to meet inductance values which are necessary for the design of the gun system.

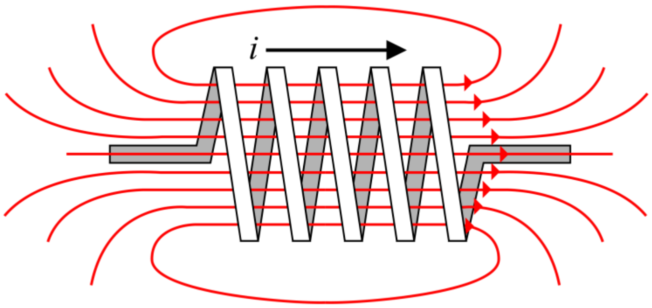


Figure 17 Magnetic Field Creation in a Basic Coil. Reproduced with permission to be used for any purpose without any conditions by the author; inductiveload.

To meet the objectives of the project the design of the coils were prioritized to produce the most efficient results. The helical geometry, as shown in Figure 22, of the coils allows for simple construction and placement on the gun coil system. The Figure depicts single layer coil geometry. Unlike the conducting rails in a railgun the coils in the coilgun provides a lower maintenance cost to the gun system. Coils are not only cost effective and simple to build, but also effective at meeting design goals.

Figure 18 Single Layer Coil Geometry Example

The coils in the MAC are the primary energy conversion component in the gun system. Without this component the gun would have no function. One of the primary benefits is the efficiency in converting electrical energy into magnetic energy for use by any system that is capable of using the magnetic energy. In transformers an efficiency of 97% to 99% can be expected. The efficiency in a coil is similar, but only in converting into magnetic energy. This is an important quality in a coil, but it cannot be assumed that the efficiency of the projectile taking that magnetic energy and translating it into kinetic energy will be equal. It can be expected that an efficiency of 30% from electric energy into kinetic energy can be experienced in high quality systems with high magnetic coupling. With low quality systems an efficiency of 0.5 to 3% can be achieved. It will be expected with the materials and quality of material that an efficiency in the range of 2-5% can be reached.

The coils can be varied in a coilgun to achieve the speeds and kinetic energy requirements for a system. The addition of coils adds complexity to the system, but also adds more points where energy can be imparted on the projectile to achieve higher speeds and kinetic energy. The subtraction of coils does the complete opposite of adding coils and can be beneficiary for smaller coilgun uses and designs. The coils are usually made of copper, but can be also made of any other electrical conductors. The differences in material that can be utilized can allow the coils to be relatively light and beneficial to design decisions. Weight is a big concern in the design of gun systems and coils allow for light alternatives to launching projectiles.

Paired with capacitors and switches the coils operate by using the natural oscillating frequency which occurs in a LC circuit. The coils cannot be useful without the supporting circuit. With their scalability and ease of construction coils can be constructed to meet different criteria for different systems. Due to its functionality and use the coils are the central components for the MAC

3.3.4 Sensors

The primary method of data acquisition for feedback control purposes will be an IR diode paired with an IR photo sensor positioned at the end of each coil. Additional circuitry will be added to transport the photo-sensor’s analog signal into the microcontroller. By powering the diodes and using resistors to sense the voltage pulses a speed reading can be determined.

3.3.5 Power Supply

In coilgun design, the entire system is greatly influenced by the capabilities of the available power supply. The amount of energy that the power supply and energy storage systems must store can be attributed to the estimated muzzle kinetic energy of the projectile. According to our research, thirty three percent efficiency of stored energy can be transmitted to the projectile with high magnetic coupling, the energy delivered by the energy storage system must be at least three times the projectile's estimated kinetic energy according to this assumption. With differencing efficiencies, a different factor will have to be utilized to get the required energy needed. In this case a factor of 10 is necessary for an efficiency of 10% for initial design calculations.

$$\mathrm{W_s} = 10\mathrm{K_E} \qquad (30)$$

Where Ws is the stored energy delivered by the power supply and power storage systems, and KE is the kinetic energy of the projectile. For reliable and safe operation of this system, the power supply and energy storage systems should exceed the capabilities of the armature. The power system of a coilgun plays an important role in the overall operation of the device. It supplies power not only to the energy storage system, but to the user interface as well. An overview of the power system can be seen in the following block diagram Figure 24.

As discussed in section 3.2.1, the incoming AC power from a standard wall outlet must be converted into DC for use in the MAC. This was done with a bridge rectifier. The power was stepped up by the transformer then converted to DC with the bridge rectifier for use by the capacitors and system controller. Alternatively, if the user wanted to mount the coilgun onto a vehicle, the vehicle's electrical system could be used. If this is the case, then no AC to DC power conversion is needed due to the vehicle's use of DC power. Only a DC to DC step-up transformer will be needed to meet the electrical requirements of the energy storage system. This particular arrangement wasn't implemented in the present generation of the MAC but can be in future designs of the system.

In addition to charging the capacitors, the power supply must provide the energy needed to run the user interface and related components. The user interface components include a led screen, and a microcontroller. Since the user interface needed to be constantly on and the capacitor bank power supply needed to be able to switch off during firing, these two supplies had to be separate. The capacitor bank power supply must be switched off during firing due to voltage reversal in the capacitor bank during projectile launch. The user interface was powered from a standard atx power supply and was constantly on during use.

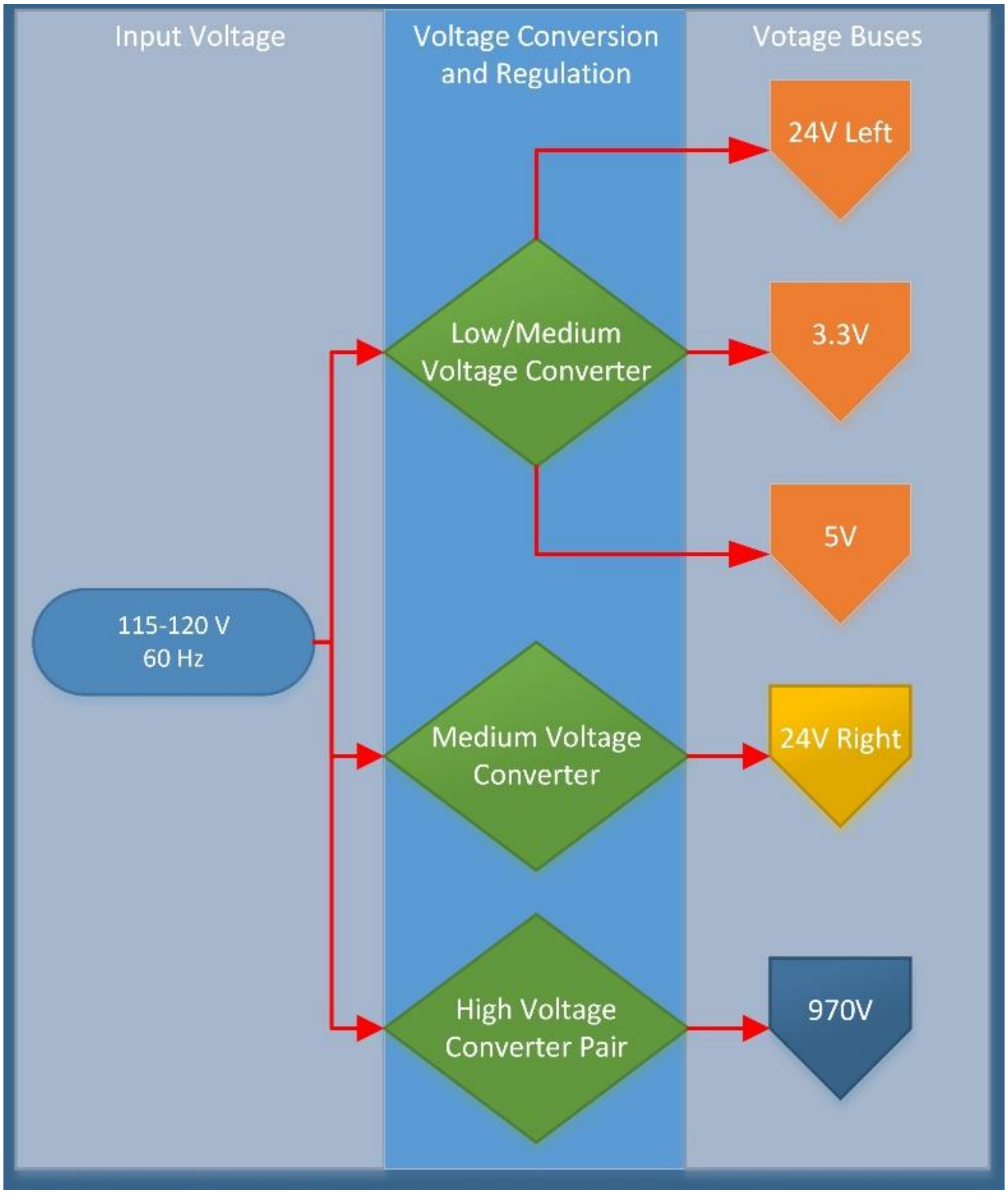


Figure 19 Power System Block Diagram

An ATX power supply was chosen due to its compact design and its output of all required voltages for user interface components. In addition, when working with high amounts of voltage, the possibility of damaging components is great. Keeping the user interface and capacitor bank power supplies separate is important so that both systems don't get destroyed if something goes wrong. The capacitor bank power supply was made from separate components, allowing for easy replacement of major components.

Multiple charge resistors were implemented into the final capacitor power supply design. This allowed for charging when the capacitor bank voltage was zero, with no damage to the other power supply components. The charge resistors were used for initial charge up and a discharge resistor was applied to discharge the high voltage capacitor bank.

A step up transformer was utilized in the power supply design. Finding a powerful enough step up transformer was a challenge. Many step down transformers exist with the opposite voltages we need on the primary and secondary windings respectively. While a step down transformer can be used as step up transformer, the secondary output rating is most likely not safe to use as input. Along with getting incorrect voltages, it is much easier to exceed the power rating and breakdown voltage of a transformer when using it in the opposite direction. Both of these lead to the breakdown of the transformer's insulation and eventually the failure of the device. Initially a step down transformer was to be used. This was due to trying to push as much current to the capacitors as possible. After many design changes, it was found that a step up transformer was needed to match the max charge voltage of the capacitors, 1kV.

Our design incorporated a voltmeter separate to the user interface. This way, the user knew how much voltage was stored in the capacitors at all times. Knowing how much charge is stored in the capacitors is necessary for proper operation and safety around the MAC. Most of the components in the power supply were chosen for their cost as well as usability.

3.3.6 Rangefinder

Finding the appropriate rangefinder involved making sure it provided a desirable maximum range, and whether it was connectable to the microcontroller. The rangefinder to be used with the coilgun, the OSLRF-01, contains a range of up to 9 meters. The desired maximum range for the coilgun was intended to be 30 feet. In order to check if the rangefinder's maximum range is around that number, all that needs to be done is simply convert the maximum range from meters to feet:

$$\mathrm{range(feet)} = \mathrm{range(meters)} * 3.2808 \tag{31}$$

$$range(feet) = (9) * (3.2808)$$

$$range(feet) = 29.5272\ ft$$

With a maximum range of 29.5272 ft, the OSLRF-01 rangefinder hence has a range that is acceptable. As for connectivity, the OSLRF-01 laser rangefinder is connectable to a microcontroller board with the use of a Molex connector. Thus, with an acceptable maximum range and being able to connect to a microcontroller board, the OSLRF-01 laser rangefinder would be suitable for the coilgun. The original plan for the coilgun involved using a rangefinder to display the distance to the target. The rangefinder was removed from the project due to time constraints.

3.3.7 Processor

The microcontroller is a very important part of the coilgun, as it is essentially the coilgun's central processing unit. When choosing a microcontroller, important qualities to look at are the clock speed, number of pins, and compatibility with other devices. Choosing the right clock speed involves making sure the microcontroller could handle the timings of different outputs triggered. The coilgun's photosensor and pulse triggering components are to operate in the microsecond range. To find a suitable clock speed, the period(in seconds) will need to be converted to a frequency (in Hertz):

$$\mathrm{T} = 1/\mathrm{f} \rightarrow \mathrm{Tf} = 1 \rightarrow \mathrm{f} = 1/\mathrm{T} \tag{32}$$

$$\mathrm{f} = 1/10-6 \tag{33}$$

$$f = 1\,MHz$$

With a required clock speed of at least 1 MHz calculated from (32), the microcontroller must be in the MHz range in order to function properly. Compatibility is also imperative when choosing a suitable microcontroller. All the different components to be used with the microcontroller need to have a compatible connectivity. Of the components originally chosen, the LCD screen can be connected via I^2C, the camera can be connected via USB, and the rangefinder (3.3.6) can be connected to a microcontroller board via a Molex connector. Thus, picking the right microcontroller would involve making sure it's connectable to these three types of connections.

One major component of microcontrollers are the GPIO pins (abbreviation of 'General-purpose input/output pins', commonly referred to as I/O pins), which are the components that send input signals and receive output signals, hence being the part that connects the microcontroller to every other component of the coilgun. As for the coilgun itself, components that receive signals from the microcontroller would include the user interface screen and the switches in coilgun (when it fires). Components that output signals to the microcontroller would include the user interface screen (buttons), the rangefinder, the ten photo-sensors, the camera, and the magazine (to list remaining number of projectiles). All in all, about twenty GPIO pins will be required for the coilgun's components to function properly.

The original microcontroller that followed the needed requirements are listed above. A microcontroller that follows the requirements listed above would be the LPC1769 Series 32-Bit ARM Cortex-M3 based microcontroller. For clock speed, the LPC1769 microcontroller has a speed of up to 120 MHz, which is an even better clock speed than what was originally desired (100 MHz). For the number of GPIO pins, the LPC1769 contains a maximum of 70 general purpose I/O pins, more than enough for what is desired for the coilgun. As for connectivity, the LPC1769 is connectable via two CAN channels, Ethernet, three I²C interfaces, a two-input and two-output I²S interface, an SPI interface, two SSP controllers, four UARTs, and a USB interface. Two of the coilgun's components listed above (the LCD screen via I²C and the camera via USB) are connectable to the microcontroller according to the list of compatible connections. While on a microcontroller board, the LPC1769 will then be connectable to the rangefinder's Molex connector.

Eventually, the LPC1769 was replaced by a different microcontroller due to timing constraints. The new microcontroller chosen was the MSP430F5529 microcontroller by Texas Instruments. The MSP430F5529 has 63 GPIO pins and a 25 MHz clock speed, both numbers lower than what the LPC1769 had, but nevertheless, would still be able to function as needed.

3.4 Possible Architectures and Related Diagrams

There have been many designs and architectures conceptualized and produced for a coilgun. Each design is unique to the specific sub-system components it utilizes. Each sub-system that makes up a coil gun can be varied to meet the needs of the product and form factor. For example, the energy storage options can vary from capacitors to inertial energy storage such as flywheels or the power source for each coil gun can also vary considerably from theoretical power supplies, such as hemopolar generators, to common vehicle alternators, grid power, and other useful sources of energy. Due to the variety in component options and selections many different coilgun architectures can be conceived.

Which leads to the greatest benefit of the coilgun, there will always be originality. The coilgun will always be able to accelerate a projectile down a barrel of coils using different energy sources, components, modes, and equipment adding originality into design. Table 5 will depict six different architectures for coilguns. For the MAC, a capacitor driven, induction armature, active stator control, advancing wave architecture was chosen.

Table 5 Different Coilgun Architectures and Designs. Permission Pending from Karl E. Reinhard for the reproduction of data in the table.

Gun Architecture (Organization)	Armature Excitation	Stator Excitation (Power Supply)	Mode of Operation
Multiple Stage Induction Launcher (Electromagnetic Launch Research Inc)	Induction	Discrete Coil (Capacitor Driven)	Advancing Wave
Traveling Wave Induction Launcher (Jet Propulsion Lab)	Induction	Discrete Coil (Capacitor Driven)	Advancing Wave
Linear Induction Launcher (Polytechnic University)	Induction	Discrete Coil (Capacitor Driven)	Advancing Wave
Pulsed Induction Launcher (UT Center for Electro-mechanics)	Induction	Discrete Coil (Capacitor Driven)	Advancing Wave
Passive Coaxial Accelerator (UT CEM)	Induction	Continuous Coil (Capacitor Driven)	Advancing Wave
Collapsing Field Accelerator (UT CEM)	Persistent	Hemopolar Generator	Receding Wave

The MAC will closely resemble the architecture of the "Pulsed Coaxial Accelerator" by the UT Center for Electro-mechanics. The velocities obtained outline the objectives which the MAC system will be fulfilling.

In the following Figures general circuit topologies for different coilguns will be shown. Inspiration for the design of the MAC was obtained from the following circuit topologies. Figure 25 is pulled from "Operational Requirements and Issues for Coilgun Electromagnetic Launchers" by Ronald J.Kaye. This architecture is a capacitor driven launcher like the MAC the Figure depicts a three stage coilgun. The first stage is energized in this example and the second stage is about to be energized. The third stage is yet to be energized. This is the most common architecture for a coilgun. This is due to the ease capacitors bring in producing pulse currents at varying time constants.

The next architecture displayed comes from the "Effect of Timing Errors on Coil-Gun Performance" by S Williamson and C.D. Horne. This architecture is also capacitor driven but has differences in the switching used. Figure 25 uses an ignitron as the switching element for the coilgun circuit. This switch is particularly useful due to its high voltage and current capability.

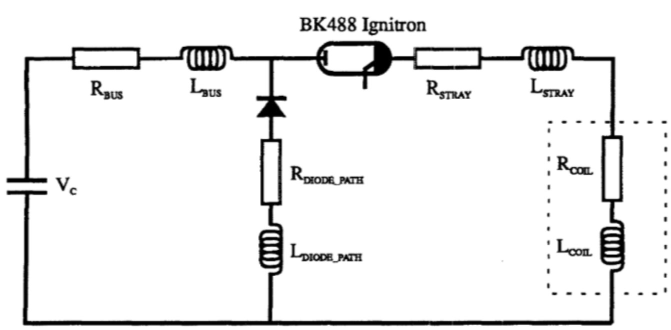


Figure 20 Circuit Model Which Uses Ignitrons as Switching Elements © [1993] IEEE

These types of switches are large and fragile due to their glass construction and use of liquid mercury. This type of switch would be more useful in a lab environment and not for the field as the MAC is meant to be used. Figure 26 uses reverse-blocking thyristor switches to recover energy from the magnetic field in the coils.

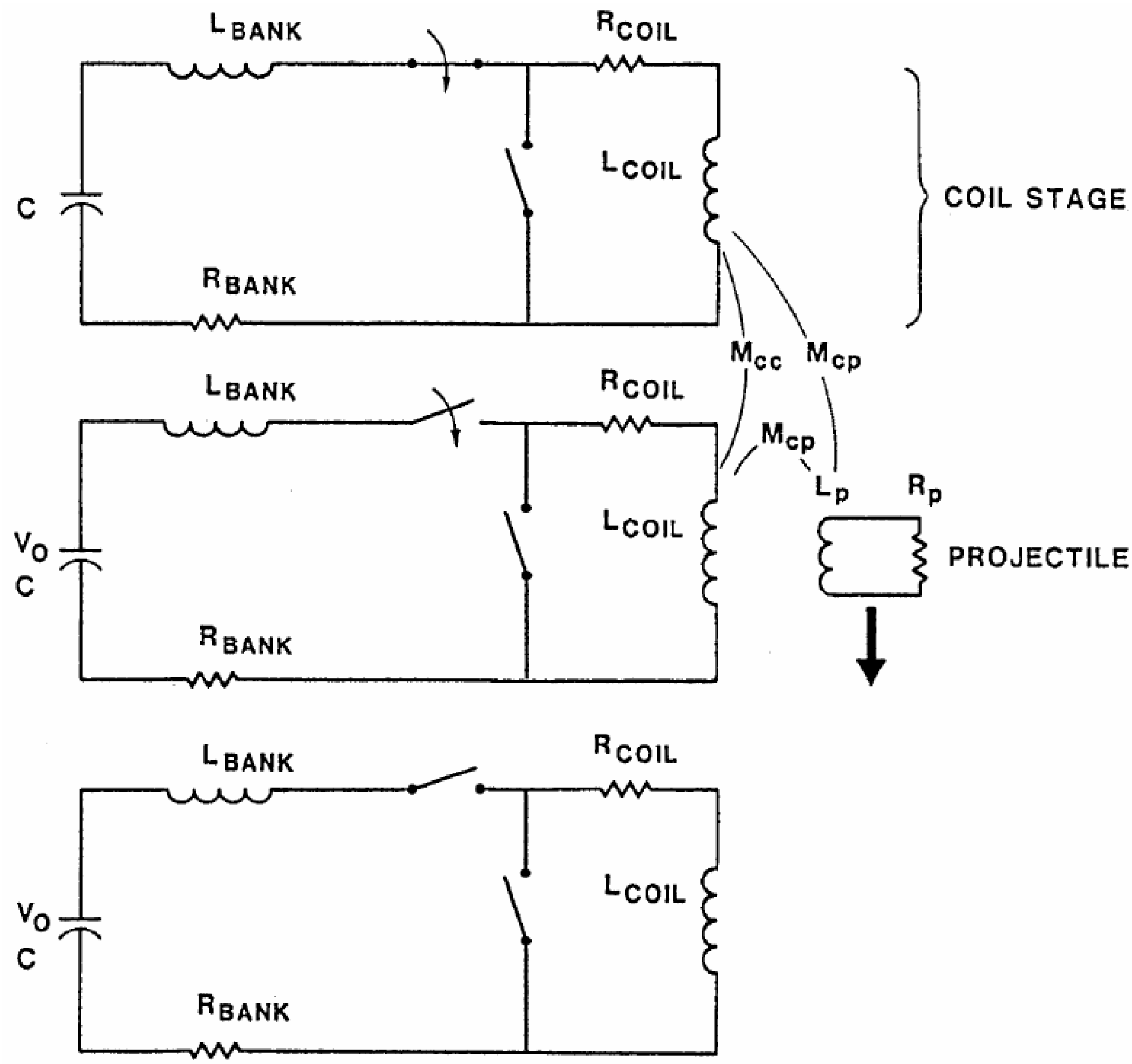


Figure 21 Sandia National Laboratories Coilgun Architecture; Capacitor Driven with Reverse-Blocking Thyristor Switches © [January 2005] IEEE

Figure 27 and 28 shows the coilgun architecture which utilizes a three-phase AC setup with a conducting sleeve used in the barrel. The conducting sleeve supports the projectile and keeps it in the area of the gun with the highest magnetic flux. This design architecture is convenient to get the current peaks needed in each stator. With the AC setup the firing sequence for the coils becomes the voltage peaks at A, -C, B and each switch is actuated every 60° of the input signal [CITATION].

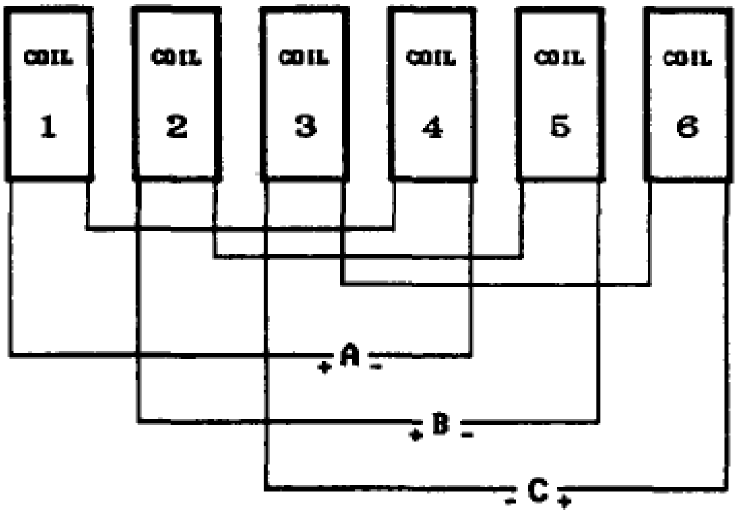


Figure 22 A Four-pole Type Coilgun Architecture © [March 1994] IEEE

The timing is now not determined by the DC LC response to applied voltage as most designs go, but by the AC response.

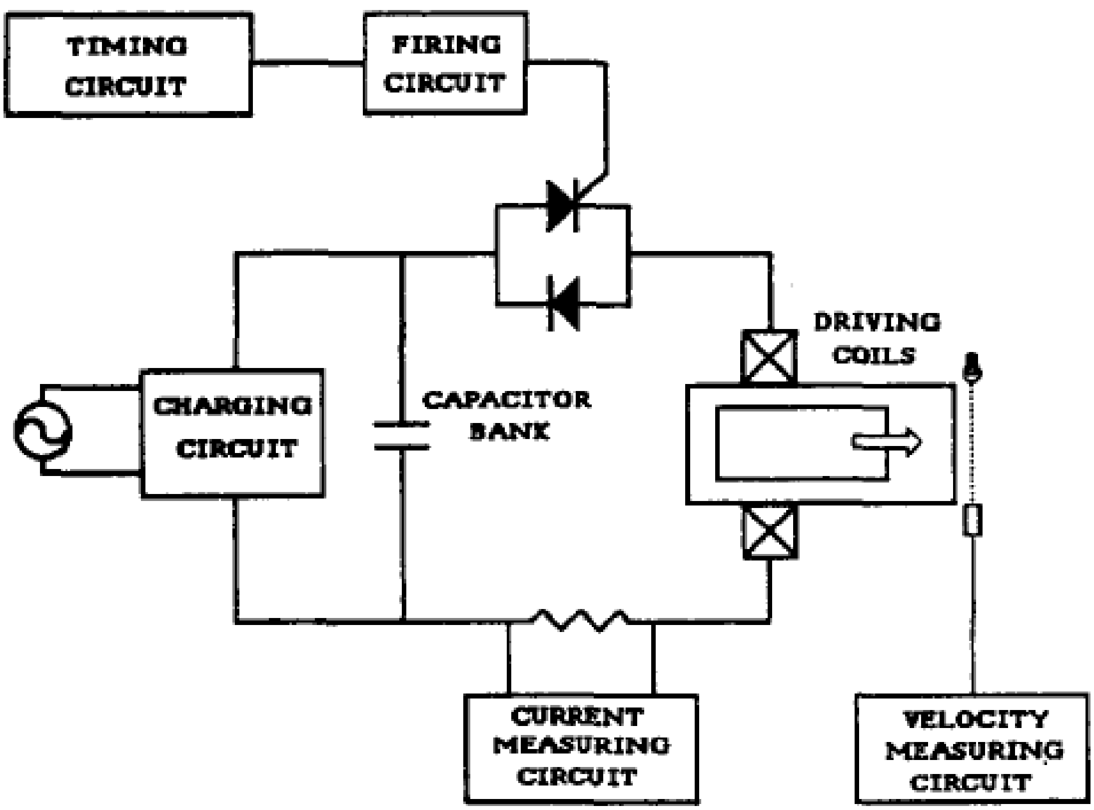


Figure 23 Experimental System Architecture for a Four-pole Type Coilgun © [March 1994] IEEE

The capacitance values and inductance values for each stator become constant and the timing is all based on the voltage applied at that point. This was an interesting concept and provided very good proof of concept for the MAC design.

3.5 Simulation

To test how the selection and configuration of capacitors would affect the performance of the coilgun, a Matlab script was developed. This script takes in descriptive characteristics of each stage from an excel spreadsheet at input. Those characteristics are: the pulse time, capacitance, inductance (calculated in the spreadsheet based on the pulse time and capacitance), initial bank voltage and capacitor resistance. It then processes those inputs and returns the total resistance for each stage, the peak current in each stage, the final and the final capacitor voltage in each stage. It also plots the current and voltage across the capacitors as functions of time for every stage in sequence.

There are also additional input parameters that are set inside the script: Coil wire gauge (AWG), coil inner diameter, coil length and number of time samples per stage. Also an array specifies which stages “start” a new bank. If the stage is not listed in said array, then it is assumed that it uses the same bank as the previous stages. When a new bank is started, its initial voltage is set to the voltage loaded from the spreadsheet. This makes the program flexible enough to be able to handle any arrangement of capacitors, be it a single bank for all coils, one bank per coil, or a combination of both.

The first part of the program is “building” a coil based on the desired inductance, inner size and length. To accurately simulate a stage’s RLC circuit, the overall resistance must be known. The two main contributors to the circuit’s resistance are the capacitor’s ESR (equivalent series resistance) and the inductor wire’s resistance. The capacitor’s ESR is known since it’s an input parameter for the function. However, the inductor's wire resistance must be calculated since the inductance value is generated by the spreadsheet, and no other attributes about it are known. The resistance of the coil is simply a function of the wire gauge used (it’s cross sectional area) and the length of wire used. The gauge is an input parameter, but the length of the wire is dependent on how the inductor is physically built. A JavaScript function was found that did just that: take in a desired target inductance, inner coil radius, coil length and wire gauge, and output the length of wire needed, its resistance, the number of turns as well as the number of layers. Although only the only needed output from this function useful for the simulation is the resistance, it can be used in other stages of the project to verify or design the coil construction. This function was then called by the main simulator script for every stage to then finally be able to calculate each stage’s resistance.

The next part of the program is determining each stages current and capacitor voltage time characteristics. For each stage, a time vector is made with the length of the number of samples per stage. It goes from zero to the pulse time for that stage. Then, this time vector is plugged into equations (I(t) from 3.3.1) and (V_c(t) from 3.3.3) which are used to find I(t) and V_0. From the I(t) of this stage, the maximum current is stored in an array that keeps all of the maximum current values for each stage. The current and voltage vectors are applied to the equations of energy in an inductor and energy in a capacitor. Those values are summed to obtain the total energy at a particular point in time. Because of conservation of energy, the only change in that value is due to resistive losses. This vector is extremely useful for observing resistive losses in the system.

The arrays for current, voltage and total energy for this stage are then appended into the “global” current, voltage and energy vectors that contain the values for the entire system. The time vector for the stage is similarly appended to the global time vector, but first needs to be offset so that the scales appear correctly. With the overall the current, voltage and energy values knows, they are graphed for easy and intuitive system evaluation and examination. See appendix C for source code.

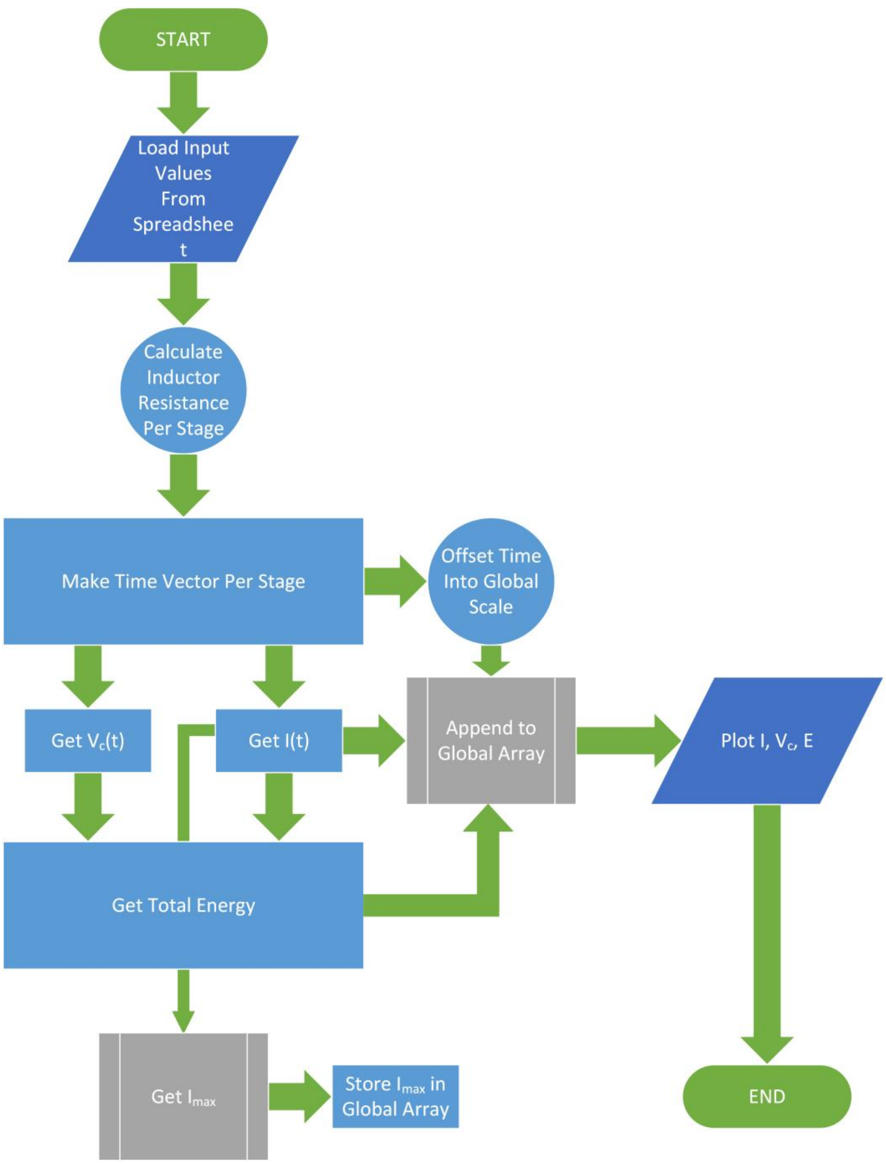


Figure 24 Simulation Script Flow Chart

4.0 Hardware and Software Design Details

This section will describe detailed design of the MAC system hardware and software. Design decisions will be justified and shown for clarity. Testing and prototype construction will confirm the design details represented below. The coilgun design is an iterative project and will require tuning to produce results which meet the goals and objectives for the system. Preliminary simulations were performed on the design and will further justify the design decisions below. Refer to section 5 of this documentation for a comprehensive summary of the M.A.C design.

4.1 Initial Design Architectures and Related Diagrams

The initial conceptual design for the MAC is shown in Figure 30. Each system is represented with data paths or power routing to their respective dependent systems. Each system displayed in the following block diagram will be expanded on in their respective sections below.

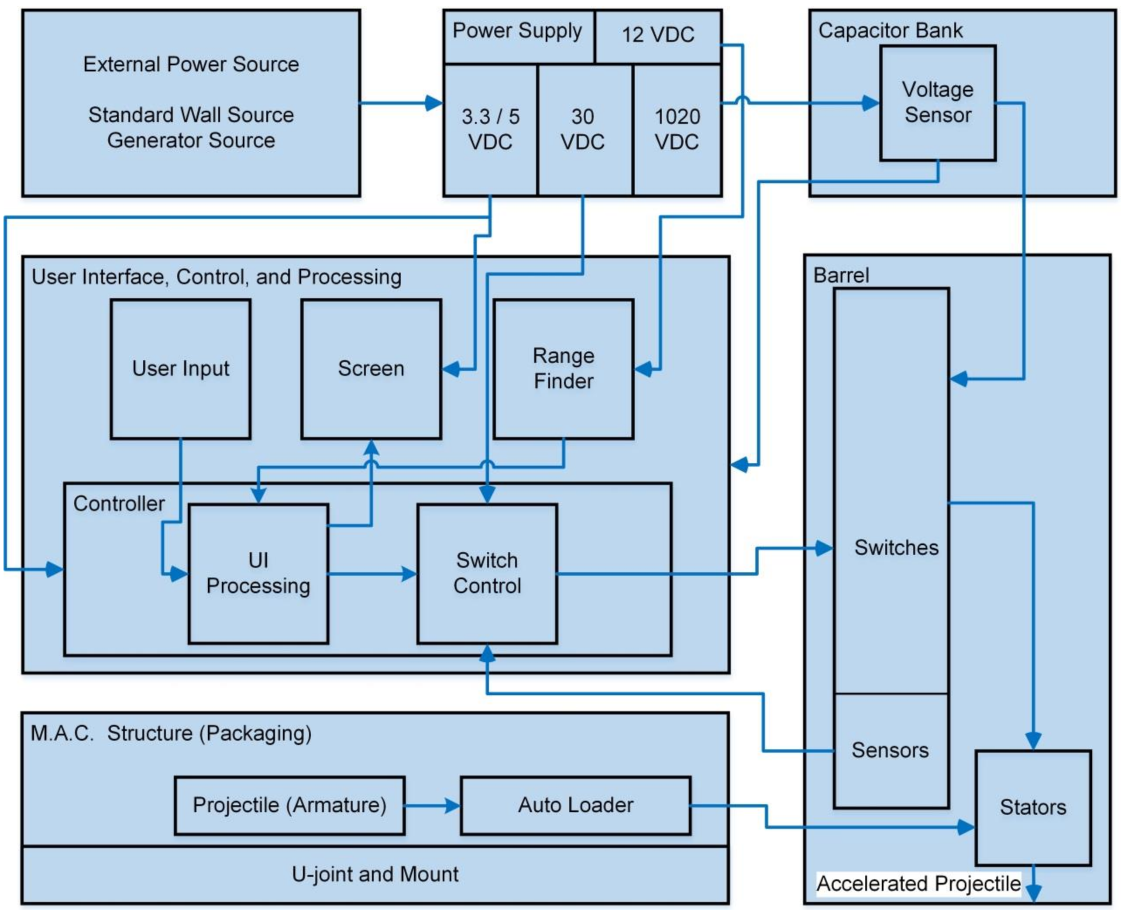


Figure 25 MAC Initial Block Diagram

Figure 30 depicts the design architecture of the coil gun with emphasis on the circuit topology of the stators and projectile. As shown the topology consists of ten coils each with its own capacitor bank except for the first two stages which share one capacitor. This is the initial design for the MAC system.

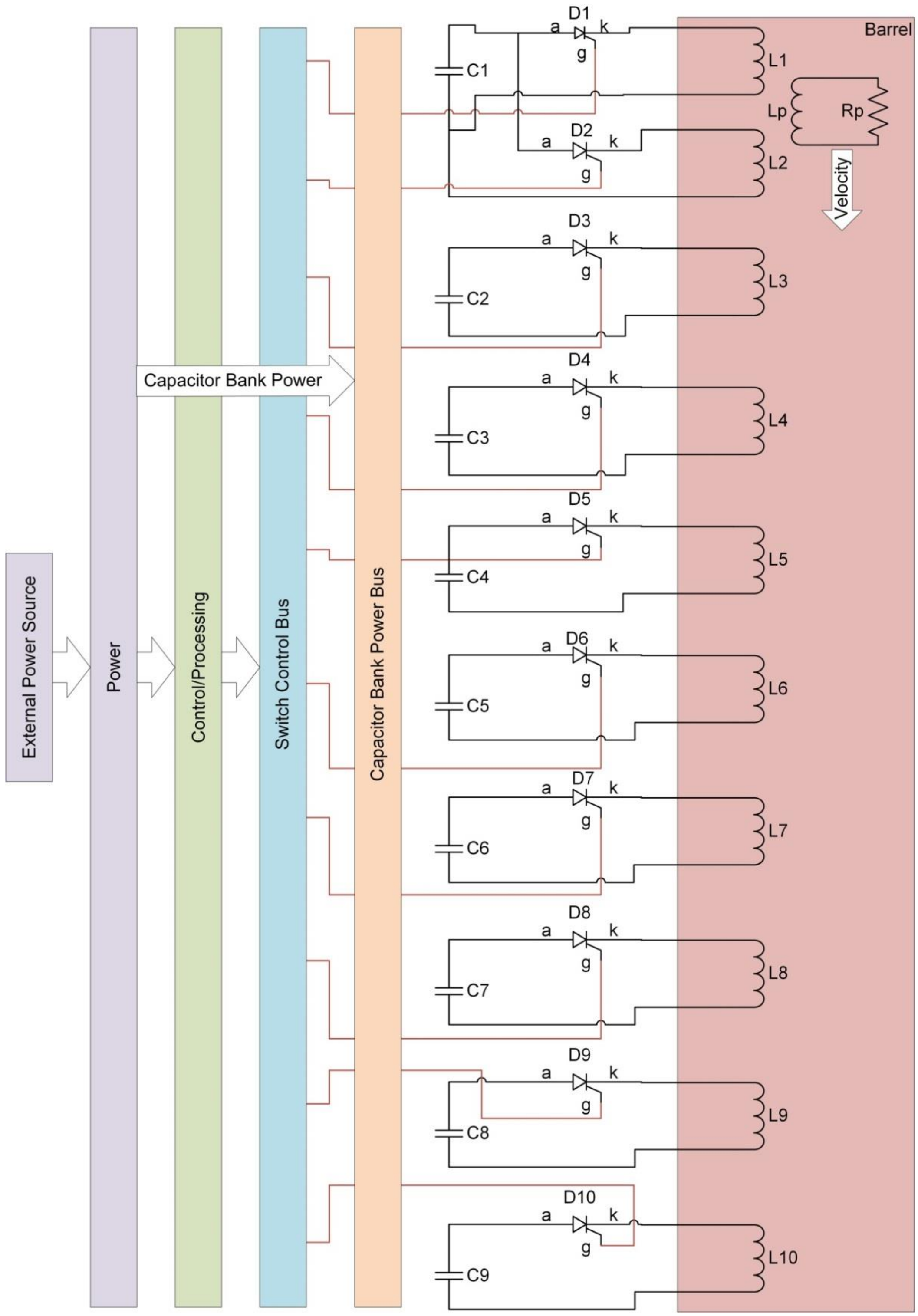


Figure 26 Initial Top Level Block Diagram Emphasizing on the Stator Coil Circuits

For the final design of the MAC system an eight coil layout was decided. The design was reduced from ten stages to eight stages due to the failure of thyristors in the testing phase of the design. With eight stages each capacitor had a pair of coil stages except for the first two stages which shared two capacitors. Figure 31 below depicts the final top level block diagram that emphasizes on the coil stages.

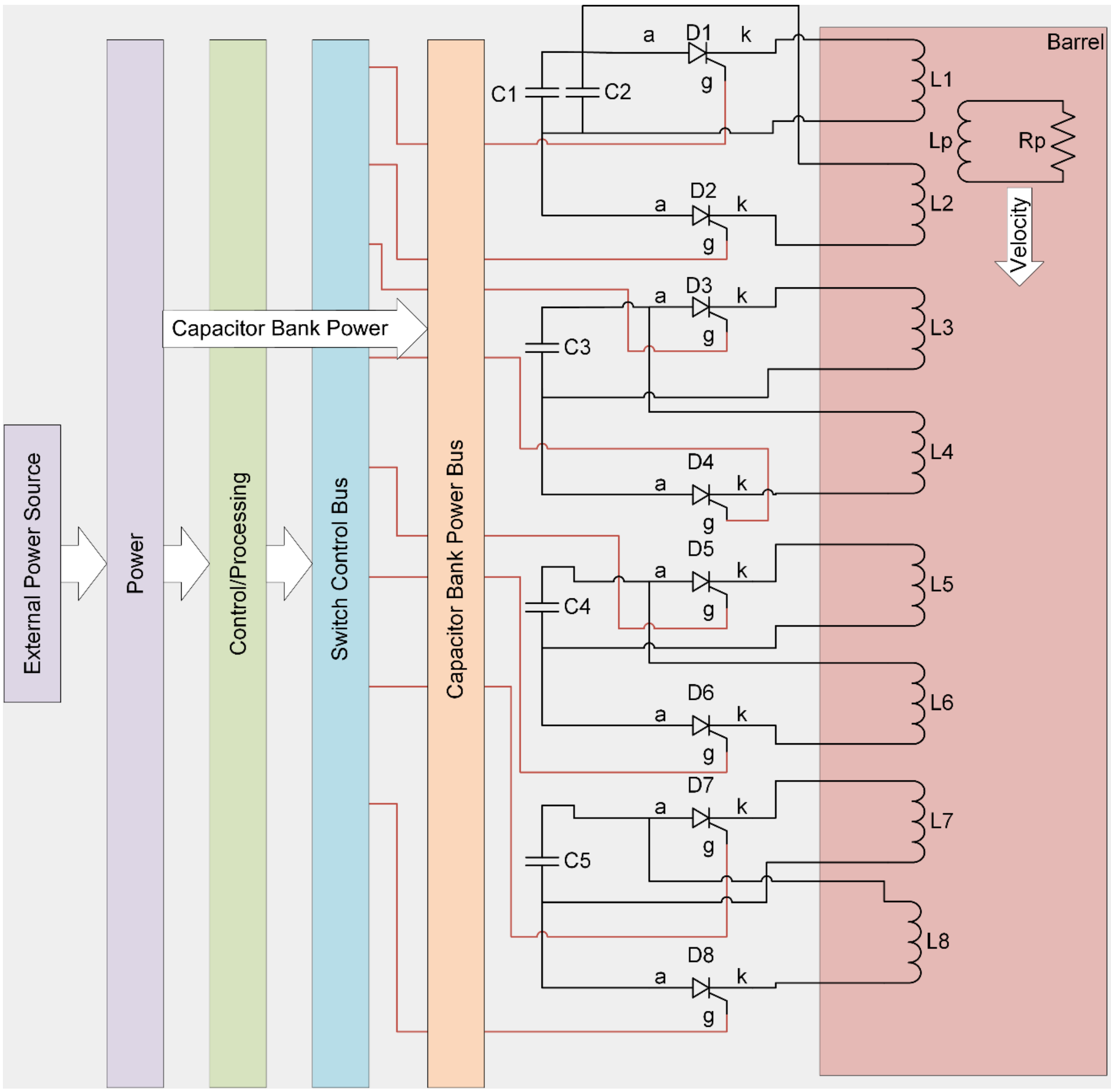


Figure 27 Final Top Level Block Diagram Emphasizing on Coil Circuits

The decisions for this architecture are based on the analysis performed on the circuit components in the following sections. The values for each component are based on timing and energy requirements needed to meet performance Figures for the coilgun. Refer to sections 4.3, 4.4, and 4.6 for design details pertaining to the architecture in Figure 31. In Figure 32 the initial design for the MAC system is rendered. This rendition of the MAC is an initial design concept. The final system design is shown in Figure 33. As it can be seen a few features were taken out of the initial design and the final design is more simplified. The full system is much larger than the initial design that was rendered. This is due to the components which were needed to construct the whole system.

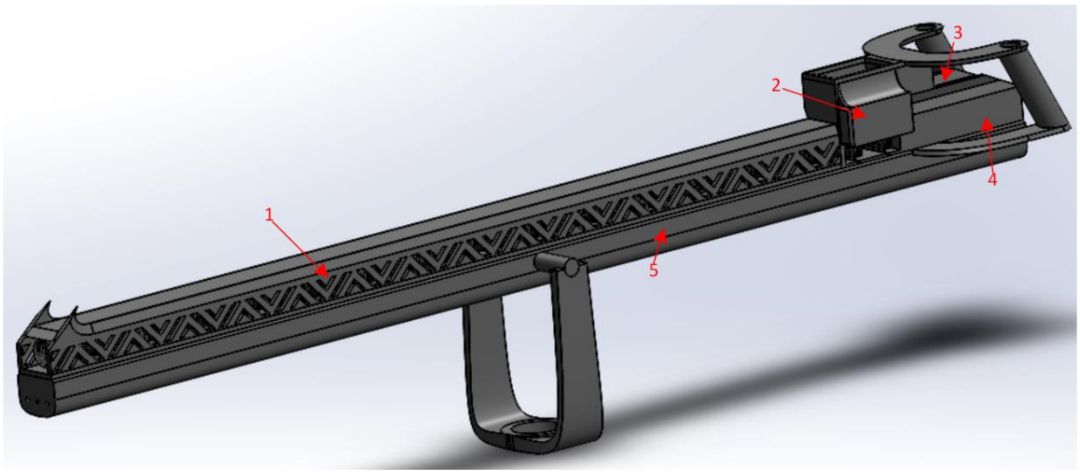


Figure 28 Initial Design Architecture for the MAC; 1- Barrel, 2- projectile loader, 3- Control / Processing 4- Power System, 5- Energy Storage

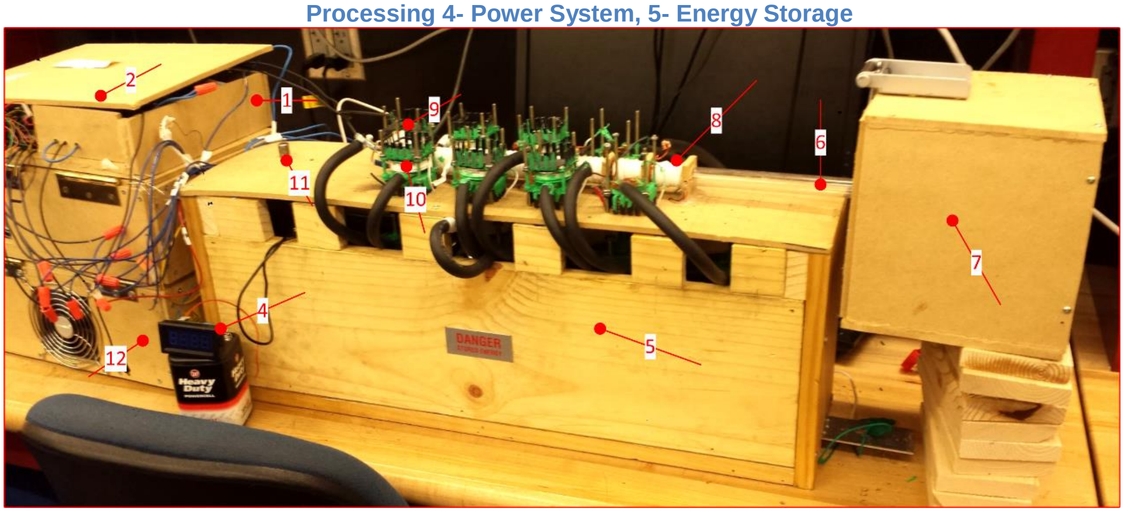


Figure 29 Final System Layout; 1- Firing Circuits, 2- LCD and UI, 4- Capacitor Voltmeter, 5- Capacitor Bank, 6- Acrylic Barrel, 7- Firing Box, 8- Coil Stage, 9- Coil Stage #1, 10- Thyristor, 11- Projectile, 12- MAC System Power Supply

4.1.1 Mission Profile

The design of the MAC is driven from the mission profile which we are trying to accomplish. This mission profile sets up the basic requirements the system must achieve. Tables 6 and 7 describe the mission profile for the MAC and the minimum design criteria that must be achieved.

Table 6 Mission Profile for Performance

Performance	Value	Unit
Muzzle Velocity	300 - 400	m/s
Projectile Mass	<15	g

Table 7 Mission Profile for System Constraints

System Constraints	Value	Unit
Barrel Length	1	m
Stator Coil Diameter	<2	cm
System Mass	<10	kg
Maximum Acceleration	80000	m/s^2

4.2 Power Supply

One of the main components of a coilgun's design is the power system. It supplies power not only to the energy storage system, but to the user interface as well. Without the power system, the rest of the design is rendered useless. A block diagram of the power system and how it relates to the other main components is shown Figure 33.

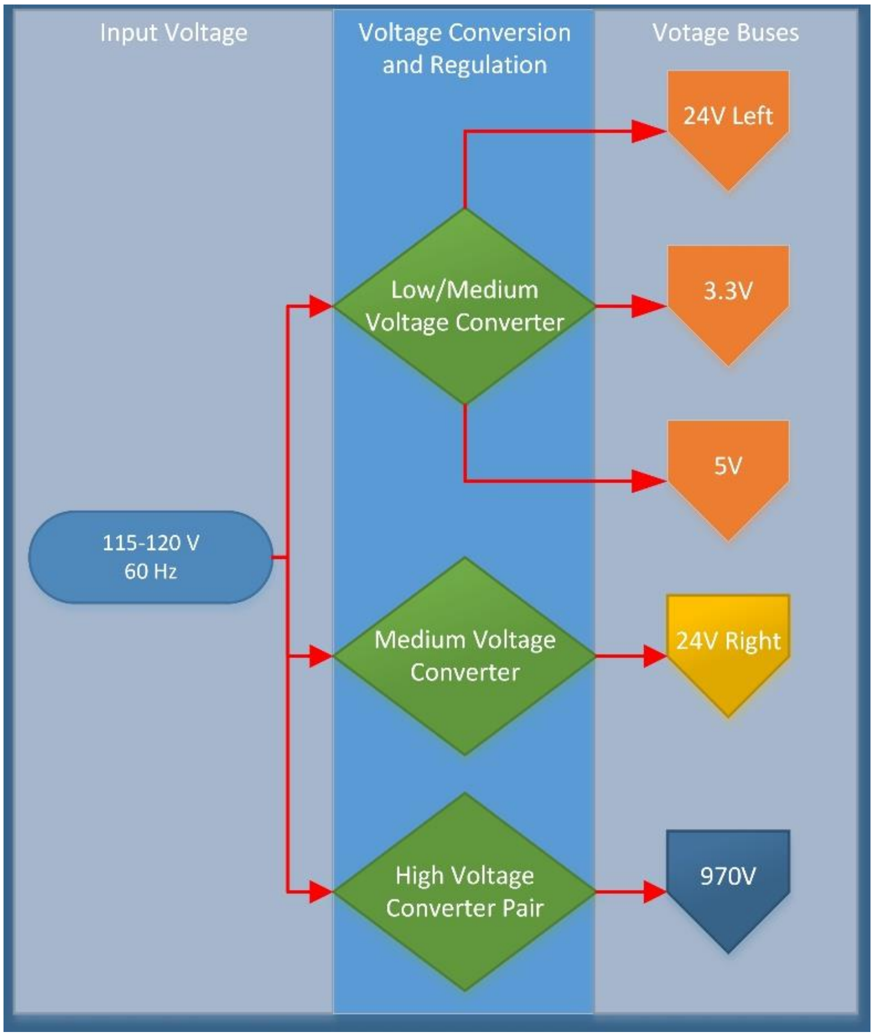


Figure 30 Power System Block Diagram

In designing this power system, there were three main components. These include the transformer, a bridge rectifier, and user interface supply. Due to the high voltage and general size of the capacitor bank, a large step-up transformer was needed. A transformer with a primary winding voltage of 120 volts and a secondary winding voltage of 1020 volts was found. The manufacturer of the transformer was Hammond Manufacturing. A picture of two of the transformers can be seen here Figure 34.

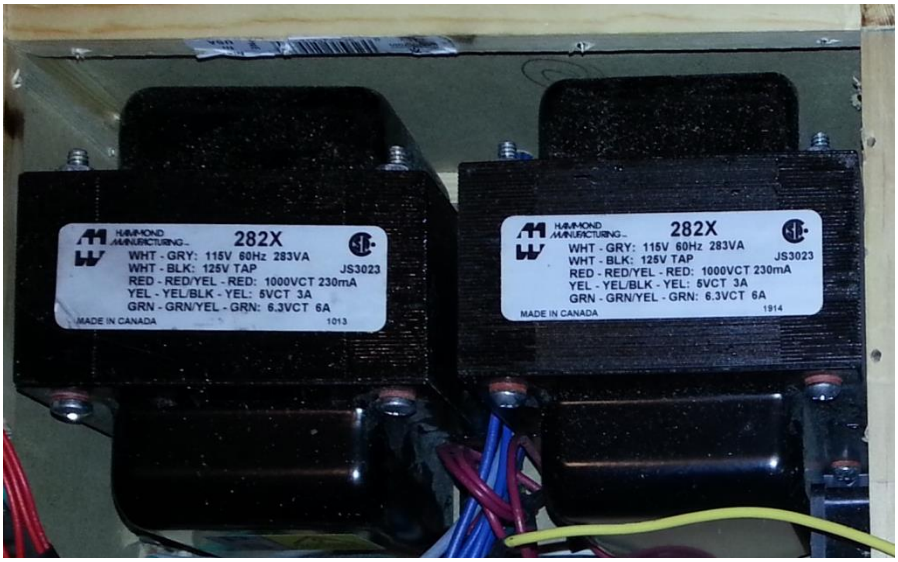


Figure 31 Hammond Manufactoring 1020V transformer

The next main component for the power supply system is the bridge rectifier. The bridge rectifier allows for converting alternating current to direct current. Buying a prebuilt bridge rectifier worked for the initial design, but was ultimately replaced with diodes arranged to create a custom bridge rectifier. When working with this much voltage, fried parts were inevitable. Getting diodes mounted to a PCB proved wasteful since multiple rectifiers were needed. We bought a prebuilt bridge rectifier from Vishay Semiconductors which was replaced by a diode bridge. Integrating this tiny rectifier into the build was easy and will aided in overall final appearance. A similar bridge rectifier can be seen here Figure 35. An external voltmeter was also purchased in order to measure capacitor bank voltage level.

Figure 32 Bridge Rectifier. Reprinted with permission from user "Metaresephotos" under the Creative Commons Attribution 3.0 Unported license

Figure 33 External Voltmeter. Reproduced with the permission pending.

The last major component for the power supply system was the user interface power supply. Because high voltage was going to be used in this design, the two power supplies were separated. A reverse voltage from the capacitors was avoided by design. With this design, the user interface could be constantly on while the capacitor charging system is turned off during projectile launch. The components of the user interface utilize different voltages, which would be a struggle to get from 1020V. The user interface screen used 5V, and the microcontroller utilized 2.4V-3.6V. A standard ATX power supply produces each one of these voltages separately and was adapted to use as the control power supply. With cost in mind, a small 200W supply was used. A similar ATX supply to the one being used is shown here Figure 37.

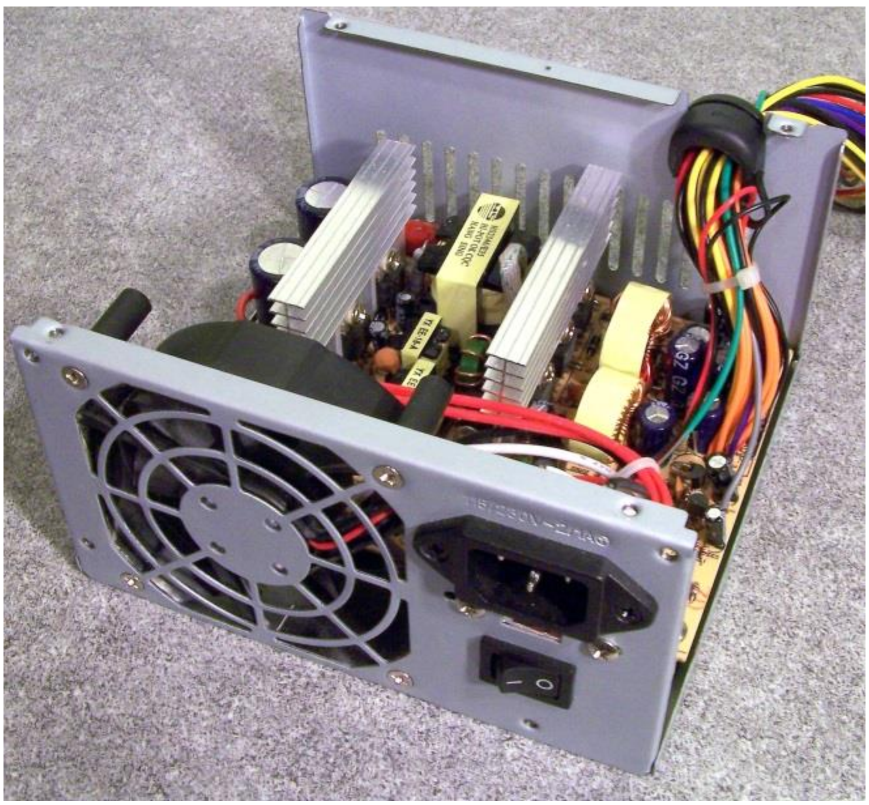


Figure 34 Power Supply for the User Interface. Reproduced with the permission from user ”mboverload” under “Public Domain”

A final circuit schematic for the capacitor charging system included multiple charging resistors. Having charge resistors allowed the power supply to charge the capacitor bank quickly without damaging any other components. Multiple resistors at 10K ohm were used. A final capacitor charging circuit schematic can be seen here, Figure 38.

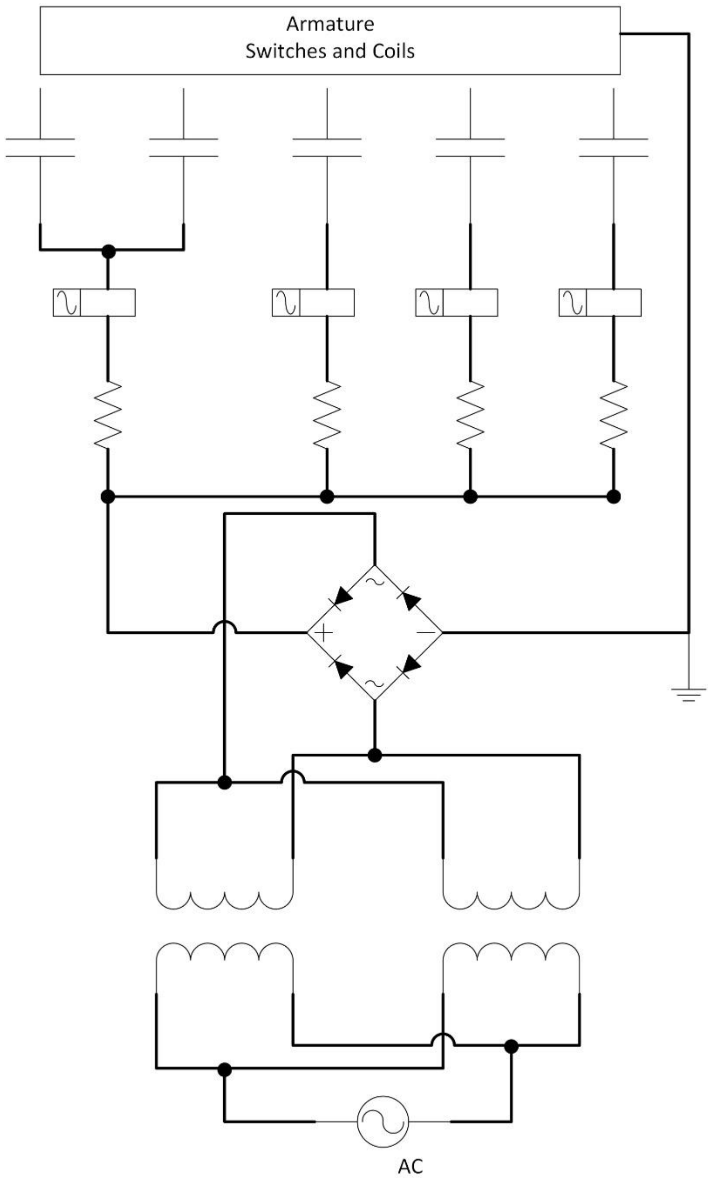


Figure 35 Capacitor Charging Circuit

4.3 Energy Storage

The operation of a coil gun depends on the extremely fast injection of current into each coil stage. As considered in 3.3.1, capacitors have the ideal characteristics required of an intermediate storage stage in a coilgun. Also, all reference designs and research [3.1] indicated that the best intermediate storage medium (between an external power supply and the coils) is one or more capacitors.

From work done in section 4.6.2.2 it was found that a certain amount of energy needed to be present at every stage to average a constant acceleration though the barrel. Also based on this same model, the required coil activation pulse time--the amount of time that the coil in each stage needs to be energized and then switched off--for each stage was determined. From those two input parameters, a computer model was developed to find the characteristic of the required RLC circuit. A combination of spreadsheet and Matlab used these input parameters to find out the inductance needed and the resulting RLC response for each stage.

The spreadsheet was created to hold input parameters and some preliminary calculations to guide the selection of input parameters in real time. All of the parameters in each stage were stored in their individual rows. A column for energy goal that each coil should reach is included for quick comparison as values are "tweaked". According to section 4.6.2.2, each coil should deliver the same amount of energy. A column for pulse time (one of the inputs) from 866μs in the first stage to 87μs in the twenty fifth stage is included and used for calculations. The other input, capacitance is given its own column as well. The capacitor's initial voltage is also included as a column. This is always the same for every stage to simplify charging and design. However, if the same capacitor is used for more than one stage, the initial voltage at that stage will depend of the voltage at the last sample of the previous stage. If this is the case, the initial voltage V_0 for that stage will be derived from the Matlab portion of the model. From the input pulse time and capacitance, the inductance needed to get the pulse time for each stage is calculated into a column using (26). Another column calculates the I_{peak} based on input C for an underdamped circuit by using (25). For higher factors of damping, the I_max calculated in the spreadsheet can be as much as two times different from the actual I_max. However, this column is still very useful for getting direct feedback for the magnitude of I_{max} as different capacitance values are added in, even if the exact values are off. The true I_{max} will later be extracted from the complete current characteristic found from matlab for each stage. There is also a capacitor ESR input column that is used to in the Matlab part of the model to determine the \alpha.

A more detailed explanation of the internal behavior of the Matlab portion is discussed in section 3.5. The source code is included in Appendix C. The Matlab script outputs the true peak current at each stage. It also delivers the inductor's DC resistance which is added to the stage's input capacitor's ESR to create the entire stage's resistance component (R). Current as a function of time, voltage as a function of time and total stage energy as a function of time are calculated and in each stage and then graphed across the entire barrel. Figure 37 depicts the first design for the capacitor bank.

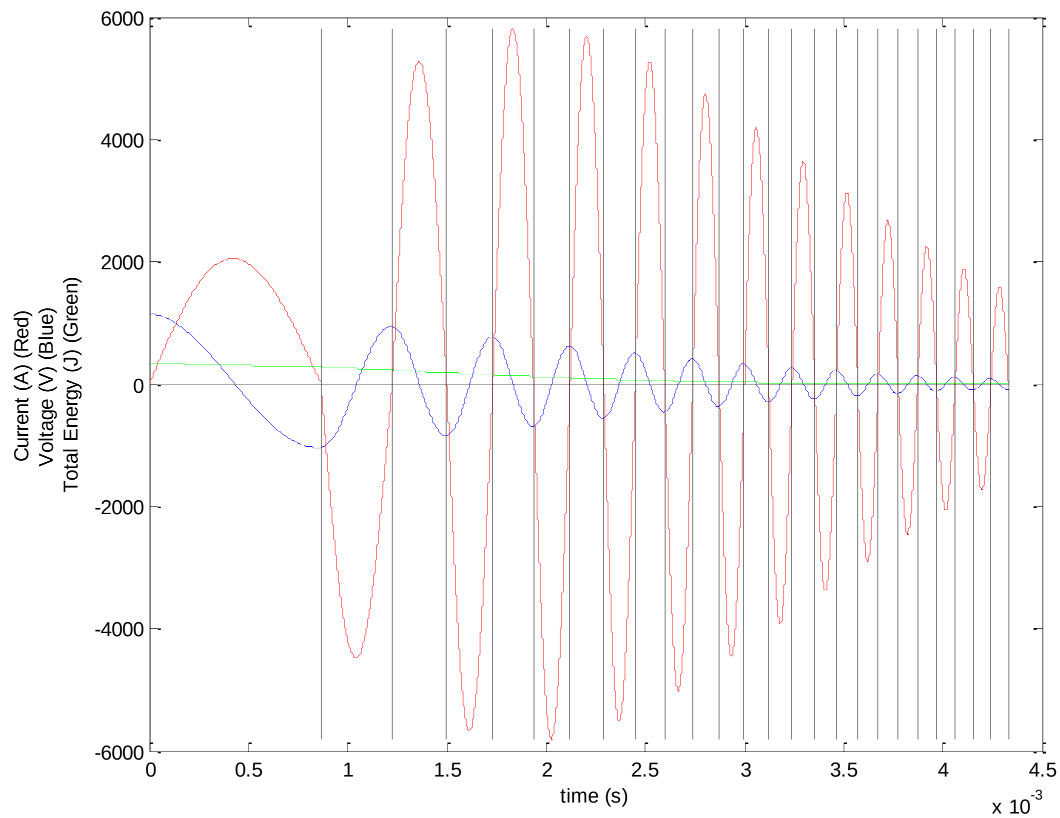


Figure 36 Current, Voltage and Energy as a function of time for the first attempted design. Black vertical lines represent stage separation.

The initial capacitor bank arrangement that was considered and analyzed was to have a single bank energizing all stages. To get a bank that would yield an appropriate pulse time, (24) was solved for C:

$$C = (\tau/\pi^2)/L \qquad (34)$$

Working from a 1.5mH minimum inductance and using the 87μs τ for the last stage, the capacitance for this monolithic bank would have to be 517μF. This capacitance would yield manageable currents below 21,350 Amps for all stages. Table 8,9,10 summarize the First design data for the simulation formed in Figure 39.

Table 8 First Design Part-A

Stage	Pulse Time (μs)	Energy Goal (J)	Capacitance (μF)	Inductance Needed (μH)
1	866	326	517	146.984309
2	359	326	517	25.21852051
3	275	326	517	14.8484305
4	232	326	517	10.55299858
5	204	326	517	8.191154798
6	185	326	517	6.694966226
7	170	326	517	5.661630271
8	158	326	517	4.90493296
9	149	326	517	4.326814073
10	141	326	517	3.870690523
11	134	326	517	3.501612572
12	128	326	517	3.196822565
13	122	326	517	2.940862995
14	118	326	517	2.722865735
15	114	326	517	2.534966005
16	110	326	517	2.371331713
17	107	326	517	2.227546476
18	104	326	517	2.100204543
19	101	326	517	1.986637302
20	98	326	517	1.884724052
21	96	326	517	1.792758233
22	93	326	517	1.709351021
23	91	326	517	1.633360663
24	89	326	517	1.563839866
25	87	326	517	1.499996088

Based from experience in researching ultracapacitors, it was assumed that the ESR for lower capacitance capacitors would be around the same magnitude. So for the first design a bank ESR of .25 Ohm was set. Because of this low ESR, the response would be underdamped. Oscillations from a single bank would be able to propagate through all stages. An extremely light exponential envelope would do little to downgrade the efficiency at all stages.

The next step was to then find capacitors to build a capacitor bank with those approximate characteristics. All aluminum capacitors were gathered in a single list. The list of capacitors was first filtered by components that had ESR's lower than 15. That subset was then filtered for the highest voltage, which was 500V in order to not necessitate too many capacitors in series, thus raising the ESR. Then the lowest capacitance component is chosen from that subset. That capacitor ended up being a United Chemi-Con 6800μF 500V capacitor with 14mOhm of ESR. Two of them connected in series brings the bank's voltage up to 1000V and the capacitance down to 3400μF. The overall ESR of the bank is then 28mOhm. Those parameters are then inputted into the simulation model. In Figure 40 the simulation for the second design can be seen. Tables 11, 12, and 13 summarize the design data for the second simulation in Figure 40.

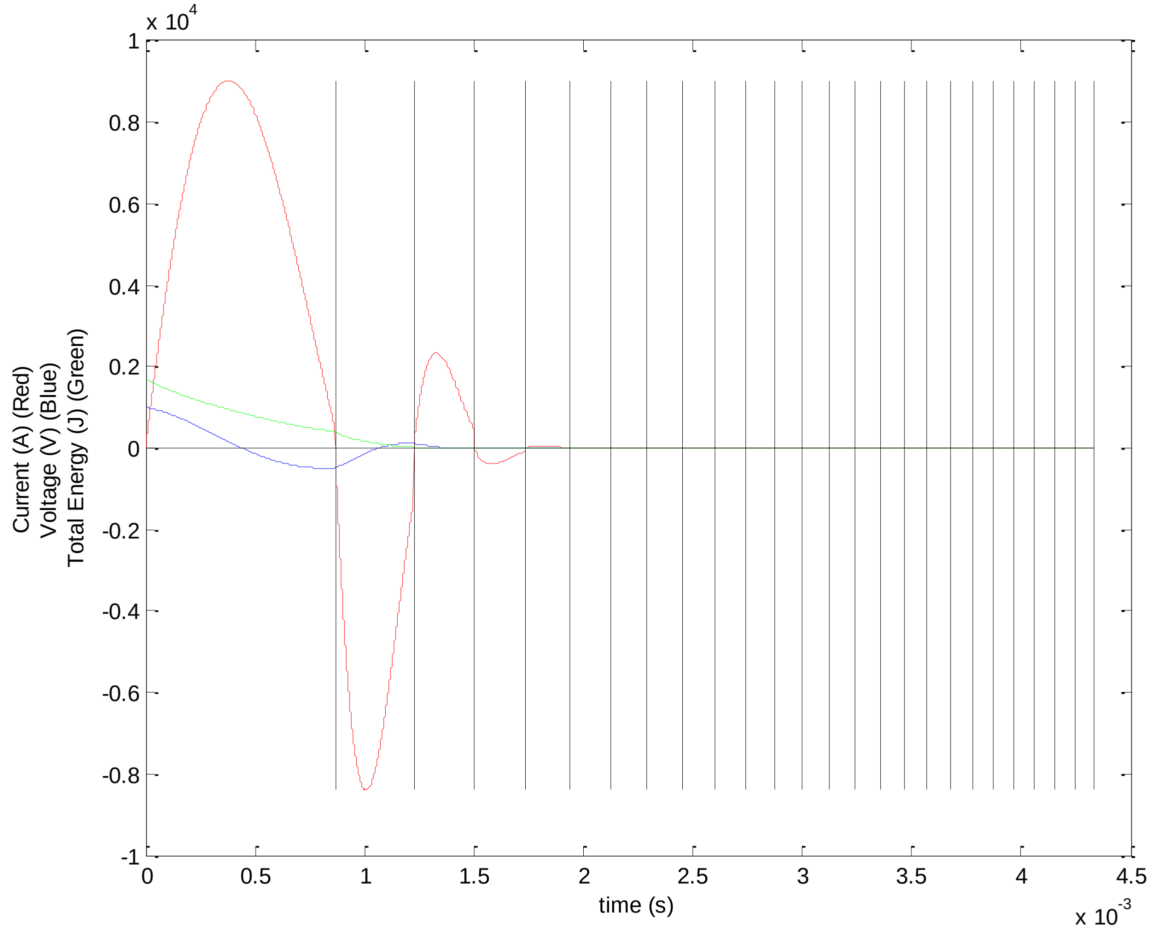


Figure 37 Current, Voltage and Energy as a function of time for the second attempted design. Black vertical lines represent stage separation.

Table 9 First Design Part-B

Stage	Initial Bank Voltage (V)	Imax (A)	Peak Energy in Inductor (J)	Inductor Resistance (mΩ)
1	1150	2051.66	309.35	34.37
2	-1038	-4478.61	252.92	13.71
3	940	5283.76	207.27	10.51
4	-851	-5666.45	169.42	9.03
5	769	5808.56	138.18	7.91
6	-694	-5800.25	112.62	7.20
7	626	5692.19	91.72	6.58
8	-565	-5512.92	74.54	6.27
9	509	5280.30	60.32	5.96
10	-457	-5017.15	48.72	5.65
11	411	4740.26	39.34	5.34
12	-369	-4461.82	31.82	5.03
13	332	4190.42	25.82	4.72
14	-300	-3919.28	20.91	4.72
15	269	3653.22	16.92	4.41
16	-243	-3396.74	13.68	4.41
17	218	3140.70	10.99	4.41
18	-195	-2899.45	8.83	4.10
19	175	2674.54	7.11	4.10
20	-157	-2456.13	5.68	4.10
21	140	2255.02	4.56	3.78
22	-126	-2071.21	3.67	3.78
23	113	1895.46	2.93	3.78
24	-101	-1735.96	2.36	3.47
25	90	1592.08	1.90	3.47

This bank using realistic components is very lacking as the simulation in Figure 40 shows. The resistive envelope is so strong by the 3th stage, the initial input energy has become extremely attenuated. It is also observed that because of the resistance, there isn't enough energy to drive the coils in any meaningful fashion after the 4th stage.

From the second design it can be concluded that too much ESR is extremely detrimental to the system's performance. Too many capacitors in series leads to a lot of parasitic loss and should be avoided if possible. When the capacitor is "empty" it just drags the rest of the circuit down with loss. The solution is to have more banks instead of one for all coils. That way, and discharge capacitor effectively gets excised from the circuit so that it no longer provided resistance. The first two stages seemed to be powered properly by the big monolithic capacitor bank. So for the next design, the first two stages can be powered by only one capacitor.

After some trial and error with the model spreadsheet, it was determined that every stage after the second should have its own capacitor. From the spreadsheet of the Digikey inventory, all 500V capacitors were filtered. Then the available capacitances that remained were tried in each stage until it would have about 20kAmps of current or less.

Table 10 First Design Part-C

Stage	Capacitor Resistance (mOhm)	Total Stage Resistance (mOhm)	Capacitor Resistance (mOhm)
1	0.25	34.62	0.25
2	0.25	13.96	0.25
3	0.25	10.76	0.25
4	0.25	9.28	0.25
5	0.25	8.16	0.25
6	0.25	7.45	0.25
7	0.25	6.83	0.25
8	0.25	6.52	0.25
9	0.25	6.21	0.25
10	0.25	5.90	0.25
11	0.25	5.59	0.25
12	0.25	5.28	0.25
13	0.25	4.97	0.25
14	0.25	4.97	0.25
15	0.25	4.66	0.25
16	0.25	4.66	0.25
17	0.25	4.66	0.25
18	0.25	4.35	0.25
19	0.25	4.35	0.25
20	0.25	4.35	0.25
21	0.25	4.03	0.25
22	0.25	4.03	0.25
23	0.25	4.03	0.25
24	0.25	3.72	0.25
25	0.25	3.72	0.25

This max current was selected because any higher would involve buying more, or more expensive thyristors for switching the stage on. This trial-and-error selection was done up to the tenth stage. Past then, it was observed that the capacitances would have to be too miniscule to keep the current within the desired range. ESR's for those low capacitance capacitors are too large, and energy density too low. Because of the necessity of balancing peak current with inductance and capacitance, the extremely short pulses of the last half of stages needed low capacitance-high energy capacitors that did not exist with acceptable internal resistances. The last 15 stages would be highly inefficient compared to the first "half". Rather than having later stages be extremely lossy and inefficient, they were removed from the design altogether. The last stage went well above the 20KA goal. This will be compensated for in the manufacturing process. Figure 41 depicts the simulation results for the final design of the capacitor bank which eliminated 15 stages down to 10 total from 25 stages. Tables 14,15, and 16 summarize the data which was used to compile the simulation result in Figure 41.

Table 11 Second Design Part-A

Stage	Pulse Time (µs)	Energy Goal (J)	Capacitance (µF)	Inductance Needed (µH)
1	866	326.0404106	3400	22.4
2	359	326.0404106	3400	3.8
3	275	326.0404106	3400	2.3
4	232	326.0404106	3400	1.6
5	204	326.0404106	3400	1.2
6	185	326.0404106	3400	1.0
7	170	326.0404106	3400	0.9
8	158	326.0404106	3400	0.7
9	149	326.0404106	3400	0.7
10	141	326.0404106	3400	0.6
11	134	326.0404106	3400	0.5
12	128	326.0404106	3400	0.5
13	122	326.0404106	3400	0.4
14	118	326.0404106	3400	0.4
15	114	326.0404106	3400	0.4
16	110	326.0404106	3400	0.4
17	107	326.0404106	3400	0.3
18	104	326.0404106	3400	0.3
19	101	326.0404106	3400	0.3
20	98	326.0404106	3400	0.3
21	96	326.0404106	3400	0.3
22	93	326.0404106	3400	0.3
23	91	326.0404106	3400	0.2
24	89	326.0404106	3400	0.2
25	87	326.0404106	3400	0.2

Although short of the initial design goals, this design still had the potential to deliver impressive performance, at a manageable budget.

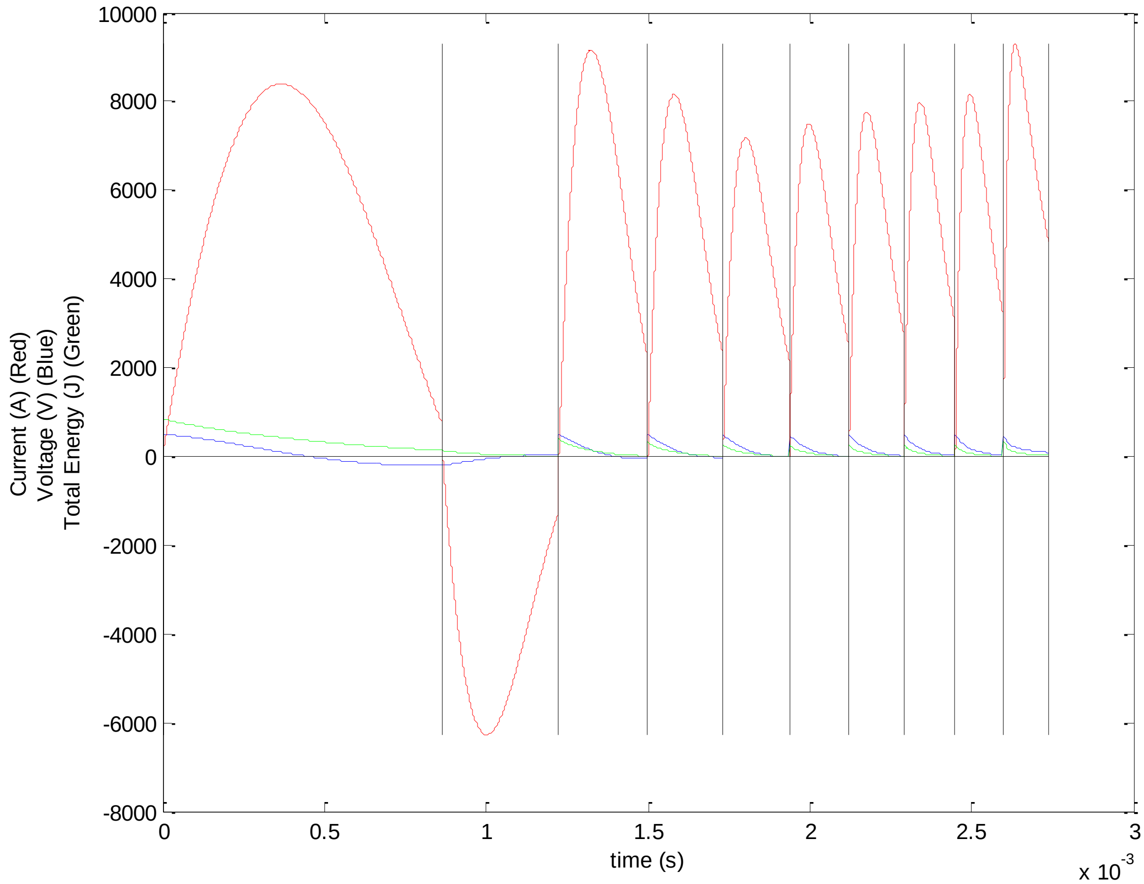


Figure 38 Current, Voltage and Energy as a function of time for the final attempted design. Black vertical lines represent stage separation.

Table 12 Second Design Part-B

Stage	Initial Bank Voltage (V)	Imax (A)	Peak Energy in Inductor (J)	Inductor Resistance (mOhm)
1	1000	8756	857	12.8
2	-451	-7328	103	5.6
3	85	1609	3	4.4
4	-9	-186	0	3.8
5	0	11	0	3.2
6	0	0	0	3.0
7	0	0	0	2.7
8	0	0	0	2.5
9	0	0	0	2.5
10	0	0	0	2.2
11	0	0	0	2.2
12	0	0	0	2.2
13	0	0	0	2.0
14	0	0	0	2.0
15	0	0	0	2.0
16	0	0	0	2.0
17	0	0	0	2.0
18	0	0	0	1.7
19	0	0	0	1.7
20	0	0	0	1.7
21	0	0	0	1.7
22	0	0	0	1.7
23	0	0	0	1.7
24	0	0	0	1.7
25	0	0	0	1.5

Table 13 Second Design Part-C

Stage	Capacitor Resistance (mOhm)	Total Stage Resistance (mOhm)
1	28	40.8
2	28	33.6
3	28	32.4
4	28	31.8
5	28	31.2
6	28	31.0
7	28	30.7
8	28	30.5
9	28	30.5
10	28	30.2
11	28	30.2
12	28	30.2
13	28	30.0
14	28	30.0
15	28	30.0
16	28	30.0
17	28	30.0
18	28	29.7
19	28	29.7
20	28	29.7
21	28	29.7
22	28	29.7
23	28	29.7
24	28	29.7
25	28	29.5

Table 14 Semifinal Design Part-A

Stage	Pulse Time (µs)	Energy Goal (J)	Capacitance (µF)	Inductance Needed (µH)
1	866	326	6800	11.18
2	359	326	6800	1.92
3	275	326	3300	2.33
4	232	326	2700	2.02
5	204	326	2200	1.92
6	185	326	2200	1.57
7	170	326	2200	1.33
8	158	326	2200	1.15
9	149	326	2200	1.02
10	141	326	2200	0.61

Table 15 Semifinal Design Part-B

Stage	Initial Bank Voltage (V)	Imax (A)	Peak Energy in Inductor (J)	Inductor Resistance (mOhm)
1	500	8390.86	393.40	9.4
2	500	-6280.46	37.81	4.1
3	500	9160.81	97.61	4.4
4	500	8163.48	67.33	4.1
5	500	7188.56	49.74	4.1
6	500	7502.11	44.27	3.8
7	500	7764.60	40.11	3.5
8	500	7986.09	36.76	3.2
9	500	8179.21	34.01	3.0
10	500	9296.31	26.20	2.5

Table 16 Semifinal Design Part-C

Stage	Capacitor Resistance (mOhm)	Total Stage Resistance (mOhm)
1	14	23.4
2	14	18.1
3	29	33.4
4	36	40.1
5	43	47.1
6	43	46.8
7	43	46.5
8	43	46.2
9	43	46.0
10	43	45.5

After more analysis and consideration, a lower count of film capacitors of a higher voltage were selected and purchased for use in the final design. This was done because they provided and even smaller ESR and would allow for energy to be recycled for the next shot. The idea of one capacitor per stage was also scrapped to make magnetic energy recycling work effectively. Because of all of this, fewer capacitors are needed (five instead of nine) and each capacitor can power at least two stages each. Five identical 970uF capacitors were used in the final design. With the newly selected capacitors, the following simulation results were obtained. In this design, the first four stages share a pair of capacitors, while every subsequent pair shares one.

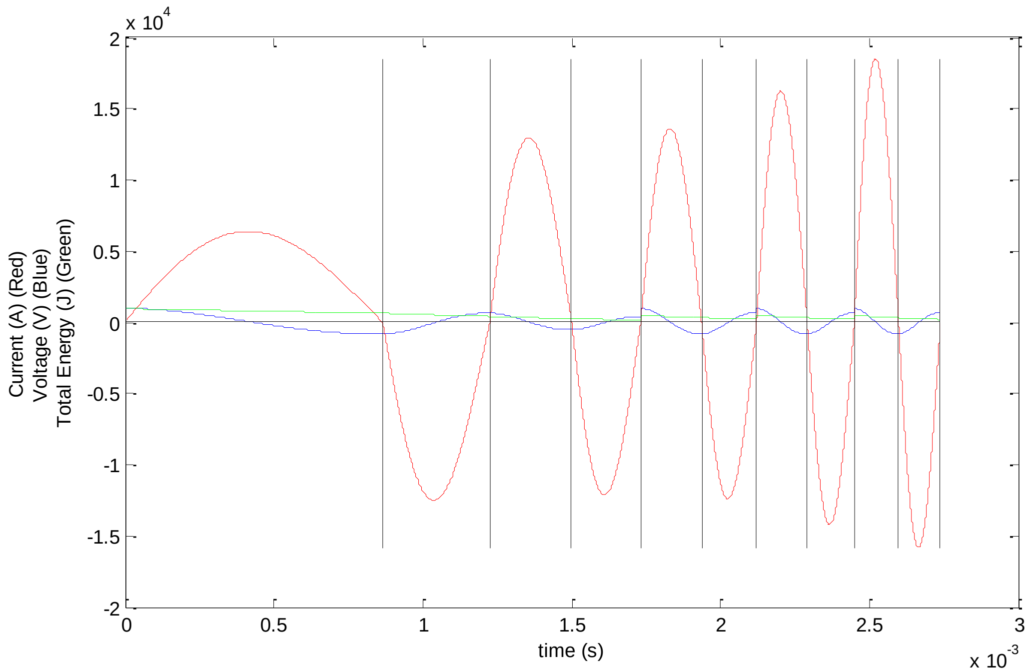


Figure 41+1 Final Design Response (Desired Resistance)

After assembly the real resistance of the entire circuit was measured. The additional 0.03 Ohm resistance present in the assembled circuit was enough to change the design so that the first bank would only power the first two stages (instead of four).The response for the final design is as follows:

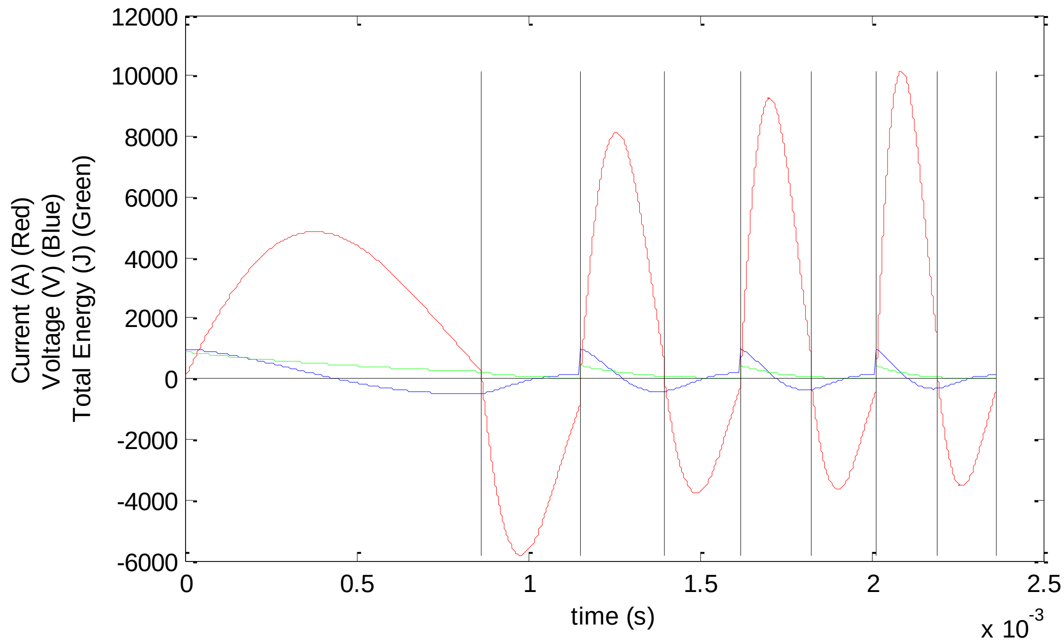


Figure 41+2 Final Design Response (Measured Resistance)

4.4 Switching

The switch control system is centered on the microcontroller being used for the MAC's user interface. When the "Fire" command is triggered, all other processes are suspended and the firing subroutine commences. The firing subroutine is responsible for turning on each coil stage at the appropriate time and make corrections to aforementioned timing in real-time based on feedback. More details on the subroutine's behavior can be found in section 4.5.2. The turn off even for each stage's coil is not controlled, and is instead "hard boiled" into the design of each stages' capacitance and inductance. In other words once a stage is turned on, it stays on for that stage's pre-determined amount of time. Besides the subroutine in the microcontroller, the switching takes in input from sensors and outputs the actual coil energization through the switches.

4.4.1 Sensors

Electrically, each "sensor" is a pairing of an infrared diode and an infrared photoreceptor. They are mounted opposite each other at the end of each coil in a fashion where the photoreceptor is aligned with the light of the diode. They are positioned in a way so that the projectile breaks the line of sight between the diode and the photoreceptor when it transits that specific area of the barrel.

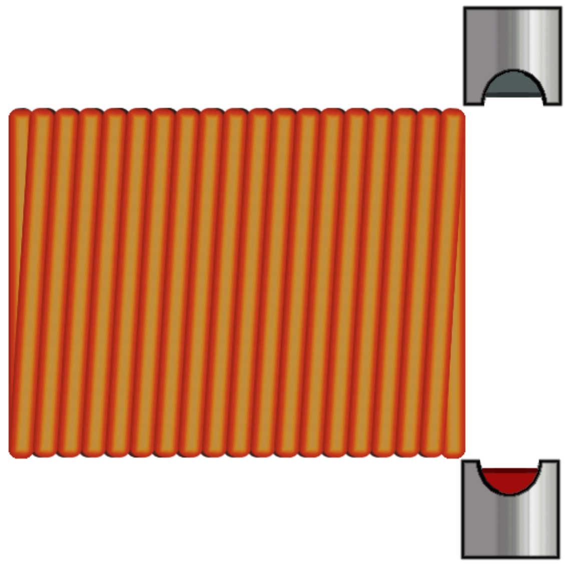


Figure 39 The led-photo sensor pair mounted in front of a coil.

At the moment it first breaks the light, it gives the control subroutine the exact current position of the projectile. Any relevant corrections to the timing of the activation of the next coil can be made. Ideally, at the time the projectile stops obstructing the light from the diode into entering the photoreceptor, another sample of the projectile's exact position is known. If no coils are energized at the time both of these samples were taken, the exact velocity of the projectile is known at that instant in time. If a coil is, or becomes energized between the time these two position samples are taken (this information is known to the firing control subroutine) a very close approximation of the projectiles speed can be determined based on the known acceleration characteristics.

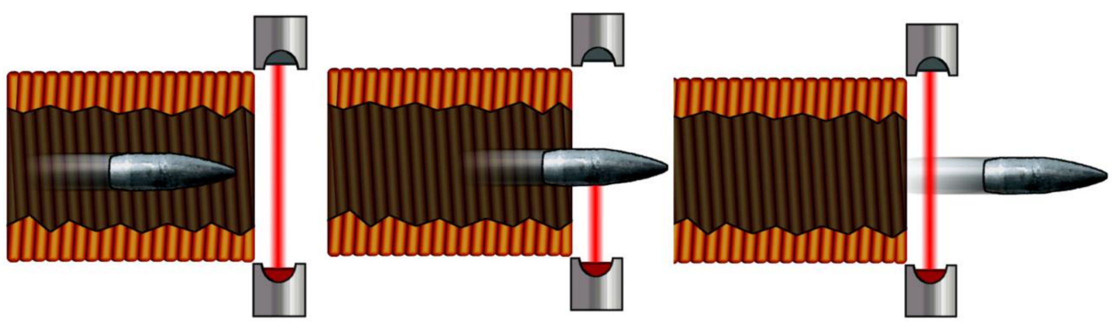


Figure 40 Step 1. Projectile still in coil. Step 2. Projectile breaks beam. Step 3. Projectile no longer obstructing beam.

The sensing system will assumed that the projectile’s length is constant so that a velocity can be measured quickly and with only one sensor. For the purposes of the control system, the acceleration profile for each stage was to be obtained empirically through testing described in section 7.1.2. Although not useful for the firing sequence, the sensor at the end of the last coil will provide the designers during the tuning and testing phase, and ultimately the end user with the final muzzle velocity and energy of the fired projectile. Rather than sensing the speed at the end of each stage, the sensors were used to immediately trigger the next stage. This provided adequate performance given the limitations of the sensors.

The component first selected for this purpose is a slot type photo interrupter with logic output made by Omron (Digikey part number Z3028-ND). By selecting this component, the assembly process was thought to be simplified. Each unit comes with the photo sensor-diode pair already mounted and aligned. Since there is no need to manually align those two parts, the assembly process was to be significantly simplified. Also, this component outputs a digital signal with a 5V high that can be through a simple voltage divider to drop it down to 3.3 V required by the controller, and then connected into the microcontrollers digital input pins without the need for any additional intermediate circuitry like an ADC. This original choice for sensing position proved to be inadequate after the barrel's inner diameter was changed during the design process. The distance between the diode and the sensor was too small for this new barrel to fit.

Thus a different sensor had to be acquired. No sensors with digital outputs at the new desired size were available for purchase so an analogue sensor with similar packaging was chose (part number 365-1629-ND). The LED end was powered by a 5V power supply with a resistor in line for current limiting. The photo-transistor end of the sensor was powered by a 5V supply line and the emitter end connected to a resistor where an appropriate voltage could be measured by the microcontroller's digital input.

4.4.2 Switches

The peak amount of current that can be managed is a critical design constraint. Given the available funds and the number of switches required for this project, it was first determined that a Thyristor capable of managing current pulses in the 20kA range would be used. The specific one first considered selected was a Vishay Hockey PUK Phase Control Thyristor that can handle a current pulse of up to 24400 Amps. The gate would have been triggered on by a 3V pulse. After choosing different capacitors with smaller capacitances and higher voltages, the maximum surge voltage needed was lowered. Thus a similar, yet more affordable thyristor was chosen that would only need to handle currents up to 18000 Amps. After more research, it was discovered that a 20V pulse would be more effective in driving the extremely short pulses.

Rather than driving it directly from the controller, a gate driver optoisolator was used. This optoisolator electrically separates the microcontroller from the thyristor, but allows the signal to be transmitted through a diode-phototransistor pair packaged in an integrated circuit. This is desirable for the overall safety of the control circuitry. If any unwanted surge in power were to propagate from the very high current coils and the very high voltage capacitors into the microcontroller, not only would it be destroyed, but possibly the other connected peripherals as well. In addition to protection, the "gate driver" portion of the optoisolator can provide the high currents necessary to switch the thyristor on (which the microcontroller could not do on its own. Ten of both the phase control thyristor and the gate driver optoisolator components will be obtained--one for each coil stage.

4.5 User Interface and Control

The User Interface and control of the coilgun is the one of the most important sub-systems. It allows the user to properly use the device. The coilgun would be useless and inefficient without the UI&C subsystem.

4.5.1 User Interface

Originally, the user interface in the coilgun was made up of different subcomponents that involved switching, choosing either a list of energies or velocities, choosing velocity speed (if list of velocities is chosen) or energy amount (if list of energies is chosen), and firing, as well as displaying the current battery charge level and the target range. The Figure 44 illustrates how the sub-routines fit in to the overall user interface component, and how the sub-routines connect to one another.

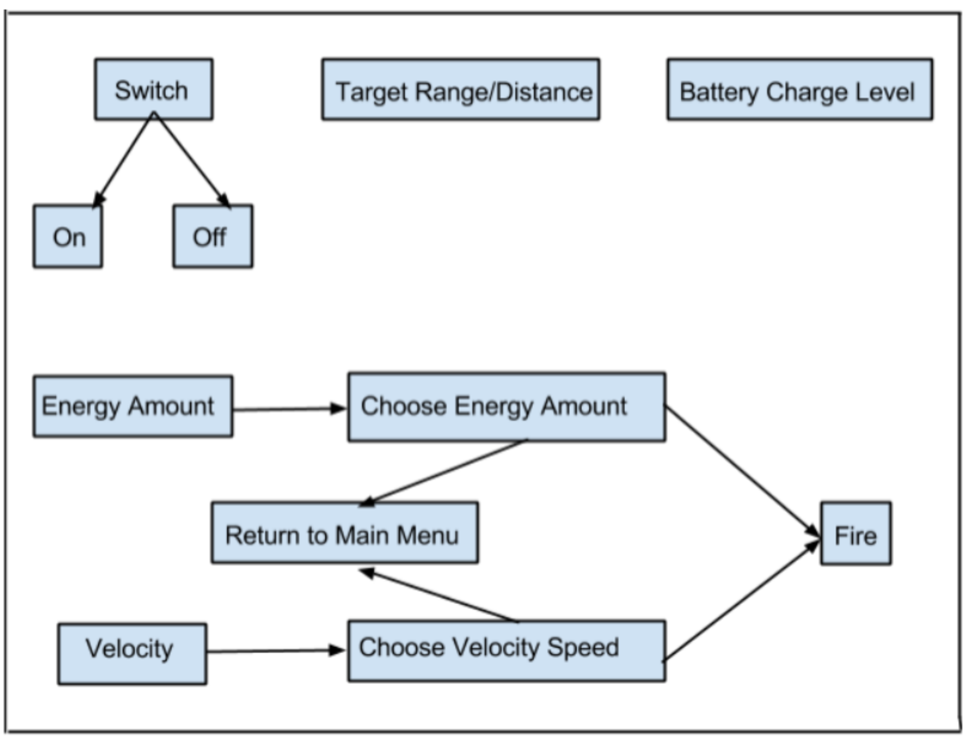


Figure 41 User Interface Flowchart

As seen in Figure 44 above, the coilgun can be easily switched on and off. One of two lists would be selected (velocity or energy), after which the user can either go back to the main menu or choose from the list of velocities or energies. After that, the user can then fire the coilgun.

4.5.1.1 Screen

To display the user interface, an LCD screen with input buttons on will be used. The LCD screen used with the coilgun will be the TM4301 LCD screen by Precision Design Associates, Inc. The screen is an LCD color display that is 4.3 inches wide and is equipped with four buttons on the left side that can be used for user input. Three of the buttons would be used as directional buttons to navigate between different options on the user interface. One button would represent the down direction, a second button would represent the left direction, and a third button would represent the right direction. The fourth button available would be used by the user to confirm a selection.

Figure 42 The TM4301 LCD Screen from Precision Design Associates, Inc. Permission is pending on the reproduction of this image from Precision Design Associates

The TM4301 LCD screen has a 480x272 resolution, a 20 ms response time, as well as an I²C bus, making it compatible with the microcontroller used for the coilgun.

Eventually, the LCD screen was replaced due to timing constraints. A much simpler LCD screen was then chosen to be used with the microcontroller. The new LCD screen was the HD44780 LCD display by Hitachi. The HD44780 screen is a simple 16x2 character display that would easily display the stage number the user desires. All it requires are 7 pins on the microcontroller to function properly (one for Register Select, one for Read/Write, one for Enable, and four for data buses).

4.5.1.2 Input

User input is very vital when operating the coilgun. The user interface code will be written in a way to take in user input and efficiently deliver the intended output. Once on, the user interface screen will display the main menu, allowing the user to choose one of two different lists of modes for the coilgun, velocity and energy. Choosing either input will then display a menu on the screen that will ask for two more inputs. These two inputs include an option to go back to the main menu, or to choose one of twenty five different modes for the coilgun to fire with. The velocity list will include twenty five different velocities that the user wishes for the bullet to travel at, while the energy list will include twenty five different energy levels that the user wishes for bullet to be fired with. Once a velocity or energy level is set, the next input would be for the user to fire the coilgun. After that, the last input left would be for the user to simply confirm a message that appears once the user interface returns to the main menu. Input in the user interface will be implemented with buttons on the left side of the user interface screen that the user will use to choose different options in the menus.

Other than the user interface screen, other kinds of input will also take place when operating the coilgun. One such input would come from the coilgun itself to report the remaining number of bullets available. Input would also arrive from the rangefinder, reporting the current distance between the target and the coilgun. The camera would also transmit input in the form of live video of whatever is in front of the direction the coilgun is facing. The coilgun's photo sensors would also input information on the bullet's velocity.

4.5.1.3 Output

The output of the coilgun and its user interface will depend on what inputs the user chooses. The switch delivers two different positions for the coilgun as outputs, on and off. Once on, the user interface will output different menus depending on the inputs the user enters. The menus include the main menu, the list menus (for a listing of both energies and velocities for the bullet), and the firing menu. In addition, the user interface screen would also output live footage of the direction the coilgun is targeting, but only if the camera is switched on. Otherwise, the user interface screen's background will simply be blank, showing no footage of any kind.

The main menu, which is the first thing that will appear on the user interface screen when turned on, will contain two different options (energy and velocity) for the user to choose from, as well as showing the current battery charge level as well as the current range of the target as outputs on the screen's top right corner.

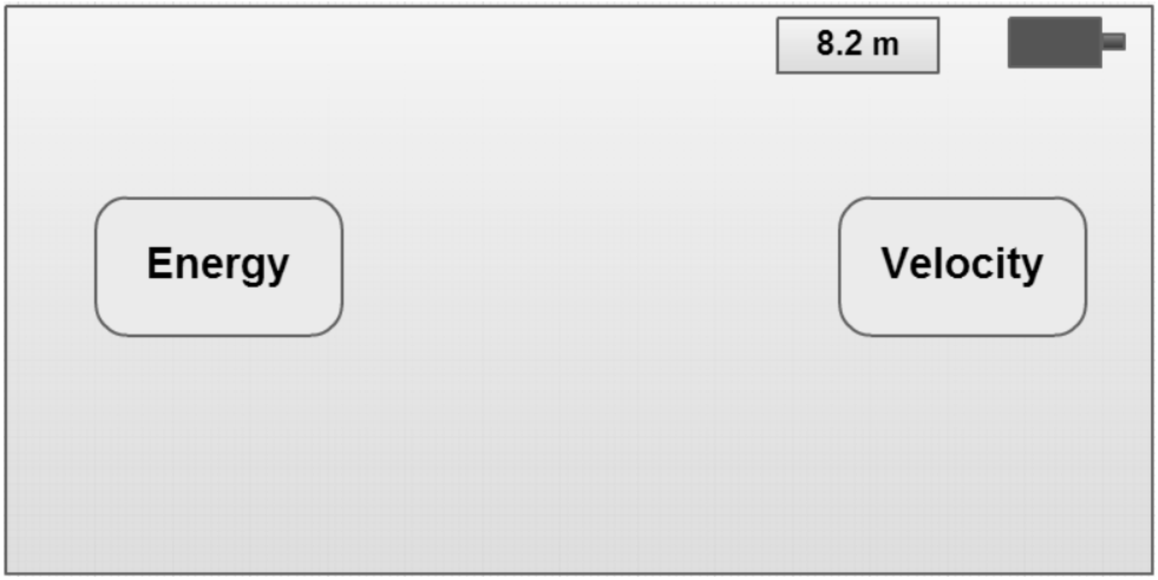


Figure 43 User Interface Main Menu

Regardless of which list the user chooses, the output on the user interface screen will generally be identical in appearance. The battery charge level and target range will remain in the same positions, with twenty five different modes to choose from. If energy was chosen, twenty five different levels of energy in increasing level can be chosen. Otherwise, twenty five different velocities in increasing level can be chosen.

Once the user specifies the amount of energy or velocity intended for the coilgun to fire with, all the user interface will output is a screen asking for the user to fire the coilgun (with the battery charge level and target range still shown). Once the user inputs the command to fire, the coilgun will then fire at the target with the exact amount of energy specified by the user. After that, the user interface will then return to the main menu.

Once the user interface returns to the main menu, and message will be shown to indicate how many more bullets are left. To remove the message, all the user needs to do is choose the option ‘OK’, and the main menu will be as it was initially.

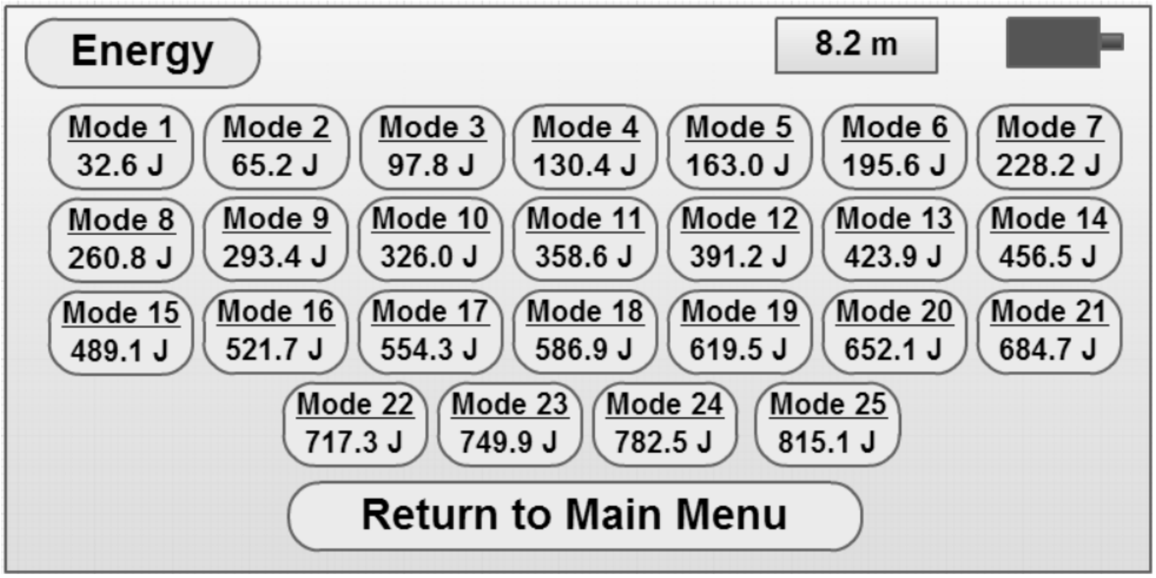


Figure 44 User Interface Energy Menu

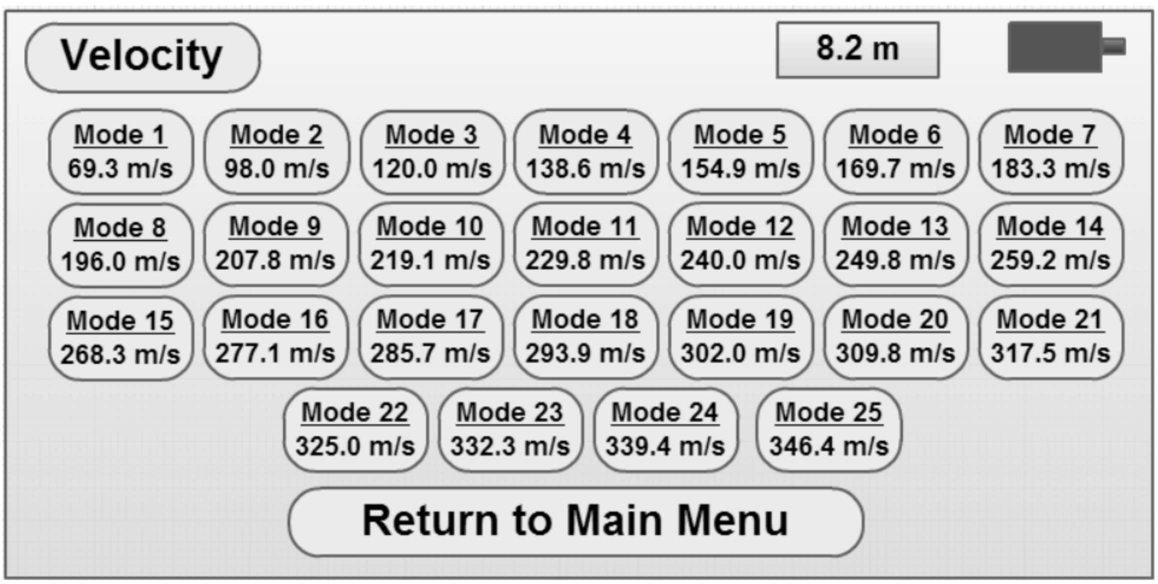


Figure 45 User Interface Velocity Menu

Figure 46 User Interface Fire Menu

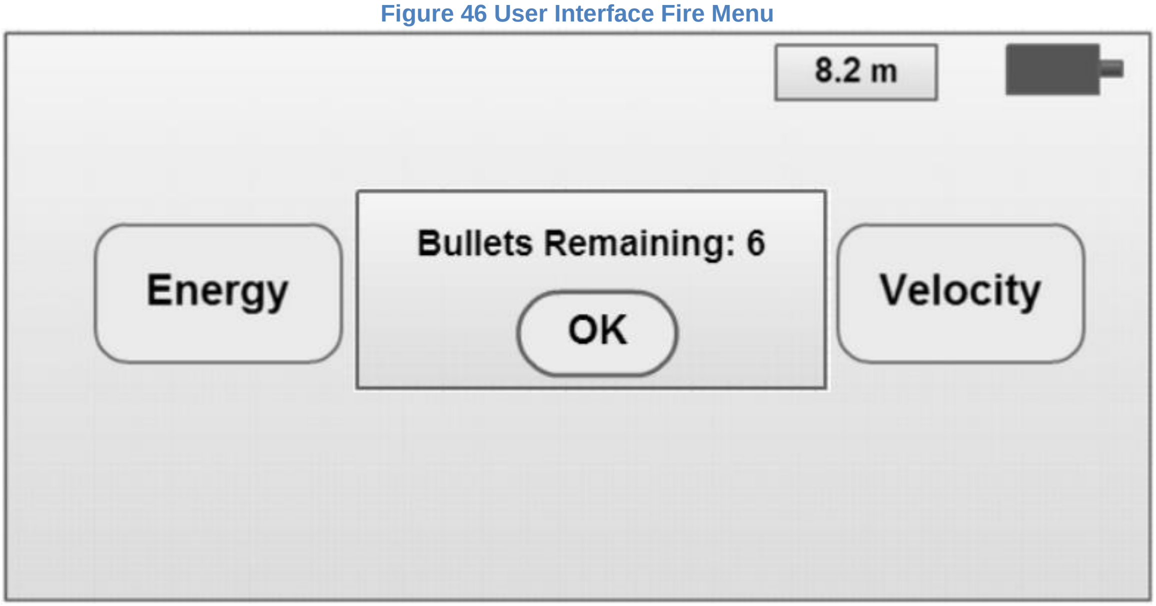


Figure 47 User Interface Main Menu Including Remaining Projectile Shots

4.5.1.4 Software

Microcontrollers understand machine code, hence certain compilers and assemblers would be used to turn high level programming languages like C and Java into machine code. So to program the user interface, the C programming language will be used. The software that is used to program the microcontroller will be Code Composer Studio by Texas Instruments. Code Composer Studio was chosen specifically because of its compatibility with ARM Cortex-M3 based microcontrollers, which is what the chosen microcontroller is. For components of the coilgun that include the camera, the LCD screen, and the rangefinder, a device driver will have to be implemented in the code in order to be able to use these devices for the coilgun's purposes.

4.5.2 Switch Control

Once the “Fire” command is issued, the switch control subroutine is initialized and utilizes positioning sensors shown in Figure 51. These subroutines handle the timing of when each coil is turned on. If all conditions were ideal, the firing sequence could be accurately calculated by applying the Newtonian kinematic equations. To simplify analysis the equations would be set up in a form where the same model can be used to describe every coil, with only the initial conditions changing. The set up system of equations would then be solved for the critical times in which the coil needs to be activated. These times could then be hardcoded into the control system. However, there are several factors that vary throughout normal operation that would bring this ideally aligned model out sync. A coil being energized too early, or even worse too late, can severely degrade the efficiency and end performance of the coil gun. One of the perturbing factors is air resistance, which varies with air temperature and altitude. Another variable factor is the force that the coil applies on the projectile. Rather than this acceleration being constant, it increases in magnitude as the projectile gets nearer to the beginning of the coil and decreases as it moves away. The force that the coil applies is also dependent on the current running through it. The way that it’s designed and bult, the current has an inverse parabolic shape, where the timing is aligned such that the peak current occurs when the projectile is closest to the edge of the coil.

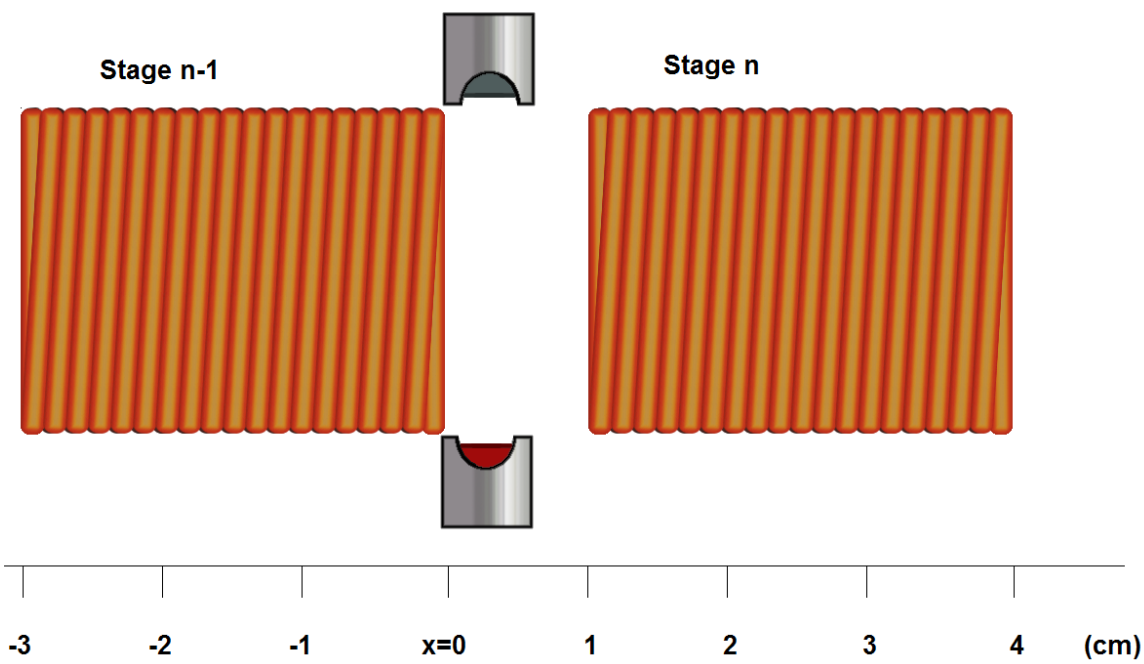


Figure 48 Scale of a Single Stage

Taking those two factors together, the acceleration was adequately approximated as constant for the design phase, but it is too imprecise for the energizing timings. In addition, the current’s pulse shape--its peak, rate or rise and rate of fall--can vary significantly from one firing to the other. As the MAC fires, heat can build up and increase the temperature of the electrical components. The conductive elements, capacitors as well as the semiconductor switches all have slightly altered behaviors at different temperatures.

Rather than trying to predict all of those variations directly, the control system would have used data from sensors mounted at the end of each coil (4.3.4) as shown in Figure 51 to measure the speed of the projectile as it exits the previous stage, and realign the timing of the energization of the next one so that it's at an optimal period. In addition to that that alignment, it would have also be able to calculate the kinetic energy of the project based on its speed as it left each stage. If the desired energy has been reached, then the next coils in the sequence will simply not be activated. Every stage has a pulse time τ derived in section (3.3.1.1) using (24). The firing control algorithm has to take the current measured velocity of the projectile and trigger the next coil in a way that allows the pulse time to be at its peak when the projectile reaches the start of the coil.

Due to signal acquisition limitations of the sensors, only the initial time in which the projectile enters into the sensor can be accurately measured. Thus, the velocity cannot be determined from one sensor alone. Because of this, the fire control routines were simplified so that the next stage in sequence immediately energizes when the projectile is sensed by the appropriate sensor.

According to the datasheet of the selected thyristor, it has a 1μs delay time from when the turn on voltage is applied to when the current starts flowing. This delay will be taken into account of the timing. Every on signal will have to be shifted up 1μs of its calculated value whenever possible. The intermediary gate driver optoisolator adds at most a 100ns delay to the switching. This amount is negligible in the timescale being considered and can safely be disregarded.

4.5.3 Rangefinder

In order for the coilgun's user interface screen to accurately display the range to the target's location, a rangefinder is required. A suitable rangefinder to use in designing the coilgun would be the OSLRF-01 rangefinder. The rangefinder is displayed in Figure 52***.*** The OSLRF-01 laser rangefinder operates by sending an outgoing laser pulse (at a wavelength of 850 nm) towards the target, which would then return to the rangefinder's receiver, calculating the range between it and the target

With an update rate of up to 50 readings per second, the rangefinder will constantly check the approximate distance to the target, which will then be displayed on the user interface's top right corner. The OSLRF-01 rangefinder can detect targets within a range of 9 meters (approximately 30 feet), which is within the intended range for the coilgun. Connecting the rangefinder to the microcontroller board can be done using a Molex connector between the two components.

Figure 49 the OSLRF-01 Laser-Rangefinder. Reproduced with permission from Lightware Optoelectronics [11]

4.5.4 Camera

In order to transmit live footage of the direction the coilgun is facing, a camera will be needed. Without the camera, the background of the user interface screen would be blank, and not allow the user to properly target the coilgun. A suitable camera to use for the coilgun's user interface would be the DSC-W100 camera by Sony.

The Sony DSC-W100 camera delivers live footage at 8.1 megapixels, has a supply voltage of 3.6 V (along with a battery that has a three hour life), and is connectable via a USB cable. Its USB connectivity makes it compatible with the microcontroller used for the coilgun. The DSC-W100 would also need to be programmed to transmit whatever footage it is recording straight towards the user interface screen. In addition to simply transmitting footage, the camera can also zoom in by a factor of 3 in the direction it's facing by adjusting a small lever on the top, providing the user with a closer image of the target on the user interface screen.

Figure 50 Sony DSC-W100 Camera

4.5.5 Microcontroller

There are several considerations that need to be considered in selecting a microcontroller. First, the number of input and output lines must be determined. This ten stage coilgun will have eleven photo sensors that need to feed into the microprocessor. The microcontroller will also need to control ten switches to trigger the pulses in each coil stage.

A suitable microcontroller needs to have these I/O characteristic. Since the needed information from the photo sensor is binary (projectile present/not present), a digital input line is suitable for all eleven photo sensor inputs. Likewise, the switches that trigger the pulses have only two states, on and off, and can be controlled by a binary output.

Operating frequency is another important consideration. Both the photo sensor inputs and pulse triggering outputs need to operate in the microsecond range. So a suitable microprocessor would have to have a clock speed that could handle such timings. Using the formula T = 1/F, 1 microsecond would equate to a clock speed of 1 MHz. So to deal with a wider range of frequencies, the coilgun will need a microcontroller with a clock speed of at least 100 MHz.

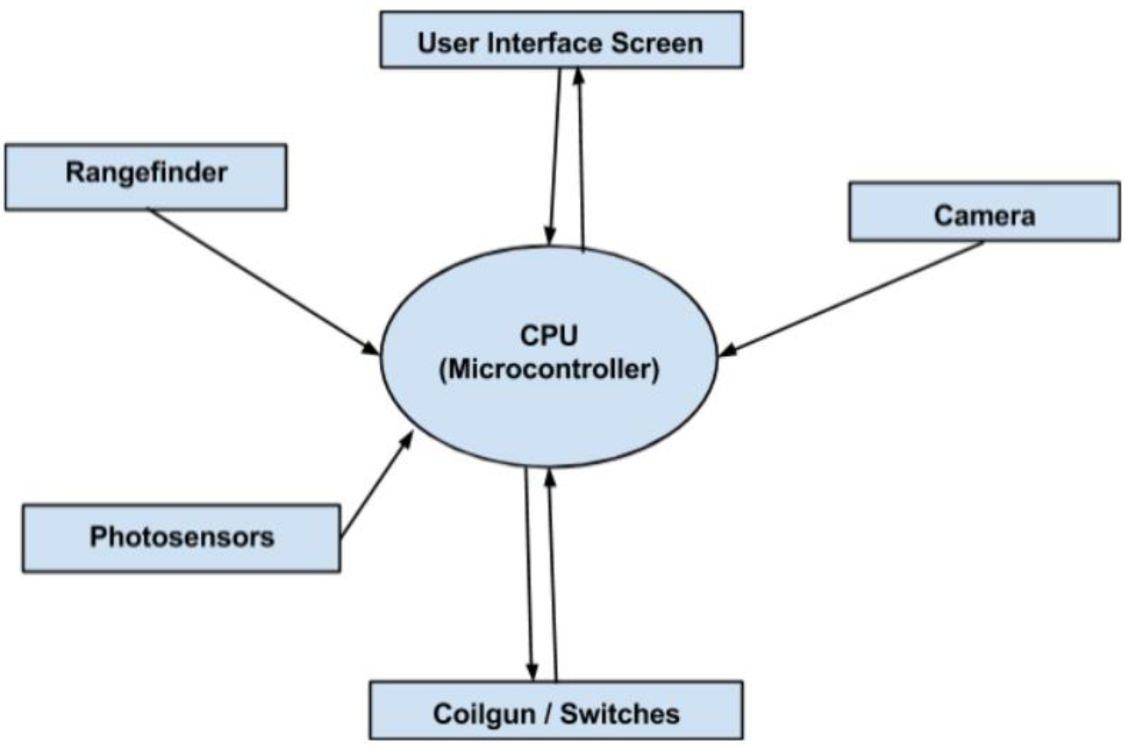


Figure 51 CPU Flowchart

As seen in the flowchart above, the microcontroller is essentially the central processing unit that unites components of the coilgun to make it function properly. A suitable microcontroller to use for the coilgun would be the LPC1769 ARM Cortex-M3 based microcontroller by NXP Semiconductors.

The LPC1769 microcontroller is built around a 32 bit processing unit, and contains a clock speed of up to 120 Mhz, which is within the desired range. It contains flash memory, with a flash size of 512 kB and a RAM size of 64 kB. In addition, the LPC1769 contains an 8 channel 12-bit ADC along with a 10-bit DAC. The microcontroller also has 70 GPIO pins (general purpose I/O pins), whose purpose is to be programmed to be an input or an output state for the coilgun. GPIO pins used for input would take in input signals from components that provide input (such as the rangefinder), while output pins would deliver output signals to where an output is needed (such as the LCD screen). With these 70 pins, the microcontroller has just enough for the coilgun's components. The LPC1769 microcontroller is connectable via two CAN channels, Ethernet, three I²C interfaces, a two-input and two-output I²S interface, an SPI interface, two SSP controllers, four UARTs, and a USB interface. It contains four timers, and has a supply voltage of 2.4 to 3.6 V. A detailed block diagram of the LPC1769 microcontroller is shown below, detailing the many different parts of the microcontroller.

The LPC1769 microcontroller contains 70 GPIO pins, which are labeled as following: P0[0]-P0[11], P0[15]-P0[30], P1[0], P1[1], P1[4], P1[8]-P1[10], P1[14]-P1[31], P2[0]-P2[9], P2[10] (which contains a LOW level during reset that starts the ISP command handler), P2[11]-P2[13], P3[25], P3[26], P4[28], and P4[29].

In addition to the GPIO pins, the microcontroller also contains pins that involve voltage. There are six ground pins labeled as V_{SS}. An analog ground pin labeled as V_{SSA} is also included, but isolated from the other ground pins to avoid errors and noise. Four supply voltage pins labeled as V_{DD}(3V3) provide power (3.3 V) to the I/O ports. Two regulator supply voltage pins labeled as V_{DD}(REG)(3V3) provide power (3.3 V as well) to the on-chip voltage regulator only. A pin labeled as VDDA is the analog pad supply voltage pin, carrying the same voltage as the other supply voltage pins (3.3 V), but is isolated to avoid errors and noise while powering the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC).

A pin labeled as V_{REFP} is the ADC positive reference voltage pin, which should have the same voltage as VDDA (3.3 V), while a pin labeled V_{REFN} is the ADC negative reference voltage pin, which should have the same voltage as the ground pins (0 V). Both of these pins must be isolated to avoid errors and noise. Their level also acts as a reference for both ADC and DAC. A pin labeled VBAT is the real-time clock (RTC) pin power supply, supplying power (3.3 V) to the RTC peripheral.

Other pins on the LPC1769 microcontroller include the TDO/SWO pin, which serves as both as a serial wire trace output (SWO) and a data out (TDO) for the joint test action group (JTAG) interface. The TDI pin is used for testing data in the JTAG interface. The TMS/SWDIO pin acts as both a test mode select pin (TMS) for the JTAG interface and a serial wire to debug data from input and output (SWDIO). The TRST pin acts as a test reset pin for the JTAG interface. The

TCK/SWDCLK pin acts as a clock in two instances, one in which it's a test clock for the JTAG interface (TCK) and a serial wire clock (SWDCLK).

The RESET pin is simply an external reset input pin. RSTOUT is a 3.3 V pin that indicates a reset state. The XTAL1 pin provides input to the internal clock generator and oscillator circuits while the XTAL2 pin provides output from the oscillator amplifier. Input to and output from the real-time clock oscillator circuit is achieved with the RTCX1 pin (for input) and the RTCX2 pin (for output). The N.C. pin is a pin that does not have a connection of any sort.

Eventually, a different microcontroller was chosen due to time constraints, removing the camera and rangefinder components, as well as replacing the LCD screen. The new microcontroller was the MSP430F5529 microcontroller by Texas Instruments. The MSP430F5529 has a clock speed of 25 MHz, 128 KB of flash memory, 8 KB of SRAM memory, 63 GPIO pins, four 16-bit timers, a real-time clock, and 16 ADC channels.

4.5.6 Printed Circuit Board

A printed circuit board was designed, printed and assembled in order to appropriately package and organize the control circuitry and its peripherals. An MSP430F5529 development board was used as the starting point for the design. Routes were made to ten optoisolator each half driven by an independent 24V power supply bus. A full bill of materials is included in section 8.2.

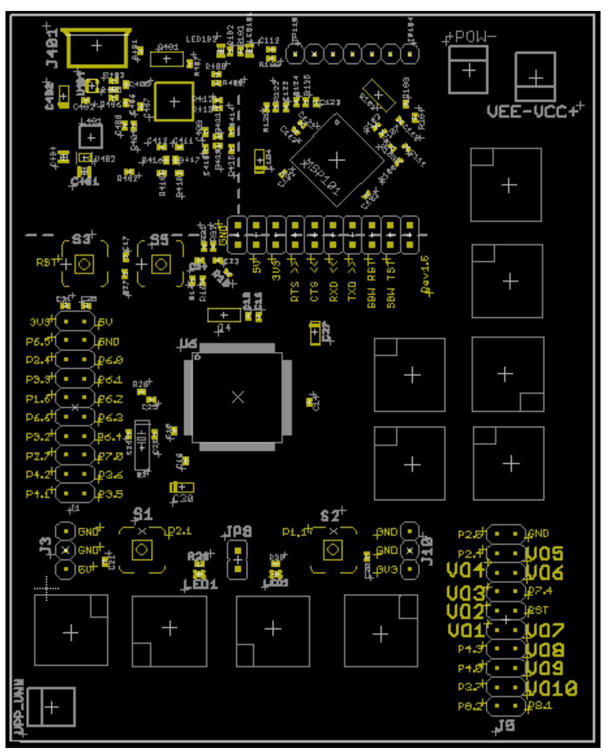


Figure 52+1 Control PCB Schematic

4.6 Barrel

The barrel of the M.A.C is designed to fit the position and velocity sensors, the stator coils, the switching for each stator circuit, and the projectile. All the components affect the geometry of the barrel except the projectile. Since the projectile is in the barrel for a fraction of a second it is not an imposing design constraint. The barrel was designed to be one meter in length and is the biggest section to the coilgun system. It will have to withstand the heating from the coils and the stresses caused by the magnetic fields produced by the stators.

The material used to make up the barrel enclosure for the coilgun would be ABS plastic. It is a material that holds up well to the temperatures that will be experienced in the coilgun, and is also an electrical insulator, which will be a benefit to the safety of the high voltage gun system. ABS is also a strong structural material that is lightweight and simple to manufacture as opposed to metal which requires machining and production lines. Composite material was also investigated for the material to be used in the construction of the barrel due to its strong, lightweight properties, but the cost for use in the MAC was too much for the budget that was allocated.

Figure 57, 58, and 59 show a depiction of the barrel design concept. The pattern of holes allows the air around the barrel to cool the coils down as they are energized. A thermal analysis would be performed if the resources are available to ensure rapid cooling and low melting possibilities for the ABS plastic.

Figure 53 MAC Concept Barrel Side Cover

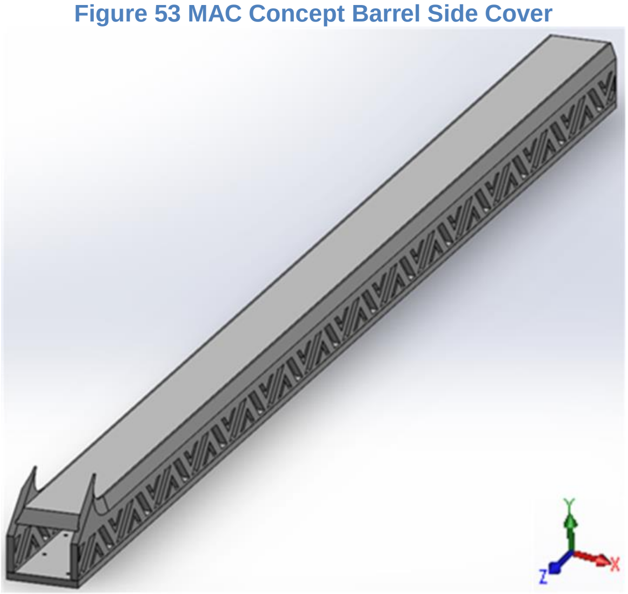


Figure 54 Concept Full Barrel Assembly

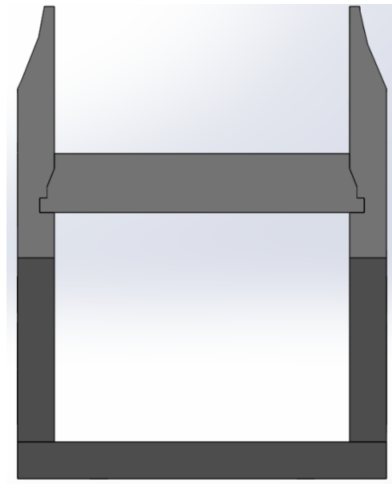


Figure 55 Concept Front Profile View of the Barrel

It can be seen in Figures 58 and 59 that there is a sliding lid to the top of the barrel. This would allow for easy construction and easy access to maintaining the coils and sensors. Table 17 summarizes the dimensions of the barrel. Length is along the z-axis, width is along the x-axis, and height is along the y-axis.

Table 17 Concept Barrel Structure Dimensions

Part	L	W	H	Unit of Measure
Barrel Side	100	0.50	3.91	cm
Barrel Sliding Lid	100	4.0	0.80	cm
Barrel Floor	100	5.0	0.50	cm

Figures 57 through 59 depict the concept design for the MAC. The final construction for the MAC turned out to be larger than the expected concept. Due to capacitor dimensions being larger than the final barrel design the final design would consist of an eight stage barrel set on top of the capacitor bank. Behind the capacitor bank featured the control and power systems for the full system. Figure 33 shows the final design and construction of the full MAC system. The barrel was designed to be made of acrylic with the coils being wound upon it at constant lengths between each stage. The position sensors for the system were positioned between the stages and holes were drilled in the acrylic to reduce occlusion of the IR beam from the photodiode.

4.6.1 Projectile

The projectile is the start of the design criteria for the coilgun system. It determines the amount of energy that is needed from each coil to accelerate it to the specified speeds. The projectile must be an electrical conductor that can be manipulated in a magnetic field, it must be simple to manufacture, it must be light weight, it must be able to handle high currents, and have a high melting point. These are the requirements of a projectile for the coilgun. Each requirement is equally important to the operation and execution of the MAC

Many conductor materials were considered for the use in the MAC Aluminum, Iron, Beryllium, and copper were all compared and contrasted to determine which would be the best conductor material. The three properties which were looked at are density, conductivity, specific heat, and the melting point. Table 18 summarizes the properties which the decision was weighed on. It was determined that the projectile would be constructed from Iron material. This is mostly due to its lower cost, ease of access, melting point, specific heat, and conductivity. Beryllium was also a good candidate due to its low density, but it is a material that is much more difficult to obtain and can be expensive.

Table 18 Projectile Conductor Properties

Material	Density (kg/m^3)	Conductivity ((10^7)*S/cm)	Specific Heat (J/g*k)	Melting Point (K)
Iron	7873	1	0.45	1813
Aluminum	2700	3.77	0.90	933
Copper	8960	5.96	0.38	1357
Beryllium	1850	3.13	1.82	1560

With the selected material to be used the projectile can be designed and dimensions can be formulated. The goal for the MAC was to have a projectile that is under 15g to launch. This was our limit to size up the projectile. Using the density of the material to be used an area was formulated. For stability in flight a projectile must be have a diameter equal to its length. This gives a ratio of 2:1 for radius to length. A radius of 6.5 mm was selected and due to the ratio for stabilized flight the length was determined to be 17 mm. Table 19 will summarize the properties of the designed projectile.

Table 19 Projectile Dimensions

Properties	Value	Unit
Radius	6.5	mm
Length	17	mm
Diameter	13	mm
Volume	1725.52	mm^3
Mass	15	g

There is one design aspect that would need more analysis in both the coilgun operation and the projectile designs. The known “rifling” of a projectile as it moves down the barrel of a conventional weapon is a very important requirement for stable flight. When rifled, the projectile can maintain a steady state roll along the center axis of the projectile as it travels through the air. This roll is not easily realizable in the design of a coilgun system due to the lack of contact with a barrel that has groves which rifle a projectile.

This concept leads to thinking out of the box in terms of being able to add a rifling effect to the projectile. One way that was investigated was the option of building a cover over the projectile that would have grooves or fins in order to spin the projectile as it is accelerated through the barrel. This concept was approached for use in the MAC system. The concept is to use a lightweight material to sheath the metal projectile described above. The material that was selected is ABS plastic. It is a lightweight strong material that can be aerodynamic and with the technology of 3-D printers can be made into any shape or size conceivable.

The design for the projectile sheath follows the concept of the Very Low Drag bullet, which takes advantage of geometry to achieve aerodynamics at supersonic speeds. This is accomplished with the use of secant ogive nose design with a boat tail design. These geometrical properties allow for higher muzzle velocities in conventional projectiles. Using this concept the projectile sheath was designed. Figures 60 and 61 show the design of the projectile sheath and the projectile which will be utilized for the MAC. Fins were not added to the design since adding rotation to the projectile is not an objective.

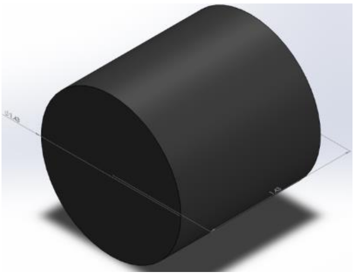


Figure 56 Projectile for use in the MAC Coilgun System. The dimensions can be found in Table 19

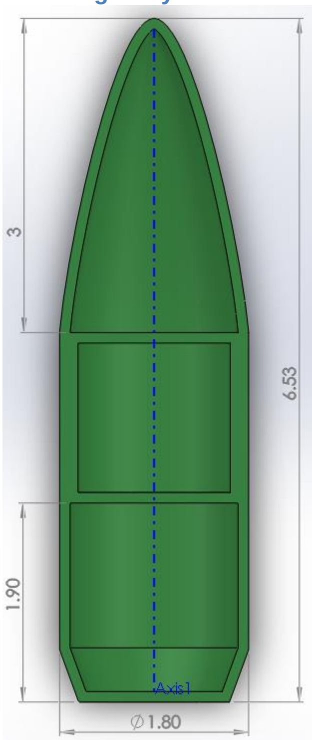


Figure 57 VLD Projectile Sheath Design. All dimensions are in cm.

4.6.2 Coils

The design of the coils is based on four different factors and is an iterative process. The four factors which impact the design of the coils are as follows;

Projectile length and diameter, kinetic energy needed per stage, peak current, time to peak current per stage. Each factor has a separate impact on the stator coils and on each other. Therefore, a process was compiled to minimize the changes in factors as others were established.

4.6.2.1 Initial Calculations

From the barrel length of 1 meter and the muzzle velocity of 400 m/s the acceleration that is needed to achieve that velocity can be calculated. By manipulating the equations of motion an acceleration of 80,000 m/s^2 was calculated. The equations that were used are the basic equations of motion for constant acceleration. In the following equation v_m is the muzzle velocity and x_b is the barrel length.

$$x_b = \frac{1}{2}\frac{V_m^2}{a} \tag{35}$$

From the acceleration calculated in (35) the force on the projectile that will be needed by every stator coil can be calculated from the basic equation

$$F = m_p * a \tag{36}$$

, where m_p is the mass of the projectile, which is given in the mission profile in section 4.1.1. This force will later determine the currents that will be needed within each stator to produce the magnetic flux that will launch the projectile. The value for (36) that was calculated is 1.412kN.

The kinetic energy at the muzzle of the M.A.C can now be calculated. This will determine the full amount of kinetic energy that will be needed to be transferred into the projectile to achieve the speeds given. The value obtained from the equation below is 1.086 kJ of energy. This value is assuming a efficiency of 100%. In a realistic electrical system the efficiency is much lower. For the design of the MAC an efficiency of 10% was assumed. Assuming the 10% efficiency the kinetic energy calculated will have to be calculated by 10 to get the realistic energy needed for each stage, which is calculated to be 10.87 kJ of energy. The equation for kinetic energy is given below along with the equation for energy in an inductor.

$$KE = \frac{1}{2} m_p v_m^2 \tag{37}$$

$$W_L = \frac{1}{2} L I^2 \tag{38}$$

4.6.2.2 Acceleration, Kinetic Energy, Velocity, and Timing Profile

The next major contributor to overall coil design and stator circuit design is the acceleration profile for the coil gun to achieve the speeds which are necessary. In a realistic coilgun the projectile is not accelerated the whole time. It is accelerated at different lengths of the barrel in shorter time periods as the projectile is accelerated. Therefore, for initial calculations it can be assumed that there will be constant acceleration in the barrel, but only initially. A thorough investigation into the kinematics and electromagnetics of each coil and how the projectile accelerated down the barrel must be performed.

This analysis is crucial in determining peak times for currents in each stator, the velocity which the projectile will have at each stage of the gun, the average acceleration, the actual kinetic energy of the whole system, and the time it takes to go through each stage of the coilgun. The current rise time from these calculations are crucial to the operation of the coils for optimal acceleration of a projectile in each stage. Table 20 shows the timing for all 25 stages of the coilgun, and the velocity properties of the coilgun. Figure 62 depicts the Velocity Profile of the projectile at each stage of the coilgun as it moves down the barrel.

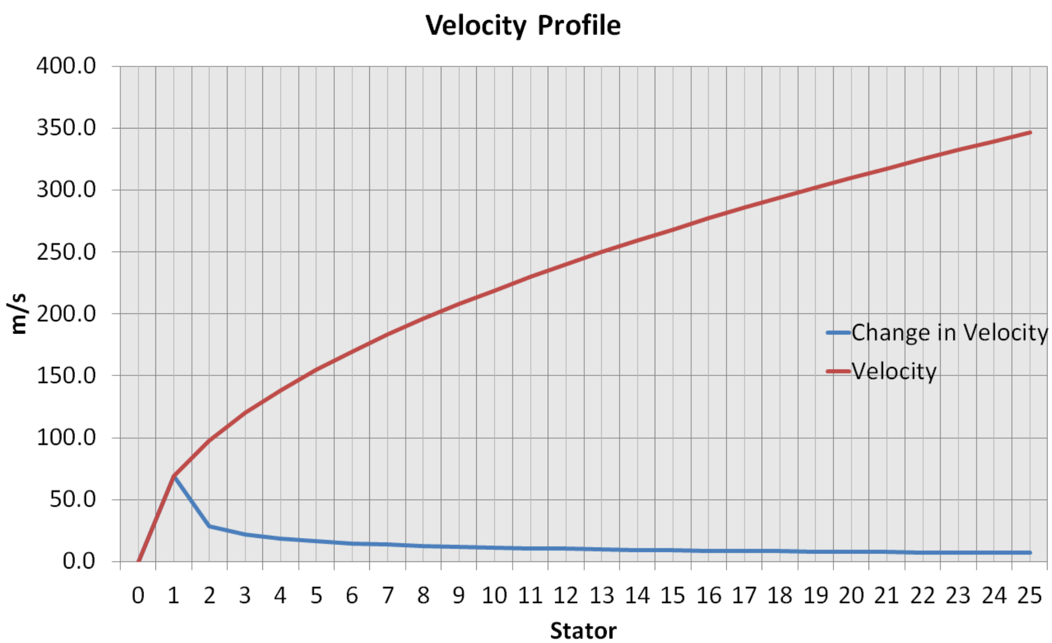


Figure 58 Velocity Profile for the MAC Coilgun

The timing and velocities will facilitate in modulating the output of our coilgun by turning on or off stages to achieve the desired speeds from the User Interface. Also these calculations can be utilized to build a 1 to 25 stage coil gun with the acceleration calculated for our design goals of $80{,}000\ m/s^2$.

As it can be seen in the Table 20 and Figure 62, the velocity of 400 m/s, which the MAC is desired to meet, cannot be reached. This is an acceptable error from ideal conditions. If a efficiency higher than 10% is achieved the velocity that was set as a goal will be reached and possibly exceeded. Figure 64 depicts the time constant that would need to be met by the LC circuit of the stator capacitor pair. The Figure also shows the current rise time which is the necessary time each stage is to be optimally energized with magnetic energy to be imparted on the projectile to meet the desired acceleration. This time is also the time it takes the projectile to move through the effective stator distance x_{eff} which is shown below in Figure 63**.** This time is based on the property that stator magnetic fields are effective a distance half the stator from the face of the stage. The effective distance is equal to $x_{eff} = \frac{x_s}{2} + x_s$. These time constant derived will assist in the design of the LC response in section 4.3.

Table 20 Kinetic Profile per Accelerating Stator Part-A

Stator	Change in Velocity (m/s)	Total Velocity (m/s)	Time Constant uS	Current Rise Time uS
0	0.0	0.0	0.0	0.0
1	69.282	69.282	866	612.372
2	28.698	97.980	359	194.635
3	22.020	120.000	275	144.562
4	18.564	138.564	232	120.185
5	16.355	154.919	204	105.066
6	14.786	169.706	185	94.518
7	13.597	183.303	170	86.620
8	12.656	195.959	158	80.420
9	11.887	207.846	149	75.386
10	11.243	219.089	141	71.193

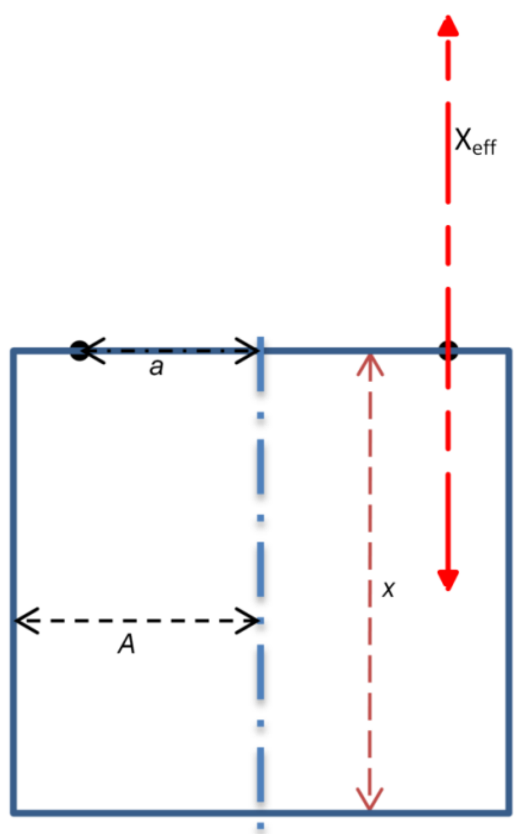


Figure 59 Stator With Effective Magnetic Field on a Projectile

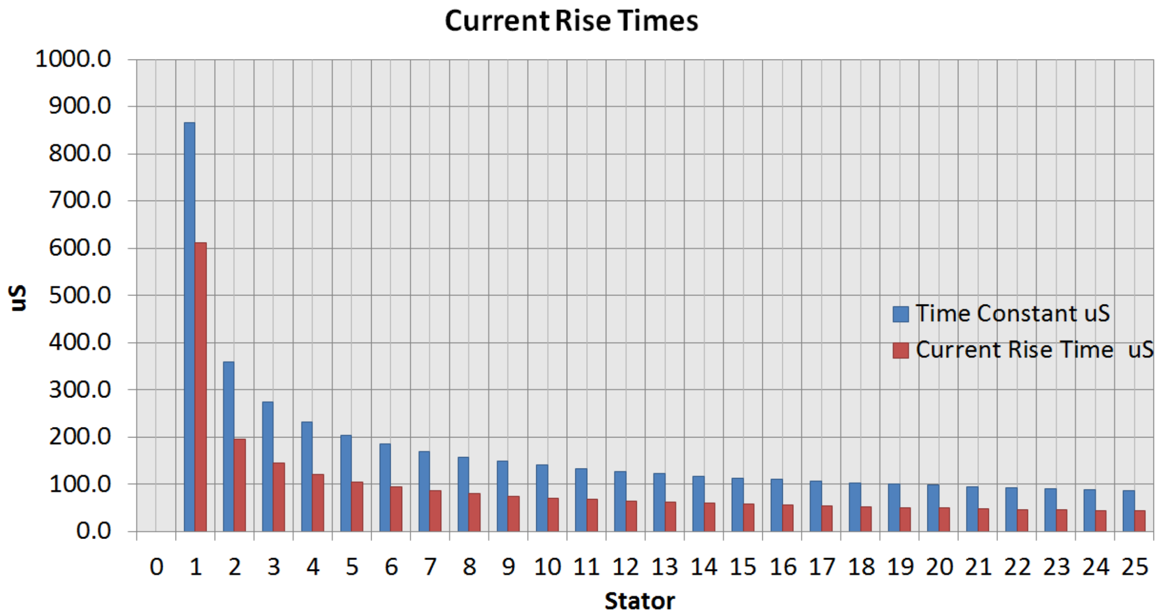


Figure 60 Time constant profile per stage. Red numbers is half a pulse. Table 20 summarizes the data points

Figure 65 depicts the kinetic energy profile as a projectile moves down the barrel picking up velocity as each stage accelerates it toward the desired velocity at the muzzle. Table 21 will show the numbers values at each stage. These values were used to obtain the energy each stator needs to impart on the projectile. The necessary kinetic energies will assist in the design of the stator circuits in section 4.3. The kinetic energy of the projectile at each stage in the table shows the ideal kinetic energy that can be achieved with 100% efficiency. The coilgun will not be experiencing such good efficiencies, due to resistive losses and magnetic losses. It is assumed, as mentioned, that an efficiency of 10% was assumed in this design. The Total Kinetic Energy Needed column is the needed energy in a system expecting 10% efficiency. If a higher efficiency is obtained, lower values will be experienced than the ones depicted in that column.

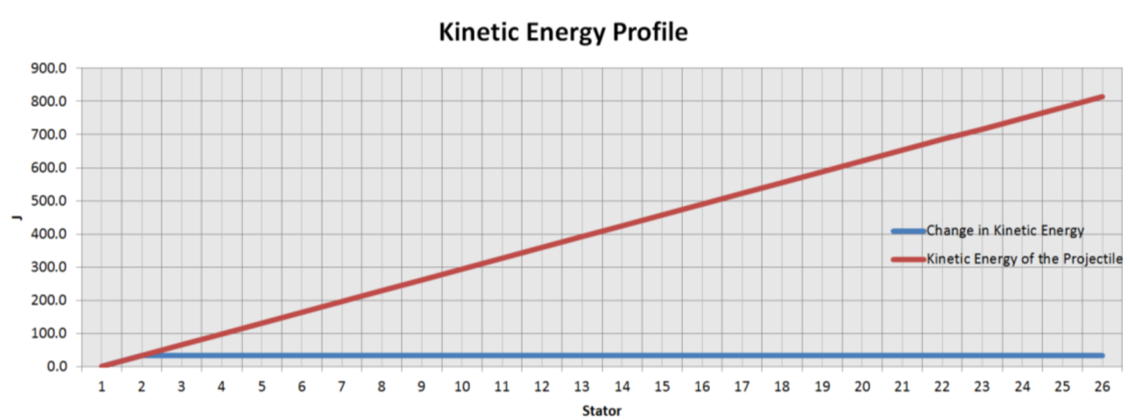


Figure 61 Kinetic Energy Profile for a Projectile Traveling Down the Barrel

Table 21 Kinetic Profiles per Accelerating Stator Part-B

Stator	Total Velocity m/s	Change in Kinetic Energy J	Kinetic Energy of the Projectile J	Total Kinetic Energy Needed J
0	0.0	0.0	0.0	0.0
1	69.282	32.604	32.604	326.040
2	97.980	32.604	65.208	326.040
3	120.000	32.604	97.812	326.040
4	138.564	32.604	130.416	326.040
5	154.919	32.604	163.020	326.040
6	169.706	32.604	195.624	326.040
7	183.303	32.604	228.228	326.040
8	195.959	32.604	260.832	326.040
9	207.846	32.604	293.436	326.040
10	219.089	32.604	326.040	326.040

With the extensive study on the profiles listed above the corrected kinetic energy of the projectile and muzzle velocity can be determined. Table 22 below summarizes the corrected values and the initial values calculated. It can be seen that the corrected values are off by 10-20%. This is an acceptable error and can be attributed to the efficiency loss in the coil circuit from ohmic heating.

Table 22 Initial Performance Calculations vs. Simulated Performance Calculation

	Kinetic Energy (J)	Muzzle Velocity (m/s)	Average Acceleration (m/s^2)	Average Velocity (m/s)	Time ms
Initial	1086.80	400.00	80000	400.00	5.00
Simulated Study	815.10	346.41	60000	233.00	5.57

4.6.2.3 Stator Length

The next step in the design process of the MAC was to obtain the desired length and diameter for the coils. The length and diameter are obtained from the projectile design. Referring to section 4.6.2.2 a stator is only useful to a projectile half the time. This means that a stator applies force to the midplane of the coil from either end. Using this knowledge and the projectile length a ratio formula can be derived based on projectile length. This formula is provided below and was used in determining the length per stator.

$$L_s = r_{coil} * L_p \qquad (39)$$

Where, L_s is the stator length, and L_p is the projectile length. With this ratio, r_{coil} the length for each stator was calculated to be, $L_S = 2(17mm) = 34mm\ or\ 3.4\ cm$. r_{coil} was selected to be two based on the variable x_{eff} described in 4.6.2.2.

The mutual inductance gradient is a major importance to the design of the coils as well. This gradient determines the amount of force in the stator and in successive stators. It is desirable to have a mutual inductance gradient down the barrel that stays approximately constant to achieve an approximately constant force and therefore acceleration. This is accomplished by modifying the length of the stators and the distance between each stator. With the above ratio in (35) a stator length of 3.4 cm was determined, but it did not produce favorable inductance values for the LC time constant shown in Table 20 and the mutual inductance gradients were too far apart.

The ratio, r_{coil}, was iterated with results from section 4.3 to determine the most optimal length ratio for the stator. The iterations determined that the length of the stator would have to be 1.58 times the length of the projectile, $r_{coil} = 1.58$. This new ratio produced the most optimal results and led to a minimum inductance value per coil of $1.509\,uH$ and a coil length of 3 cm using the equations (2), (3), and (4). This was all done for the first design of the coil gun as mentioned in section 4.3, which involved lower currents and constant inductances of $1.5\,uH$ each coil. As it has been mentioned in section 4.3 the timing produced from these inductances would not work with the energy (38) and timing required (24), as shown above in Table 20 and 21 Therefore it was concluded in order to meet timing and energy constraints the currents had to increase and the inductances had to be varied in each stator with new capacitor values and voltages.

The second design called for larger currents and different inductances. In this iteration of design the inductance values were provided by the capacitor bank requirements as in Table 11 in section 4.3. At this time the capacitor bank was still applied to all the coils and did not produce favorable results. The coils were held off on design and the only constraint kept constant was the $1.5\,uH$ minimum inductance, which is based on 14 AWG wire. Until favorable timing could be met a design for the coils could not move forward.

For the final design of the LC circuit in section 4.3 the inductances were standardized. Higher currents were determined for use through the coils to meet the timing constraints for each stage as in Table 15. The calculated currents and the low resistance requirements for the inductors determined that 11AWG would be used. Fusing current was a big concern in the beginning of the design process, but after discovering Onderdonk's equation for fusing currents it was calculated that the 14 AWG wire could handle the current pulses which the capacitor banks would output.

With the final design of the stator circuits, the inductances can be used to design each coil. Each coil has a different inductance. This will contribute to coils with more turns than others. The lengths will be fixed at 3 cm as stated above with a bore diameter of 1.9 cm. Any inductance higher than 1.5 uH will require multi-layer coils to accommodate the inductance values with fixed dimensions as stated. Table 23 below will summarize the basic dimensional requirements of each coil. Table 25 will list each single layer inductor per stage and list the properties that were calculated. Table 24 will list the multi-layer inductor properties per stage which were calculated. As can be seen in the tables mentioned previously the coilgun stages are evenly divided into two types of inductors; single layer and multi-layer inductors.

Table 23 Stator Coil Basic Parameters

Dimensions / Parameters	Value	Unit
Wire Gauge	14	AWG
Coil Length	3.002	cm
Bore Diameter	1.900	cm
Bore Diameter Plus Wire Diameter	2.13	cm
Stator Gap	1.000	cm
Outer Diameter	Variable per stator	cm
Inductance	$\mathrm{L_{coil}} > 0.5$	uH

Table 24 Initial Multi-layer Stator Defining Properties

Stage	L uH	N	$\frac{N}{layer}$	Layers	Outer Diameter (cm)	Wire Diameter (mm)	Wire Length (m)
1	11.18	32	12.75	2.51	3.31	2.35	2.27
2	1.92	16	12.75	1.25	2.84	2.35	0.99
3	2.33	17	12.75	1.33	2.84	2.35	1.07
4	2.02	16	12.75	1.25	2.84	2.35	0.99
5	1.92	16	12.75	1.25	2.84	2.35	0.99

Table 25 Initial Single-layer Stator Defining Properties

Stage	L (uH)	N	$\frac{N}{layer}$	Layers	Wire Length (cm)	Wire Diameter (mm)	Wire Length (m)
6	1.57	11.755	N/A	1	79.004	2.35	0.790
7	1.33	10.819	N/A	1	72.715	2.35	0.727
8	1.15	10.060	N/A	1	67.615	2.35	0.676
9	1.02	9.475	N/A	1	63.679	2.35	0.636
10	0.61	7.327	N/A	1	49.245	2.35	0.492

The preceding tables have shown the initial coil inductances and their dimensions. After testing the first coil and determining the speed which the projectile was accelerated at a new table of coil inductances were derived to match the realistic acceleration and kinetic profile of the projectile in testing. With this new profile and efficiency a new table of inductances can be created. The following tables will show the new inductance values and dimensions which the final coil and barrel setup will have.

Table 26: Final Coil Design Parameters per Stage

Stage	L uH	N	$\frac{N}{layer}$	Layers	Outer Diameter (cm)	Wire Diameter (mm)	Wire Length (m)
1	83.045	77	17.9	4.3	3.57	2.35	5.27
2	4.549	38	17.9	2.12	2.54	2.35	0.99
3	6.618	27	17.9	1.51	2.98	2.35	1.07
4	5.427	25	17.9	1.45	2.45	2.35	0.99
5	4.63	23	17.9	1.29	2.54	2.35	0.99
6	4.024	22	17.9	1.17	2.44	2.35	0.99
7	3.568	21	17.9	1.12	2.02	2.35	0.99
8	3.200	20	17.9	1.06	1.98	2.35	0.99

4.7 Packaging

The high power environment of the MAC coilgun system requires that the packaging be primarily made of an insulator to reduce the chance of shock or system failure. A very good insulator that can be utilized for the MAC is ABS plastic. ABS is also a strong material and can be used for the structure of the MAC. It has been determined that for ease of prototyping, 3-D printers will be used to produce the parts necessary for the MAC structure and projectiles. This allows for freedom in the quality and design of the structural components of the MAC. This also will be aesthetically pleasing, which is always a benefit in any device.

Unfortunately for the final design access to 3-D printers became difficult and costly to the project size and weight. Therefore, the system was primarily constructed from wood to reduce cost and keep a material that is a good insulator. The wood provided ease of manufacturability and concept design tailored to the size of the final components. In figure 33 the final design configuration can be seen constructed of wood.

4.7.1 Projectile loader

The Magnetic Accelerator Cannon will utilize a projectile loader to bring rapid reload times to the MAC system. A servo with three arms will be implemented in the projectile loader that has been designed below in Figure 66 and 67. This servo will allow only one projectile in the chamber as the gun is fired. When a signal is sent from the controller to the servo during recharge times a new projectile will be loaded into the breach. This servo will be mounted internally and under the rectangular outcrop of the design shown below. Attached to the projectile loader will be the controls and power system shelf. Attached to the projectile loader are the handles for use by users to aim the coilgun. The autoloader will be 3-D printed for prototyping.

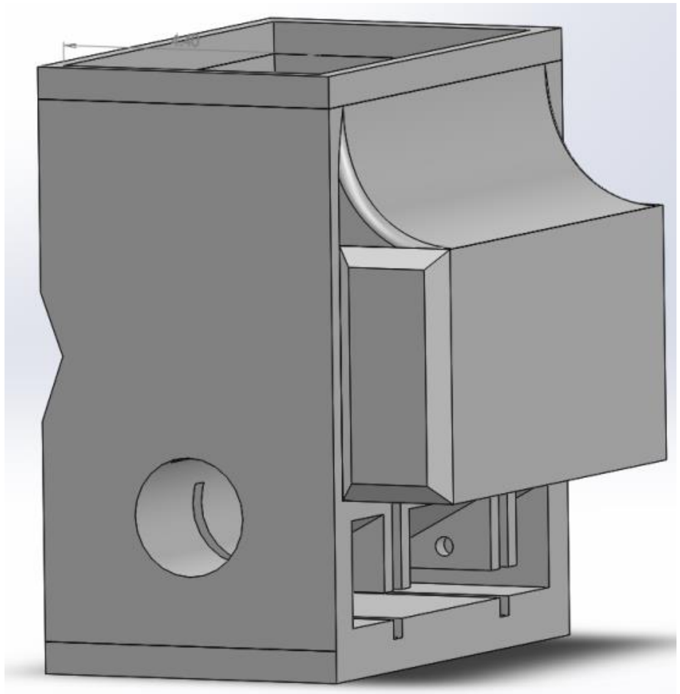


Figure 62 Projectile Loader Full View

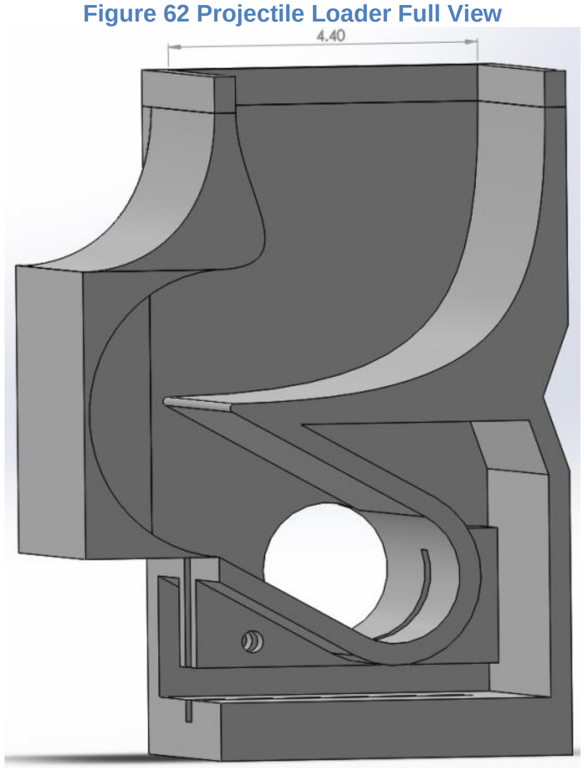


Figure 63 Projectile Loader Internal View

For the final design the autoloader had to be redesigned due to lack of access to a 3-D printer. Acrylic was chosen to be the material to be used due to its ease of manufacturability, low cost, and high strength. Figure__ shows the design for the autoloader in the final design. The servo mentioned above would be placed behind the loader with a wheel and pinion to push the projectile into the barrel. The servo would be driven by the microcontroller in the control circuits.

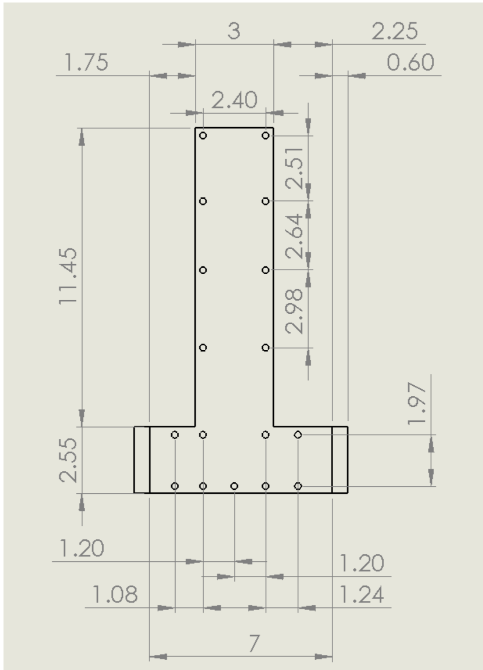


Figure 64 Final Autoloader Dimensions in cm

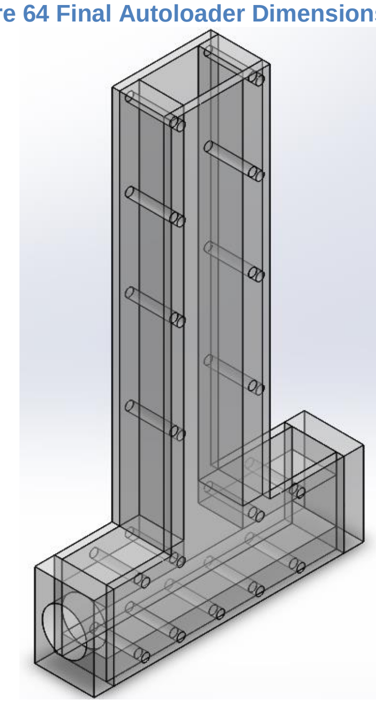


Figure 65 Final Autoloader Design; Acrylic Render

4.7.2 Stand

The MAC is not designed to be man portable. It is designed to sit atop a Humvee or other emplacement that could utilize a large azimuth angle and reasonable elevation angles. The MAC mount will be able to turn 360 degrees azimuth and ±40 degrees elevation. Ball bearing joints will be utilized in the MAC support arm at the top of the U-joint and at the base of the joint. In Figure 68 the U-joint is shown without the MAC attached.

Figure 66 MAC U-joint and Support Beam

The support beam is positioned at the center of gravity, C.G., of the gun system which allows for a more balanced gun system. The azimuth bearing for the U-joint stand will be fastened to a strong static or mobile structure for support. In the case of this project it will be a static support structure for demonstration, testing, and display. The stand, displayed in Figure 69, is shown with the MAC attached. The static structure which the U-joint is fastened to is omitted and will be modified in order to mount the gun safely and securely.

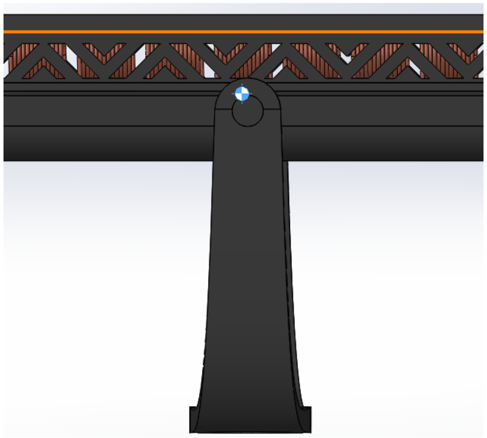


Figure 67 MAC Full U-joint with MAC Attached at CG

The static structure is already built and made of 2”x4” wood. It is a triangular mount with significant height in order to demonstrate the coilguns ease of use and movement. The mount can be adapted to fit applications as necessary. The stand was designed for strength for a previous use and will be sufficient to handle the weight of the coilgun and its support system. When the coilgun is needed for adaption to a Humvee or other position of full 360 degree view the specifications can be adapted to meet application needs.

The U-joint, like the packaging for the gun, will be 3-D printed ABS plastic which is both durable and strong enough to handle the stress the gun will put on the stand. Finite Element Analysis (FEA) was performed on the stand model with a constraint of 100 N of total force on the elevation bearing joints to confirm a realistic design safety factor of ~1.5 for the joint.

In Figure 70 the FEA analysis for the stand can be found. Displacement and factor of safety was analyzed. The software also takes into account Von Mises stress at major joints. Since there is not a concern for major stress at the ball bearing joints in preliminary studies, Von Mises stress was omitted from the analysis. When a more concise stress analysis is needed Von Mises stress will be taken into account. Table 26 summarizes the important numbers recovered from the FEA study.

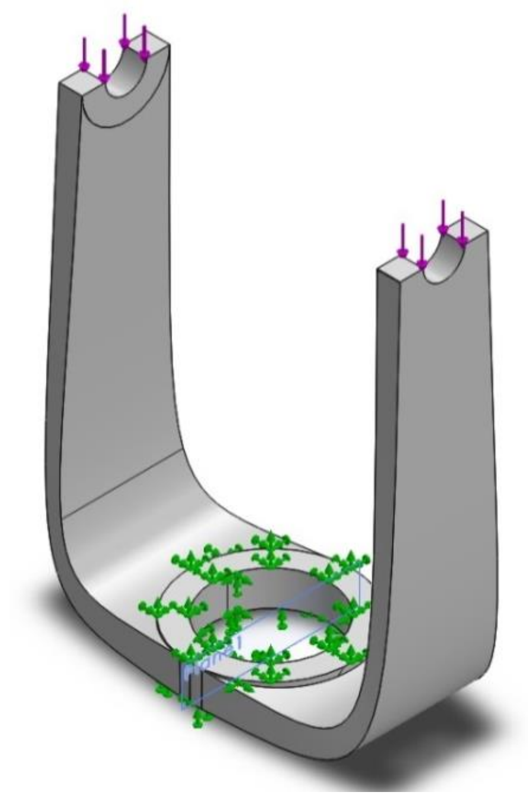


Figure 68 Initial Fixture and Force Points for MAC U-joint FEA. Force is colored purple, Fixture points are in green.

Table 27 FEA Simulation Results

Material		Displacement	Factor of Safety
ABS Plastic	Minimum	0 mm	1.312
	Maximum	0.505 mm	1.651

The above simulation results show that the preliminary design of the U-joint passes the required parameters that were imposed on the design. As it can be seen the factor of safety is within 20% of the desired value of 1.5. This is an acceptable result for a preliminary study. The displacement of the U-joint arms is at a maximum of 0.5mm. This is also acceptable and results in an acceptable preliminary mount. The FEA performed confirms the desired results and can be approved for use as the primary mount for the MAC provided unnecessary stresses are not experienced by the coilgun.

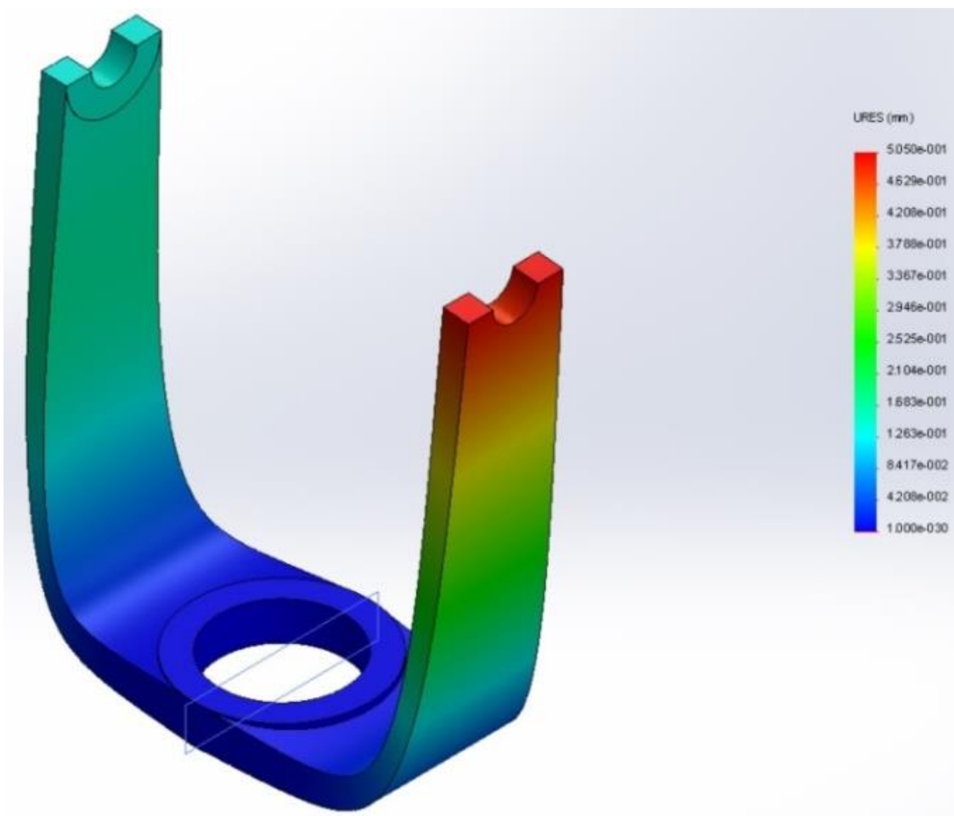


Figure 69 Displacement analysis. Red signifies maximum displacement. Blue is zero displacement.

5.0 Design Summary of Hardware and Software

The following sections will cover the explicit design summary for the Magnetic Accelerator Cannon. It will feature schematics, part lists, diagrams, and major system summaries. There will be five major sections that will be covered. The first system to be covered will be the power supply for the MAC, next the energy storage system, then the control and user interface, the barrel, and last the packaging.

5.1 Power Supply

As discussed in previous sections (3.2.1 AC to DC Power Supply, 3.3.5 Power Supply, and 4.2 Power Supply), the power supply system is summarized in the block diagram in Figure 70.

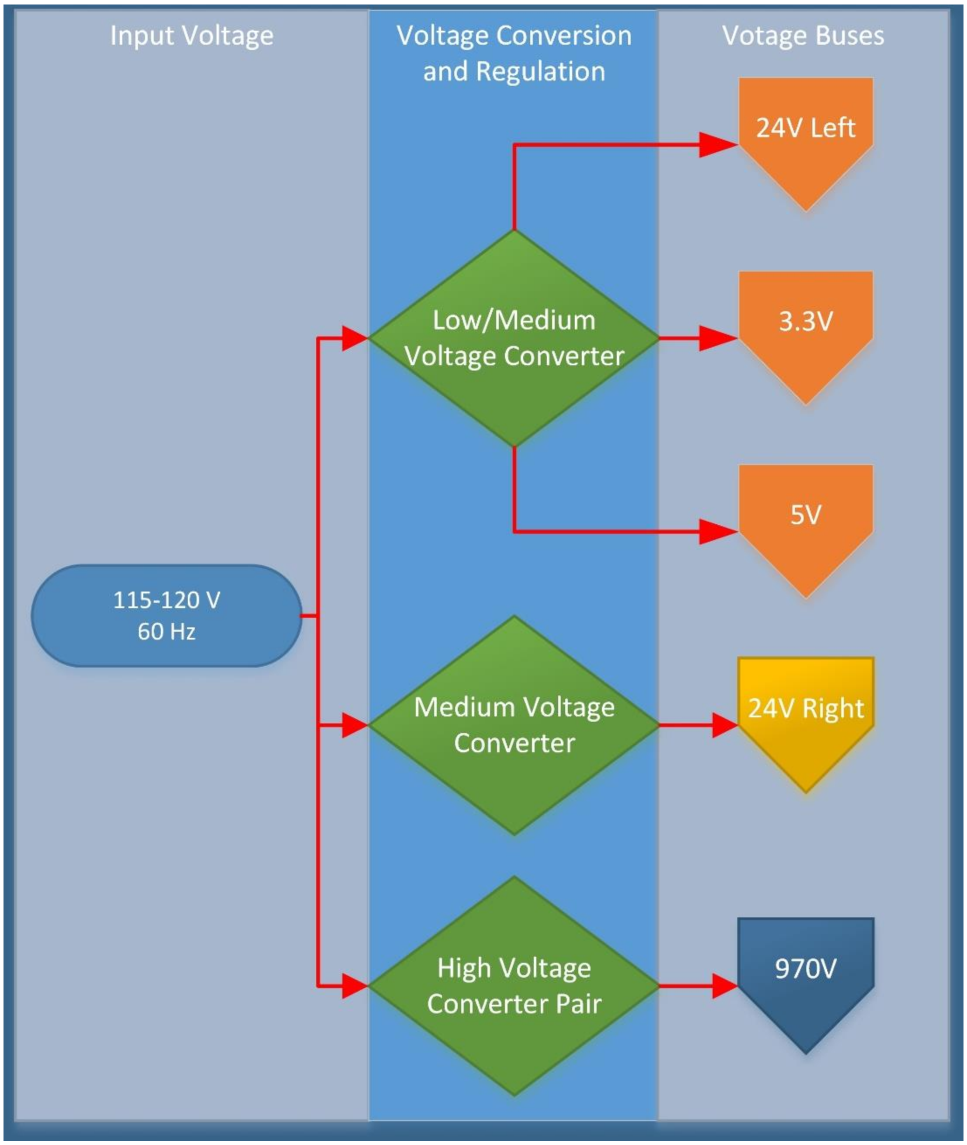


Figure 70 Power System Block Diagram

The schematic of the power system can be seen in the following figure, Figure 71. The power system has two different constraints to meet. Charge the capacitor bank to the required voltage of 1000 V, and to provide power to the microcontroller (3.6 V), the UI screen (5 V), the 24V switch control circuits for odd and even coils. It was determined that a maximum amp pull from the 120 V 60 Hz wall outlet would not exceed 30 A. With this in mind, 14 AWG wire was utilized to connect from the wall to the transformer. A primary switch was used to pass current and apply voltage to the MAC. This toggle switch is rated to withstand the maximum amperage that will be experienced in the power supply circuit. To reduce cost, an external power supply was utilized to power the UI controller and screen. This was determined to be the most cost efficient direction to take with controller power supply.

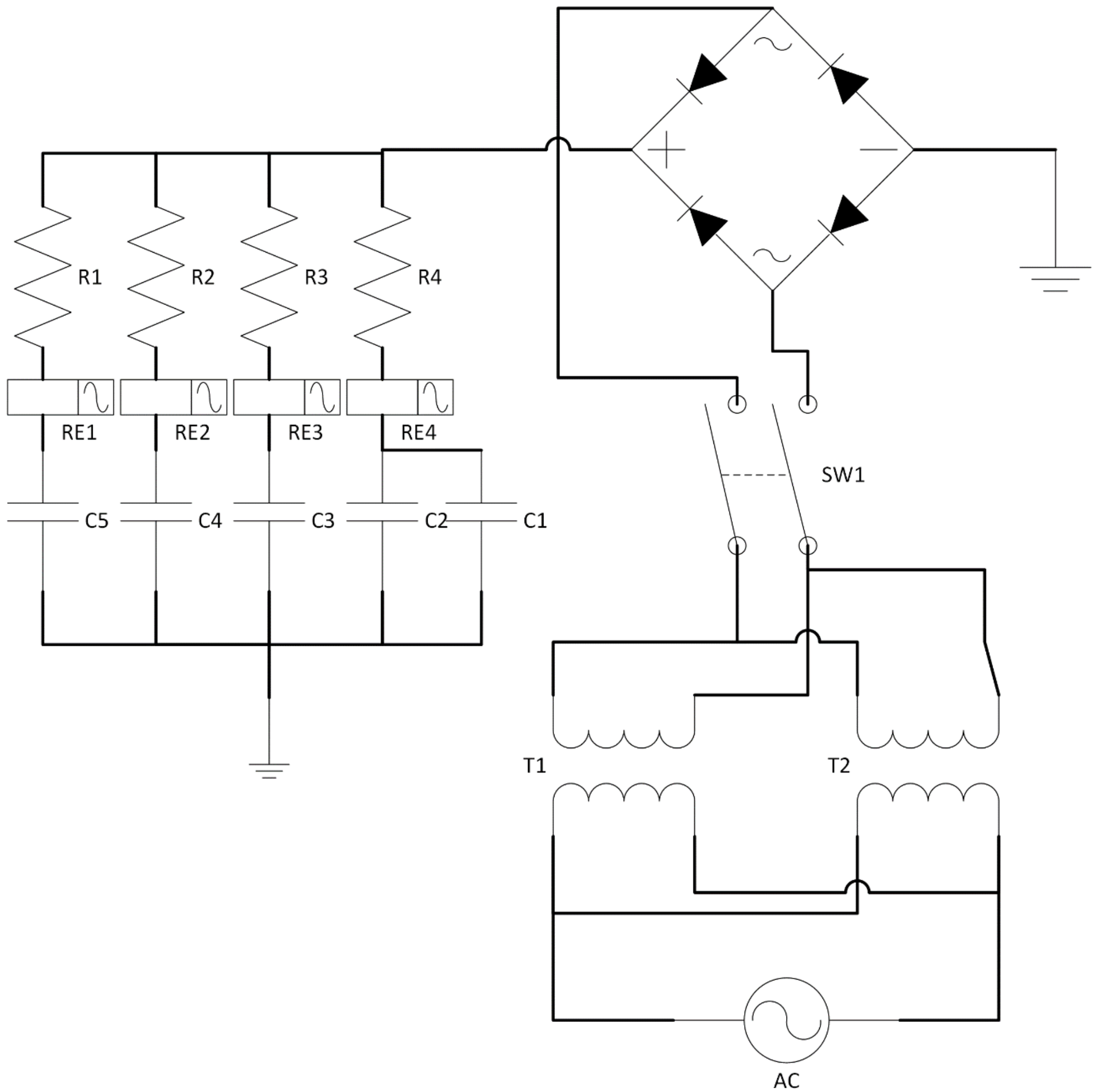


Figure 71 Power Supply Schematic for Capacitor Charging

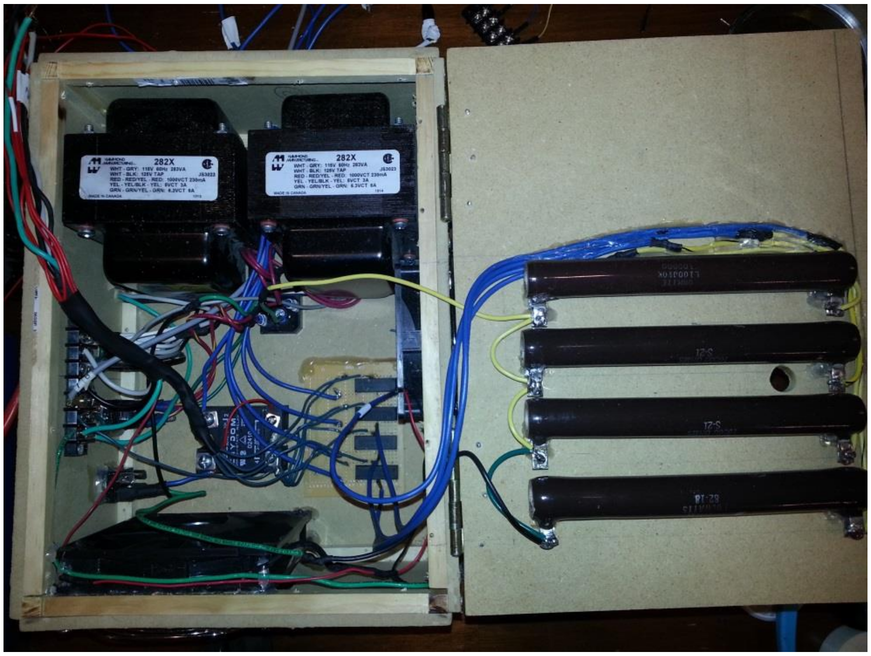


Figure 72 Power Supply Box

When charging from a standard 120v wall outlet, a transformer steps up the voltage and a bridge rectifier converts the alternating current to direct current. This allows the capacitor bank to charge quickly through a bank of 100W charge resistors. An external voltmeter was mounted to the final design to monitor capacitor charge while charging and in fire mode. Knowing how much charge is stored in the capacitors is necessary for proper firing and safety around the device. Relays between capacitors will allow discharging certain coils and allowing for quicker charging of the capacitors if some is depleted. When dealing with this much power, cost of components is a big factor. Since no expense could be spared on the capacitor bank and armature, building the power supply to a budget was important. Most of the components in the power supply were chosen for their cost as well as usability.

Table 28 Power System Part List

Component	Value	Supplier	Unit Cost	Quantity	Total Cost
Bridge Rectifier	1200 V, 35 A	Digikey	$2	1	$2
Transformer	1020V	Digikey	$140	2	$280
Charge Resistors	10KΩ	Skycraft	$7	4	$28
Switch	Toggle	Home Depot	$6	3	$18
Power Supply	200 W	Skycraft	$8	1	$8
Wire	14 AWG	Skycraft	$2/ft.	6	$12
TOTAL				17	**$**348

5.2 Energy Storage

The intermediate media for storing energy between the external power supplies before delivering energy to the coils were selected to be capacitors. A total of 5 capacitors were used. Each pair of stages shares a single capacitor, with the exception of the first two stages, which will share the same capacitor. This was chosen instead of using one bank for all coils, or using multiple capacitors per coil to reduce the resistance, ESR, internal to the capacitor. The capacitors and wiring interfaces were found to be the most resistive elements in each stage's circuit.

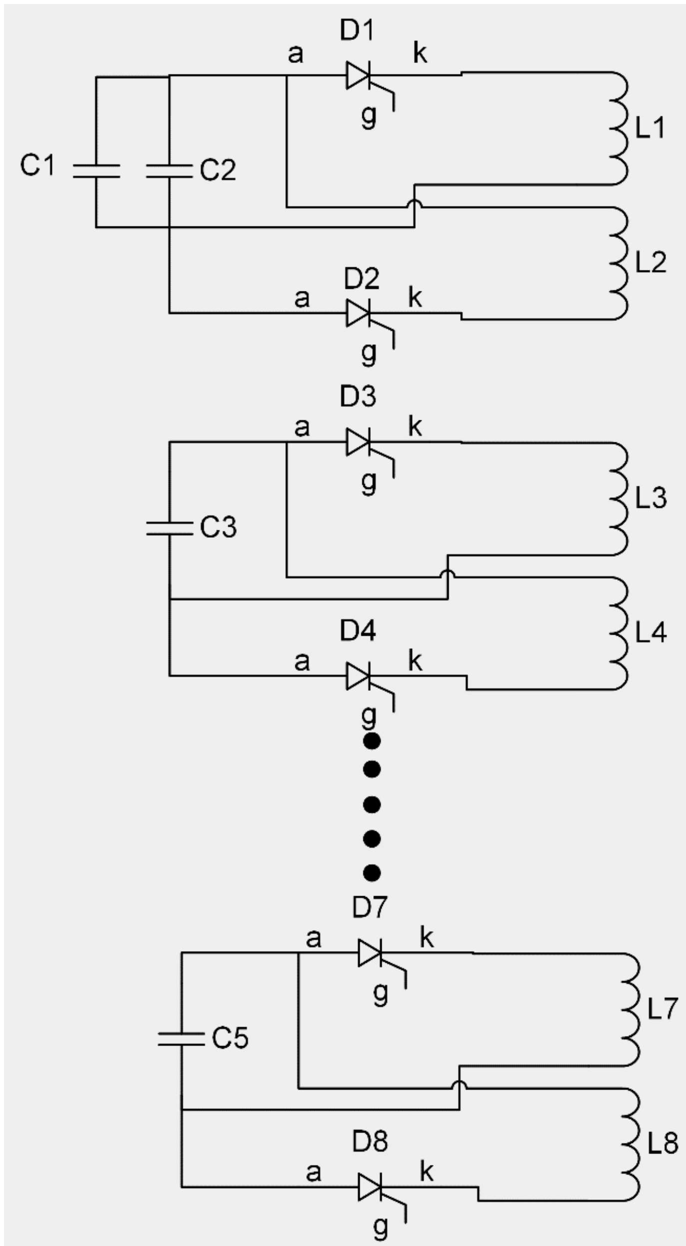


Figure 73 Condensed Capacitor Circuit for the Stator Stages

The capacitance values were selected with the prime objective of making the current pulse width equal to the time required for each stage as specified in section 4.6.2.2.

Table 29 Final Capacitor Part List

Component	Value	Supplier	Unit Cost	Quantity	Total Cost
970 uF Capacitor	970 uF	Digikey	$114.62	5	$573.10
TOTAL				5	

The RLC responses for each stage were calculated by taking into account the selected capacitor values determined by the corresponding computed inductance, and circuit resistance values. These values were then simulated using a purpose made Matlab simulation. This simulation doesn't take into account the effect of the projectile due to its complexity in calculation, but is appropriate to gauge the effectiveness of the selected components, and the corresponding pulse times. The results obtained from the Matlab simulation for the final capacitors chosen are shown below:.

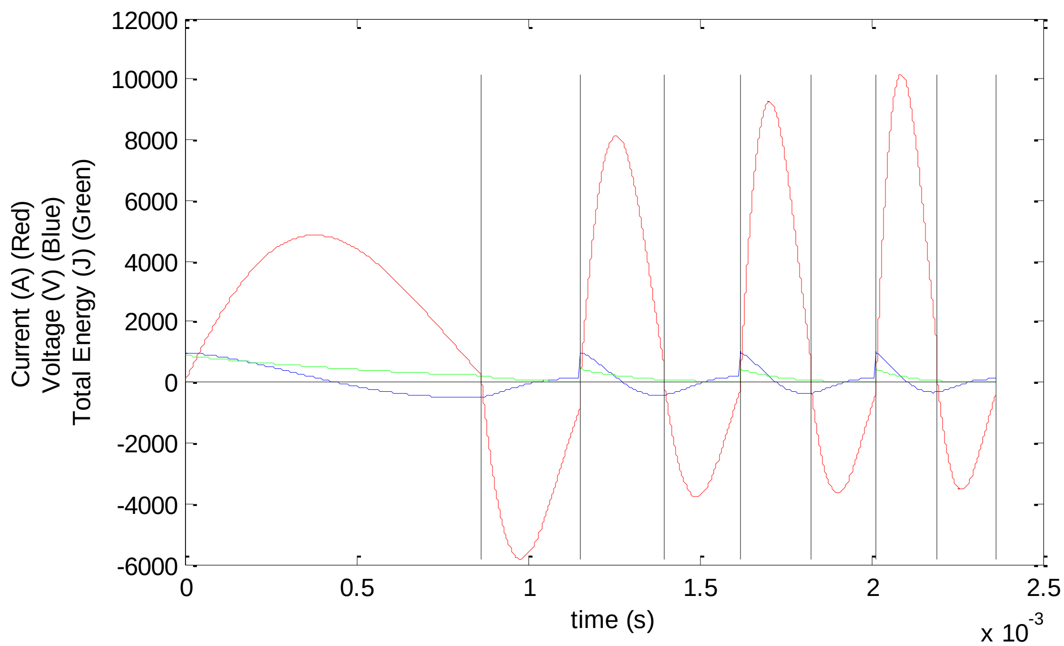


Figure 74 Final Design Response

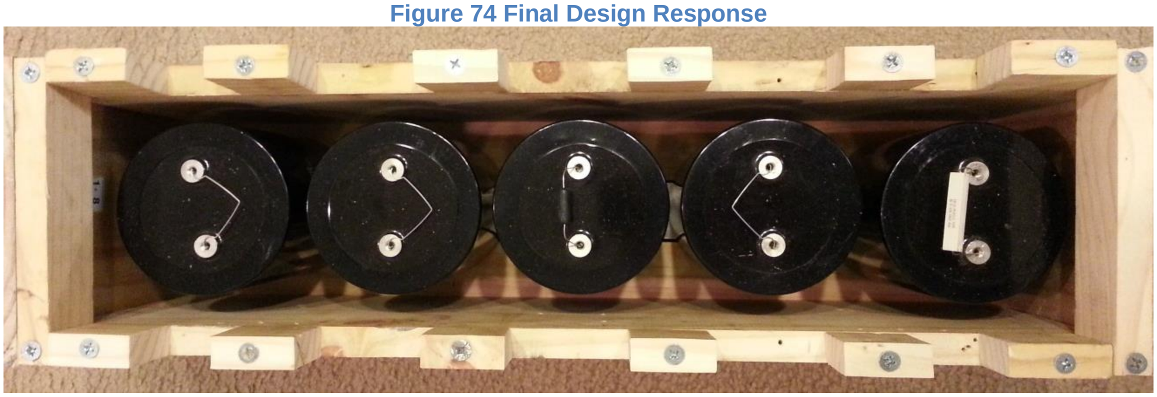


Figure 75 Capacitor Bank. 5 capacitors Top down view.

Figure 76 Capacitor Bank Iso-View

5.3 Control and UI

User interface and controls are two of the most important parts of the coilgun. Without them, the user would not be able to even operate the MAC. A switch will either turn the coilgun on or off. Once on, the user interface LCD screen, which will be mounted on behind the auto loader, will display the main menu. The main menu can be seen in Figure 74.

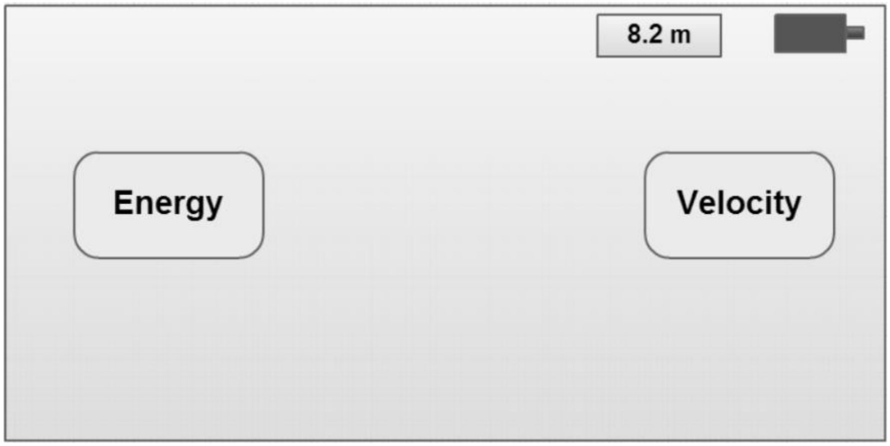


Figure 77 User Interface Main Menu

The main menu will display live real-time footage of the target the coilgun is aimed at downrange. Imposed on the footage of the downrange target the capacitor charge level and the distance to target will be shown. Due to a limitation in the laser ranging, the current version of the targeting system will be able to give accurate range information up to 9 m or 30 ft. downrange.

The user will have two options for MAC operation. The first option will be the muzzle energy mode. In this mode the user will have the choice of between a list of energy levels. Each energy level will have a number of stators attached to it. When the number is selected the preselected stages will energize and launch the projectile to the specified muzzle energy. The second option the user can make is the muzzle velocity mode. In this mode the desired muzzle velocity can be selected from a list of values. Each value has a coil referenced. When the command to fire is enacted from the trigger, the coils, which will achieve that muzzle velocity, will be energized and the projectile will be launched. After the launch sequence is completed in whichever mode is selected the menu will show the number of shots remaining at that selected mode based on the capacitor charge level. The input from the photo sensors will provide information on the bullet's velocities to the user via the LCD screen. The following diagram in Figure 75 will display the CPU flowchart which will be followed within the software in the controller.

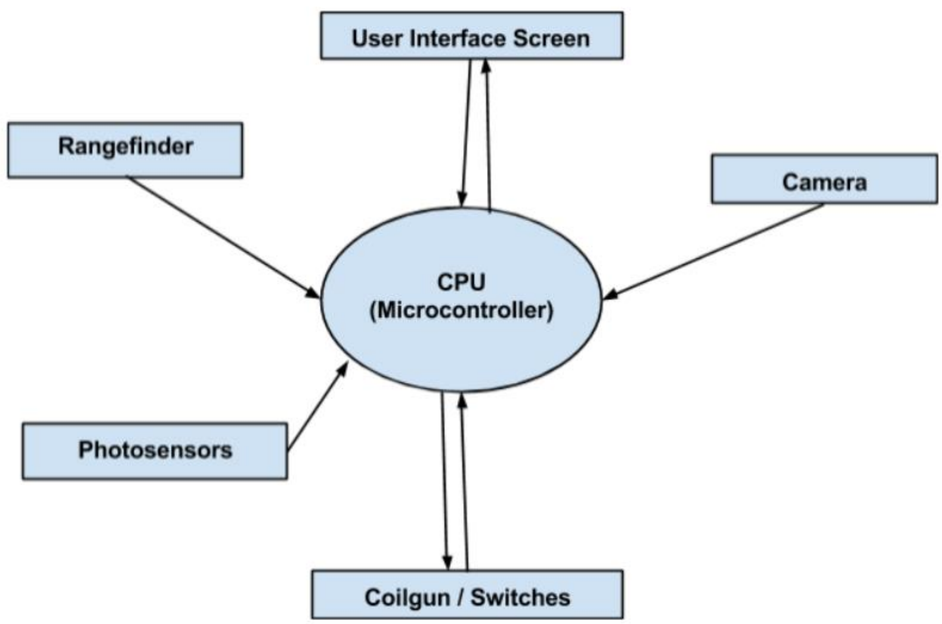


Figure 78 CPU Flowchart for use with the UI

The user interface itself will be developed through the C programming language. It will be developed to be a graphical user interface, allowing interaction from the user. The IDE that will be used will be Code Composer Studio. This specific IDE was chosen for its compatibility with ARM Cortex-M3 based microcontrollers, such as the LPC1769 microcontroller which was chosen for the MAC. Table 30 will display the part list for the control and UI system. This includes the thyristor switches needed in the stator circuits. The assembled PCB for the MAC can be seen in figure 76.

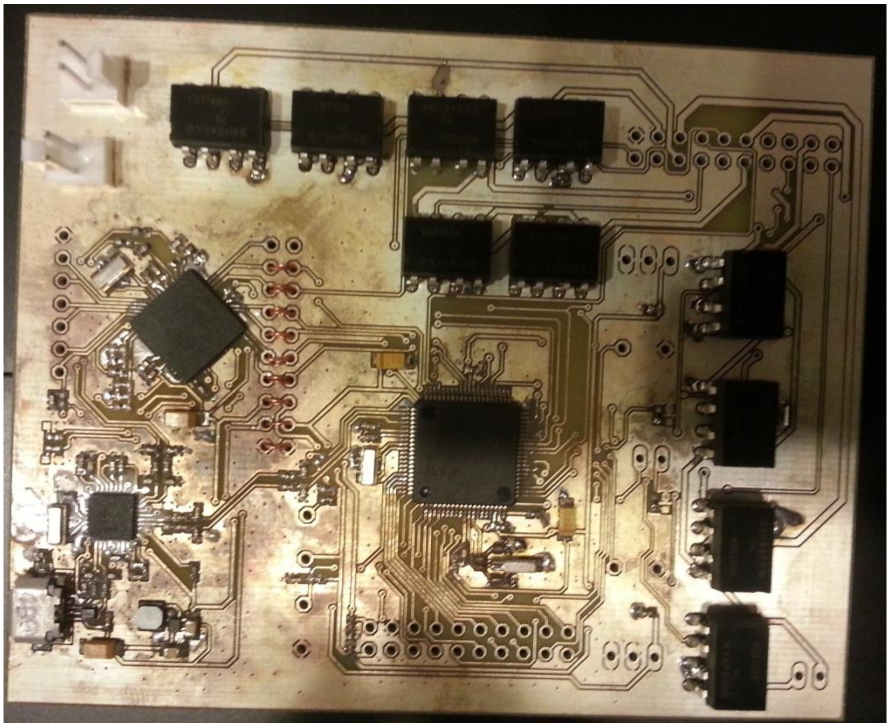


Figure 79 PCB assembled by QMS. Contains the microcontroller and Optoisolator for firing.

Table 30 Control System Parts List with Budget

Component	Supplier	Unit Cost	Quantity	Total Cost
Thyristor	Mouser	$155	10	$1,550
Optoisolator	Digi-Key	$1	10	$14
Photointeruptor	Digi-Key	$6	10	$60
LCD Screen	Digi-Key	$105	1	$105
Rangefinder	Lightware Optoelectronics	$100	1	$100
Microcontroller	Future Electronics	$9	1	$9
Molex Connector	Digi-Key	$6	1	$6
Camera	-	$0	1	$0
Sockets	Various	$5	4	$20
Microcontroller Board	-	$24	1	$24
USB Cable	-	$0	1	$0
I2C Cable	-	$4	1	$4
TOTAL			**42**	**$1892**

5.4 Barrel

The barrel was designed to provide structure to the stator coil circuits. The stator coil circuits were designed using the RLC responses which were simulated in the

Matlab environment. The simulation provided the necessary coil inductances that would be required to operate the coilgun at the most optimal state. Each stator will have the same dimensions. Each will be 3cm in length and have a bore diameter of 1.9 cm. These basic dimensions, derived from the projectile design in section 4.6.1, provided the requirements necessary to compute the turns in each coil that would achieve the required inductances. The coil inductances would range from 0.61 uH to 11.18 uH of which each will have its own number of turns and/or layers to achieve the inductance values. Table 31, 32, and 33 summarize the inductor values which were designed and the properties which each inductor will have.

The barrel will also contain the energy storage components, also known as the capacitors for this design architecture. These components will be ideally positioned in the under barrel of the coilgun. This area of space under the barrel was designed to hold each stator circuit in order to minimize resistive losses due to long wire lengths. This space is meant for the switches as well as the wiring for the whole coilgun.

Table 31 Stator Coil Basic Parameters

Dimensions / Parameters	Value	Unit
Wire Gauge	11	AWG
Coil Length	3.002	cm
Bore Diameter	1.900	cm
Bore Diameter + Wire Diameter (11 AWG)	2.13	cm
Stator Gap	1.000	cm
Outer Diameter	Variable per stator	cm
Inductance	$L_{coil} > 0.5$	uH

Table 32 Multi-layer Stator Defining Properties

Stage	L uH	N	$\frac{N}{layer}$	Layers	Outer Diameter (cm)	Wire Diameter (mm)	Wire Length (m)
1	11.18	32	12.75	2.51	3.31	2.35	2.27
2	1.92	16	12.75	1.25	2.84	2.35	0.99
3	2.33	17	12.75	1.33	2.84	2.35	1.07
4	2.02	16	12.75	1.25	2.84	2.35	0.99
5	1.92	16	12.75	1.25	2.84	2.35	0.99

Table 33 Single-layer Stator Defining Properties

Stage	L (uH)	N	$\frac{N}{layer}$	Layers	Wire Length (cm)	Wire Diameter (mm)	Wire Length (m)
6	1.57	11.755	N/A	1	79.004	2.35	0.790
7	1.33	10.819	N/A	1	72.715	2.35	0.727
8	1.15	10.060	N/A	1	67.615	2.35	0.676
9	1.02	9.475	N/A	1	63.679	2.35	0.636
10	0.61	7.327	N/A	1	49.245	2.35	0.492

Testing will be performed to determine if there will be interference in the switching circuits from the electromagnetic interactions produced by the high current pulses in each transmission wire. This will also apply to the wires connecting the sensor network to the controller and the controller circuits behind the projectile loader. Table 33 will list the parts necessary for the coils and their associated cost.

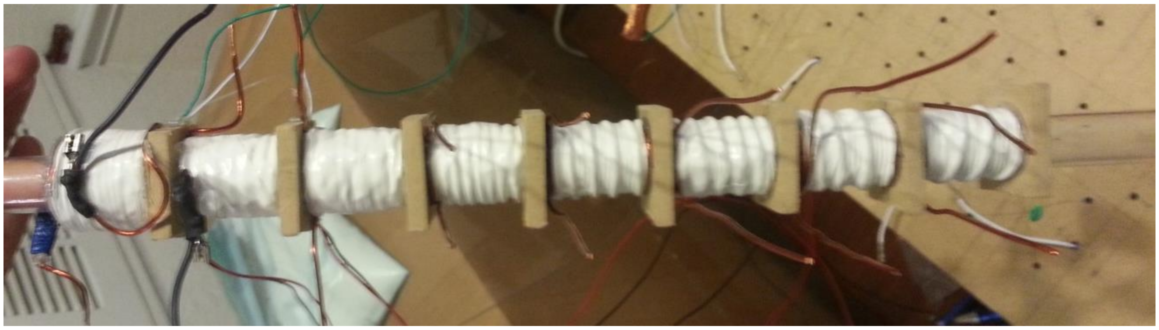


Figure 80 Barrel with eight stages

Table 34 Barrel Part List and Budget

Component	Value	Supplier	Unit Cost	Quantity	Total Cost
Magnet Wire	14 AWG; 40 ft.	TEMCo	$12.75	2	$25.50
Insulation Resin	4 oz.	TEMCo	$20.00	2	$40
Homemade Coil Winder	-	Owned material	0	1	0
Wood	-	Owned	$0	Unknown total	$0
Ball Bearings	-	Owned	$0	3	$0
Servo Motor	-	Owned	$0	1	$0
TOTAL				**9**	**$65.50**

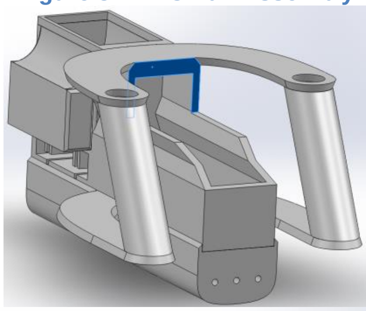
5.5 Packaging

The Packaging of the MAC will encase all the previous systems developed. Preliminary designs for the packaging of the MAC are shown in Figures 76, 77, 78, and 79. These views are shown to paint a full picture of the concept form of the MAC.

Initially the main goal of the packaging was to construct it completely of ABS plastic using a 3-D printer. ABS is a versatile material that adds rigidity and excellent electrical isolation. This will assist in the isolation of the high power currents which will be experienced in the stator circuits during projectile excitation. The bulk of the MAC structure would of consisted of ABS plastic and would of allowed for easy integration of components at the designed locations. But due to cost and access to a 3-D printed the initial design could not be constructed. With future revisions and designs a smaller form factor utilizing ABS plastic could be utilized.

The final packaging design was constructed and designed out of wood materials. This provided the necessary robustness that was needed for the big components in the whole system. The current version can be seen in Figure___ below. This is the final overall prototype design that was constructed. As it can be seen the design is very different from the concept design. This is due to the sheer size of the capacitors and power system which consist of 70% of the whole system weight and size. The barrel, as it can be seen is a very small part of the whole system. With optimizations to the size of the components a more robust smaller form factor can be designed.

Figure 81 MAC Full Assembly



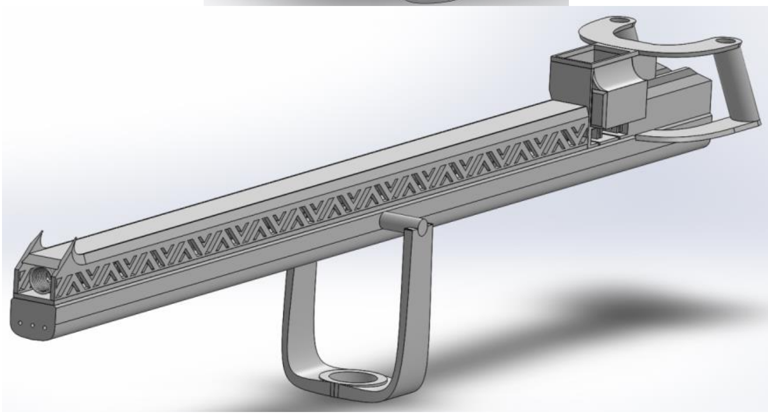


Figure 82 MAC Control and Projectile Loader.

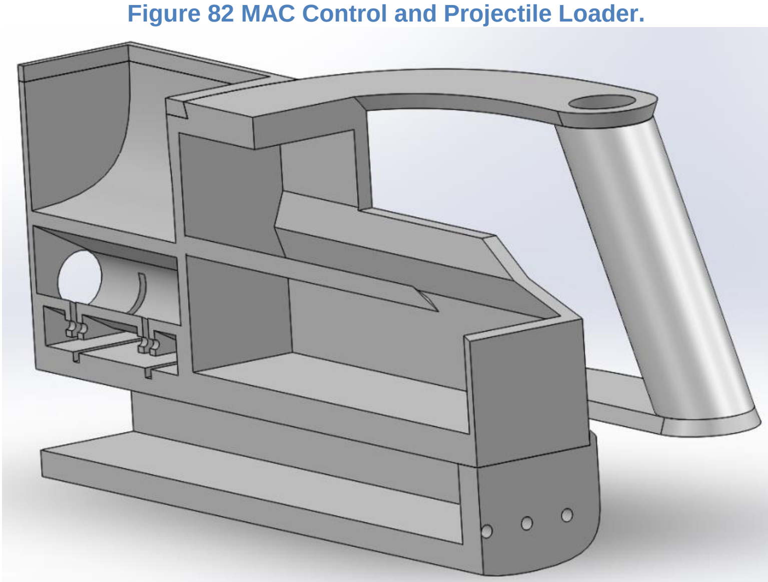


Figure 83 MAC Control and Projectile Loader Cut Away

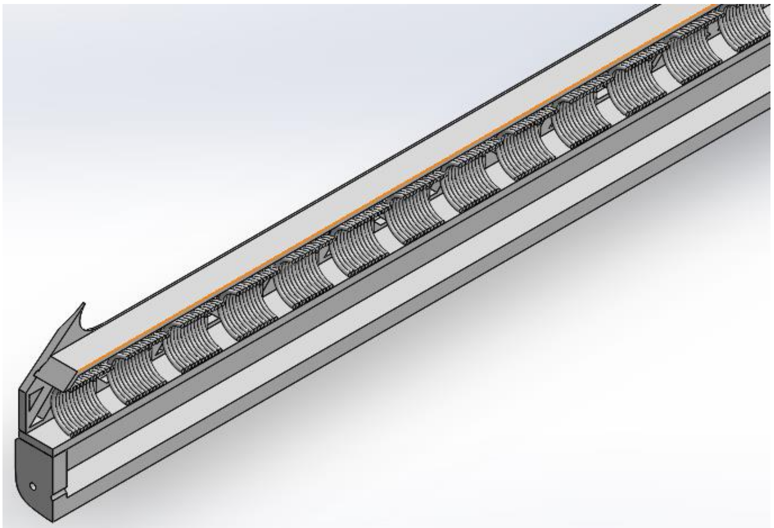


Figure 84 Barrel Section View With Under Barrel Wire Deck

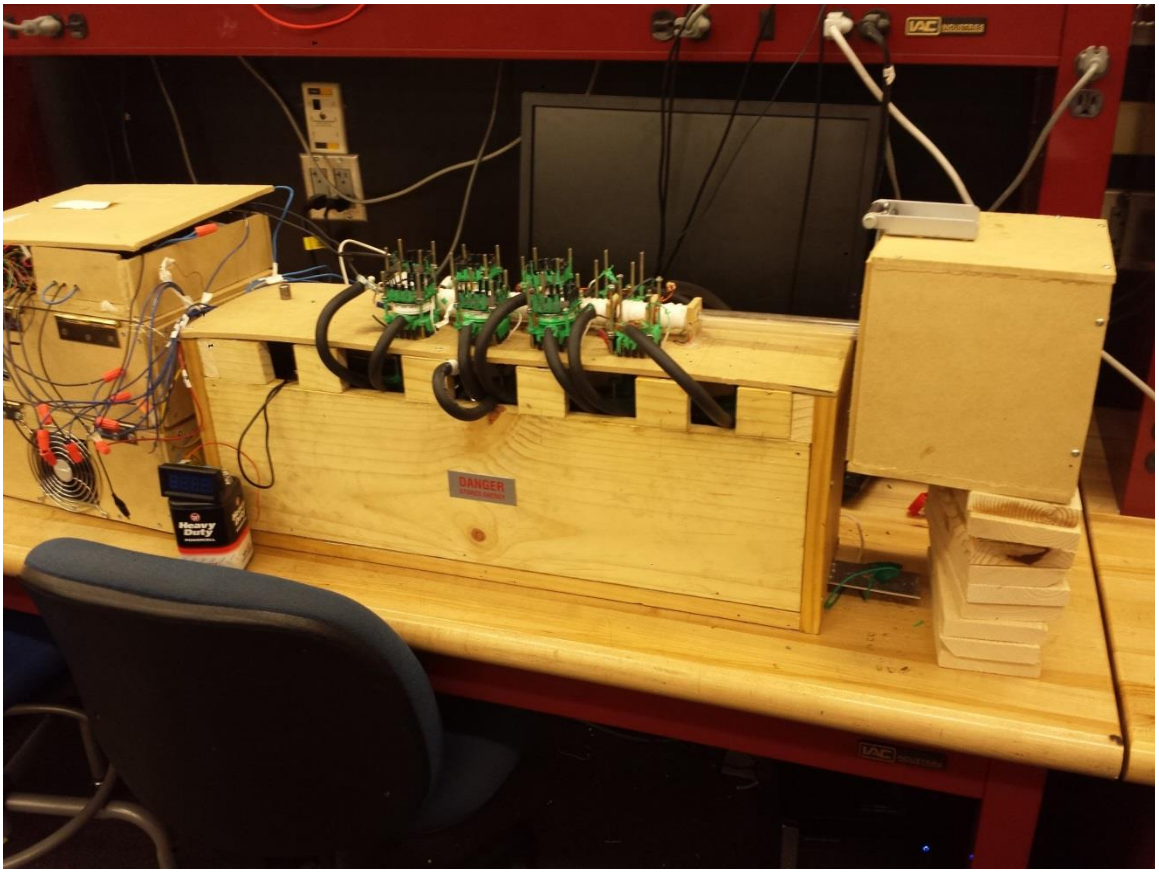


Figure 85 Final Design of the Full Packaging

6.0 Project Prototype Construction and Coding

In order to properly construct the design for the MAC, which was determined in the preceding sections, each system must be assembled and constructed properly and efficiently. The following sections will describe the process and needed equipment to accomplish the design which was produced in this documentation. The sections will cover software through hardware in each respective system.

6.1 Software

The MAC system features a full User Interface for operation of the system. Software is a necessary utility in the use of the software and the computations which are needed to be accomplished in order to operate the MAC and enable proper launch sequencing. In the following sections the user interface and launce sequence designs will be described. Flowcharts will be included for clarity and ease of understanding. The operations of the coilgun will not be simple to implement. Programming and use of a microprocessor is needed to accomplish the goals which were set for this project.

6.1.1 UI Coding Plan

The user interface of the coilgun will be programmed in C via the Code Composer Studio IDE for its compatibility with the microcontroller being used. It will be written in a easy to follow method while maintaining a clear path between different menus a user would utilize.

main():

The 'main' function is a standard for any C-language program. It is where the program's local variables are located, and it is also where the program remains while being executed. Execution in the coilgun will take place as long as the ON switch is enabled. The interface screen will be on by this switch as well. When the coilgun is switched to standby the program will exit 'main' and will not be executed until the coilgun is switched out of standby.

menu():

The 'menu' function will represent the main menu of the user interface screen, and will be the first thing that a user will interact with. The 'menu' function will display battery level and target range on the top right. There will be a choice for the user. Either a list of energy levels or a list of velocities which the coilgun operates will be the two options for a user. In the background of the display screen live footage of the range and target will be shown. The footage will come from an external camera. The footage will be implemented in all functions. Choosing either of the two options will lead to two different paths. If 'Energy' is chosen, the path will then lead to the 'energy' function. Otherwise, choosing the 'Velocity' option will yield a path that leads to the 'velocity' function.

energy():

If the user chooses 'Energy', the 'energy' function will then be the next function following 'menu'. Like the 'menu' function, the 'energy' function will display the target range, battery level, and live footage of the direction the coilgun is facing on the user interface screen. Also, choosing 'Energy' will cause the user interface screen to display the word 'Energy' on the top left corner. Another difference between the 'energy' and 'menu' functions is that instead of asking the user to choose between two different options, there will be twenty five different options to scroll through. Each represents a different energy level in Joules. These energy levels will be represented in the code as variables, starting with e1 through e25. If the user wishes to return to the main menu, there will be an option on the bottom of the user interface screen to return to the main menu. Doing so will call the menu() function, reverting back to the original function that was displayed on the user interface screen. Once the desired amount of energy is chosen, the program will move to the final function of both paths, the fire() function.

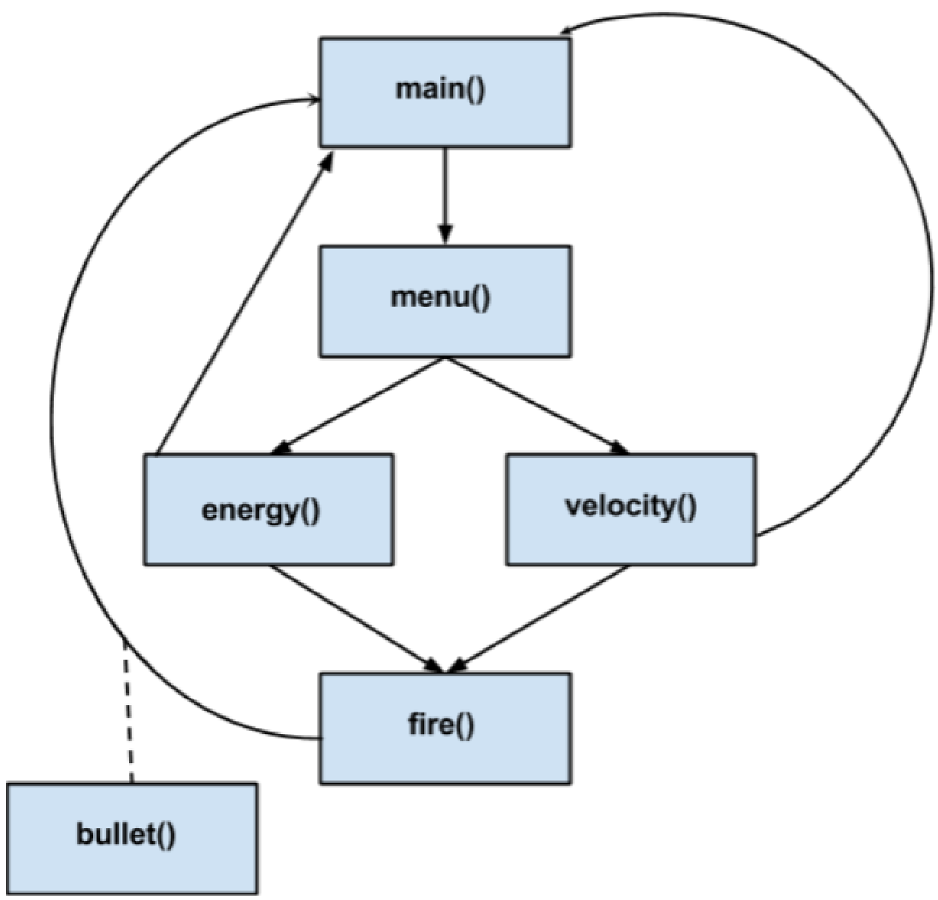


Figure 86 Coding Flowchart

velocity():

If the user chooses 'Velocity', the 'velocity' function will then be the next function following 'menu'. The 'velocity' function is very similar to the 'energy' function in that they both display the target range, battery level, and live footage of the direction the coilgun is facing on the user interface screen. They both also offer the user twenty five different options to scroll through and choose. And there is an option on the bottom of the user interface screen to return to the main menu too, which will call the menu() function and revert back to the original function that was displayed on the user interface screen. However, instead of the word ‘Energy’ on the top left corner of the user interface screen, the word ‘Velocity’ will be displayed. Also, while the twenty five different options in the ‘energy’ function represent different energy levels, the options in the ‘velocity’ function represent different velocities (in m/s). Just as the energy levels in the ‘energy’ function were represented by variables, so will the velocities in the ‘velocity’ function, labeled v1 through v25. Once the desired velocity is chosen, the program will move to the final function of both paths, the fire() function.

fire():

The final function in the two paths previously discussed. Like the ‘energy’ and ‘velocity’ functions before it, the ‘fire’ function also includes the target range, battery charge level, live footage of the direction the coilgun is facing, as well as on option to return to the main menu. However, unlike the ‘input’ function, the user either chooses the only option available (which is ‘Fire’), or return to the main menu. Once the ‘Fire’ option is chosen, the ‘menu’ function is called, and the user interface screen returns to the main menu.

bullet():

An additional function included after the ‘fire’ function ends. The ‘bullet’ function Is called whenever the ‘fire’ function calls the ‘menu’ function after it ends. The ‘bullet’ function basically displays a message over the main menu, indicating how many bullets are left in the coilgun. In addition to displaying the remaining bullets based on capacitor bank charge, the message includes a selection labeled ‘OK’, which if chosen, ends the ‘bullet’ function.

6.1.2 Launch Sequence Coding Plan

Once the fire() function is called, all other processes are suspended for the up to 10ms that it would take for the firing sequence to complete in the lowest speed setting. The process of the firing sequence is as follows: First the velocity is measured from the sensor. Then the kinetic energy can be calculated from the velocity. If the kinetic energy is above or at the selected firing energy, then the firing sequence is complete. If it isn't then the adjusted timing is used to activate the next coil. This cycle continues until the last coil is fired, or if the kinetic energy target has been reached. Once the firing sequence is done, the normal operations in the microcontroller can resume. The launch sequence will coded in C and will follow the flow chart in Figure 83.

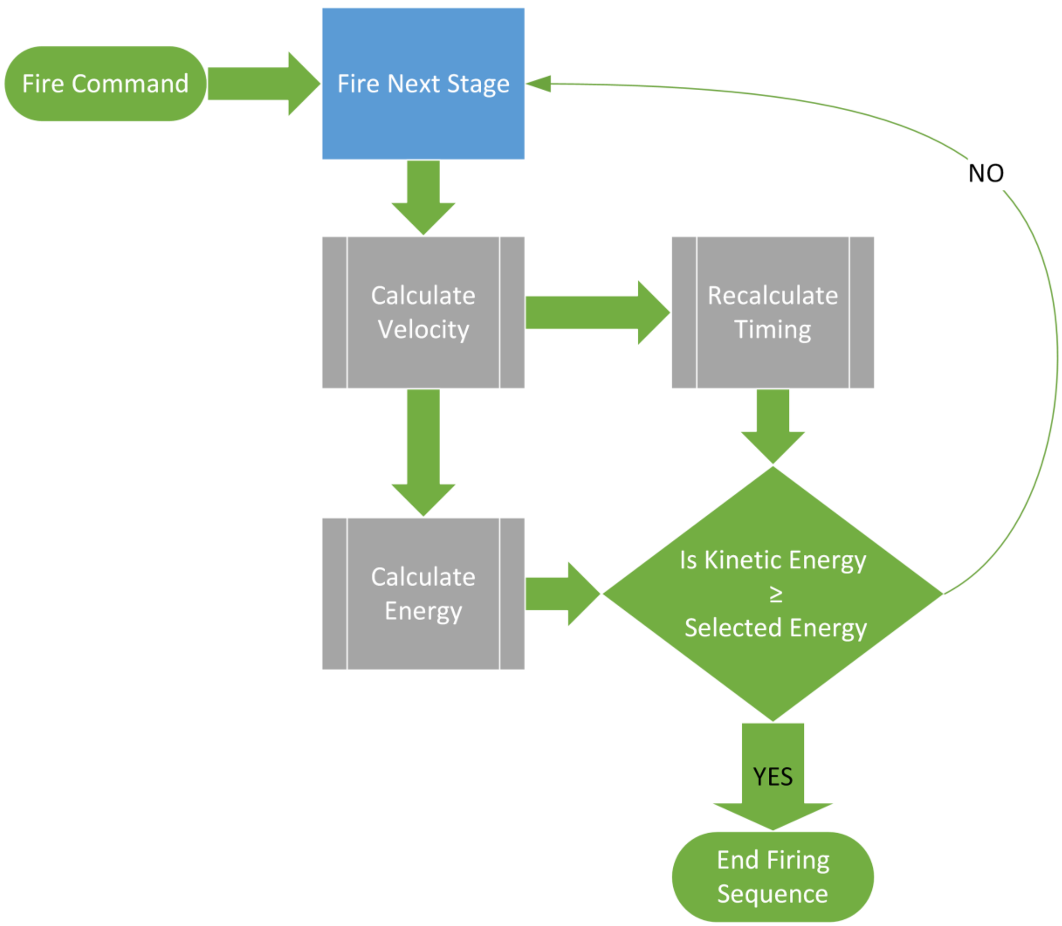


Figure 87 Launch Sequence Flowchart and Process

The number of cycles it takes to execute each part of the firing algorithm will be measured. If the computation time exceeds the amount of time it would take for the projectile to reach the optimal position for coil activation, then further optimizations will be needed. If helpful for increasing performance, specific blocks will be programmed in assembly. Lookup tables may be used instead of calculations for the timing offsets to decrease the launch sequence's processing time.

6.2 Hardware

The following sections will highlight the hardware that will be utilized in the construction of the MAC prototype for testing. Each major hardware component is listed and described how it will be integrated into the prototype design of the MAC. There are many methods of construction for each component and will be investigated thoroughly to determine the most efficient method for the MAC system.

6.2.1 Capacitor Bank

The electrical connections from each capacitor into its respective coil, as well as indications of the connection of the control lines are illustrated in Figure 30. Capacitors will be mounted along the underside of the barrel in a separate compartment close to its matching coil in order to minimize losses during transmission. A conductive plate that joins the coil to the capacitors will be mounted into the case. The capacitors' screw terminals will mount to said terminal. These same terminals will be used to fasten the capacitors to the rest of the MAC.

6.2.2 Power Supply

The power supply consists of a low voltage supply and a separate high voltage system used to power the onboard controller. With the materials available boxed were created out of wood with ventilation to house the power supply, power supply switching, and charge resistors. This box would be mounted to the back of the MAC system to power the system up. In Figure 84 an image of the completed box is shown. The top box houses the switching circuit power supplies along with the microcontroller UI supply. This is the box where most of the circuit interfacing will be done due to the switching lines and positioning sensor lines.

Due to the size and power constraints of the system, a PCB was counterproductive to the design of the system. The components of the power supply also contributed to the lack of use for a PCB in the power system. The possibility of high voltage discharge was high and could lead to catastrophic failure of the entire coilgun system. Due to voltage being reversed in the capacitors during firing, the power supply needed to be turned off during the entire firing process. The final capacitor charging schematic can be seen here, Figure 85. The following Images depict the final design of the MAC power supply.

Figure 88 MAC Power System Modular Boxes

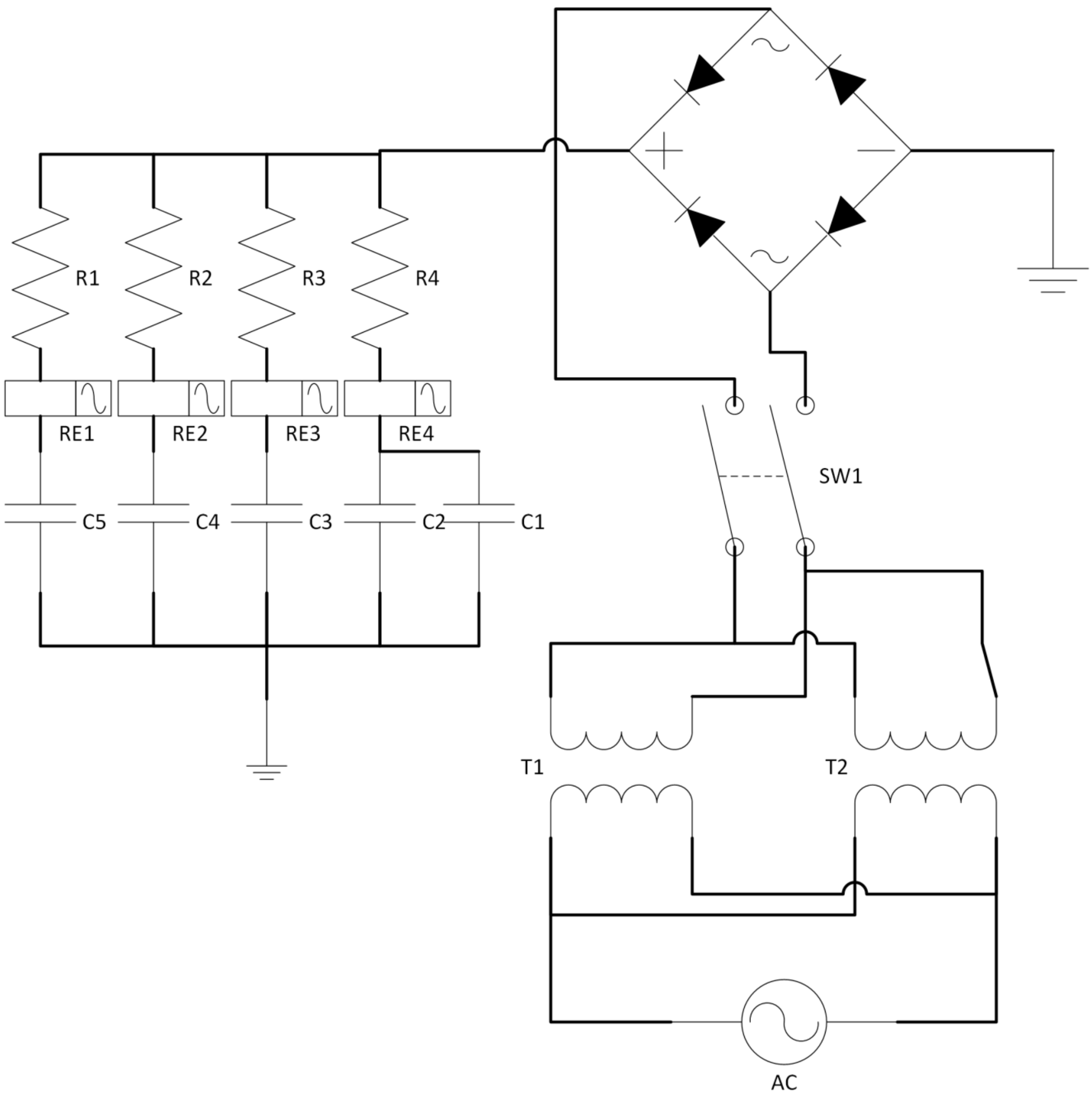


Figure 89 Capacitor Charging Circuit

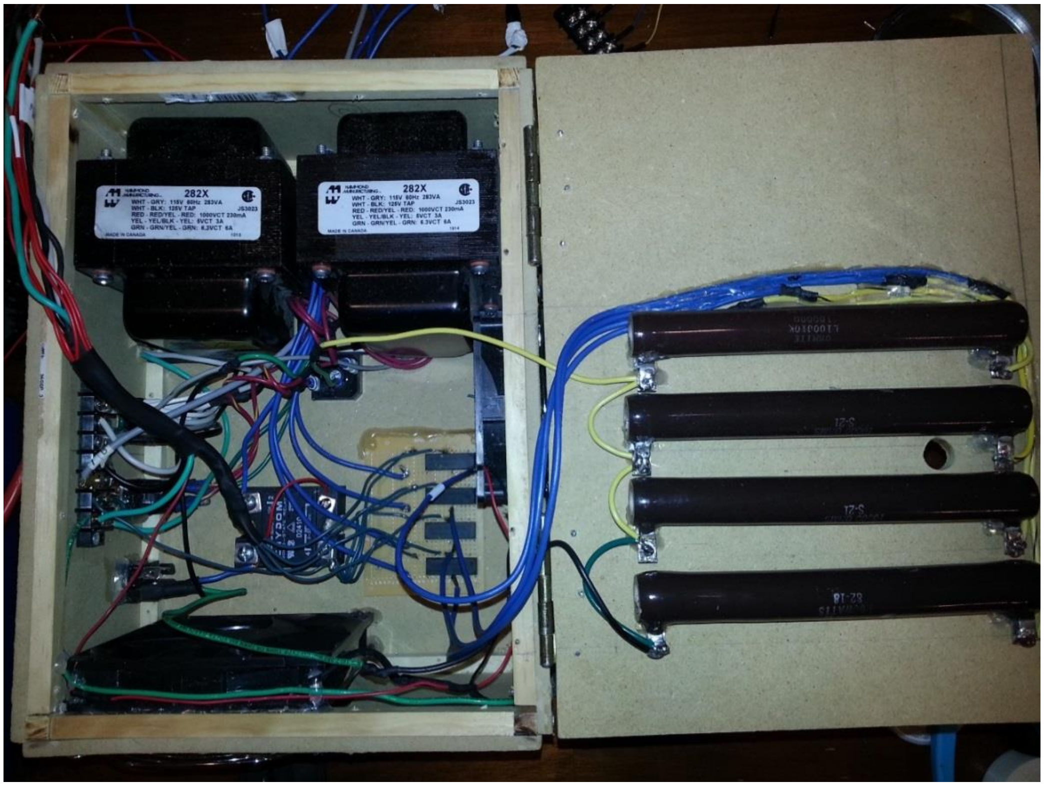


Figure 85 Capacitor Charging box

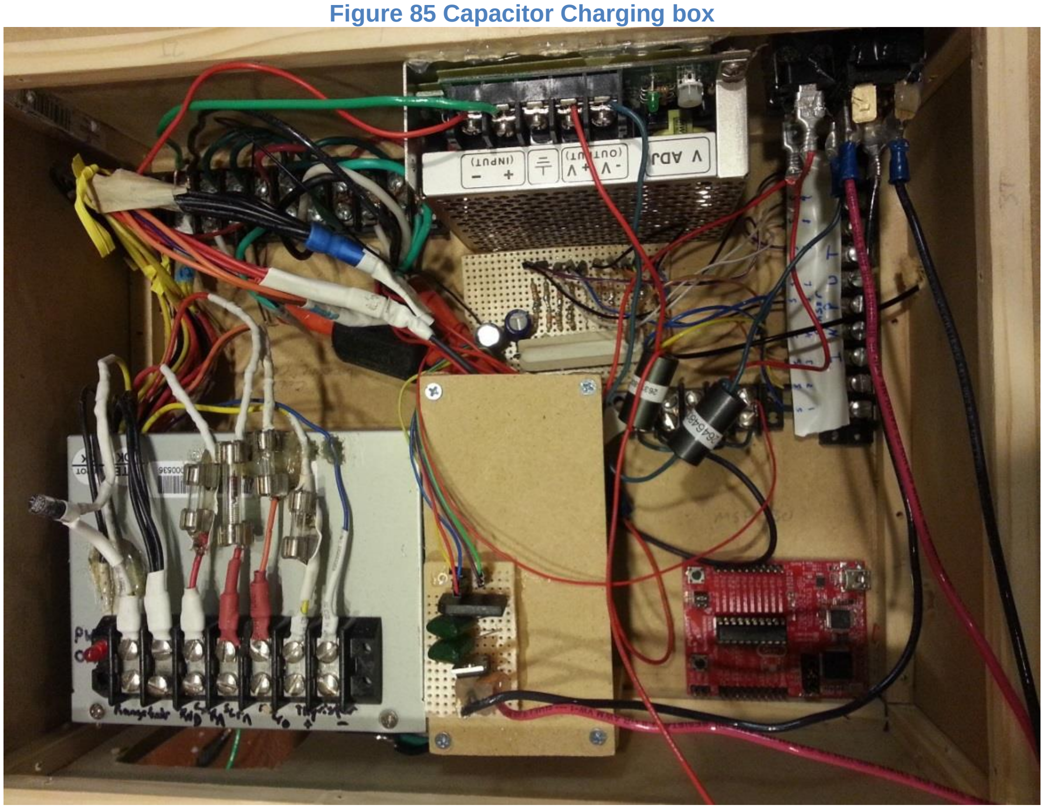


Figure 86 User interface supply box

6.2.4 Coil Winding

There will be eight different coils in the MAC system, which will all be multilayer coils. To get the inductances that were determined for each stator circuit, each coil has to be wound perfectly. If a winding is not correct, different inductances can occur, which produce unfavorable results in the LC circuit of each coil stage. In order to accurately wind the stators to spec as indicated in Table 34 and 35 a manual winder mmwas constructed out of wood, bolts, and washers.

Table 35 Multi-layer Stator Coils

Stage	L uH	N	$\frac{N}{layer}$	Layers	Outer Diameter (cm)	Wire Diameter (mm)	Wire Length (m)
1	11.18	32	12.75	2.51	3.31	2.35	2.27
2	1.92	16	12.75	1.25	2.84	2.35	0.99
3	2.33	17	12.75	1.33	2.84	2.35	1.07
4	2.02	16	12.75	1.25	2.84	2.35	0.99
5	1.92	16	12.75	1.25	2.84	2.35	0.99

Table 36 Single-layer Stator Coils

Stage	L (uH)	N	$\frac{N}{layer}$	Layers	Wire Length (cm)	Wire Diameter (mm)	Wire Length (m)
6	1.57	11.755	N/A	1	79.004	2.35	0.790
7	1.33	10.819	N/A	1	72.715	2.35	0.727
8	1.15	10.060	N/A	1	67.615	2.35	0.676
9	1.02	9.475	N/A	1	63.679	2.35	0.636
10	0.61	7.327	N/A	1	49.245	2.35	0.492

A homemade winder was constructed to develop the eight coils needed for the eight stages of the coilgun system. A 5/8th bolt and 5/8th iron tube, which was cut to length, was used to wind the coils. Using washers the coils could be confined to makeshift bobbins in order to make the multilayered coils that were desired. Hot glue was also used to keep winding in place while the coil was being made. This substance allowed for near perfect coils to be wound and it also allowed for easier disassembly if the coil encountered a problem. In Figure 89 the coil winder that was built can be seen. In Figure 89 the bolt-tube-washer-nut system can also be seen which was utilized to make the coils.

Figure 90 Home Made Coil Winder

6.2.5 Coil Mounting

The coils will be mounted on acrylic tubing of ¾" diameter. This tubing will assist in serving as a full barrel but also mounting for the position sensors and coils. Acrylic is a strong material and can handle the stresses which the stages will be putting on the barrel. This also allows for easy assembly of the full system since each stage will be made individually after another has been tested. The tube as seen in figure__ provides the support each stage needs to be held in place and not allowed to move.

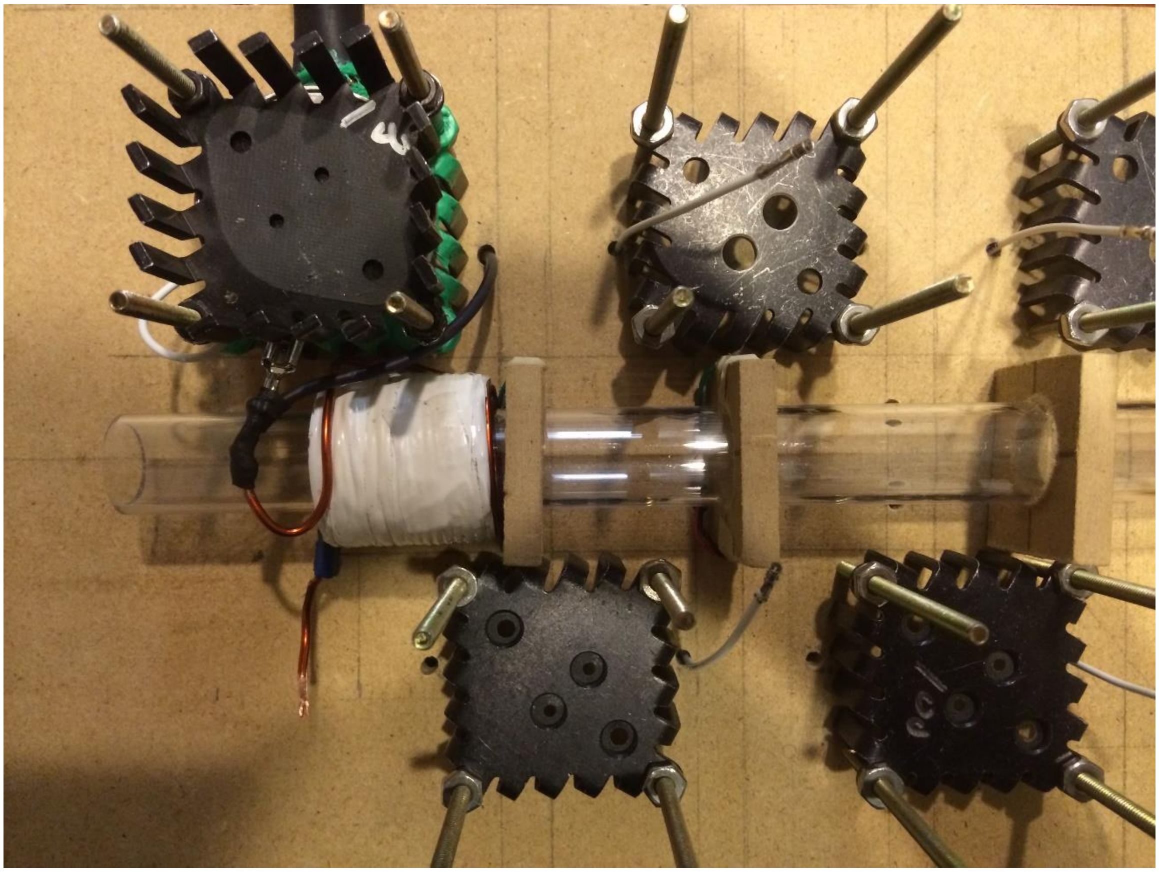


Figure 91 1st Stage Coil Mounted on the Acrylic Barrel. Thyristors are to either side.

6.2.6 Sensor Mounting

The sensors as mentioned in section 4.4.1 will be utilized as depicted in Figures 42 and 43. Due to the fact that the barrel, where the sensor will be mounted, is 3-D printed the sensors will be easy to mount in the walls in between each stator stage. The sensors will be implemented and integrated seamlessly into the barrel of the coilgun. This will be one of the final steps in the prototype construction of the MAC. Each sensor will require tuning in the timing it takes for the signal to reach the switch control and switch control to send an actuating signal to each thyristor switch in each stator circuit.

6.2.7 Projectile Manufacturing

As mentioned in previous sections, 3-D printing technology will be utilized for prototyping the MAC. This will be similar in the projectile construction of the MAC system. As mentioned in section 4.6.1 a sheath will be used to enclose the solid metal projectile in an aerodynamic casing. This casing can be easily manufactured and modified to suit the needs of the MAC system. The sheath is a casing, therefore, it will be printed in two halves. In Figure 86 half the sheath is shown with a fully assembled version of the sheath side by side. A Dimension st1200 3-D will be utilized to print many projectile sheaths for use and testing. An initial batch would be required to start testing.

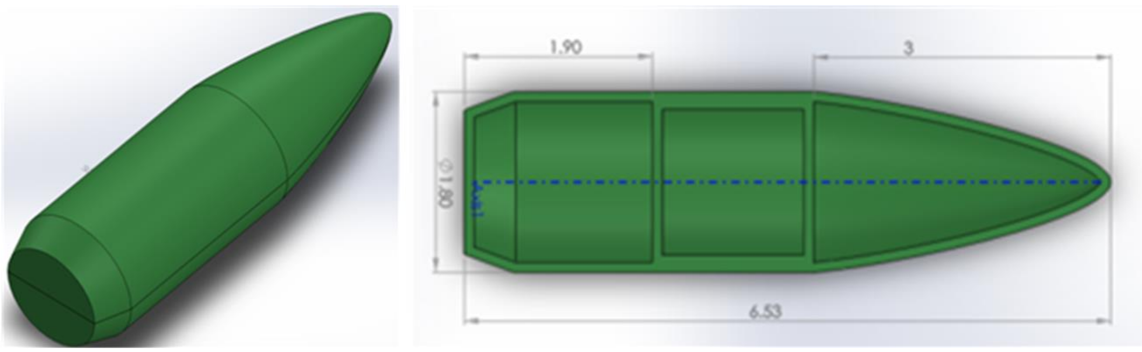


Figure 92 Projectile Sheath in Full Assembly and Half Assembled

6.2.8 Projectile Loader

The Magnetic Accelerator Cannon utilize a projectile loader to bring rapid shot reload times to the system. A servo with three arms will be implemented in the projectile loader that has been designed below Figure 87. This servo will allow only one projectile in the chamber as the gun is fired. When a signal is sent from the controller to the servo during recharge times a new projectile will be loaded into the breach. This servo will be mounted internally and under the rectangular outcrop of the design shown below. As with most of the structural components of the MAC system a 3-D printer will be utilized to print out the projectile loader with the dimensions specified by the projectile. If errors are made in the design it is possible to manufacture a new prototype piece for the projectile loader. This applies to damaged structural components as well.

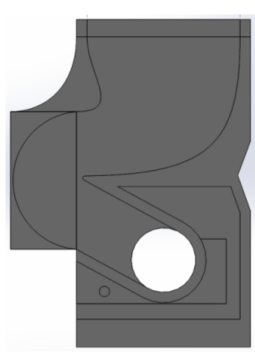


Figure 93 Projectile Loader which Features a Hopper

7.0 Project Prototype Testing

This project will require a lot of testing to achieve the results determined in the simulations which were performed in the Matlab coding environment. Efficiency is very important in the MAC system and will be closely matched with proper testing and tuning as will be mentioned below. Safety is a concern in the operation of the MAC. High voltages are achieved and high currents are utilized. This can be hazardous and can be deadly to the operator. Safety is covered thoroughly to ensure safe reliable operation of all the MAC's sub-systems.

7.1 Safety

The Magnetic Accelerator Cannon will be capable of launching relatively massive projectiles at very high velocities. Because of this, similar precautions and use habits familiar to firearms users will be employed. Among these precautions, "The Four Rules" of firearms safety are applicable to the MAC:

"The Four Rules"

1. Treat the firearm as if it's charged and loaded at all times--even when it is known not to be.
2. Never point the muzzle at anything you aren't willing to destroy
3. Keep your finger off the trigger until you're ready to fire
4. Be sure of the target and what is beyond it

Almost all negligent discharge has happened when it was assumed that the device was not loaded or ready to fire. Always assuming that the device is lethal is an additional barrier that protects the user and those around him or her. Care will be taken to not allow the muzzle to covering anything that that is fragile or alive. Keeping trigger finger off the trigger until just before firing is another safeguard against accidental firing. Any involuntary movement or fall can cause the finger to trigger the firing mechanism at the wrong time. The MAC will always be mounted in a fashion where there will be a sturdy backstop so that the projectile cannot penetrate through it. All operators will be instructed of these rules before use.

To reduce the risk of accidental discharge, a bright yellow highlighter will be placed inside the loading chamber in a manner that is visible from the outside of the MAC so that it is clear when the MAC has no projectile in the chamber as well as serving as a stop for any projectiles to be unknowingly loaded. Also, the capacitor bank will remain discharged at all times, except right before firing.

In addition to its desired kinetic output characteristics, the MAC's circuitry has voltages up to 500V that are known to be within the range where dielectric breakdown of the human skin occurs. This provides a potential shocking hazard if these parts are handled improperly. Part of the design of the overall packaging of the MAC involves isolating these potentially dangerous electrical terminals from the end user. However, such finished product casings will not be present during the assembly and testing phase, and these will be exposed to special care will be taken in handling high voltage components. To safely discharge the bank during the testing phase, a circuit of three incandescent light bulbs connected in series is the ideal sink for the stored energy (3.1.2).

Another safety point to consider when assembling testing and operating the MAC is the rangefinder's laser. The OSLRF-01 rangefinder emits laser radiation at a wavelength of 850 nm, which is known to be harmful to the human eye. As with any laser, no one should look directly at the laser beam. Proper warning labels will be placed near the laser emitter indicating of such hazard. The previous precautions of not having individuals downrange from the MAC's muzzle are doubly important because of the possible eye damage from the laser radiation.

7.1.1 Location

Until the MAC's final maximum output velocity is known, all full power firings will occur outdoors in a yet to be determined open field with the projectile sink immediately in front of the barrel. Once the maximum velocity is known to a high degree of confidence, and it is determined to be safe for indoor use, then testing can continue in indoor environments. If not, then safety will take priority at the expense of convenience and testing will continue outdoors.

7.1.2 Individual Coil Tuning

The amount of energy transfer from the coil to the projectile falls within a wide range of values. As a result, only an approximate estimation of the acceleration and other kinematic behaviors is known at present. For a stage to be turned on at the time where energy transfer efficiency will be maximized, the projectiles velocity and position must be known with a much greater degree of precision than current known modeling predicts. The control system needs to make timing adjustments in a microsecond scale, so the highest accuracy and precision values must be known. Also because of the energy transfer from inductor to projectile, the current predicted pulse width will most likely be shortened by a magnitude uncertain with analytical analysis.

In addition to helping make timing better, testing components one at a time will allow other problems in design and assembly to be identified quickly and prevent such errors into cascading into the assembled prototypes and final products. For each coil, the following steps will be taken: First, each stage's coil will be constructed to the specifications laid out in section 4.6.2.3 using the process described in 6.2.3. That stage's sensor will be mounted at the correct placement in front of that stage's coil. The sensor is then connected to the prototype controller where the actual velocity and energy amounts added to the projectile can be measured. Also, oscilloscope probes will be connected across the capacitor bank to measure the time response of the RLC harmonic. Depending on the oscilloscope used, the high voltage measured may need to be scaled by an external circuit. From the measured speed/energy and harmonic behavior, analysis can be done to determine if and how the coil and capacitor bank can adjusted be to compensate for shortened pulse due to transfer into kinetic energy. Each stage will be tested in the aforementioned fashion both individually, and with the next and previous stages positioned to account and measure the effects of the coil-to-coil inductance that will be present in the final product. As necessary, adjustments will be made stage by stage as the MAC is fully assembled. Once assembly is complete, a good deal of data about the individual effects of each stage will be known. These will be used to guide any additional adjustments to the pulse enabling sequence timing.

7.2 Projectile Sink

The projectile sink will essentially be the testing target for the MAC coilgun during calibration and range testing. This will be used for tuning, test firing, and demonstration uses. Since this piece of equipment will be utilized in varying cases it must be designed to withstand a beating from the projectiles being launched. The design is simple. The sink will be a box made of wood and thick plexiglass. Inside the sink will be sand and there will be a platform rising from the center of the box. This platform will hold the target which the coil gun will be aimed at. This target will be determined at a later date and will consist of many different materials.

The materials can range from wood to metal. It would be essential to test the coilgun against all types of objects which are appropriate. This sink will be utilized for all testing purposes and demonstrations. Until the coilgun is calibrated, one of the sides (designated as the normal to gun face) will be put right up against the coilgun muzzle. This provides safety in that the projectile will be enclosed in the sink the second it is fired. It is not necessary to move the projectile sink away from the muzzle of the coilgun until it is properly calibrated. Then range tasting with the sink can be performed. Since this item is not a major component that affects the design of the MAC it will be fully designed at a later date

7.4 Range Testing

In order to test out the coilgun's rangefinder; a range test will need to be implemented. The range testing will check if the coilgun's rangefinder can accurately detect the range from the gun to the target. Since the rangefinder his a range of 9 meters, nine different ranges will be used for the test, one for each increment of a meter. Each test will involve three parts. First part will involve making sure that whatever range is listed on the user interface matches the current testing distance between the coilgun and the target. Second art would make sure that (with the correct range) the coilgun shoots the object without any issues. The final part of a test would simply check if there are any additional errors with the coilgun at all. Once all three parts are cleared for all nine tests, it would mean that the rangefinder is getting the range accurately as intended, and thus making the coilgun itself accurate as it should.

Testing Procedure for Each Test

1. Position the target X-meters away from the muzzle of the coilgun

2. Ensure safety procedures are being followed
3. Connect the coilgun to a power source
4. Switch the M.A.C on
5. Go through the appropriate UI menus to get to use the Velocity/Energy mode
6. Position the target in the crosshairs of the camera
7. Confirm the range from the laser range finder on the targeting screen
8. Clear the range of non-essential personnel
9. Check capacitor charge, and wait for banks to charge if needed
10. Fire the MAC
11. Allow the coilgun to recharge
12. Repeat procedure for every meter from 1 to 9 m

Table 37 Range Testing Test Rubric

Test	Is the Range displayed Correctly?	Does the Coilgun Fire Correctly	Were There Any Errors?	Description
1	Yes / No	Yes / No	Yes / No	
2	Yes / No	Yes / No	Yes / No	
3	Yes / No	Yes / No	Yes / No	
4	Yes / No	Yes / No	Yes / No	
5	Yes / No	Yes / No	Yes / No	
6	Yes / No	Yes / No	Yes / No	
7	Yes / No	Yes / No	Yes / No	
8	Yes / No	Yes / No	Yes / No	
9	Yes / No	Yes / No	Yes / No	
10	Yes / No	Yes / No	Yes / No	

The table above will be used during range testing, with the only data to add being a ‘yes’ or ‘no’ for the different tests. In case a result from a test isn’t what was desired, troubleshooting will take place to pinpoint the cause of the error. If the range display on the user interface screen is not displaying the correct range, the distance between the coilgun and the object will be checked once more to see if it really is at the testing distance. If the distance between the coilgun and the object is indeed correct despite what’s displayed in the range display, then it could possibly be an error in the code that would need to be fixed as soon as possible.

If the coilgun didn’t shoot properly, then the issue may be as trivial as there being no more bullets, or could possibly be due to the fact that there is an error in the launch sequence code. Any other errors experienced during testing should be put through troubleshooting to pinpoint where the issue originated and to prevent further mistakes from happening again.

7.5 User Interface Testing

Testing the user interface involves making sure operating the user interface screen produces the desired results. When testing, four different tests will need to be taken, one for each user interface menu.

Test 1 (UI Main Menu) [for reference, please check Fig. xx the one for ui main]:

- -Is the battery displayed and showing the correct charge level? [Y/N]
- -Is the range displayed and showing the correct value? [Y/N]
- -Does the background display live footage from the camera? [Y/N]
- -Do the input buttons function in the menu correctly? [Y/N]
- -Are the options ‘Energy’ and ‘Velocity’ correctly displayed? [Y/N]
- -Does choosing the ‘Return to Main Menu’ option in other menus display the main menu as it was originally displayed? [Y/N]

Test 2 (Energy Menu) [for reference, please check Fig. xx the one for ui energy]:

- -Is the battery displayed and showing the correct charge level? [Y/N]
- -Is the range displayed and showing the correct value? [Y/N]
- -Does the background display live footage from the camera? [Y/N]
- -Do the input buttons function in the menu correctly? [Y/N]
- -Does choosing the ‘Energy’ option in the main menu open up the Energy Menu? [Y/N]
- -Is the word ‘Energy’ correctly displayed on the top left corner? [Y/N]
- -Are the 25 modes of energy displayed in numerical order? [Y/N]
- -Do the energy values listed match those in Fig. xx (ui energy figure)? [Y/N]

Test 3 (Velocity Menu) [for reference, please check Fig. xx the one for ui velocity]:

- -Is the battery displayed and showing the correct charge level? [Y/N]
- -Is the range displayed and showing the correct value? [Y/N]
- -Does the background display live footage from the camera? [Y/N]
- -Do the input buttons function in the menu correctly? [Y/N]
- -Does choosing the ‘Velocity’ option in the main menu open up the Velocity Menu? [Y/N]
- -Is the word ‘Velocity’ correctly displayed on the top left corner? [Y/N]
- -Are the 25 modes of velocity displayed in numerical order? [Y/N]
- -Do the velocity values listed match those in Fig. xx (ui velocity figure)? [Y/N]

Test 4 (Fire Menu) [for reference, please check Fig. xx the one for ui fire]:

- -Is the battery displayed and showing the correct charge level? [Y/N]
- -Is the range displayed and showing the correct value? [Y/N]
- -Does the background display live footage from the camera? [Y/N]
- -Do the input buttons function in the menu correctly? [Y/N]
- -Is the ‘Fire’ option correctly displayed? [Y/N]
- -Does choosing the ‘Return to Main Menu’ option in other menus display the main menu as it was originally displayed? [Y/N]
- -After firing the coil gun, is the main menu displayed with a message displaying the correct number of bullets along with an option listed as ‘OK’? [Y/N]

- -After firing the coil gun, does choosing 'OK' in the message over the main menu remove the message and display the main menu as it was originally displayed? [Y/N]

In the tests if 'Yes' was chosen for every question then that would indicate that the user interface is functioning as intended. Otherwise, there may be an issue with the user interface code, in which case debugging will have to be performed to find the root cause of the error.

7.6 Power and Charging

When operating the Magnetic Accelerator Cannon, there are initial procedures to follow before use. First, the user should be qualified to use the cannon;If not, then qualified personnel would need to be present. Ensure all electrical equipment is away from hazards that could lead to damage of the device or injury to the user. Assume that all wires are energized to high voltages. Never assume that a wire is safe to touch even if it's insulated. Ensure that all spectators are at a safe distance and are not in the test firing range. After all of these procedures are followed, the firing sequence can begin.

Procedures for Powering Up the MAC

1. Ensure that the initial procedures have been followed
2. Turn on MAC main power supply switch
3. Determine that everything is operating to spec.
4. Switch circuit loop switch to "charging circuit"
5. Switch on the negative capacitor line switch
6. Capacitor charge switch can now be turned on
7. Carefully watch the voltmeter until 900V is displayed, the capacitor charge switch can be turned to the off position after reaching this value.
8. Turn off the negative capacitor switch
9. Firing process can now be initiated as stated above in section 7.4
10. Turn on the negative capacitor switch
11. Switch circuit loop switch to "discharging circuit"
12. Wait for the voltmeter to read 0V and check all power circuits for damage, if none continue operation

Powering down the device is just as important as starting up the device. When the cannon is going to be stored, the user can switch on the discharge circuit to completely discharge the capacitors of all voltage. Once the capacitor's voltmeter reads zero, the cannon can be stored. As always, use caution when working near high power devices.

8.0 Administrative Content

The two sections below will describe the intended budget and timeline for the MAC project. These administrative requirements will be followed as closely as they can be. As it is well know the engineering process deviates heavily from proposed timelines and budgets due to realistic constraints and design flaws. The timeline will assume a margin of error and will utilize a 5% margin on deadlines and milestones.

8.1 Parts Lists and Budget

The budget for the MAC project will be split evenly between group members. Due to winnings of $2000 from a business pitch competition, and funding for $653 from The Boeing Company through UCF the balance for the project is set at $2653 to be allocated for the whole system. From this sum of money the group has determined that if the budget were to exceed the allocated funds, then each member would contribute equally to the remaining balance to be paid for parts and equipment. The next few tables will list the budget for the MAC project. A summary will be shown in Table 37 and each subsystem, Tables 38 to 42, will follow with its own budget table.

Table 38 MAC Budget Summary

Sub System	Cost
Power Supply	$93.00
Energy Storage	$458.00
Structure	$0
Control / Processing	$1,892.00
Acceleration System	$150.00
Total Cost	-$2,568.00
Allocated Funds	+$2,653.00
Balance	+$85

Table 39 Power Supply Budget

Component	Value	Supplier	Unit Cost	Quantity	Total Cost
Bridge Rectifier	1200 V, 35 A	Digikey	$2	1	$2
Transformer	1020V	Digikey	$140	2	$280
Charge Resistors	10K Ω	Skycraft	$7	4	$28
Switch	Toggle	Home Depot	$6	3	$18
Power Supply	200 W	Skycraft	$8	1	$8
Wire	14 AWG	Skycraft	$2/ft.	6	$12
TOTAL				17	$348

Table 40 Energy Storage Budget

Component	PN	Supplier	Unit Cost	Qty.	Total Cost
6800uf Capacitor	E37F501CPN682MFE3M-ND	Digikey	$84	1.00	$84
3300 uF Capacitor	E37F501CPN332MDE3M-ND	Digikey	$57	1.00	$57
2700 uF Capacitor	E37F501CPN222MDA5M-ND	Digikey	$47	1.00	$47
2200 uF Capacitor	E37F501CPN222MDA5M-ND	Digikey	$42.60	6.00	$256
Red LED 600V DC High Voltage Meter	N/A	jennyear / Ebay vendor	$15	1.00	$15
Total				10	$458

Table 41 Structure Budget

Component	PN	Supplier	Unit Cost	Qty.	Total Cost
Wood	N/A	Owned	$0	Various	$0
Plexiglass	N/A	Owned	$0	6	$0
Misc Supplies	N/A	Skycraft	-	-	$325.50
Total					$325.50

Table 42 Control / Processing Budget

Component	PN	Supplier	Unit Cost	Qty.	Total Cost
Thyristor	844-ST780C04L0	Mouser	$155	10	$1,550
Optoisolator	ACPL-W340-500E-ND	Digi-Key	$1	10	$14
Photointeruptor	EE-SX461-P11	Digi-Key	$6	10	$60
LCD Screen	230-1004-ND	Digi-Key	$105	1	$105
Rangefinder	OSLRF-01	Lightware Optoelectronics	$100	1	$100
Microcontroller	LPC1769FBD100,551	Future Electronics	$9	1	$9
Molex Connector	1301190003	Digi-Key	$6	1	$6
Camera	DSC-W100	-	$0	1	$0
Sockets	-	Various	$5	4	$20
Microcontroller Board	-	-	$24	1	$24
USB Cable	-	-	$0	1	$0
I2C Cable	-	-	$4	1	$4
Total				42	$1,892

Table 43 Barrel budget

Component	PN	Supplier	Unit Cost	Qty.	Total Cost
Magnetic Wire	MW0360	TEMCo	$12.75	2	$25.50
Insulation resin	IR001	TEMCo	$20.00	2	$40.00
Manual Winder	-	EBAY	$60.00	1	$60.00
Projectile Metal Rod	8890K2	McMaster Carr	$12.06	2	$24.12
Total				7	$149.62

Table 44 PCB parts List

Reference Designator	Value	Device	Package
+POW-		2 pin header	22-23-2021
C14	100n	C-EUC0402	C0402
C15	220n	C-EUC0402	C0402
C16	220n	C-EUC0402	C0402
C17	1n	C-EUC0402	C0402
C18	470n	C-EUC0402	C0402
C19	100n	C-EUC0402	C0402
C20	100n	C-EUC0402	C0402
C21	100n	C-EUC0402	C0402
C23	10p	C-EUC0402	C0402
C24	10p	C-EUC0402	C0402
C25	12p	C-EUC0402	C0402
C26	12p	C-EUC0402	C0402
C27	4u7	CPOL-EUA/3216-18R	A/3216-18R
C28	100n	C-EUC0402	C0402
C29	100n	C-EUC0402	C0402
C30	10u	CPOL-EUA/3216-18R	A/3216-18R
C31	100n	C-EUC0402	C0402
C101	470n	C-EUC0402	C0402
C102	220n	C-EUC0402	C0402
C103	100n	C-EUC0402	C0402
C104	10u	CPOL-EUA/3216-18R	A/3216-18R
C107	220n	C-EUC0402	C0402
C110	10p	C-EUC0402	C0402
C111	10p	C-EUC0402	C0402
C112	1n	C-EUC0402	C0402
C113	100n	C-EUC0402	C0402
C121	100n	C-EUC0402	C0402

C122	*33p*	*C-EUC0402*	*C0402*
C123	*33p*	*C-EUC0402*	*C0402*
C401	*1u*	*CSMD0805*	*CSMD0805*
C402	*100n*	*C-EUC0402*	*C0402*
C403	*4u7*	*CPOL-EUA/3216-18R*	*A/3216-18R*
C404	*1u*	*CSMD0805*	*CSMD0805*
C405	*22p*	*C-EUC0402*	*C0402*
C406	*22p*	*C-EUC0402*	*C0402*
C407	*100n*	*C-EUC0402*	*C0402*
C408	*100n*	*C-EUC0402*	*C0402*
C409	*22p*	*C-EUC0402*	*C0402*
C410	*22p*	*C-EUC0402*	*C0402*
C411	*22p*	*C-EUC0402*	*C0402*
C412	*22p*	*C-EUC0402*	*C0402*
IC401	*TUSB2046BIRHBIRHB*	*TUSB2046BIRHBIRHB*	*RHB_S-PQFP-N32*
J1		*PINHD-2X10*	*2X10*
J3	*PWR*	*PINHD-1X3*	*1X03*
J5		*PINHD-2X10*	*2X10*
J10	*PWR*	*PINHD-1X3*	*1X03*
J401		*USB_MICRO_FLIPPED*	*HIROSE-ZX62R-B-5P*
JP1	*+5V*	*JP1M*	*JP1M*
JP2	*+3V3*	*JP1M*	*JP1M*
JP3	*GND*	*JP1M*	*JP1M*
JP4.1	*SBW_TST*	*JP1M*	*JP1M*
JP4.2	*SBW_RST*	*JP1M*	*JP1M*
JP4.3	*SBW_NC*	*JP1M*	*JP1M*
JP6.1	*TXD*	*JP1M*	*JP1M*
JP6.2	*RXD*	*JP1M*	*JP1M*
JP6.3	*CTS*	*JP1M*	*JP1M*
JP6.4	*RTS*	*JP1M*	*JP1M*
JP8	*LED1_PWR*	*JP1E*	*JP1*
L401	*2.2uH (NR3010T2R2M)*	*L-NR3010*	*L-NR3010*
LED1		*LEDCHIPLED_0603*	*CHIPLED_0603*
LED2		*LEDCHIPLED_0603*	*CHIPLED_0603*
LED101	*red*	*LEDCHIP-LED0603*	*CHIP-LED0603*
LED102	*green*	*LEDCHIP-LED0603*	*CHIP-LED0603*
MSP101	*MSP430F5528IRGC*	*F55[0/1/2]X---RGC64*	*RGC64*
OPTO1	*VO3150A*	*VO3150A*	*8-DIP*

OPTO2	*VO3150A*	*VO3150A*	*8-DIP*
OPTO3	*VO3150A*	*VO3150A*	*8-DIP*
OPTO4	*VO3150A*	*VO3150A*	*8-DIP*
OPTO5	*VO3150A*	*VO3150A*	*8-DIP*
OPTO6	*VO3150A*	*VO3150A*	*8-DIP*
OPTO7	*VO3150A*	*VO3150A*	*8-DIP*
OPTO8	*VO3150A*	*VO3150A*	*8-DIP*
OPTO9	*VO3150A*	*VO3150A*	*8-DIP*
OPTO10	*VO3150A*	*VO3150A*	*8-DIP*
Q2	*32.768kHz*	*MS3V-T1R*	*MS3V-T1R*
Q4	*CSTCR4M00G15L99*	*MURATA-FILTER_CSTCR6M00G53Z*	*MURATA-FILTER_CSTCR*
Q101	*PIEZO_CSTCR4M00G15L99*	*MURATA-FILTER_CSTCR6M00G53Z*	*MURATA-FILTER_CSTCR*
Q401	*CSTCR6M00G15L99*	*MURATA-FILTER_CSTCR6M00G53Z*	*MURATA-FILTER_CSTCR*
R14	*100R*	*R-EU_R0402*	*R0402*
R15	*1k4*	*R-EU_R0402*	*R0402*
R16	*1M*	*R-EU_R0402*	*R0402*
R27	*47k*	*R-EU_R0402*	*R0402*
R28	*0R*	*R-EU_R0402*	*R0402*
R29	*470R*	*R-EU_R0402*	*R0402*
R30	*470R*	*R-EU_R0402*	*R0402*
R31	*27R*	*R-EU_R0402*	*R0402*
R32	*27R*	*R-EU_R0402*	*R0402*
R101		*470R-EU_R0402*	*R0402*
R102		*390R-EU_R0402*	*R0402*
R103	*27R*	*R-EU_R0402*	*R0402*
R104	*27R*	*R-EU_R0402*	*R0402*
R105	*1k4*	*R-EU_R0402*	*R0402*
R106	*1M*	*R-EU_R0402*	*R0402*
R109	*47k*	*R-EU_R0402*	*R0402*
R121	*220k*	*R-EU_R0402*	*R0402*
R122	*220k*	*R-EU_R0402*	*R0402*
R124	*240k*	*R-EU_R0402*	*R0402*
R125	*150k*	*R-EU_R0402*	*R0402*
R401	*33R*	*R-EU_R0402*	*R0402*
R402	*10k*	*R-EU_R0402*	*R0402*
R403	*1k5*	*R-EU_R0402*	*R0402*
R404	*47k*	*R-EU_R0402*	*R0402*

R405	22R	R-EU_R0402	R0402
R406	22R	R-EU_R0402	R0402
R407	1k5	R-EU_R0402	R0402
R408	15k	R-EU_R0402	R0402
R409	15k	R-EU_R0402	R0402
R410	22R	R-EU_R0402	R0402
R411	22R	R-EU_R0402	R0402
R412	15k	R-EU_R0402	R0402
R413	15k	R-EU_R0402	R0402
R414	15k	R-EU_R0402	R0402
R415	15k	R-EU_R0402	R0402
R416	22R	R-EU_R0402	R0402
R417	22R	R-EU_R0402	R0402
R418	15k	R-EU_R0402	R0402
R419	15k	R-EU_R0402	R0402
S1		PB	PBTH
S2		PB	PBTH
S3	RST	PB	PBTH
S5	BSL	PB	PBTH
TP104	TEST_PIN2	PINHD-1X1	1X01
TP105	TEST_PIN2	PINHD-1X1	1X01
TP106	TEST_PIN2	PINHD-1X1	1X01
TP107	TEST_PIN2	PINHD-1X1	1X01
TP108	TEST_PIN2	PINHD-1X1	1X01
TP109	TEST_PIN2	PINHD-1X1	1X01
TP110	TEST_PIN2	PINHD-1X1	1X01
U6	MSP430F5529IPNR	F552X---PN80	PN80
U402	TPS62237DRY	TPS6223X_DRY_6	DRY6
U404	TPD2E001DRLR	TPD2E001	TPD2E001-DRL
VEE-VCC+	22-23-2021	22-23-2021	22-23-2021
VPP_VNN	22-23-2021	22-23-2021	22-23-2021

8.2 Timeline

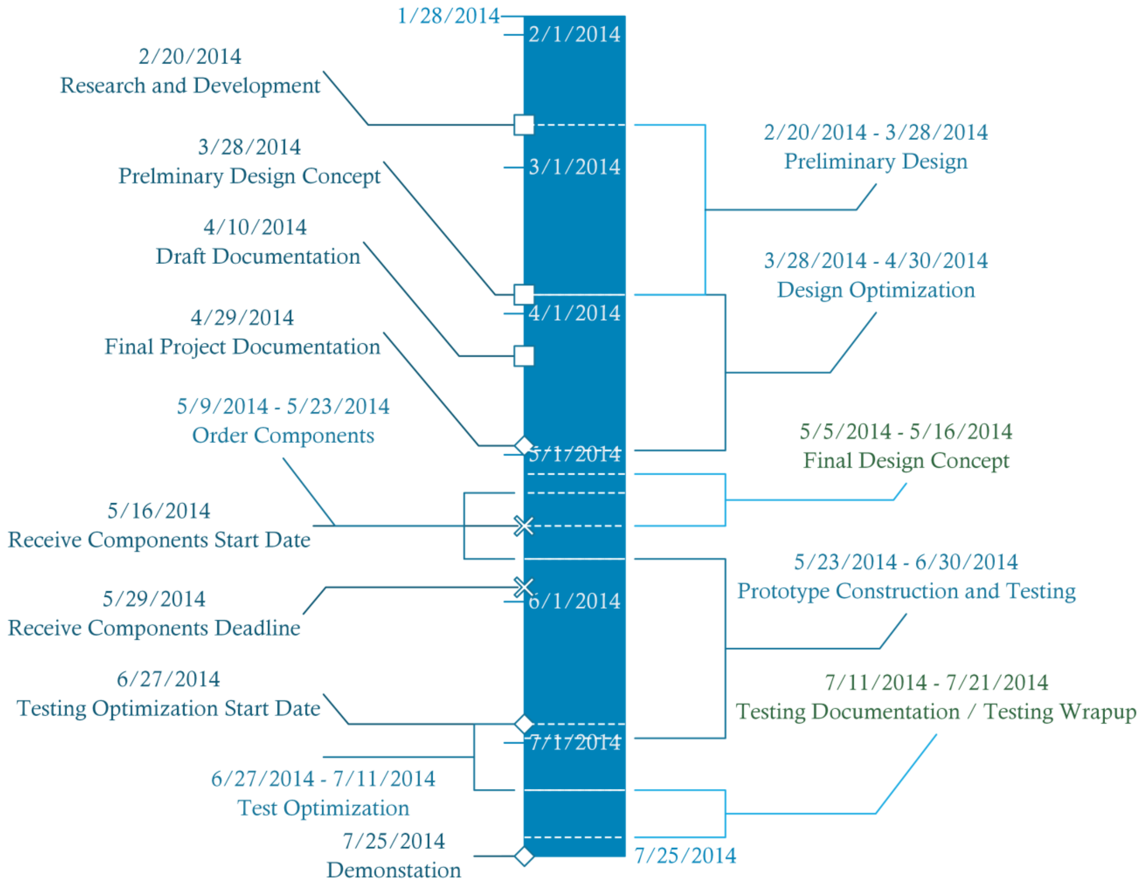


Figure 94 Project Timeline and Milestones

Appendices

Appendix A – Copyright Permissions

Permission to use 600V Digital Voltmeter picture: Pending

Dear User Iawoo,

I am building a coilgun for my senior design project and most likely going to buy your 0.56” 600V digital voltmeter. Could I have your permission to use the picture of your voltmeter in my project documentation?

Thanks much,

Eric Shields

Email sent 4/22/14

Permission to use Table 5 in section 3: Pending

Sent

From: alberto_bird@knights.ucf.edu

Sent: Thu 4/24/14 11:54 AM

To: reinhrd2@illinois.edu (reinhrd2@illinois.edu)

Hello Karl,

My name is Alberto Bird, I am an undergraduate Electrical Engineering student at the University of Central Florida. I am in my Senior Design 1 class and my group and I are designing a coil gun for our senior design project. I found your thesis through extensive search and have found it very informative to the development of my groups project.

I am emailing you is to ask for permission to duplicate some tables and figures from your thesis for the use in the research section of the project documentation. If you would like specifics I can reference the tables and figures I would like to use.

Please let me know of any concerns or conditions you have regarding the use of the material in your thesis.

Best Regards,

Alberto Bird

UCF Electrical Engineering Student

E: alberto_bird@knights.ucf.edu : C: 727-365-3021

Permission to use the TM4301 Touchscreen: Allowed

Received
Hi Omar,

Thanks for your interest in our TM4301 touchscreen. Please feel free to use the image in your report.

Regards,

Phil Wills

Precision Design Associates, Inc

736 Johnson Ferry Road, C270

Marietta, GA 30068

770-971-4490

Sent
Omar Aboueljoud

Sat 4/26/2014 6:19 PM

Sent Items

To:

sales@pdaatl.com;

Hello. I am a student at the University of Central Florida currently taking a Senior Design course. I am writing a report that involves one of your products, specifically, the TM4301 LCD screen. I am asking for permission to use an image of the screen in the report.

Omar Aboueljoud

[3] PDA TM4301: 4.3in PCAP Touch Module, Precision Design Associates, Inc., Marietta, GA, USA, 2014, pp. 1.

Permission to use the OSLFR-01 Rangefinder

Sent
On 26 Apr 2014, at 8:43 PM, Omar Aboueljoud <aboueljoud@knights.ucf.edu> wrote:

Hello. I am an engineering student at the university of Central Florida currently in a Senior Design course writing a report that involves researching your OSLRF-01 rangefinder. I was wondering if it was alright to use the block diagrams in the rangefinder's user manual as well as any formulas included. In addition to the block diagrams, I was also wondering if I could get permission to also use the image of the OSLRF-01 rangefinder itself in my report as well.

Omar Aboueljoud

Received
No problem Omar. Please use whatever information you need.

Regards,

Tracy Portman

LightWare Optoelectronics (Pty) Ltd

E-mail: info@lightware.co.za

Tel: +27 (0)12 661-6960

Fax: +27 (0)86 552-3724

Mobile: +27 (0)82 331-5331

www.lightware.co.za

Permission to use the LPC176x/5x Block Diagram

Sent
Hello. I am a student at the University of Central Florida currently taking a Senior Design course. Currently, I am conducting research for designing a product, some of which involves one of your products. I was wondering if I could be granted permission to use block diagrams found in the LPC176x/5x user manual in writing my report.

Received
Hi Omar,

Yes you can use the block diagrams found in the user manuals in your report.

Thanks,

NXP Technical Support

Please let us know if this does not resolve your inquiry. Your ticket will remain closed if we do not hear from you.

Best Regards,

The NXP Technical Support Team

NXP Semiconductors

Appendix B – References

[1] S. Hartman and A. Young, “Nail Coil Gun,” Group 20, UCF Senior Design, Orlando, FL, December 2012

[2] B. Hoehn, K. Ng, R. Reid, and J. Niederhausern, “Coil Gun with Targeting System,” Group 8, UCF Senior Design, Orlando, FL, Fall 2010

[3] M. R. Sandford. (2013, July 10). AC/DC: The Tesla–Edison Feud [Online]. Available: http://mentalfloss.com/article/30140/acdc-tesla%E2%80%93edison-feud

[4] E. Coates. (2013). Transformers and Rectifiers [Online]. Available: http://www.learnabout-electronics.org/PSU/psu11.php

[5] K. E. Reinhard, “A Methodology for Selecting an Electromagnetic Gun System,” CPT, US Army, Texas, 1992

[6] OSHA Electrical Safety [Online]. Available: https://www.osha.gov/Publications/electrical_safety.html

[7] Shoubao Liu; Jiangjun Ruan; Daochun Huang; Zilin Wan, "Analysis of inductive coil gun performance based on field coupling circuit method," Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International , vol., no., pp.845,849, 17-20 May 2009

[8] Kaye, R.J., "Operational requirements and issues for coilgun electromagnetic launchers," Magnetics, IEEE Transactions on , vol.41, no.1, pp.194,199, Jan. 2005

[9] Grover. W. Frederick, “,” in *Inductance Calculations Working Formulas and Tables, 2004 Dover ed.New York: D. Van Nostrand, 1946*

[10] LPC176x/5x User manual, Rev. 3.1, NXP Semiconductors, Eindhoven, Netherlands, 2014, pp. 12.

[11] OSLRF-01 Laser rangefiner Product manual, Revision 2, LightWare Optoelectronics (Pty) Ltd, South Africa, 2014, pp. 1,3

Appendix C – Simulator Source code

load_from_spreadsheet.m

```
filename= 'rlc calculations.xlsx';

stgs = xlsread(filename,  'A2:A26');

firing_period = xlsread(filename, 'B2:B26'); %In us

inductor_energy_needed = xlsread(filename, 'C2:C26'); %in Joules

capacitance = xlsread(filename, 'E2:E26'); %in uF

capacitance = capacitance.*10^-6; %in F

inductance_needed = xlsread(filename, 'F2:F26'); %in uH

inductance_needed = inductance_needed.*10^-6; %in H

inductance_needed_mh = inductance_needed * 10^3; %in mH

vc_initial =  xlsread(filename, 'G2:G26'); %in Volts

i_max = xlsread(filename, 'H2:H26'); %in Amps

peak_L_energy = xlsread(filename, 'I2:I26'); %in Joules

inductor_resistance = xlsread(filename, 'J2:J26'); %in mOhm

capacitor_resistance = xlsread(filename, 'K2:K26'); %in mOhm

resistance = xlsread(filename, 'L2:L26'); %in mOhm

resistance = resistance.*10^-3; %in Ohm
```

make_inductor2.m

```
function [ resistance, turns, level, diammax, meters ] = make_inductor2(inductance, inner_diameter, coil_length, wire_gauge)

%Output

%resistance - Ohms

%turns - number of turns
```

%level - number of layers

%diammax - outer diameter mm

%meters - length of wire in meters

%Input

%inductance mH

%inner_diameter mm

%coil_length mm

%wire_gague AWG

%Translated from http://www.coolcircuit.com/tools/multi_layer_coil_calculator/lO.js

%LM = eval(form1.LM.value); %Inductance?

%dM = eval(form1.dM.value);

%lM = eval(form1.lM.value);

%DM = eval(form1.DM.value);

%wM = eval(form1.wM.value);

%WM = eval(form1.WM.value);

%inductance = eval(form1.inductance.value)*LM;

MM_PER_INCH = 25.4;

%gauge = form1.gauge.options[form1.gauge.options.selectedIndex].text;

diameter = inner_diameter*1/MM_PER_INCH; %diameter = eval(form1.diameter.value)*dM;

coilLen = coil_length*1/MM_PER_INCH; % coilLen = eval(form1.coilLength.value)*lM;

gauge = [

[1 0.2893 0.1264]

[2 0.2576 0.1593]

[3 0.2294 0.2009]

[4 0.2043 0.2533]

[5 0.1819 0.3195]

[6 0.1643 0.3952]

[7 0.1466 0.4981]

[8 0.1306 0.6281]

[9 0.1165 0.7925]

[10 0.1039 0.9988]

[11 0.0927 1.2600]

[12 0.0827 1.59]

[13 0.0739 2.00]

[14 0.0660 2.52]

[15 0.0589 3.18]

[16 0.0525 4.02]

[17 0.0469 5.05]

[18 0.0418 6.39]

[19 0.0374 8.05]

[20 0.0334 10.1]

[21 0.0299 12.8]

[22 0.0267 16.2]

[23 0.0239 20.31]

```
[24 0.0213 25.67]
[25 0.0191 32.37]
[26 0.0170 41.02]
[27 0.0153 51.43]
[28 0.0136 65.33]
[29 0.0123 81.22]
[30 0.0109 103.2]
[31 0.0098 130.9]
[32 0.0088 162.0]
[33 0.0079 205.7]
[34 0.0071 261.3]
[35 0.0063 330.7]
[36 0.0057 414.8]
[37 0.0051 512.1]
[38 0.0045 648.2]
[39 0.0040 846.6]
[40 0.0036 1079.0]
[41 0.0032 1323.0]
[42 0.0028 1659.0]
[43 0.0025 2143.0]
[44 0.0023 2593.0]
[45 0.00206 3348.0]
];
```

```
selected_gauge = gauge(wire_gauge,:);
wireSize = selected_gauge(2);
res = selected_gauge(3);

currentInd = 0;
turns = 1;
diamavg = 0.0;
diammax = diameter;
turnsPerLevel = coilLen / wireSize;
while ( currentInd < inductance )
%start while
diamavg = 0.0;
diammax = diameter;
tempTurns = turns;
  while ( tempTurns > 0.0 )
  if ( tempTurns < turnsPerLevel )
   %start if
   diamavg = diamavg + diammax * tempTurns;
  %end if
  else
   %start else
   diamavg = diamavg + diammax * turnsPerLevel;
   %end else
  end
```

```
  diammax = diammax + (2.0*wireSize);

  tempTurns = tempTurns - turnsPerLevel;

  end%end while ( tempTurns > 0.0 )

diamavg = diamavg/turns;


diammax = diammax * 25.4;


currentInd = ( diamavg / 1000.0 ) * diamavg * turns * turns / (( 18.0 * diamavg ) + ( 40.0 * coilLen ));

turns = turns + 1;

end %end while ( currentInd < inductance )

feet = ( diamavg * turns * 3.14159 ) / 12.0;

meters = feet * 0.3048;


resistance = (res * feet ) / 1000.0;

level = turns / turnsPerLevel;

%disp_samep( Roundoff( resistance ), Roundoff((wireSize*1000)/wM), Roundoff(turns), Roundoff(feet/WM), Roundoff(diammax/DM), Roundoff(level), Roundoff(turnsPerLevel));


end
```

stages_multibank.m

```
clc;

hold off;
```

```
%clear;


vc_initial = 42;

%Read values from spreadsheet

if ~(exist('filename'))

    load_from_spreadsheet

end


inner_diameter = 19; %mm Inner diameter

inductor_length = 30; %mm Inductor length

gauge = 11; %AWG Gauge


fs = 25; %Number of firing cycles


%new_bank_at = [1, 3, 4, 5, 6, 7, 8, 9, 10];%Stages in which the voltage will go back to 100%

new_bank_at = [];


inductor_resistance = zeros(fs, 1);

I_max = zeros(fs, 1);


for j=[1:length(inductance_needed)]

    l = inductance_needed_mh(j);

    [r, turns, level, diammax, meters] = make_inductor2(l, inner_diameter, inductor_length, gauge);
```

```
    inductor_resistance(j) = r;
end

resistance = inductor_resistance + capacitor_resistance/1000;

alpha = (resistance)./(2.*inductance_needed);

beta = sqrt(1./(inductance_needed.*capacitance)-resistance.^2
./(4.*inductance_needed.^2));

%Considering stage 1 only
%n = 1000;

%t = linspace(0, fs.*firing_period(1)*10^-6, n);

%I = (vc_initial(1)./(beta(1)*(inductance_needed(1)))).*exp(-
alpha(1).*t).*sin(beta(1).*t);
%Vc = vc_initial(1).*exp(-alpha(1).*t).*cos(beta(1).*t); %Capacitor voltage


n = 100000; %Samples per stage
%t = zeros([1 n*fs]);
%I = zeros([1 n*fs]);
%Vc = zeros([1 n*fs]);
```

```
V0 = zeros([1 fs+1]);

if ~(exist('V0_init')) %Keeps voltages goign lower and lower through repetitive sims
    V0_init = vc_initial(1);
end

V0(1) = V0_init;

prev_start = 1;
prev_end = n;
t = [];
Vc = [];
I = [];
E = [];
start_i = 1;

stage_lines = zeros([1 fs]);
for i=[1:fs]

    t_stage = linspace(0, firing_period(i)*10^-6, n);

    if length(t) > 0
        t_normalized = linspace(t(length(t)), t(length(t))+firing_period(i)*10^-6, n);
    else
```

```
    t_normalized = linspace(0, firing_period(i)*10^-6, n);
  end


  I_stage = (V0(i)./(beta(i)*(inductance_needed(i)))).*exp(-alpha(i).*t_stage).*sin(beta(i).*t_stage);

  Vc_stage = V0(i).*exp(-alpha(i).*t_stage).*cos(beta(i).*t_stage); %Capacitor voltage


  mx = max(I_stage);

  if (mx < 0.1)

    mx = min(I_stage);

  end

  I_max(i) = mx;


  if any(i+1==new_bank_at) %Checks if it's a new capacitor bank on the next stage

    V0(i+1) = V0_init;

  else

    V0(i+1) = Vc_stage(length(Vc_stage));

  end


  E_stage = .5*capacitance(i).*Vc_stage.^2 + .5*inductance_needed(i).*I_stage.^2;


  t = horzcat(t, t_normalized);

  I = horzcat(I, I_stage);
```

```
    Vc = horzcat(Vc, Vc_stage);
    E = horzcat(E, E_stage);



    stage_lines(i) = t(length(t));

end

%HOLD ON
plot (t, Vc, 'b', t, I, 'r', t, E, 'g')
hold on;
xlabel('time (s)');
ylabel ({'Current (A) (Red)'; 'Voltage (V) (Blue)'; 'Total Energy (J) (Green)'});

plot([0 max(t)], [0 0], 'k');
for i=[1:length(stage_lines)]
    plot([stage_lines(i), stage_lines(i)],  [min([I(:);Vc(:)]) max([I(:);Vc(:)])], 'k');
end

%xlswrite(filename, V0', 'F2:F27') %in Volts

%plot (t, I)
```