Magnetic Accelerator Cannon (MAC)

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***Abstract* — The objective of this project was to design and implement an electromagnetic launcher system (EML) for a small projectile. This launcher system was also designed to enable the user to select the projectile's kinetic energy from a range of options. The type of EML chosen was a coilgun: a series of electromagnets that are energized in sequence to pull a projectile forward. The project also includes a power supply subsystem to charge the capacitors that deliver pulsed power to the electromagnets. The power supply also powers the low to medium voltage electronics. In addition, a user interface and control subsystem was implemented to enable advanced user interaction and regulation of the other subsystems.**

***Index Terms* — Coil Gun, Coilgun, Electromagnetic Launch System, High Voltage, Photointerruptor, Capacitor Bank, Stators, Inductors, Less-than-lethal, Railgun, SCR, Thyristor.**

I. Introduction

The development of projectile launchers with chemically propelled projectiles reached a plateau more that seventy years ago. Since then, only marginal improvements have been made. This project, the Magnetic Accelerator Cannon (MAC), has the potential to advance the state of projectile launch by leveraging high power electronics and advances in electrical energy storage technology. The idea of using electromagnetic fields to accelerate projectiles is not new. Evolving energy storage capabilities however, indicate that a practical product with capabilities that match or 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. These advantages include reduced maintenance and most importantly, the ability to dynamically alter the projectile's energy.

One of the main motivations for this project was that it incorporated major aspects of the Electrical and Computer Engineering curriculum like Electromagnetic Fields, Power Systems, Control Systems and Embedded Systems. It's also a project with a fun end product—something that shoots. It also can serve as a platform for future development and improvement.

The electromagnetic launch system arrangement chosen was that of a coilgun: a coaxial series of electromagnets that turn on and off in a sequence such that they pull an iron projectile forward.

In order to reach the aforementioned goal of having user-defined output kinetic energy, only the number of stages needed for the target energy to be achieved are activated. Energy left in the unused charged capacitors is then used to charge the discharged capacitors accelerating the charging process for the next shot.

The project was divided into subsystems for administrative purposes and ease of design. It is illustrated in the following diagram:

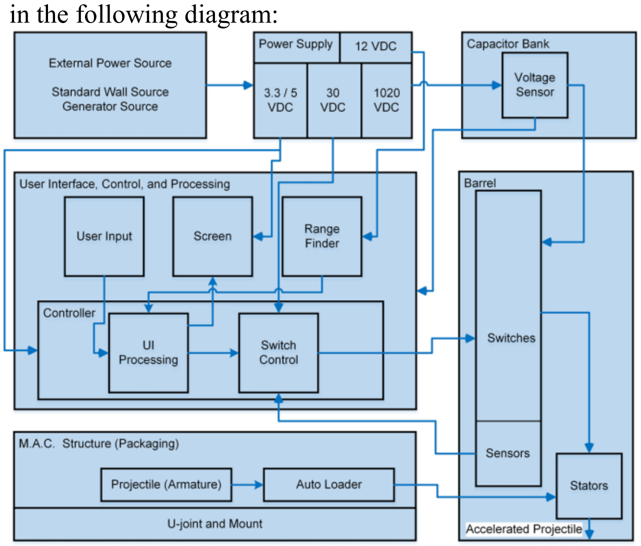

Fig. 1. Diagram showing systems and subsystems hierarchy.

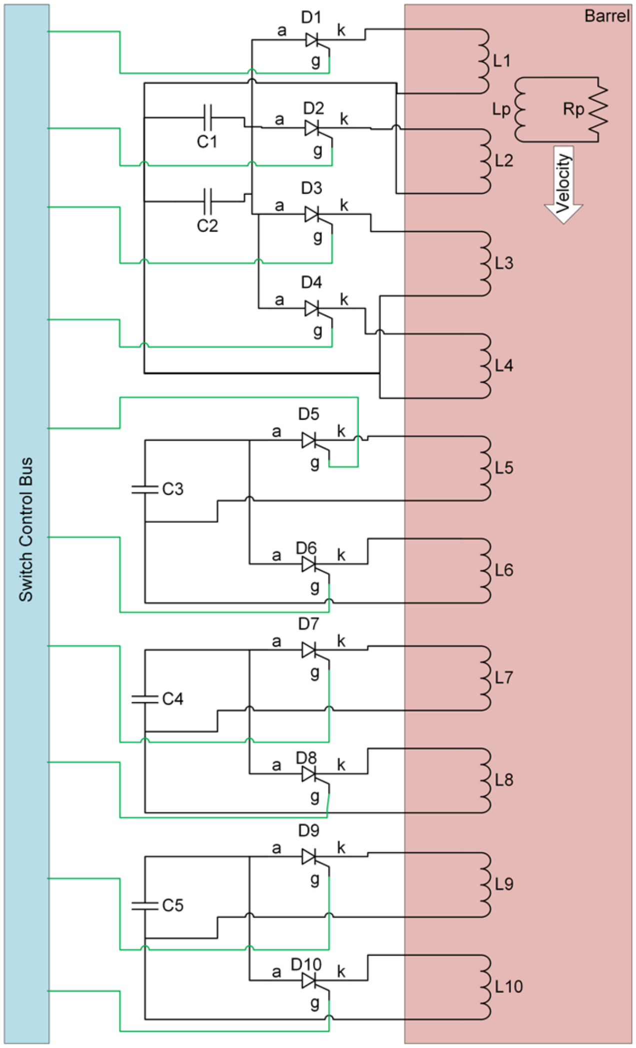

Fig. 2. Diagram showing all relevant components during firing sequence.

II. RESEARCH

Before starting the design of this project, several past projects and papers with coilguns of varying levels of complexity were researched. These previous works provided crucial information for the design of the MAC.

A. Previous UCF Projects

Two previous UCF projects with similar goals were studied [1][2]. They provided good information on construction and assembly as well as theory--especially in relation to charging circuitry.

B. Army Graduate Thesis

A graduate thesis was published by Captain Karl E. Reinhart of the U.S. Army in 1992 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.

The thesis also 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. Capacitors can deliver a large amount of energy very quickly and have been proven to be the ideal component for pulsed power applications like this project.

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. 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 [3]. During design, this objective had to be balanced with having to keep the projectile from coming into direct contact with coils or sensors. The coil, barrel and projectile sizes were selected to balance these two opposing objectives.

C. Sandia National Laboratory

The Sandia National Laboratory has produced many coilgun topologies for research and military uses. This particular report incorporates the concepts and lessons learned from operation of all the various designs. The paper was used as a reference design criteria for the MAC

The research paper that was investigated describes the armature of the coilgun as a shorted coil. This significantly reduces computations needed to solve the interactions between projectile and coils. Since the projectile is a shorted coil it can be modeled as a resistance in series with an inductor.

The paper also emphasizes 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 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%. [4] This analysis gave an efficiency objective for the project.

D. Coilguns.info

The website coilguns.info is a renowned resource for building coilguns. It is referenced by almost every hobbyist's project and senior design group that builds a coil gun. The webmaster, known as "Barry", has designed and assembled five different coilguns with exhaustive accompanying documentation, including equations, measurement results and computer simulations of different components.

All the coilguns he has 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 for practicality with this helpful tool. The RLC simulator was instrumental in helping increase the understanding of RLC circuits and how to properly simulate them [5].

E. 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 also contains the most basic equations for all situations which arise with the use of inductors, or the construction of inductors [6].

III. KINEMATIC MODELING

A desired velocity had to be chosen based on an estimated 10% electrical to kinetic energy efficiency and the affordability of high power energy storage. The chosen target velocity was 400 m/s. Although not ultimately achieved, this target velocity was the starting point to selecting all the appropriate capacitors and winding the inductors to the correct specifications. From this velocity, the acceleration that each stage needed to provide could then be calculated. From this kinematic model, the amount of time that the projectile spends within the critical regions of the stage (from -1/2 of the stator length before the face of the stator to 1/2 of the coil length to the right of the stator) can be solved for. Once that information is known, the right capacitor-inductor combination can be obtained.

IV. ENERGY STORAGE AND INDUCTANCE VALUES

Because of the conclusions of every research source and reference design, the intermediate medium for storing energy between the power supply and the coils was chosen to be an array of capacitors. Yet, the characteristics of both the individual capacitors and their overall arrangement in the MAC remained an open question.

To select the right arrangement and components, some key objectives were kept in mind. The first was the amount of energy stored in the capacitor (a function of both the capacitance and voltage). However it was the second consideration that proved the most important: how a capacitor component would interact with its stator stage both in relation to the half-wave period of its oscillation and the magnitude of the magnetic field that the capacitor-stator pair would produce. For this reason the capacitor and stator inductance values had to be designed together.

The magnitude of the magnetic field was not analyzed directly. Instead, the amount of energy stored in the magnetic field was used for design analysis because of ease of computation. After the first stage was built, each subsequent stage was built based on the measured velocities. Based on those velocities, the actual acceleration delivered by each coil was known to a high degree of certainty. Using this experimental data proved to be adequately accurate.

The other critical capacitor-stator interaction was its half-wave period. For optimal coilgun operation, a stator can only be active up until the projectile reaches the middle of the stator. If the stator remains active after this point, the projectile experiences "suckback" where force is applied in the opposite direction of desired motion. Thus, a stator needs to be completely inactive by the time the projectile reaches the stator's midpoint. Because of the massive voltages produced when attempting to force a current to stop flowing in an inductor, the natural oscillation produced when a capacitor discharges into an inductor must be leveraged. The circuit can be easily disconnected when the current reaches zero after the first peak in the oscillation. This half-cycle is then used as the pulse to activate the coil. The amount of time that this pulse is active for is expressed by the formula.

$$\tau = \pi\sqrt{LC}\,. \tag{1}$$

The capacitor and inductor values for each stage needed to produce a firing period as indicated by the kinematic modeling and subsequent speed measurements.

In this capacitor-stator interaction, the capacitor acquires charge opposite its initial polarity as the energy stored in the stator's magnetic field flows back into the capacitor. This could be solved in one of two ways:

1) By adding additional resistance to this RLC circuit to create a damped response.

2) By using the energy "recycled" from a stage to power the next stage.

Since efficiency was the primary design goal, option 2 was chosen.

Because of budget considerations, it was established that the MAC would have ten stages. Given all the aforementioned constraints, a very large set of commercially available capacitors were weighed against each other in regards to each component's ESR, energy storage cost and practicality of bank assembly with the aid of spreadsheets and some scripting.

Five identical 1000V polymer film capacitors were chosen for energy storage. Their 970uF capacitance allows it to be paired with a relatively high inductance stator to provide the right pulse time. One of the desired characteristics of this coilgun is to design each stage such that each delivers approximately equal amounts of energy into the projectile. This will keep the projectile's acceleration relatively constant. The well know equation for energy stored in an inductor:

$$W_L = \frac{1}{2}LI^2 \quad (2)$$

Keeping the inductance of the stator from getting too low is critical in order to achieve this objective without needing currents at unmanageable levels.

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 pulse time needed for each stage was obtained from the kinematic modeling. The results obtained from the Matlab simulation is graphed:

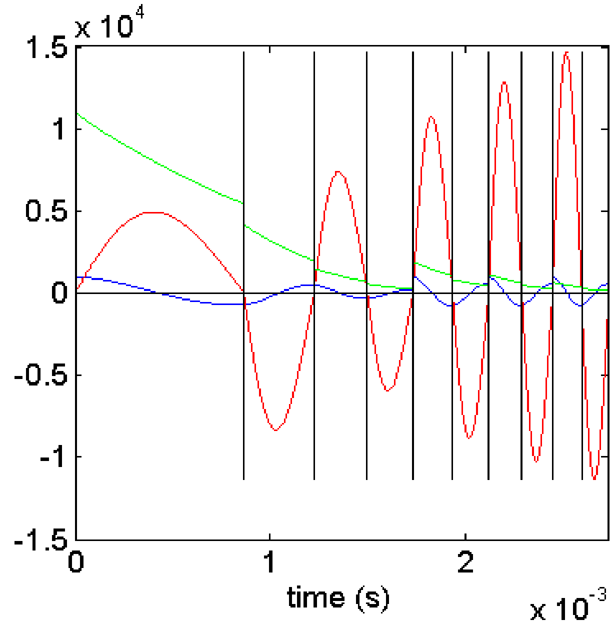

Fig. 3: Red: Current (Amps) Blue: Capacitor Voltage (Volts). Green: Total stage energy (Joules scaled 130% for clarity). Black vertical lines denote a new stage. Note how total stage energy increases when a new capacitor stage is introduced.

After the first stage was created, the measured velocities were incorporated into the design so that more accurate pulse times could be obtained.

V. Fire Control

In order to correctly activate the stators in the right sequence and at the right time, position sensors were mounted at the end of each coil and software was used to activate the stators. In addition to the sensors at the end of each stage, a sensor mounted one stage length away (3 cm) from the last stage was added to accurately measure the final muzzle velocity. The sensor consists of an infrared LED paired with a phototransistor sensitive to the same wavelength. As the projectile passes the sensor, the light from the LED is interrupted and the phototransistor switches off. Hence, the time in which the projectile reaches any of the points where a sensor is mounted can be known.

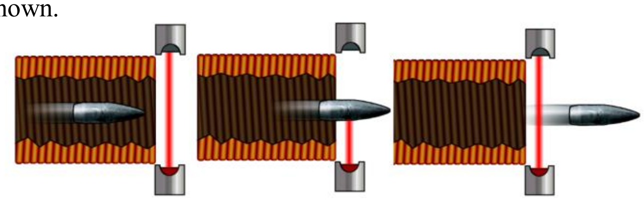

Fig. 4. Projectile still in coil. Step 2. Projectile breaks beam. Step 3. Projectile no longer obstructing beam.

The collector terminals of all eleven photodiodes were connected to the control circuit's 3.3V output through a resistor to limit the current flow. When the beam isn't obstructed, a voltage can be measured between the emitter and ground (logical high). When the beam is obstructed, the phototransistor closes the circuit and there is a very small voltage drop between the emitter and ground (logical low).

At the instant the obstruction is detected, the projectile will be at the optimal position for the next stage to turn on. Thus the microcontroller processes the received signal from the sensor and indicates to the next stage to turn on.

In order to switch the large currents that flow through the stator, a silicon controlled rectifier (SCR)—a type of Thyristor—is used to switch each stage. Each SCR requires a 20V gate-drain pulse to optimally drive extremely short gate pulses (~10us). An optocoupler (or optoisolator) provides electrical isolation between low voltage microcontroller and the high voltage SCR while also providing the 20V pulse needed to drives the thyristor gate.

This closed control system ensuring that the any chaotic variations in the expected firing timing are compensated for.

VI. User Interface

A LCD display shows the current voltage level of the capacitor bank. A separate two text line LCD shows the current firing mode and distance to target. Due to the limitation of the laser rangefinder used [7], the current implementation of the targeting system will only be able to give accurate range information up to 9 m or 30 ft.

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 to be activated associated with it. When the level is selected, the necessary 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. As with the previous mode, each value has a coil count associated with it. When the command to fire is enacted from the trigger, the number of coils which can achieve that muzzle velocity will be energized and the projectile will be launched. The output from the last two photo sensors will provide the projectile's velocities to the user via the LCD screen.

All the programing for the microcontroller was done with the C programming language. The IDE that was used was Code Composer Studio. This specific IDE was chosen for its compatibility with the MSP430 architecture which is used in the MAC.

VII. Barrel and Coils

The barrel was designed to provide structure to the stator coil circuits. All ten stator coils are mounted coaxially with the support of an acrylic tube. With an outer diameter of 18mm and an inner diameter of 16mm, it tightly couples with the stator on the outside while leaving good margin on the inside of the tube for the projectile.

The stator coil circuits were designed based on inductances determined in section III. A coil winder was purpose-built for this project.

After the first stage coil was built, the next coils in sequence were built based on the pulse time based the real-world measured velocities produced by the previous coils. This guaranteed that any unforeseen variation from the theoretical calculations did not severely change the desired performance of the device.

Fig. 5. Fixed magazine holds up to nine projectiles.

At the starting end of the barrel a non-removable magazine hold nine projectiles and enables quick reloading and optimal positioning of the projectile for starting the firing sequence. The clear acrylic case allows the user to quickly ascertain the number of projectiles left to fire while also providing clear information on the state of the projectiles in case of the unlikely event of a loading malfunction.

Each stator will be 3cm in length and have a bore diameter of 1.9 cm. These basic dimensions, derived from the projectile, provided the requirements necessary to compute the turns in each coil that would achieve the required inductances. The coil inductances would range from 2 uH to 39 uH of which each will have its own number of turns and/or layers to achieve the inductance values.

VIII. Power Supply

The MAC's power supply consists of two main parts. The first is the high voltage charging circuit for the capacitors. The second is low/medium voltage power supply for the microcontroller, switches and other peripherals. Both parts are connected to the same connector that interfaces with a standard US 120V wall outlet. A primary switch will be used to power the MAC. The overall power supply architecture is summarized in the following figure:

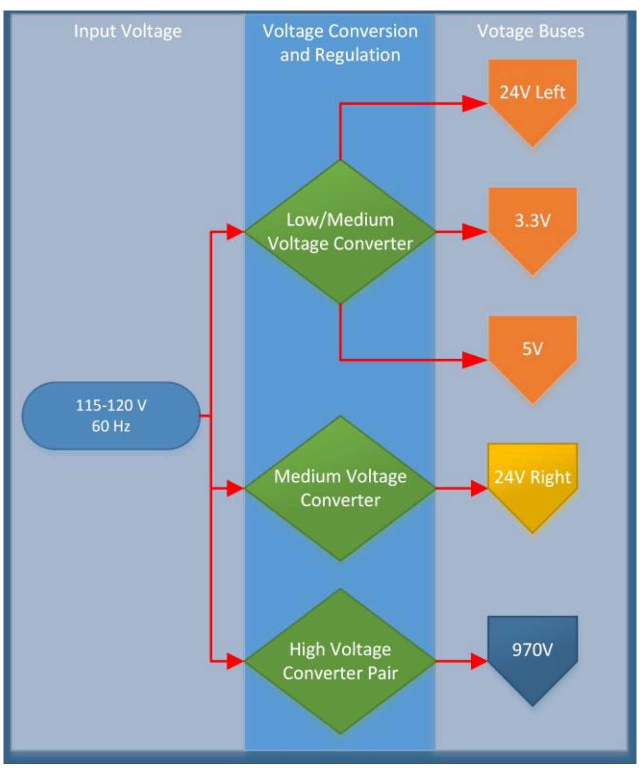

Fig. 6. Topology of power supply components.

The high voltage portion of the power supply is connected to two identical 1020V transformers. These two particular models were chosen for their balance between current capacity and cost. The stepped up 1020V outputs of both transformers are tied together and connected to a bridge rectifier where they produce a 970V DC output. This DC output is then split into the four separate capacitor banks where the line goes through a power resistor to regulate the current. The separate banks can be switched to be configured in parallel by actuating a relay. This allows current to flow in-between capacitors at different charges, accelerating the charging. Before the MAC fires, the charging circuit needs to be switched off so that the reversal of capacitor polarity present in typical operation of the MAC doesn't produce a voltage difference larger than the charging circuits are rated for. A schematic of the entire high voltage charging system can be seen in the following diagram:

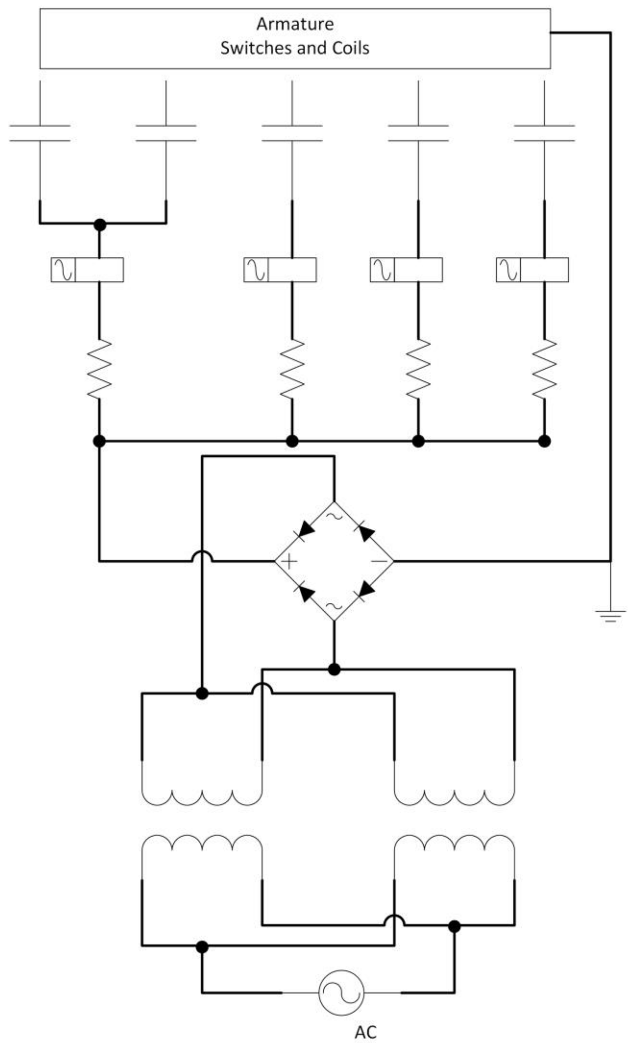

Fig. 7. Capacitor charging circuit (High Voltage).

Two 24V lines with separate groundings are needed to drive the thyristors. This is because the thyristors need to drive capacitor-stator pairs of alternating polarity. All the odd-numbered stages are driven by the thyristors to the left of the barrel and only fire when its respective capacitor is charged positive relative to the charging circuit. The even-numbered stages are driven by the thyristors to the right of the barrel and are only fired when the capacitor it is paired with is charged negative relative to the capacitor charging circuit. This reversal of polarity happens naturally as each stator-capacitor pair charge and discharge in a normal oscillation half-cycle due to firing. Since the stages are always fired in order, each stage will be at the correct polarity when its time comes to fire. The thyristors and their respective grounds were arranged in this "left-right" standard not only because it simplified the control wiring, but also because it creates the shortest wiring path between the capacitor terminal and the coil.

Both the high voltage and the medium voltage circuits were packaged in a single, secure enclosure. Two fans provide ventilation for these power components and the enclosure features a door for easy maintenance access.

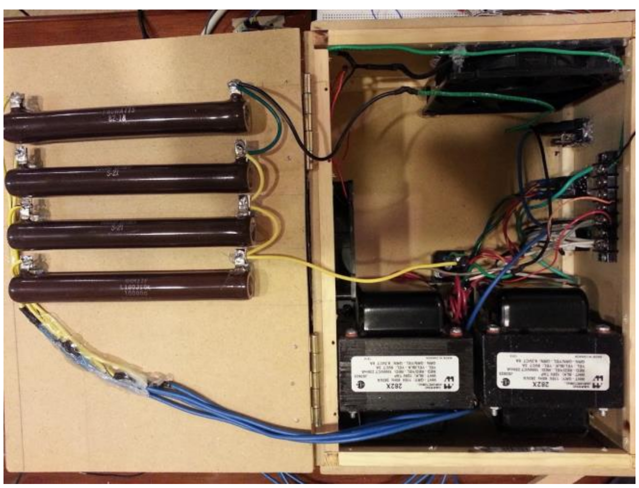

Fig. 8. Capacitor charging circuit (High Voltage).

The Low/Medium voltage supply is derived from a standard ATX power supply that provides all of the necessary low voltage to power the microcontroller, one side of thyrisors, the range finder and LCD display. It is packaged in the same enclosure as the microcontroller PCB and is mounded below the LCD displays.

IX. Packaging

The packaging of the MAC encases and combines all the subsystems developed. The MAC can be transported as a single unit without assembly or disassembly. Since resistive losses in the transmission of energy from capacitors into the coils via the thyristor can severely decrease the efficiency of the device, all of these components were mounted in an arrangement where the distance between all of the components is at a minimum. This short distance combined with the large wire used in this circuit (1 AWG) dramatic reduces resistive losses and increases the overall efficiency of the MAC.

At the base of the MAC, all five capacitors are mounted in a row as pictured below:

Fig. 9. Exposed capacitor enclosure. The first "level" of the MAC.

The power and control sub-systems enclosures were attached at the same level as the capacitor bank and behind the first coil.

The second level is mounted on top of the capacitor enclosure, obscuring the capacitors and protecting them and the user from accidental contact. The second level contains all the wiring for the thyristor control lines and grounds as well as the signal and power lines for the sensors attached to the bottom. The surface of the second level contains the barrel down the middle with the coils and sensors arranged in proper sequence as well as the thyristor aligned arranged in a “zig-zag” pattern aligning with the appropriate stators and corresponding polarity of current flow.

X. Conclusion

Although the desired research-lab-grade efficiencies weren’t reached, the MAC is still able to deliver a respectable amount of kinetic energy. More efficient semiconductors and denser high power energy storage will certainly bring EML systems closer to becoming a practical product. Many of the design decision in this platform can be expanded upon to produce a practical commercial product.

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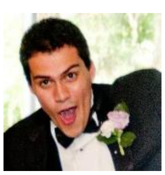
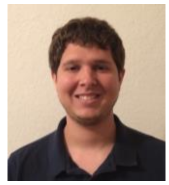
Biographies



Wesley Lima will earn his Bachelors of Science in Electrical Engineering in August 2014. He is interested in pursuing a career designing and developing cutting edge products in the defense and communications industries. He programs for fun and is an active percussionist. Sometimes he even dabbles into music production.



Alberto Bird is a senior at the University of Central Florida and will receive his Bachelors of Science in Electrical Engineering in August of 2014. Throughout his time at the university Alberto interned at Earthrise Space Inc. from May of 2011 to May 2014. There he participated in team Omega Envoy designing avionics, power, and communication systems for a lunar lander and rover. His primary interests lie in the electronics of military and aerospace systems. Alberto plans to work in the emerging space industry in his career.

Eric Shields is an Electrical Engineering senior at UCF. He has gained experience in various electrical and mechanical systems by working with what he loves: everything from mopeds to computers. Eric enjoys water and snow sports when he’s not working on his latest project. His future plans include developing and improving current electric automotive technology with an eye toward their implementation in motorsports**.**

Omar Aboueljoud is a Computer Engineering student at UCF expecting to graduate in August. Has an interest in computer architecture, and plans to work for a local engineering firm while continuing his education with a MBA program.

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