DESIGN PROJECT REPORT

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**Project title:** Demonstration of Electromagnetic Propulsion through Coil Gun Development

**Team members:** Brady Davis

Grant Brinker

Evan Seabaugh

Maxwell Ryan

Alex Wortmann

**Customer(s):** Missouri S&T Department of

Electrical and Computer Engineering

**Advisor(s):** Dr. Robert Woodley

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**Instructor:** Dr. Robert Woodley

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Table of Contents

[1 Introduction 2](#_Toc1317632585)

[1.1 Executive Summary 3](#_Toc1482636387)

[1.2 Background and Problem Statement 3](#_Toc571287383)

[1.2.1 Existing Works 3](#_Toc1157188478)

[1.2.2 Global and Societal Context and Motivation 3](#_Toc1055935491)

[2 Design and Methods 4](#_Toc2079981916)

[2.1 Goals 5](#_Toc941062178)

[2.1.1 Goal 1: Conduct Research 5](#_Toc1965210034)

[2.1.2 Goal 2: Finalize List of Hardware Components 5](#_Toc975655364)

[2.1.3 Goal 3: Design 5](#_Toc1003256247)

[2.1.4 Goal 4: Prototyping 6](#_Toc1010196061)

[2.1.5 Goal 5: Verification and Validation 6](#_Toc294905737)

[2.2 Deliverable(s) 7](#_Toc1575215028)

[2.3 Specifications and Requirements 7](#_Toc1755115747)

[3 Technical Approach and Results 9](#_Toc1029090382)

[3.1 Final Design 10](#_Toc814923224)

[3.2 Results 16](#_Toc1128000821)

[4 Management 16](#_Toc2110386884)

[4.1 Project Milestones 17](#_Toc1872423975)

[4.2 Encountered Challenges and Lessons Learned 17](#_Toc1630920317)

[4.3 Team Ethics Discussion 17](#_Toc1288508835)

[4.4 Budget 17](#_Toc2048355910)

[4.5 Funding Source 17](#_Toc1182490812)

[4.6 Human Safety Assessment 17](#_Toc1655174507)

[4.7 Member Credentials and Responsibilities 17](#_Toc2144581405)

[4.7.1 Teamwork 17](#_Toc637708099)

[4.7.2 Brady Davis (brady.davis@mst.edu, CpE major): 17](#_Toc1179149327)

[4.7.3 Grant Brinker (gsbfy2@mst.edu, EE major): 17](#_Toc249965299)

[4.7.4 Evan Seabaugh (emshbg@mst.edu, EE major): 17](#_Toc1818112807)

[4.7.5 Maxwell Ryan (maxwell.ryan@mst.edu, EE major): 17](#_Toc2082539432)

[4.7.6 Alex Wortmann (amwpnd@mst.edu, CpE major): 17](#_Toc33087035)

[5 Conclusions and Future Work 17](#_Toc936409424)

[5.1 Conclusions and Lessons Learned 17](#_Toc1994446676)

[5.2 Suggested Improvements 17](#_Toc1934076445)

[6 References 17](#_Toc384858246)

# Introduction

## Executive Summary

The goal of this project was to develop a functional coil gun that the Missouri S&T ECE Department could use as a demonstration during tours of the department for the purpose of recruiting new students. Aside from being something new that the average person has not seen before, a coil gun demonstrates electromechanical and electromagnetic principles which allows prospective students to observe first-hand what they can learn from the Department.

This device was developed entirely by our project team, as the only feature provided was the ammunition: steel 15.6g, 5/8” balls. To determine the quality of the device, the ECE Department judged the product based on muzzle velocity. To give this project an aspect of originality, the coil gun was designed to be portable by using a docking mechanism to charge the gun with a standard wall plug, as well as eye-catching, with a completely custom 3D-printed housing. The other major factor considered in this project was safety. It should not harm any user in any way (when used as intended), should be easily held and activated by an average adult, and should be capable of operating when powered by any standard US wall outlet.

## Background and Problem Statement

The ECE department previously had a coil gun to show the principles of electromagnetics. Since then, the employee who originally built it has left the university. The motivation behind this project is to use the coil gun to aid in admissions visits. Missouri S&T has a larger goal of increasing the student population to 12,000 students over the next 5-10 years. Using this coil gun as a recruitment aid will increase the ECE department’s admissions numbers which directly aids in the university’s larger goal. Providing this visual demonstration of electromagnetics creates an “awe-factor” for prospective students who might witness the operation of the coil gun. Bearing witness to this electric exemplification of what you can learn in the ECE department at Missouri S&T gets these potential S&T students excited about ECE and shows exposes them to the possibilities of getting hands-on experience at this university.

### Existing Works

Coil guns have been in existence for some time and several products exist on the market which are publicly available for individuals to purchase. Some of the most well-known designs are the GR-1 Anvil, the EMG-02, and the Coil Accelerator. Some of their characteristics are provided in Table 1 below.

Table 1: Available coil gun products and their descriptors [1] [2] [3]

|  |  |  |  |
| --- | --- | --- | --- |
| Product | Muzzle Velocity | Semiautomatic | Cost |
| GR-1 Anvil | 75m/s | Yes | $4450 |
| EMG-02 | 75m/s | Yes | $3220 |
| Coil Accelerator | 53m/s | Yes | $1900 |

Although these products are highly capable, their downside is the high cost. Our design aimed for a much lower cost, making the technology more accessible to potential customers. This was accomplished partly by removing the semiautomatic capability which, for the application as a demonstration tool, is not a necessity. The product was also expected to have a lower muzzle velocity. Although this reduces the impression made on observers, it helps reduce both the cost of the product and the potential risk to observers should something go wrong. Because of these benefits, the product being designed is superior to other available solutions for the application being considered.

### Global and Societal Context and Motivation

Developing a potentially dangerous product such as a coil gun creates numerous implications about the use of the products, as well as safety concerns. Producing any sort of weapon might cause some concerns in the population to arise about potential safety issues. People tend to be wary of unregulated dangers to society and developing a product that could be used as such would be grounds to cause such worries. Because the coil gun our team has developed was handed off to the university, any concerns about malicious use are mitigated. However, this doesn’t put any safety concerns to rest. Regardless of the intent of the user, a product that is not guaranteed to perform safely can still cause damage if it fails in a dangerous manner. These potential issues, therefore, must be addressed during the design and testing of the product. Once safety concerns are mitigated, use of the coil gun can commence.

As previously mentioned, the goal of this product is to help Missouri S&T reach its recruitment goals and boost enrollment in the ECE Department. Finding future college students interested in Missouri S&T and, more specifically, electrical and computer engineering, has become more difficult over the past several years. Additionally, many electrical engineering principles are seen every day in smartphones and other technologies which makes impressing students with these principles much more difficult. This product addresses these issues by displaying these principles in a much more uncommon and unfamiliar way, thereby kindling a deeper interest in the electrical and computer engineering fields and Missouri S&T as a whole.

# Design and Methods

In the original proposal, the goals for the project were to develop a coil gun which maximizes accuracy and distance, minimizes cost, and acts as a safe yet effective demonstration tool for the ECE Department. To accomplish these goals, the project was designed with six coil stages, a 32mF capacitor bank, a 380V maximum charge, high-power high-speed MOSFETs, and an aesthetically pleasing 3D printed body, all of which are detachable from the AC-DC power supply.

As testing proceeded, many problems were encountered with the MOSFETs used to enable the coils. Although two MOSFETs were used to switch each coil, they failed into a short circuit condition as current approached the rating of a single FET. This prevented the team from reaching any significant projectile speed without damaging components. Other failures which occurred were damaged gate drivers and repeated uncontrollable toggling of FETs which led to dead components. Exact causes and solutions to these issues could not be found.

Because of these issues and a shortage of time and budget, scope was reduced to a single coil stage. Other changes to the tasks include moving towards IGBTs instead of FETs because of their higher ampacity and high switching speed and moving the gate driver to the coil board to reduce the effects of inductance loops. Both decisions were arrived at by discussing issues and solutions with Dr. Jonathan Kimball.

## Goals

### Goal 1: Conduct Research

Developing a custom coil gun required extensive initial research by the design team. Every member of the group played a role in becoming a “subject matter expert” regarding one of the aspects of the project. Most notably are the calculations and simulations needed to make design decisions. Things such as the configuration of the coils, the coil timing, and magnetic flux optimization required significant resources to make decisions.

### Goal 2: Finalize List of Hardware Components

The team developed a finalized Bill of Materials (see 4.4 Budget) based on information that was gathered in the research phase. Materials for testing and development were procured primarily from online distributors such as Digikey.

### Goal 3: Design

The following section details the various high-level systems that were used for coil gun development. See 3. Technical Approach and Results for more detailed description. Budgetary restraints were a major challenge for these tasks because during system testing, there were several components that were damaged and had to be replaced.

1. **Task 3.1: AC-DC Rectifier**

**Description**: The coil gun required a circuit to take the 120VAC input from a wall outlet and output approximately 24V. This is to power the desired capacitor charging IC. An off-the-shelf solution was chosen to minimize failure points and allocate resources towards other systems.

1. **Task 3.2: Coil System**

**Description**: The coil gun required a custom designed circuit to energize the coil stages. To allow optimization later in the design process, it was decided that the coils would be custom would and designed in house using an X-Winder filament winder. The physical dimensions of the winding determined the coils’ electrical properties. See 3 Technical Approach and Results for a description of the coil design decision.

1. **Task 3.3: Capacitor Bank**

**Description**: The capacitor bank was one of the most influential portions of the project. To achieve the longest range and best speed out of the projectile, the arrangement of the bank was determined to minimize the effects of ESR and drain at each stage for maximum output. No modifications were made from the original proposal.

1. **Task 3.4: Charging System**

**Description**: The charging system powers the capacitor bank until the system reaches the operating voltage of 380V. Toggling the current through the capacitor bank was one of the main challenges and verified the necessity for a custom firing system. The primary challenge was designing the biasing resistors of the circuit to create the desired output voltage and current.

1. **Task 3.5: Coil Firing System**

**Description**: The coil firing system created a surge of current from the capacitor bank to the coils. This is what launches the projective via the magnetic field produced in the coils. Difficulty was experienced in selecting the proper switch to allow current to the coil. Problems with flyback diodes were also experienced.

1. **Task 3.6: Control System and Display**

**Description**: The control system consisted of one main PCB with a microcontroller and interfaces with the trigger, voltage sensor, discharge system, LCD, and all other I/O. These circuits, while on individual boards, all connected back to the control board to have one central location for interfacing with the coil gun assembly. The coil gun required a system to display information to the user for safety and knowledge of the system state. The display system has individual indicators to denote charging, charged, and discharging states. An LCD was used to provide voltage readings and percentage charge and discharge during those states. The embedded code of the coil gun sends and receives feedback based on the current system status.

1. **Task 3.7: De-Energizing System**

**Description**: There is a MOSFET switch to bring discharge power resistors in parallel with the capacitor bank to discharge and de-energize the bank. This was a critical safety step for testing and during normal operation of the coil gun. A challenge this presented was how to effectively dissipate the heat generated. The resistor values were chosen to allow for a time constant to draw minimal current, while still being able to de-energize within a reasonable timeframe.

1. **Task 3.8: Mechanical Body and Structure**

**Description**: The Mechanical Structure is comprised of the innermost layer of protection for the user. This includes parts that cover electronics and internal PCB assembly structures. These form the basic supporting backbone of the coil gun. The mechanical body surrounds the mechanical structure and the electronics. This mechanical structure provides a second layer of protection to all end users handling the gun. This body also includes all aesthetic and decorative pieces to improve the appearance of the coil gun.

### Goal 4: Prototyping

Each custom component of the design was prototyped, and later realized with a custom printed circuit board. This allowed for our prototype units to be run under close-to-expected conditions. Prototyping in this fashion allowed us to design and manufacture second revision boards which helped to make system changes.

### Goal 5: Verification and Validation

Verification happened on the component and system levels. Testing plans were developed using inspiration from organizations such as the NRA and the US military, or from standard work procedures for high energy and kinetic devices. Lab equipment was used to verify each component described above in the Design section. The subsystem-level tests took components and group them together based on function (coil and barrel, capacitor bank charging/discharging circuit, it, etc).

## Deliverable(s)

The final design consists of a handheld coil gun and docking station for charging. The handheld portion is attached to the docking station to charge the internal capacitors before firing the projectile. Once this is complete, as indicated via LCD, the trigger can be pulled and the projectile is launched.

## Specifications and Requirements

Table 4 shows the requirements developed for the project. These requirements were developed using information from various interviews with stakeholders along with a set of restrictions given to us by the ECE department. To determine the scope of our project and possible approaches to our problems, our team interviewed Dr Kimball, Dr. Shamsi, Dr. Kosbar, and Mr. Wolfgeher. During these interviews there was an emphasis on creating a safety briefing for the end users. It was also suggested that we implement different power levels for safer demonstrations indoors.

Table 2: Test Metrics

|  |  |  |  |
| --- | --- | --- | --- |
| **ID** | **Title** | **Test process** | **Verification/Expected Outcome** |
| 1 | Rectifier | 1. rectifier will be connected to a wall outlet  2. multimeter will be used to measure the output voltage from the rectifier | Rectifier outputs 24V DC with less than 1V ripple |
| 2 | Charging Circuit | 1. logic signal will be sent to the circuit  2. voltage across the capacitor bank will be monitored over time using a multimeter and a timer | The capacitor bank charges to 380V within 1 minute |
| 3 | Discharging Circuit | 1. logic signal will be sent to the circuit  2. voltage across the capacitor bank will be monitored over time using a multimeter and a timer | The capacitor bank charges to 380V within 1 minute |
| 4 | Firing Circuits | 1. signal will be sent to electrically connect the capacitor bank to the coils  2. voltage across the capacitors and the coils will be monitored using a multimeter | The energy stored in the capacitors is dissipated through the coils and the voltage across the capacitors decreases below 100mV |
| 5 | Optical Sensors | 1. Teensy microcontroller will be connected to the optical sensor on a breadboard and programmed to write to the Serial monitor when the sensor sends a signal | A message is received on the Serial monitor when the optical sensor is stimulated |
| 6 | Voltage Monitor | 1. voltage will be applied to the voltage monitoring circuit using a DC power supply  2. The signal from this circuit will be fed to a Teensy microcontroller which will display this voltage on the Serial monitor  3. The reading will be compared to the output voltage of the power supply | The voltage monitoring circuit can measure voltages from 0V to 400V within 1V of the actual value |
| 7 | Display | 1. display will be connected to a Teensy microcontroller which will be programmed to send the values of several variables to it | The display shows the values of the variables sent to it |
| 8 | Trigger Mechanism | 1. The trigger will be connected to a Teensy microcontroller which will be programmed to send a message to the Serial monitor when the trigger is pressed. | A message is received on the Serial monitor when the trigger is pressed |

Table 3: Test Metrics

|  |  |  |  |
| --- | --- | --- | --- |
| **ID** | **Title** | **Test process** | **Verification/Expected Outcome** |
| 1 | Control Logic Circuit | 1. The Teensy microcontroller will be programmed to interface with the triggering mechanism, charging and discharging circuits, coil toggling circuit, optical sensors, display, and voltage monitoring circuit  2. It will also be programmed to send messages to the Serial monitor when the trigger is pressed, toggling circuits are enabled, or the optical sensors are stimulated, and to send voltage data to the display | All possible interactions with the control circuit are processed properly based on the criteria that each individual component must meet |
| 2 | Capacitor Bank | 1. The charging circuit, discharging circuit, and coil toggling circuit will all be tested in quick succession to confirm that they operate as intended when they are all connected to the capacitor bank | Each component meets its success criteria when in the combined subsystem |
| 3 | Coil and Barrel | 1. Activate the coil toggling circuit with a ferrous projectile placed within the barrel | The ferrous projectile exits the end of the barrel purely due to the magnetic force exerted by the coils. No other forces may be exerted on the projectile parallel to the barrel’s central axis during this test |
| 4 | Mechanical Integration | 1. Connect the electrical subsystem to the mechanical subsystem  2. Check that there are no exposed electronics and no points where an electric shock or other significant injury could be delivered | All electronics are contained within an insulative housing. An electrical shock cannot reasonably be delivered while using the device |

Table 4: Requirements Matrix

|  |  |  |  |
| --- | --- | --- | --- |
| **Ref No.** | **Requirement** | **Description** | **Test Metric** |
| 1 | Coil gun shall fire a 5/8" steel ball as a projectile | This requirement is set in the project description | Refer to Test 2-3 |
| 2 | Coil gun shall derive power from a 120V, 15A wall outlet | This requirement is set in the project description | Refer to Test 1-1 |
| 3 | Capacitor bank shall not exceed 32,000uF | This requirement is set in the project description |  |
| 4 | The voltage on the capacitor bank shall not exceed 400V DC. This must be verified using a measuring system | This requirement is set in the project description | Refer to Test 1-6 |
| 5 | Coil gun shall be portable and untethered from the AC-DC rectifier and charging circuit | A portable system would be more interesting to operators and spectators |  |
| 6 | Optical sensors shall be used to estimate the exit velocity of the projectile | Position data can be used to calculate the velocity so we can have telemetry about our system's performance. | Refer to Test 1-5 |
| 7 | Capacitor bank shall be de-energized when capacitors are exposed or immediately following a firing transient | De-energizing the high voltage source drastically reduces chances of injury. | Refers to Test 2-2 |
| 8 | During testing, the projectile shall be fired into an energy absorbing material | Reducing the chances of ricochet reduces the chances of injury due to the projectile |  |
| 9 | During testing, the charge level of the capacitor bank shall be verified in discrete energy steps leading up to a full charge | Charge data can be used to calculate the energy so we can have telemetry about our system's performance. | Refer to Test 2-2 |
| 10 | A non-inductive, resistive load shall be used to test the current draw on the bank. | The current output of the capacitor bank needs to be within a reasonable level for the safety and longevity of each capacitor. | Refer to Test 1-3 |
| 11 | The NRA safety rules shall be used to develop specific testing plans. | The NRA is an authority on safety that is relevant to the project |  |
| 12 | PPE such as safety glasses and closed toed shoes shall worn during operation. | PPE increases safety |  |
| 13 | Bystanders shall go through a safety briefing before the coil gun is operated. | A safety briefing increases safety |  |
| 14 | There shall be a system to prevent the capacitor bank being energized by unauthorized users | A "lockout" or safe firing system increases safety. |  |
| 15 | Input voltage shall be taken from a 120V wall outlet | Main firing power in the project is specified by the ECE department |  |
| 16 | Capacitance shall be no larger than 32,000 uF | A capacitance limit is set by the ECE department |  |
| 17 | Voltage across capacitors shall not exceed 500V | This limit ensures the capacitors will not be a safety hazard to the user |  |
| 18 | The Projectile shall be a 5/8" steel ball bearing | A projectile size and shape set by the ECE department |  |
| 19 | The Length of barrel shall not exceed 24" | A barrel length set by the ECE department |  |
| 20 | The Coil gun shall be portable and be able to fire without a tether | The coil gun needs to be easily moved |  |
| 21 | The Coil gun shall have no more than 12 individually controlled coil stages | A self-imposed limit has been set on the number of stages to keep this project within budget |  |
| 22 | Team shall practice safety while working on the coil gun's hardware | The hardware can present a danger during testing and should be handled with proper PPE |  |
| 23 | Coil gun operator and bystanders shall wear appropriate PPE and follow safety guidelines | PPE and Safety Guideline Plan developed by V&V team lead |  |

# Technical Approach and Results

## Final Design

There are many different functions which the electrical subsystem must perform to ensure safe and effective operation of the product. These functions include connecting/disconnecting from the power supply, charging/discharging the capacitor bank, measuring capacitor voltage, displaying system information, receiving the trigger signal, and firing the system. To accomplish these functions, the subsystem is broken up into several PCBs and devices which are shown below in Figure 1.

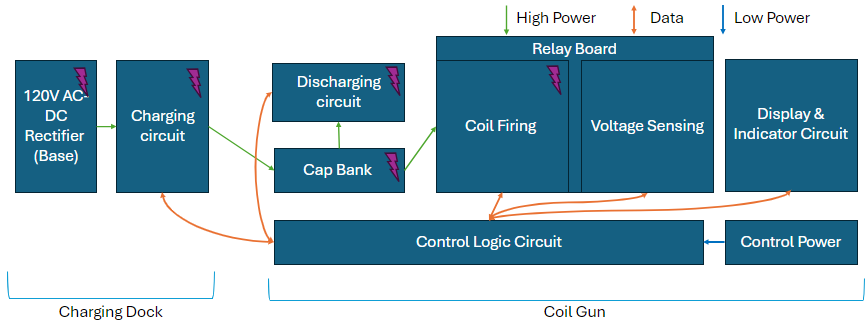


Figure : Block diagram of the electrical subsystem

Division of system functions was driven by safety and functionality. To increase the safety of the system, high voltage was isolated as much as possible from interfaces and contact points such as the charging dock connection. This interface in particular inspired the development of Relay Board which makes it so that the connectors do not have high voltage, greatly reducing the risk of electric shock. This board also handles discharging and voltage sensing because of its proximity to high voltage and power resistors in the system.

The Control Board handles several logic-level functions such as receiving the trigger signal, sending the fire, charge, and discharge signals, receiving voltage measurements, and displaying information on the LCD. The Charging Board interfaces with the power supply and receives the signal from the Control Board to charge the capacitor bank. The capacitor bank is housed on its own PCBs due to its size and copper requirements. Lastly, the Coil Boards house the coils themselves and MOSFETs to toggle current flow, flyback diodes to prevent large transients, and gate drivers for operating the FETs.

The control board consists of a Teensy 4.0 microcontroller, switching DC power supplies, and connectors to interface with other boards within the system, as well as the trigger and LCD. Power for the control board and other logic-level circuitry is supplied by an on-system battery. The schematic is shown below in Figure 2.

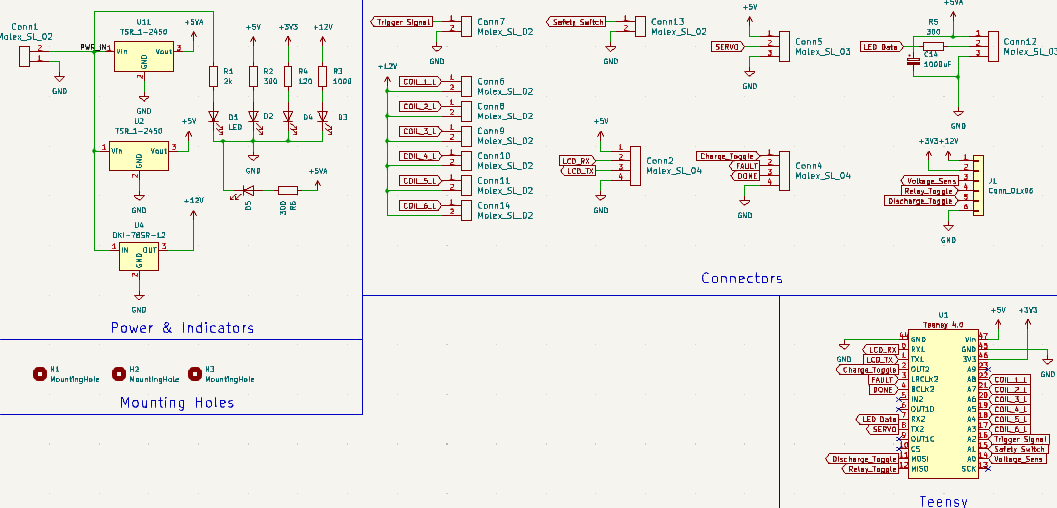


Figure : Control Board schematic

In revision 1, this board also contained the gate driver circuitry used to control the MOSFETS for toggling the coils. However, it was found that the distance between the control board and coil board creates a large inductance loop which causes ringing, distortion, and in severe cases, repeated toggling of the FETs, resulting in system failure. Because of this, the gate drivers were moved to the coil board for Revision 2. The Revision 2 board is shown below in Figure 3.

A green circuit board with white text

Description automatically generated

Figure : 3D model of Control Board

The AC-DC rectifier receives 120V, 15A, 60Hz from a wall outlet and converts it 24V DC for high-power systems within the gun. This supply is directly interfaced with by the Charging Board shown below in Figure 4.

A computer circuit board with many wires

Description automatically generated

Figure : Charging Board schematic

The primary functionality of this board is handled by the LT3751EFE#PBF charging IC. Most of the components on this board are external circuitry for the charging IC which receives the 24V supply and uses a transformer to increase it to much higher voltages for the capacitor bank. The remaining circuitry on this board is a set of switches for controlling the voltage level to charge to and interfaces. The Revision 1 board is shown below in Figure 5.

A green circuit board with many small objects

Description automatically generated

Figure : 3D model of Charging Board

Once the board was manufactured and tested, its operation was incredibly reliable. Thus, no second revision was required for the board.

The capacitor bank was divided into two large PCBs, each containing 16 1mF capacitors. This board is shown in Figure 6.

A group of black barrels

Description automatically generated

Figure : 3D model of Capacitor Boards

The Relay board utilizes two relays to cut off high voltage from the connections between the charging dock and the gun. Control of this is accomplished through a relay driver IC and a logic signal from the microcontroller. The board also has an N-Channel MOSFET and gate driver to low-side toggle the power resistors for safe, fast discharging of the capacitor bank. The power resistors are 4 1kΩ 150W resistors in parallel for an effective 250Ω of resistance. Lastly, the board contains a simple voltage divider and op amp buffer circuit for measuring voltage on the capacitor bank. The full schematic is shown below in Figure 7.

A computer screen shot of a diagram

Description automatically generated

Figure : Relay Board schematic

Apart from a new op amp which has the same package as the original one chosen, the Revision 2 board is essentially the same as the first revision. The final board is shown below Figure 8.

A green and black circuit board

Description automatically generated

Figure : 3D model of Relay Board

Finally, the Coil Boards contain the coils themselves and the circuitry necessary to toggle them. Two N-Channel MOSFETs with large heatsinks are utilized to handle the amount up to 800A instantaneously traveling through the coil. A gate driver is used to control them and an in-line resistor is used to prevent over-currents from damaging the gate driver. Flyback diodes are used in parallel with the coil to prevent large negative voltage swings from damaging the FETs. Lastly, a 1uF capacitor is placed between power and ground to reduce the inductance loop in the system. The schematic is shown in Figure 9.

A diagram of a circuit board

Description automatically generated

Figure : Coil Board schematic

As mentioned previously, the gate drivers were initially on the Control Board. However, inductance loops forced the team to move these to the Control Board instead. The first revision also featured a Y-rated capacitor and separated ground planes. However, voltage referencing issues caused this to be removed. The 1uF capacitor was also added for the second revision. The final board is shown below in Figure 10.

A green circuit board with black and red components

Description automatically generated

Figure : 3D model of Coil Board

Other standalone components include the trigger which is used to fire the gun, and LCD which displays voltage measurements, copper bus bars for connecting high current devices, and the barrel for containing and directing the 5/8” steel ball projectile. Wires and other interfacing components are also present.

The Relay Board and up to six Coil Boards are designed to mount directly to copper bus bars to ensure plentiful ampacity. Capacitor boards mount to the sides of the gun, power resistors mount to the top, and the Control Board sits in the stock. The mechanical housing is fully 3D printed and contains the previously mentioned boards, as well as the barrel, trigger, LCD, and necessary connections. Because the mechanical subsystem was designed after Revision 2 boards, no changes were required following the initial design.

Finally, the software subsystem consists of a Teensy 4.0 running C++ embedded software. Prior to charging, the Teensy awaits a signal sent by the operator. Upon receiving this signal, an interrupt-based program causes the Charging Board to be enabled, thereby charging the capacitor bank to 100V, 200V, or 380V depending on the operator’s selection. The Teensy receives voltage measurements from the Relay Board and displays them by on the LCD using UART communication. Percent charge is also displayed. In this state, the gun can either be discharged or fired. If a discharge command is received, The Teensy sends a signal to Relay Board to enable the power resistors. If the trigger is pressed, another interrupt is enabled which then performs the firing sequence. Here, a pulse on the order of 100us is sent to each Coil Board with a short delay in between to quickly toggle their MOSFETs and discharge a small amount of the capacitor bank through each stage. This causes each stage to increase the acceleration of the projectile, thereby firing the gun. Following this sequence, the discharge resistors are enabled to remove any excess charge on the gun.

The final product is shown below in Figures 11 and 12.

A machine on a table

Description automatically generated

Figure : Coil gun housing

A machine with many parts on it

Description automatically generated

Figure : Internal components of coil gun

## Results

Basic unit-testing was required for every PCB made, involving testing for continuity between pins that were supposed to be connected and discontinuity between pins that were not supposed to be connected. Once connections were verified, a board would be powered and the proper voltages were to be verified at all connections throughout the board. After these basic tests were performed, the boards would be deemed ready for subsystem-level testing.

The first subsystem-level testing that occurred was performed on the charging board. This was necessary because the functionality of this board was necessary to perform system-level testing. Without the charging board, there was not a good way to charge the capacitors to 100+ Volts. The charging board testing began with flipping the DIP switches on-board so that it was configured to charge to 100V. The output of the board was connected to an oscilloscope so the output waveform could be viewed and compared to that which was given in the datasheet for the charging integrated circuit (IC) used. The charging board was then connected to the power supply, configured to 22V. Once the output was verified, one 1 mF capacitor was connected to it, to verify that it would charge. However, charging did not work immediately. The voltage on the output began to rise, but quickly fell and stayed low. After probing the error and undervoltage/overvoltage protection pins, it was determined that the IC was entering its overvoltage state, so the power supply was configured to output its minimum voltage (~20.9V). The overvoltage biasing resistors were then replaced to account for a higher voltage threshold. The undervoltage biasing resistors were also replaced to allow the input voltage to swing lower. Once these modifications were completed, charging to 100V was attempted again and was successful. The board was then configured to charge to 200V and tested. This was followed by a 380V test. Both tests were successful.

Once the charging circuitry was working properly, the next step was to verify the discharge circuitry. However, the discharge circuit was broken due to the board being powered before an unpowered unit test was completed. Because of this, discharging was initially performed by using a benchtop power supply to toggle a relay that would connect the capacitor(s) to the discharge resistor bank. This was quickly verified by connecting 15V to the switching side of the relay and measuring a change in voltage across the resistor bank once the coil side of the relay was connected to the power supply.

Initial subsystem-level testing began with a setup including the charging board, one 1 mF capacitor, 1 coil board, the control board, the barrel, and the 5/8” steel ball. For these tests, the charging board was, at first, configured to charge the capacitor to 100V, then the control board was programmed to toggle the MOSFETs on the coil board for 1 microsecond. This testing resulted in the explosion of one of the diodes in the control board, leading to a pause in testing and reconsideration of the design. It was shortly after this that revision two hardware for coil board, relay board, and control board began development.

Once revision two hardware were developed and manufactured, their associated unit tests were performed. After this, the team began full-scale testing again, connecting charging board, sixteen 1 mF capacitors via capacitor board, control board, relay board, a coil board, the bus bars, and the discharge resistors, and the trigger. The charging board was once again configured to 100V, and the control board was programmed to turn on the coil board MOSFETs for 10 microseconds. To verify the charging voltage, a multimeter was connected to the bus bars. To verify other voltages within the system oscilloscope probes were attached to the power net, the drain of the MOSFETs, the gate of the MOSFETs, and the control signal for toggling the MOSFETs. With the voltage on the power net and the voltage on the drain of the MOSFETs the oscilloscope was used to approximate the current passing through the coil via the equation . This testing proved to successfully toggle the current through the coil at the desired interval, so the on-time for the transistors was increased until 100A was reached. At this point, the charge voltage was increased to 200V, and the process was repeated. Then the charge voltage was increased to 380V, and the oscilloscope was disconnected from the power nets to avoid damaging the oscilloscope. This entire process was then repeated with the entire capacitor bank.

The main issue discovered during this testing was that once the current spiked to over 100A, both MOSFETs on the coil board failed short, dumping all the power out of the capacitor bank. After a few failed attempts at getting the system to work, several MOSFETs had been destroyed and the team was left with less than the amount that were required to fully populate 6 coil boards, so the design was, once again, reevaluated. It was determined that the system should be working at more than 100A, so more MOSFETs were purchased. In addition, the team gained access to the use of a current probe so the current through the coil could be accurately measured.

After acquiring the current probe, the same setup as before was put together, and similar testing was performed. For this testing, the capacitor bank was charged to 380V and the on interval for the MOSFETs began at 10 microseconds. After a successful test at 10 microseconds, the on-time was stepped up to 40 microseconds, but at that point, the MOSFETs began to fail with some very odd results. The waveform can be seen below in Figure 13. This same result repeated itself multiple times, so it was determined that something was inherently wrong with the system or test setup, but it was not determined what exactly that problem is.

A screen shot of a graph

Description automatically generated

Figure 13: Results from failed MOSFET tests

# Management

## Project Milestones

Appendix 1 shows the Gantt chart for the project. Each sub-system had a unique set of steps to take it through a design phase, through manufacturing, and finally to the verification and validation phase.

In February, many delays in PCB manufacturing were caused by Lunar New Year which effectively pushed back the entire schedule. Great efforts were made in the following weeks to make up for lost time. Additionally, as with many projects, integration of components and subsystems took much longer than expected, further delaying the schedule. By the time of the Poster Presentation, there was not enough time or money to redesign components to fix known issues. Because of this, the deadlines for system-level testing and integration could not be met.

## Encountered Challenges and Lessons Learned

* Alex: Some challenges Alex faced were mainly time commitment conflicts. He is heavily involved on the Mars Rover Design Team and thus has a large time commitment that was set before senior design started. Therefore, he could not put as much time as he would have liked toward senior design.
* Evan: During this project the main challenge Evan faced was the large number of parts that needed to be designed. Balancing the entire mechanical design of the coil gun while maintaining other curricular activities quickly became an obstacle. The solution to this problem was to find external help with the creation of the parts. Another member of the Mars Rover design team was able to help review and design some critical parts to relieve this burden.
* Brady: Most of Brady’s issues revolved around managing his time between involvement in the Mars Rover Design Team and working on the project. This resulted in several weeks were Brady was unable to put more 10 or more hours into coil gun development.
* Grant: Grant’s primary challenges were a result of outside time commitments. He was heavily committed to work on the Mars Rover Design Team, as well as maintaining a 4.0 GPA, which reduced the amount of time he could spend on the project.
* Max: Max’s primary challenges were facing time commitment issues. As a student worker in the department of Admissions, as well as the Peer Mentor for the Student Design Center, he found himself working many problems at once. Completing more deliverables earlier on in the design cycle (i.e. in the first semester) would have helped push the project along further.

Some team-wide challenges were a lack of high-power design knowledge and the initial scope that was set by the team. After the team's first attempt at controlling high power went poorly the team contacted Dr. Kimball to review our current designs and advise the next revision of boards. As for the large scope that was set the team increased budget many times through many sources and even went to the university with a proposal to gain more money which was successful.

## Team Ethics Discussion

Over the course of this project, our team has worked well together. Given most of us have worked together previously, we have a good sense for how to collaborate fairly while also effectively. Regular meetings were held weekly to decide on part choices, integration, circuit theory, and many other pertinent subjects for the design of the coil gun. During these discussions, it was always important that we let each team member have input on the decision-making process to foster a good team environment. When an idea was presented in the group, first the team would pause and analyze the practicality of the idea. Then, once the team agreed, we would either simulate or integrate the new idea into our design or continue to brainstorm. One such example is how we decided to handle charging with our project. One team member pitched the idea of using a specific charging IC. Since integrating this particular IC would be a new experience for all of our team members, each team member vocalized their concerns. Through these questions and disagreements, we realized the other options presented would be less efficient and more costly. The comparison we drew from these concerns raised by others on the team helped us further flesh out our design but also continue in agreement.

## Budget

Below is the original budget for the project.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Quantity** | | **Unit Price** | | **Total Price** | |  | **Notes** |
| Item Name | Min | Max | Min | Max | Min | Max | Lead Time |  |
| Capacitors | 32 | 32 | $13 | $13 | $400 | $400 | purchased | 400V, 32mF |
| MCU | 1 | 1 | $33 | $33 | $33 | $33 | purchased | Teensy 4.0 |
| Transistors | 5 | 20 | $0.5 | $5 | $10 | $25 | available | partial |
| Diodes | 8 | 16 | $0.3 | $2 | $5 | $16 | available |  |
| Power Supply | 1 | 1 | $15 | $30 | $15 | $30 | available |  |
| Capacitor Charger | 1 | 1 | $12 | $18 | $12 | $18 | available |  |
| Photo-Sensors | 1 | 8 | $3 | $6 | $6 | $24 | available | partial |
| Batteries | 2 | 4 | $1 | $5 | $4 | $10 | available |  |
| Magwire | 1 | 5 | $15 | $30 | $30 | $75 | available |  |
| Housing | 1 | 1 | $150 | $200 | $150 | $200 | available |  |
| Trigger | 1 | 1 | $11 | $11 | $11 | $11 | purchased |  |
| Safety | 1 | 1 | $5 | $5 | $5 | $5 | purchased |  |
| Servo | 1 | 1 | $3 | $3 | $3 | $3 | available |  |
| LCD | 1 | 1 | $25 | $26 | $25 | $26 | purchased |  |
| Total |  |  |  |  | $709 | $876 |  |  |

Table 5: Budget (updated 12/07/2023)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | SKU | Qnty | Cost | Total |
| Capacitor | ALF70C102EH400 | 32 | $12.37 | $395.84 |
| MCU | Teensy 4.0 | 1 | $33.24 | $33.24 |
| LTEAD | Multiple items | 1 | $25.56 | $25.56 |
| Amazon | Multiple items | 1 | $24.34 | $24.34 |
| Amazon | Multiple items | 1 | $21.27 | $21.27 |
| Bambu | Multiple items | 1 | $132.95 | $132.95 |
| JLCPCB | custom | 1 | $208.63 | $208.63 |
| Coil FETs | FDL100N50F | 12 | $16.60 | $199.20 |
| PCB Components | 584-LT3751EFE#PBF | 6 | $10.97 | $65.82 |
|  | 284-HS1501KJ | 4 | $11.11 | $44.44 |
|  | 579-MCP1416T-E/OT | 25 | $0.62 | $15.50 |
|  | 80-ESK108M6R3AG3AA | 2 | $0.34 | $0.68 |
|  | 80-ESH108M035AL3AA | 3 | $0.70 | $2.10 |
|  | 187-CL31A106KAHNNNF | 10 | $0.12 | $1.21 |
|  | 80-R60QF14704001K | 10 | $0.31 | $3.07 |
|  | 78-VS-8EVL06-M3/I | 5 | $0.59 | $2.95 |
|  | 588-WA-T220-101E | 3 | $2.15 | $6.45 |
|  | 942-IRF540ZPBF | 5 | $0.93 | $4.65 |
|  | 667-ERJ-3EKF4022V | 10 | $0.02 | $0.19 |
|  | 71-CRCW060318K2FKEAC | 10 | $0.02 | $0.16 |
|  | 603-2512FKE7W0R08E | 10 | $0.52 | $5.21 |
|  | 655-2454982-2 | 2 | $0.96 | $1.92 |
|  | 994-GA3460-BL | 2 | $20.34 | $40.68 |
|  | 621-1N5408G-T | 40 | $0.28 | $11.32 |
|  | 588-WV-T264-101E | 15 | $2.26 | $33.90 |
|  | 726-BTS3800SL | 3 | $0.95 | $2.85 |
|  | 769-AECN11012 | 3 | $38.77 | $116.31 |
|  | 844-IRF740ASPBF | 3 | $2.28 | $6.84 |
|  | 71-CRCW2512649KFKEG | 5 | $0.37 | $1.85 |
|  | 71-CRCW25125K60FKEG | 5 | $0.38 | $1.90 |
|  | 494-MCP6497T-E/SN | 3 | $0.76 | $2.28 |
|  | Shipping | 1 | $10.69 | $10.69 |
|  | Tax Est | 1 | $23.87 | $23.87 |
| Magnet Wire | 16SNS10 | 1 | $129.27 | $129.27 |
| Bus Bars x2 | 7354\_24\_0 | 1 | $83.29 | $83.29 |
| Barrel | 9176T3 | 1 | $6.00 | $6.00 |
| Fasteners |  | 1 | $100.00 | $100.00 |
| 2nd Rev Boards |  | 1 | $300.00 | $100.00 |
| TOTAL SPENT: |  |  |  | $2,166.43 |

Table 6: Budget (updated 5/10/2043)

Overall, most of the difference between the estimated budget and the actual budget comes down to research and development for different technologies to have the coil gun project meet the set requirements. As the scope was initially set for a complete system, as opposed to a proof of concept like some of the other teams, the budget had to expand several times to accommodate the necessity of new components and to offset damaged components during testing. Subtracting from the R&D components, the initial budget holds true, and the sub $1000 price is consistent with original project projections.

## Funding Source

The initial project budget of $400 came from the Department of Electrical and Computer Engineering. Following this, each team member donated $120. The first semester poster presentation prize of $200 was put towards the project as well. Team members’ parents were contacted in an effort to provide additional funding. Parent donations combined to $700 from various sources. Finally, an additional round of department funding was secured for $300. This put the final budget at $2200.

## Human Safety Assessment

There are several risks towards operators, bystanders, and other humans associated with the project with varying likelihood and severity. These risks are shown below:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Catastrophic (5) | Mechanical failure of body |  | Electrical shock at max charge |  |  |
| Major (4) | Projectile impact on human | Capacitor explosion | Shorting capacitors |  |  |
| Moderate (3) |  |  | System overheat |  |  |
| Minor (2) |  |  |  | Solder burn during fab |  |
| Insignificant (1) |  |  | Fumes from 3D printing |  |  |
|  | Rare (1) | Unlikely (2) | Possible (3) | Likely (4) | Almost Certain (5) |

Table 7: Human Safety Risk Matrix

There are some risks that are posed to both the operators of the coil gun, as well as any observers or bystanders. The table below covers the potential effects of each risk, as well as mitigation plans for each risk.

|  |  |  |
| --- | --- | --- |
| Risk | Effects | Mitigation Plan |
| Electrical shock at max charge | * Severe injury or death | Double walled enclosure of high voltage components. Operator training. Safety switch on system. |
| Shorting capacitors | * Major energy release | Cover terminals in insulating material. |
| System overheats | * System malfunction or damage | Ensure proper cooling and heat dissipation for electronics. Regulate high voltage energy dissipation. |
| Capacitor explosion | * Release of harmful gas | Rigorous testing of capacitors’ limits and enclosure to limit gas and temperature effects. |
| Solder burns from fabrication | * Personnel injury * Damage of components | Enforce safe soldering practices. |
| Mechanical failure | * System malfunction or damage * Exposure of high voltage systems | Limit testing system before electrical integration. Remote trigger system used during testing to allow for ample personnel separation. |
| Projectile impact on human | * Personnel injury or damage | NRA gun safety rules shall be followed during operation. |
| Fumes from 3D printing | * Personnel injury | 3D printing shall be done in a well-ventilated room. |

Table 8: Human Safety Risk Mitigation Plans

## Member Credentials and Responsibilities

### Teamwork

To design a system that performs to these standards, the team of engineers on this project had to exhibit expertise in multiple fields of study. Starting with Evan, who has experience with mechanical design and was responsible for the structural basis of the system, this project required a mechanical design that could integrate the designed parts while maintaining functionality and portability. He used finite element analysis, materials sciences, and computer-aided design to complete the mechanical design of the coil gun. Developing the hardware required knowledge of circuit development/analysis, as well as working with integrated circuits and other off-the-shelf components that were used in the design. Grant and Brady both have plentiful experience in this realm, including the debugging and testing of custom hardware. The hardware required a software element to enable full functionality. C++ was used to allow for rapid analysis and response of feedback from the rest of the system. Alex lead the software design because of his experience with creating and testing embedded code from multiple design teams/internship experiences. Finally, the creation of a coil gun is inherently a dangerous project. Care was taken to minimize the harm to its users and any bystanders. This device is only intended to serve as a demonstration of electromagnetic principles and will not be used to injure anyone. Max lead development of testing plans, safety standards, standard operating procedures, and validation tests to ensure that the process of creating a coil gun was not only safe but could be evaluated for constant feedback.

While the team has a solid background in many multidisciplinary areas, this project presented challenges that push the team members outside of our comfort zones. Designing around high-power applications was one of the first challenges the team faced. While most dangers are self-evident when working with high voltage, some design requirements such as isolation for the microcontroller and signaling systems exposed a knowledge gap in our team. Eager to bridge this gap, we met with Dr. Kimball to discuss what potential mistakes in design we could have made and what pitfalls to look out for. Additionally, our team was not experienced with newer IGBT technology, and we initially struggled with integrating and properly driving these hybrid parts. After a failed testing session, we decided to split ways and conduct independent research on potential problems and through our studies we were able to find potential solutions for toggling these parts. Although we have not fixed every issue with our project, we have learned how to better approach and learn newer technologies and subjects.

### Brady Davis:

**Member profile:** Mr.Brady Davis will serve as the team lead for the project as well as the power electronics lead. Brady has experience in developing both hardware and software for several different projects for the Mars Rover Design Team. He has also designed and tested hardware for Garmin Ltd. And Chamberlain Group LLC as an intern. Brady will be in charge of ensuring that team meetings occur on a regular basis and outside of the normal schedule when necessary. He will also ensure that reasonable progress is being made towards the completion of the project as defined by the Gantt Chart. Brady will also keep track of the team budget. As the power electronics lead, he will distribute the design of the power system as necessary, hold meetings as necessary, and ensure the success of the power system through design reviews.

### Grant Brinker:

**Member profile:** Mr. Grant Brinker has PCB design experience from the Mars Rover Design Team and Caterpillar, Inc. He was responsible for the design of the control hardware and ensuring that control hardware integrates with the power electronics, embedded software, and mechanical system properly. He assisted in designing and manufacturing the Coil Boards and performed unit testing on all Coil Boards. Grant also conducted preliminary calculations and theoretical analysis for design of the system using MATLAB, as well as time and frequency domain analysis of experimental results obtained during testing sessions.

### Evan Seabaugh:

**Member profile:** Mr. Evan Seabaugh has electrical and embedded design experience from his two internships at Hunter engineering and DE design works. He has also been a part of the Mars Rover and formula electric design teams. In his free time, he has taken on serval projects including modifying 3D printers and automating a garden. He will be responsible for the mechanical design of the coil gun. This consists of designing and manufacturing the body of the coil gun, mounting brackets, and providing a base for all subsystem components to fit to.

### Maxwell Ryan:

**Member profile:** Mr. Maxwell Ryan will serve as the Verification and Validation lead for the project. He has circuit/PCB design, manufacturing, and integration experience through the Mars Rover Design Team. He also has had cross-disciplinary leadership experience and incident management experience through MRDT as well. Additionally, he has had practice in safety protocol integration, functional safety process compliance, and validation process development from two internships with Caterpillar Inc. As the V&V lead, Max oversaw developing test plans and enforcing safety standards, aided in experiment set-ups and design, and worked in manufacturing.

### Alex Wortmann:

**Member profile**: Mr. Alex Wortmann has embedded code experience through the Mars Rover Design Team and Caterpillar Inc. He will be mainly responsible for embedded code and integration with electronics hardware. This will consist of holding meetings about software requirements and deadlines. He will be in charge of communicating with hardware leads to ensure that software integration with hardware will go according to plan. He will also be assisting in the electrical hardware, and mechanical design.

# Conclusions and Future Work

## Conclusions and Lessons Learned

During the implementation of this project, many issues were found, many of which were solved and some remained unsolved. Many of these issues stem from the design choice of using MOSFETs as a power toggling system. During testing many MOSFETs were damaged or destroyed, causing delays in the project timeline. The group learned many lessons from dealing with the MOSFET issues. The main lesson learned was that even though things work in theory and simulation that is not always the case in physical testing, that's why testing is important. The group also learned to reach out and use resources available to them, whether that be the internet or those more knowledgeable on a subject. Throughout this project many of the more basic issues encountered would have been caught or thought about through design reviews with more knowledgeable people.

Overall, the team is satisfied with the result of this project. Although the product ended up not working, the experience and knowledge gained is much more important. The team worked well throughout the year to attempt to push this project to completion. Although a large amount of time was spent on this project, most team members’ time commitment was limited by other commitments with outside organizations. The team considers the project a success because of the experience gained, even through the product was not a success.

## Suggested Improvements

Given an additional 6 months of development, the team would begin with further fundraising and research into switching methods for the coils. Many problems experienced were due to MOSFET failures. Therefore, looking into IGBTs, solid-state relays, and other switching methods stands as a promising avenue to take for further development. Effort would also be placed into better isolation between logic-level components and high voltage and current to create a safer and more robust system.

Once switching of the coils, and more importantly, movement of the projectile, can be achieved safely and reliably, testing efforts would be shifted to working on timing and getting all six coil stages functioning well. Finally, full system assembly would occur, and regular system testing would commence. A 3D printed housing would be created for the charging dock as well to improve the aesthetic quality of the full product, thereby achieving the final goal of creating an effective demonstration tool for the ECE Department.

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