Final Review and Conclusions of the Pistol Recoil Simulator

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April 30, 2024

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Executive Summary

A common issue in the firearms industry is testing products, which is difficult for two reasons: the forces involved in firing a gun are immense and the cost of ammunition is very high. For companies that manufacture firearms, there is no easy way around the issue of testing since the guns themselves must be shot to be properly tested. Companies that make gun accessories, such as optics, can test their product without a firearm; however, when the gun is taken out of the testing environment, it results in inaccurate tests, especially when testing pistols. To solve this problem, the Test Rig Capstone team, consisting of James Blaine, Megan Montgomery, Jarrett Sech, Gabriel Turbay, Alexis Urquhart, and Alan Wagner, will work with sponsors SATOP and Sellmark to create a device that can accurately simulate pistol recoil. SATOP is a state-funded initiative that helps connect companies with Capstone teams and is the channel through which Sellmark was able to propose this project. Sellmark is a company focused on outdoor products such as optics and tripods, with six different brands under its umbrella.

For a solution to be considered successful, Sellmark has several criteria that the team needs to meet. The most important requirements include hitting the minimum acceleration of 700 G's horizontally, simulating both horizontal and rotational recoil, and having good repairability to ensure the machine has a long lifespan. After using several techniques to aid in idea generation and design selection, the team decided to move forward with a spring-powered force generation system that impacts a pistol-simulating mount. The entire assembly will consist of an enclosed table, a force-generating mechanism, an accessory mounting system, and an electrical system. These components will work together to ensure reliable operation without complicated maintenance, as seen in Figure 1.

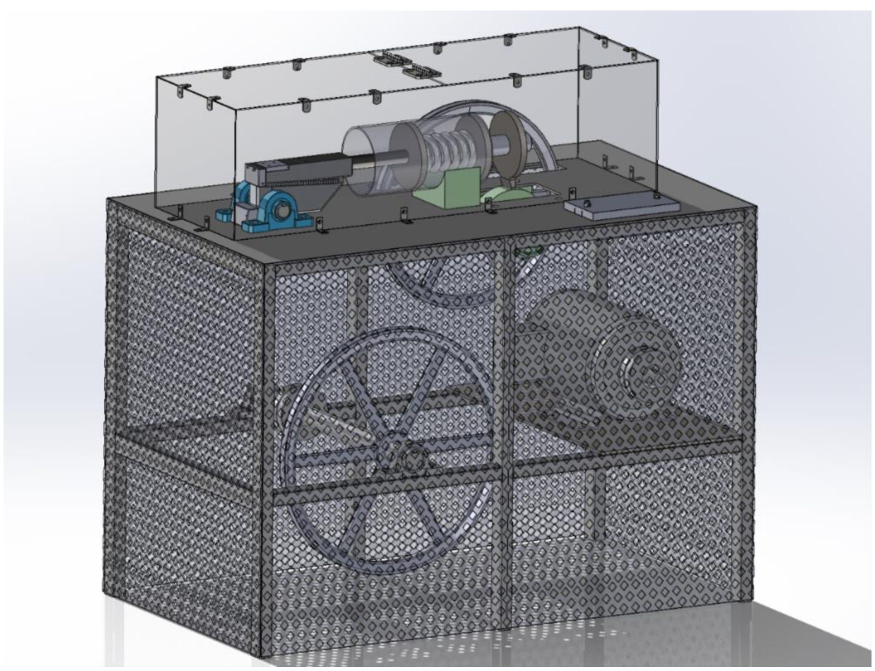

Figure 1: Final Assembly of Pistol Recoil Simulator

The force generation system will operate using a cam and spring system powered by an electric motor. This motor will use four belt pulleys to transfer force to the cam, which will then push against a plate. These pulleys will be geared for torque, to ensure the motor is powerful enough to compress the spring. The spring will be housed in an enclosed cylinder so, in case of a spring failure, spring shrapnel will be contained. At the front of the spring will be a front plate and striking rod, which will collide with the optic mounting system. The mount is designed to convert the linear force of the striking rod into two axes. This is achieved with a pivot and slide mechanism that will move similarly to a firing pistol upon impact. The mounting mechanism is also designed with modularity in mind, allowing for easy switching between different mounting patterns. In addition, worn parts such as the spring are easily swappable to reduce maintenance. The entire system will be powered by the electrical subsystem and mounted to a custom-welded table designed to house the assembly. The electrical system will be controlled by an Arduino and has robust fail-safes in place to prevent any injuries to the user.

Following the initial completion of the design in the fall semester, several updates were requested as issues were found. These issues were identified through a combination of sponsor feedback, observations in the CAD, and the construction of a full-scale mounting prototype. The biggest changes include adding a sleeve bearing to the back plate of the force generation system to prevent jams, switching from sprockets and chains to pulleys, shortening the mounting system to better replicate the recoil force when firing a pistol, and implementing a linear slide to the mount for smoother operation.

To help inform both the changes implemented above and to catch any future issues in manufacturing and assembly, the team used several risk analysis techniques. The first of these is a Failure Mode, Effects, and Criticality Analysis (FMECA), which is a standardized method of identifying potential failure points and assigning them scores for perceived impact and importance. With this method, the team identified a few key failure points to address: the frame's joints, the direction of force exerted by the cam, the spring compression distance, and the reset time of the mounting system. To determine how to address these issues, three other risk analysis methods were used: Fault Tree Analysis, Five Whys, and Fishbone Analysis. These analysis tools are more geared toward identifying the causes of failure points rather than determining what the failure points will be. Fault Tree Analysis uses a top-down approach to break down a high-level failure point to its root causes. For example, friction between the slide and base could be caused by poor tolerance. Five Whys takes a simpler approach; for every event, ask "Why did this happen?" When building the mounting prototype, several issues were encountered and the five whys were used to determine the causes of these failures and correct them. Lastly, the Fishbone Analysis identifies factors causing an overall effect by categorizing different aspects of the higher-level function. This was used to identify the underlying issues that led to the back plate of the mounting system not fitting properly.

Following risk analysis, construction of the system began, which was not without significant challenges that needed to be overcome. For the force generation system, many of the parts were submitted to the FEDC to be water jetted to ensure they were made to the team's specifications. The first big issue encountered was trying to attach the aluminum cylinder to the steel mounts. The original plan was to weld it, but upon consulting with FEDC staff, the decision was made to drill holes and use screws to mount it instead. Another issue came when attaching the steel back plate to the aluminum cylinder. Similarly to mounting the aluminum cylinder to the steel mounts, welding would not work, so a new back plate was made from aluminum to weld to the cylinder. Lastly, there were challenges when fabricating the threaded center rod. The 1/8' thread was too large for any taps that were available in the FEDC, so the threads had to be made manually on a lathe. For the table, the structure was hand welded, with the biggest setback being that the wrong length of steel was ordered so a section of the table had to be cut out and re-welded. When making the mounting, the largest components were submitted to be CNC milled, while the smaller parts were hand milled. When submitting the parts to be machined, a few small changes were made to accommodate the capabilities of the machine shop. Lastly, the electrical system was implemented within a 3d printed housing, and all the wires were soldered together and packaged inside.

Having constructed the system, the individual parts needed to be verified. For the table, a load was placed on the center and it was visually examined for any signs of stress, which it passed. The mounting system also functioned as expected, and a fit-check was performed to ensure all the parts moved smoothly and without friction. The force generation was tested to ensure that it could move as intended without a spring inside. It initially failed the test, but the problem was addressed with a threaded rod support and it was then able to pass. Lastly, the electrical systems were tested to ensure that the Arduino, VFD and motor were all wired and operating correctly. The test was successful, with the motor responding quickly to commands.

Despite passing the verification tests, the system still does not meet multiple design requirements that were set by Sellmark. These issues can be addressed with a few modifications that can be performed after delivery. In addition, the team will continue to correspond with Sellmark over the coming week to ensure they have the information necessary to operate and maintain the test rig.

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Glossary

Abbreviation/Variable	Definition
a_m	Desired Acceleration of the Mount
AC	Alternating current
ASME	American Society of Mechanical Engineers
bpm	Beats Per Minute
CAD	Computer Aided Design
COTS	Commercial-off-the-shelf
DC	Digital current
E-OFF	Emergency Off
FEDC	Fischer Education Design Center
FMECA	Failure mode, effects, and criticality analysis
FRE	Free recoil energy
FTA	Fault Tree Analysis
Grain	Unit of weight (1 grain = 0.065 gram)
HOQ	House of Quality
Hz	Hertz
IIAE	Independent, Intuitive, Averaged Evaluation Matrix
k	Spring Constant
m_m	Mass of the Mount
m_s	Mass of the Striking Rod
OSHA	Occupational Safety and Health Administration
PRS	Pistol Recoil Simulator
RPN	Risk priority number
SAE	Society of automotive engineers
SATOP	Space Alliance Technology Outreach Program
SNPS	Solution Neutral Problem Statement
t	Time
V_E	Velocity of the projectile in feet per second
V_{PG}	Velocity of propellant gases in feet per second
VFD	Variable frequency drive
W_{BS}	Work Breakdown Structure
W_{SS}	Weapon Shock Simulator
W_E	Weight of projectile in grains
W_F	Weight of firearm in pounds
W_{PG}	Weight of propellant gases in grains
x	Distance the spring is compressed

Introduction

Team Introduction

The second semester of the Texas A&M Mechanical Engineering Capstone allows students the experience of working on a full design, build, test cycle in teams of six. The SATOP Test-Rig Capstone team consists of six members: James Blaine, Megan Montgomery, Jarrett Sech, Gabriel Turbay, Alexis Urquhart, and Alan Wagner. The project was sponsored by two groups: SATOP and Sellmark.

SATOP is a Texas-funded initiative that "provides technical assistance to small businesses [and] start-ups" [1]. They support companies by discussing problems and requirements. From there, they provide a 40-hour technical assistance program or connect them to a Texas A&M Capstone Design team. The initial consultation is free and increases a company's chance of solving their engineering problems.

Sellmark is an outdoor products company. Their motto is "We are dedicated to building Brands That Sell" [2]. They are the owners of six brands: Sightmark, Pulsar, Firefield, Kopfjaeger, Bullet Safe, and Inforce. Most of their products focus on gun optics and accessories, such as lasers, night vision, and scopes. Consequently, they must test the quality of the accessories to ensure they will last through the forces of recoil, the backward force felt when shooting a gun, through the duration of their warranty.

Problem Introduction

Sellmark currently owns two recoil simulators. These simulators use the energy generated by two compressed springs in parallel to create an impact force on a strike plate. Though these simulators are sufficient when recreating a rifle's recoil, they cannot reproduce the high rates of acceleration seen during pistol recoil. The test rigs also only move in a straight line, whereas pistols move backward in a line and rotate around a point. Because of this difference, Sellmark must go to the shooting range to fire up to 3,000 rounds to test pistol optics, which is time-consuming and expensive. Though they have searched, they have not found any currently existing systems to replicate pistol shock.

Sellmark and SATOP have asked the capstone team to design, build, and test a pistol recoil simulator to accurately test their pistol optics for warranties. Sellmark requires that the pistol recoil simulator can test three thousand times the Earth's gravitational acceleration every second. The test rig should house a variety of gun accessories. After discussing the problem statement and requirements with Sellmark, SATOP, and Texas A&M professors, the team believes that the expectations are reasonable if the target acceleration is minimized due to safety concerns when testing the simulator.

Solution Neutral Problem Statement

The SNPS for the Texas A&M capstone team is as follows:

"Build a device that will recreate the shock of pistol recoil to test the quality of optics and other accessories."

Initializing The Design

After creating their solution-neutral problem statement, the team conducted research on what makes the pistol's recoil more aggressive than a rifle, as well as what current test rigs are on the market. At the same time, the team was talking with the sponsors to make needs and requirements tables, to have numerical goals and constraints. Once the research and requirements were completed, the team could then proceed with idea generation and concept selection.

Background Research

Physical Concepts

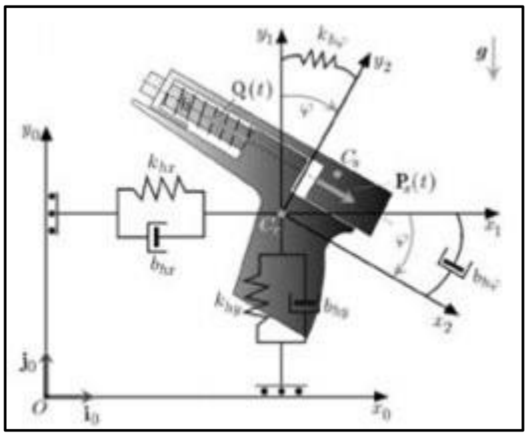

Figure 2: Free Body Diagram of a Fired Pistol [3]

The team began their research by determining the difference between pistol recoil and rifle recoil. Because of the weight and method of holding, recoil forces cause a pistol to pivot around a shooter's wrist, as well as move backward. However, in rifles, recoil forces typically only force the firearm backwards into the shoulder. A pistol's movement is seen in a free body diagram in Figure 2. The two reactionary forces cause optical accessories to experience a large shock force after the bullet is fired, found through Equation 1.

Equation 1

$$FRE = \left(\frac{W_F}{64.34}\right)\left(\frac{W_E V_E + W_{PG} V_{PG}}{7000 W_F}\right)^2$$

Market Research

There are current products on the market used to simulate the recoil of various guns. The researched products include the Re:Test weapon recoil shock simulator [4], the Leonardo DRS Weapon Shock Simulator [5], and the Laser Shot Simulations gas apparatus [6]. These products are capable of recreating rifle recoil. However, they either can not reach the initial shock or recreate the proper movement to simulate pistol recoil.

Outside the recoil simulator market, the team found that jackhammers can reach the speeds and forces needed for this solution. Rammer hammers utilize a hydraulic system to return over 16,000 lbs up to 645 bpm [7]. They also minimize sound output, reducing potential long-term eardrum damage [8]. After further research, however, it was concluded that hydraulic machinery is too expensive to operate and maintain and is prone to leaks.

Summary

Though there are recoil simulators that can be used to simulate gun recoil, none of them meet all of Sellmark's needs. The simulators on the market do not account for the rotational motion or acceleration needed to accurately test pistol accessories. There are potential solutions found in other markets, but the current budget does not allow for these more expensive alternatives.

Customer Needs Analysis

Upon assignment of the project, the team received a preliminary information packet from Sellmark. These documents, as well as the initial meeting needs analysis interview with Sellmark and SATOP, were used to create a list of customer needs. The first iteration, seen in Appendix

Appendices

A. 1, varies from the needs determined in January of 2024. Table 1 shows the up-to-date needs, along with an importance rating for each need. The ratings are on a scale of 1-5, with 1 meaning they would appreciate it but it is not necessary, and 5 meaning the features must be met for the project to be considered a success.

Table 1: Final Needs Table for Pistol Recoil Simulator

Customer Need	Importance (Appreciated [1] – Necessary [5])
Can simulate pistol recoil	5
Can simulate both horizontal and rotational recoil	5
Can hit the minimum force requirement in the X- axis (3,300 G's)	5
Can simulate rifles or other firearm recoil	1
Is 24" W x 57" L x 36" H	3
Has easily replaceable components	4
Can operate in temperatures up to 100F	5
Is powered by 120V, 60Hz, 1 Phase input	3
Can be partially disassembled/reassembled to move	4
Is quiet	4
Is designed with safety features to minimize risk	5
Can simulate 3000 fires	5
Fast operation between impacts	4
Can be bolted into a concrete slab	3
Inexpensive to operate	4
Is safe to operate	5
Can attach optics with various hole patterns	5

Design Requirements

To create constraints and goals, the team wrote a requirements list. The Customer Needs Table, seen in Table 1, was placed into a House of Quality (HOQ), as seen in Appendix

A. 2. The HOQ models a comprehensive understanding of all needs that are required to begin designing, the importance of each need in relation to the other needs, and how they will affect each other. The HOQ helped the team conclude there is a strong need for accurate shock forces and fact cycle times. The team also determined that the number of custom parts should be minimized to include only necessary items so that servicing and replacing parts is more approachable and cheaper.

Because safety was deemed a necessary attribute in Table 1, additional research was conducted on industry standards and codes from OSHA and ASME. OSHA code 1910.138(a) was used as a requirement [9]. Though they were not used as requirements, additional codes and standards helped inform decisions made throughout the design process. The first of these is OSHA code 1910.95(a), which requires a company to provide noise protection and annual training about the effects of high noise levels for long durations to machine users [10]. The next code is ASME code Y14.5, which specifies standard dimensions and tolerances when creating CAD and G-codes [11].

Using the needs table, HOQ, and OSHA code 1910.138(a), the team made a requirements table, seen in Table 2. It should be noted that, because only quantifiable needs were put on the table, the signal and maintenance aspects were omitted. The required force was found by reorganizing the mechanical energy conservation and linear and angular momentum conservation equations. The workout of the equation can be seen in Appendix A. 3. The machine should be capable of creating forces higher than seen in Table 2. However, the project will only be tested as a proof of concept before giving it to Sellmark at the end of the semester to ensure student safety.

Table 2: Requirements Table

Requirement #	Source	Metric	Importance	Required Values	Units
1	Team	Force	4	1000	lbs
2	Sponsor	Acceleration X	4	700	G's
3	Sponsor	Acceleration Y	4	420	G's
4	Sponsor	Continuous Operation	4	3,000	Cycles
5	Sponsor	Frequency	4	1	Hz
6	Sponsor	External Temperature	3	100	F
7	Sponsor	External Humidity	3	75	% Humidity

8	Sponsor	Size	2	24"x57"x36"	Inches
9	Sponsor	Mounting Pattern	3	3	Interchangeable Patterns
10	OSHA	Two-hand start	4	Yes	-

Functional Model

After developing the requirements list, the team drew a black box model to embody the intended inputs, outputs, and function of the design, seen in Appendix A. 4. From this black box model, a more detailed functional model was developed to identify the flow of inputs and outputs through the system to assist in creating solutions. The functional model helped the team determine how to best organize inputs and outputs during design and what functions are needed to get between the two points.

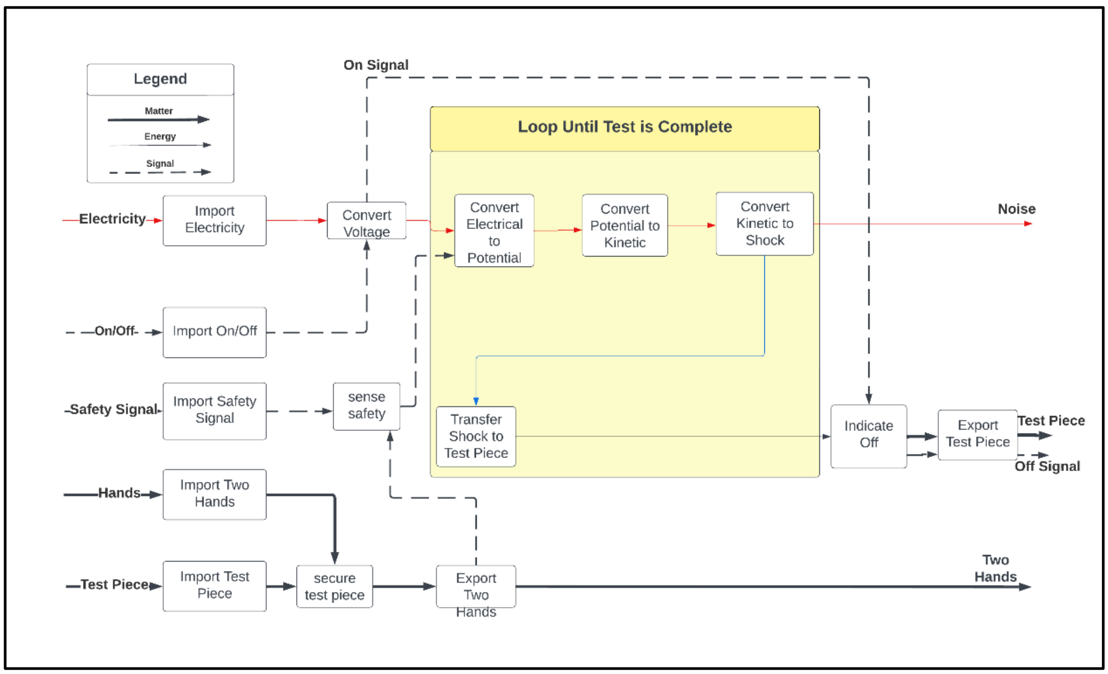

Figure 3: Functional Model for the Pistol Recoil Simulator

From the functional model, pictured in Figure 3, the most significant paths for the design of the device were identified as the force conversion path, containing the conversion of electrical to kinetic energy (seen in red), and the shock transfer path, containing the conversion of kinetic energy to shock felt by the mounted optic (seen in blue). After identifying these paths, the team began to generate designs that would meet the needs determined by the functional model. Once this process was completed, a final design was judged using IIAE matrices and Pugh Charts.

Current System

Overview

After the Pre-Design phase, the team selected a single spring-powered force-generation system that impacts a mount that recreates the movement of a pistol. This system was determined to have several advantages, including rapid cycle time, simple maintenance, accurate recreation of accelerations, and relatively low cost. The entire assembly, as seen in Figure 4, consists of four subsystems: Mounting, Force Generation, Table, and Electronics.

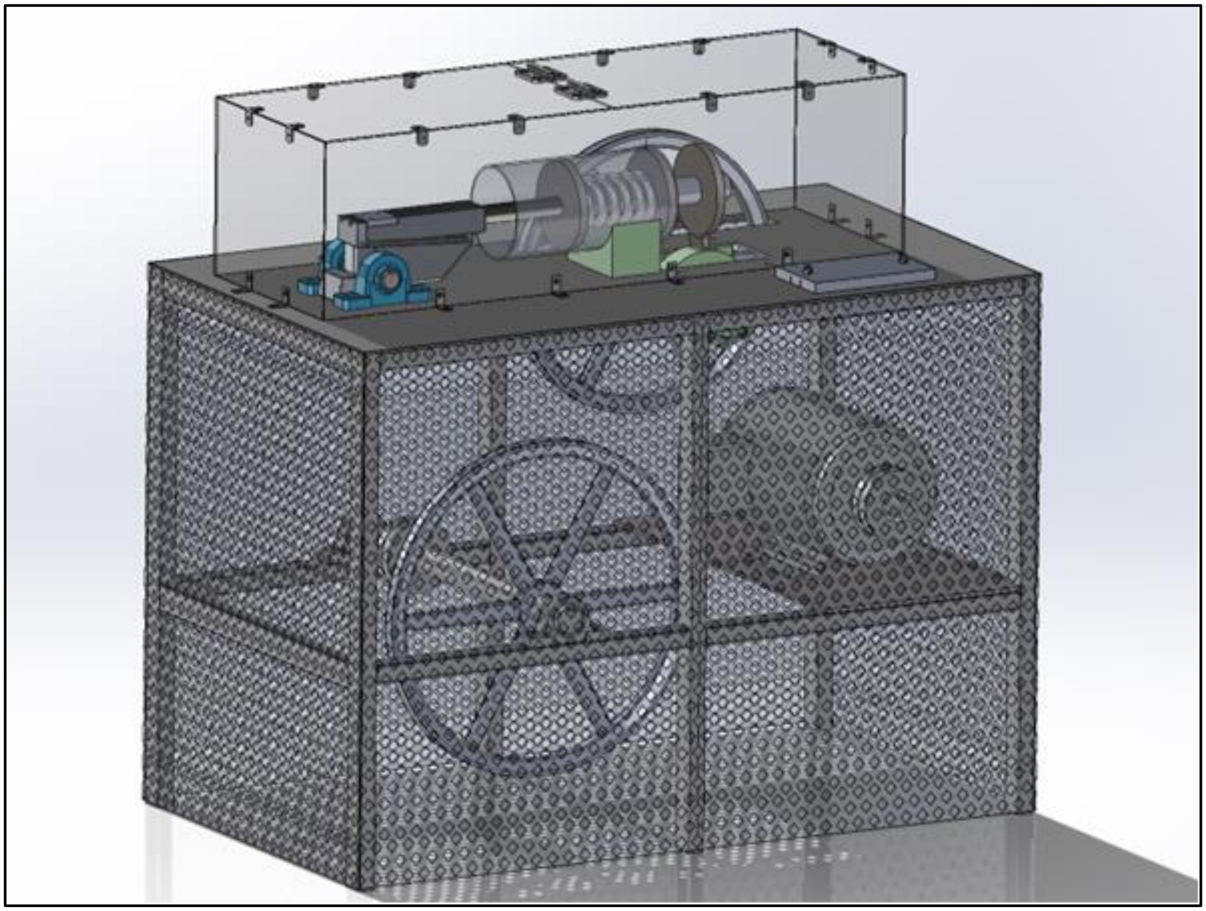

Figure 4: Pistol Recoil Simulator Final Assembly

These subsystems are designed to interface together to be capable of accurately recreating the accelerations that a pistol optic will experience under fire in the x and y axis. The force generation system, powered by the electrical system, uses a cam to compress a spring. Upon release, the spring collides with an attached metal rod with the accessory mount. Upon experiencing impact, the mount will slide back and pivot, simulating the motion of pistols during recoil. The mount then resets itself to prepare for the next strike. This process is designed to repeat itself 3,000 times. All three previously mentioned subsystems are mounted to a custom-manufactured table that was designed to handle the high forces and vibrations the system will experience.

Mounting

The first subsystem to be covered in this report is the mounting mechanism. This mechanism consists of a sliding and pivoting mounting point for the optics to be tested.

Functions

The goal of the mounting subsystem is to recreate the motion that a pistol makes when fired. The two main components of this motion are sliding and pivoting. Most pistol optics are mounted to the slide of the pistol, meaning that they must be able to survive the violent forward and backwards motion caused by gas exiting the pistol. Similarly, when fired the4 pistol will rotate in the user's hand, and this motion must be recreated as well.

Design Decisions

The main components that will make up the mounting system are pictured in Figure 5; however, the parallel resting plate meant to keep the slide parallel to the table and in line with the striking rod when in the resting position is located directly under the slide base and is obscured. The two shaft collars used to secure the mounting system laterally on the keyed shaft are also omitted from the figure to provide easier viewing.

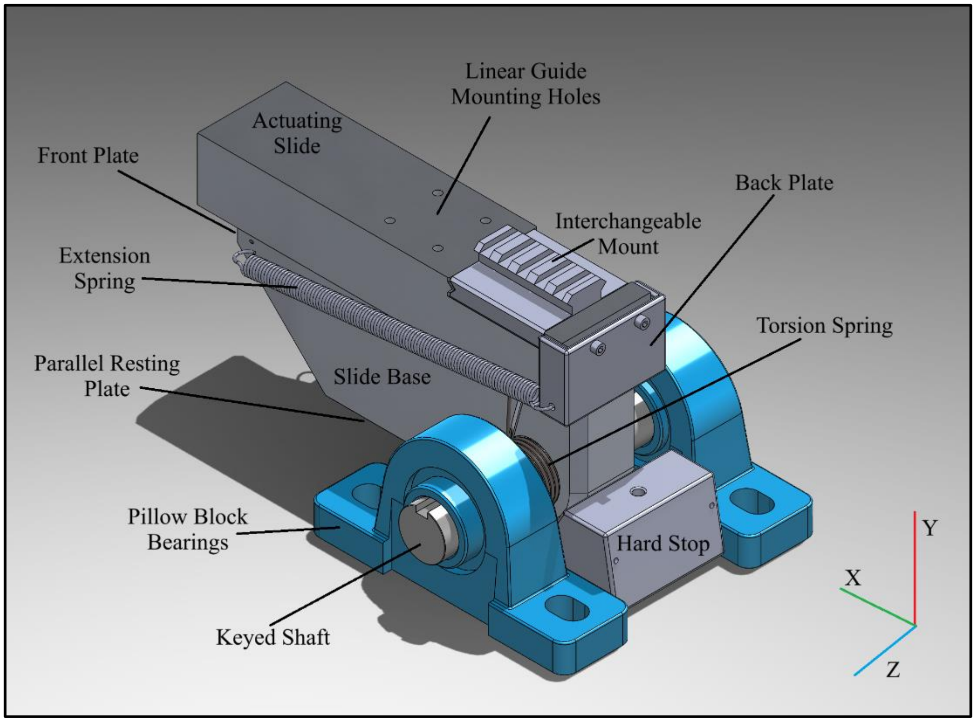

Figure 5: Mounting Mechanism in Resting Position with Labeled Components

The mounting system will be directly attached to the tabletop using four ½" bolts seated in the mounting holes of the two pillow block bearings. The parallel resting plate and hard stop will also be directly attached to the tabletop using two ¼" flat headed bolts and 3 ¼" machine screws respectively. The bearings will be secured to the 1" diameter keyed shaft using a set screw. The bearings will allow for the system to rotate about the z-axis, allowing for forces to be felt in both the x and y axis. The keyed shaft will hold the slide base and torsion springs used to simulate the damping of a correctly operated pistol. The torsion springs will also allow for the mechanism to reset to resting position. The slide base, along with the torsion springs, will be secured to the shaft using a built-in key and held laterally by two shaft collars. A linear guide will be installed between the slide base and actuating slide. The rail guide will be secured to the slide base and the slide carriage will be secured to the actuating slide allowing for motion in the x direction. The interchangeable mounting mechanism will be inserted into the actuating slide and secured by two ⅛" set screws that will also act to secure the back plate to the actuating slide. The back plate will act to secure the two extension springs, meant to simulate the function of a recoil spring in a real firearm, to the actuating slide. The extension springs will also be secured to the slide base in a similar manner by utilizing the front plate.

The mounting system is meant to simulate the dynamics of a pistol as it is firing as closely as possible to produce forces in the x and y directions similar to those experienced by a discharging pistol. To do so, the mounting system will function by being hit by the striking rod. This will cause the slide to begin moving in the negative x direction, inducing acceleration on the test specimen. As the actuating slide begins to move, a negative moment will be generated about the z-axis, causing acceleration in both the x and y axis. The extension springs will also begin to dampen the motion of the slide, like a recoil spring would in a real firearm. After the actuating slide reaches the limit of its range, a large shock event will occur, increasing the rate of rotation before the extension springs work to return the actuating slide to its resting position. As the system continues to rotate about the keyed shaft, the torsion springs will begin to work to dampen the motion, simulating the dynamics of a pistol about a wrist joint. As the system reaches an inclination of 30° from parallel, the hard stop will prevent further rotation and the torsion springs will begin to pull the system back to parallel before the next impact.

Throughout the design process, the team went through several iterations before landing on the final design. The initial design, shown in Figure 6, had several issues that needed to be fixed. The first was the lack of linear rail, which would significantly affect how reliably the slide would be able to move back and forth. Secondly, the height of the pivot point needed to be changed. Initially, it was designed to pivot around the equivalent of the bottom of the pistol handle, but it was then determined that pistols rotate around the user's hand. To accommodate for this, the height of the mount was reduced.

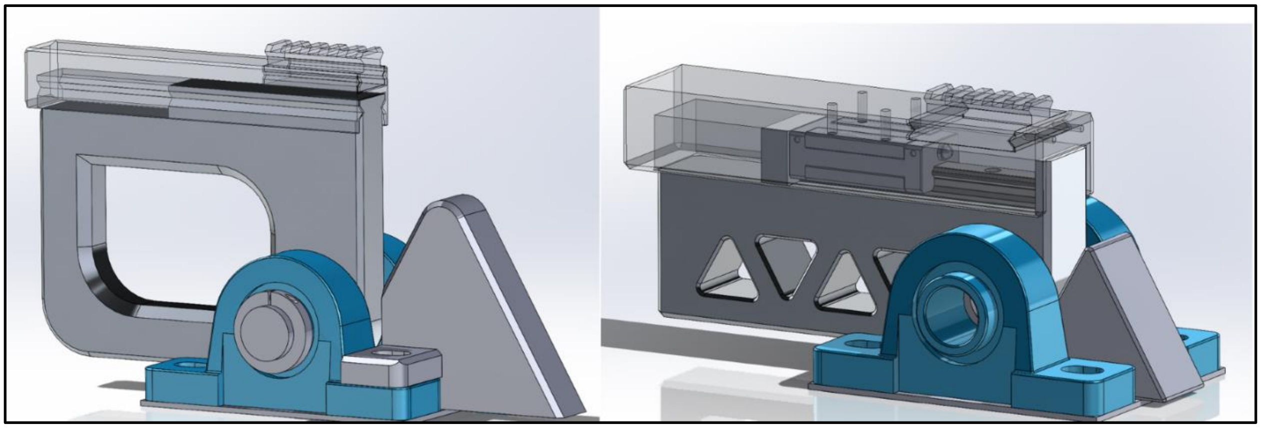

Figure 6: Original Mounting Design (left) New Mounting Design (right)

The newer mounting design shown in Figure 6 was better, but still had some issues. The triangle cutouts were intended for weight reduction, but due to their complexity to machine they were removed for the final iteration. The other large changes were made to the hard stop and mounting module, which were made easier to machine as well. Lastly, a large chamfer was added to the front of the slide base to prevent it from colliding with the striking rod. With all of these changes added, the final design of the mount can be seen in Figure 7.

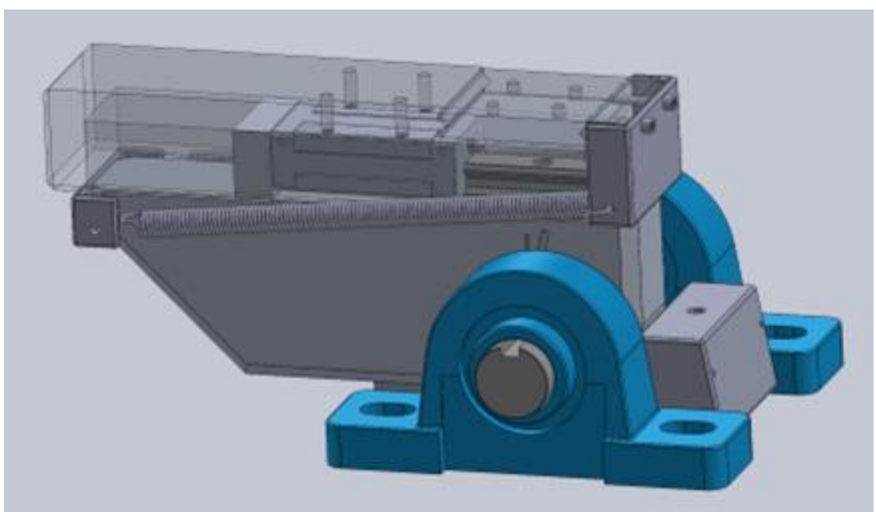

Figure 7: Final Mounting Design

Construction

When constructing the mounting mechanism for the PRS the parts were split into two main categories: CNC Manufacturing and Manual Manufacturing. The parts categorized as requiring CNC Manufacturing contained complex geometries or otherwise contained features that would prove difficult to create manually. The parts assigned to this category were the Slide Base, Actuating Slide, and Hard Stop. The Slide Base and Actuating Slide were chosen to be CNC Manufactured due to the level of precision needed to maintain clearances within the mechanism to allow the mount to move freely. The Slide Base and Actuating Slide additionally contained features, such as the keyed hole in the Slide Base and the Interchangeable Mount slot in the Actuating Slide, that would be difficult to create manually with any precision. The team chose to manufacture the Hard Stop using CNC to reduce the fabrication time required. The remaining custom parts (the Parallel Plate, Front Plate, Back Plate, and Interchangeable Mount) were categorized as requiring Manual Manufacturing. These parts contained simple geometries and features that could be easily manufactured using manual machinery. A manual mill was used to machine the Parallel Plate and Interchangeable Mount while the Front and Back Plates were manufactured using a bender.

During the construction of the Mounting System several design changes were implemented to improve the functionality of the system or adapt to manufacturing limitations. The first, and most significant change made to the mounting system was made to the Parallel Plate. To ensure a solid connection and reduce the number of fasteners used in the PRS the Parallel Plate was constructed out of steel, instead of aluminum, and welded directly to the Table. The Parallel Plate was also shortened by 0.1” to account for the height of the sound dampening material added to the top of the Parallel Plate. The second design change to the mounting system made during the manufacturing process consisted of changing the threaded holes previously present in the back of the Actuating Slide to through holes. The purpose of this change was to improve the stability of the Interchangeable Mount by clamping the actuating slide between the Interchangeable Mount and a screw. The final design change to the Mounting System was made to the Hard Stop. After receiving the Hard Stop from CNC Manufacturing it was discovered that the part contained no holes as specified in the part drawings. The mounting holes for the Hard Stop were thus manually manufactured using a manual mill. For ease of manufacturing the mounting holes were changed to three triangularly spaced 3/8-16 tapped holes used to directly bolt the Hard Stop to the Table.

After implementing the design changes to the Mounting System, the mechanism was mounted to the Table using four 3/8” bolts and accompanying locknuts and washers. Before fully securing the Mounting System in place the acting slide was aligned parallel to the Striking Rod and rotated 30° to hit the Hard Stop to prevent any interference or alignment errors when the system was running. A shaft color was also secured to the Keyed Shaft opposite of the Torsion Spring to ensure the Slide Base would remain parallel to the Striking Rod. After fully assembling the mounting mechanism, rubber was added to the Parallel Plate to reduce impact noise when the system resets.

Usage

The user can swap interchangeable mounting patterns out easily. To do so, locate the screws on the back of the actuating slide and unscrew them. Slide the mount out horizontally and align the new mount with the actuating slide. Slide it in, then rescrew the screws onto the back.

Force Generation

The next subsystem in the team's design is force generation. The current force generation subsystem consists of the power transmission section and spring compression/striking mechanism.

Functions

The main purpose of the force generation sub system is to generate enough force to compress a spring to the correct length and instantly release it, creating a high instantaneous striking force that will generate the necessary acceleration on the mount.

Design Decisions

The power transmission is comprised of a motor, a middle shaft, and a cam shaft. There will be four two belt groove pulleys on said shafts and motor to magnify the torque and generate the necessary compression force. Firstly, a 3.95" outer diameter pulley will be attached to the motor. This pulley will transmit rotational energy to the middle shaft which has a diameter of 1-7/16" and is made of steel. This middle shaft has two pulleys. The first is 18.75" in diameter and connects to the motor pulley with two v-belts. The second pulley on this shaft has a diameter of 3.95". The small pulley on the middle shaft will be connected to a 15.75" pulley situated on the cam shaft. All pulleys will be secured to their respective shafts with set screws and a key system.

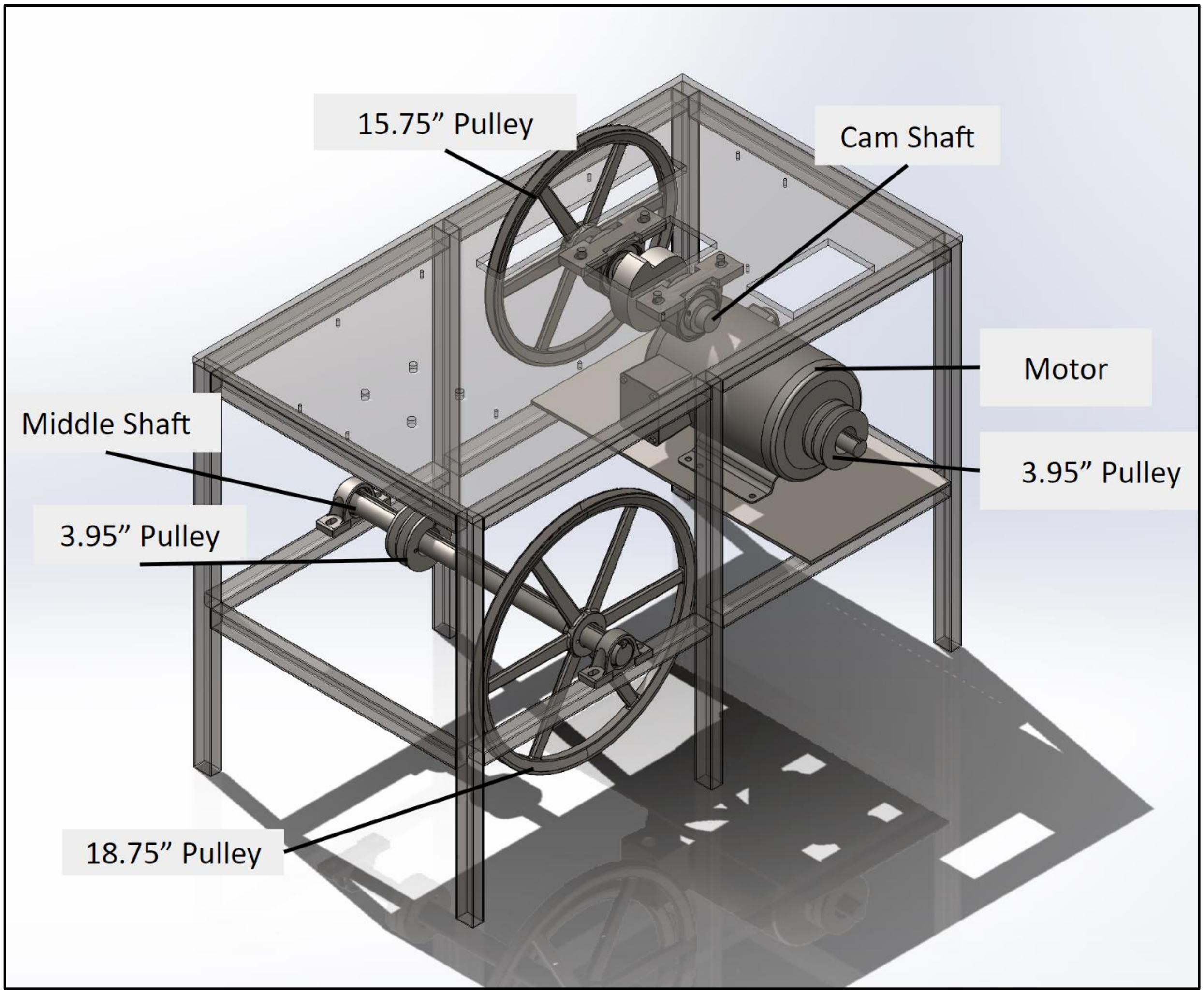

Figure 8: Table with Power Transmission

On the camshaft there is a cam which is also secured with set screws and a key. This cam translates the shaft torque into a horizontal force on the load plate, which will compress the spring and generate the necessary instantaneous force on the slide. The spring mechanism is comprised of three circular plates, a striking rod, a containment cylinder, and the spring as seen in Figure 8: Table with Power Transmission. The first plate is the load plate, it has a protrusion that the cam will use to push the plate. As seen in Figure 9 there is a center shaft that connects the load plate to the center and front plates. The load plate will be attached to this shaft via a screw and two nuts, this was chosen over welding to be able to remove the load plate and switch the spring if necessary. The purpose of this load plate is to harness the rotational energy of the cam to be able to compress the spring.

Apart from the load plate the shaft also has the containment cylinder, middle plate, and spring. The middle plate will have a hole through its middle so that the shaft can move freely. To secure this plate it will be welded to the rim of the containment cylinder. This containment cylinder will rest on a custom metallic stand made for the cylinder's dimensions to prevent any unwanted movement. The spring will be contained inside the cylinder, it will be secured by the center rod and the containment cylinder. Furthermore, at the end of the shaft is the front plate with the striking rod. This front plate will be welded onto the shaft, and it will move as the load plate moves. The movement of the load plate will cause the front plate to compress the spring and instantly release. Finally, the striking rod will be welded onto the center of the front plate. This rod is what will transfer the kinetic force of the spring into the mount subsystem to create the necessary acceleration.

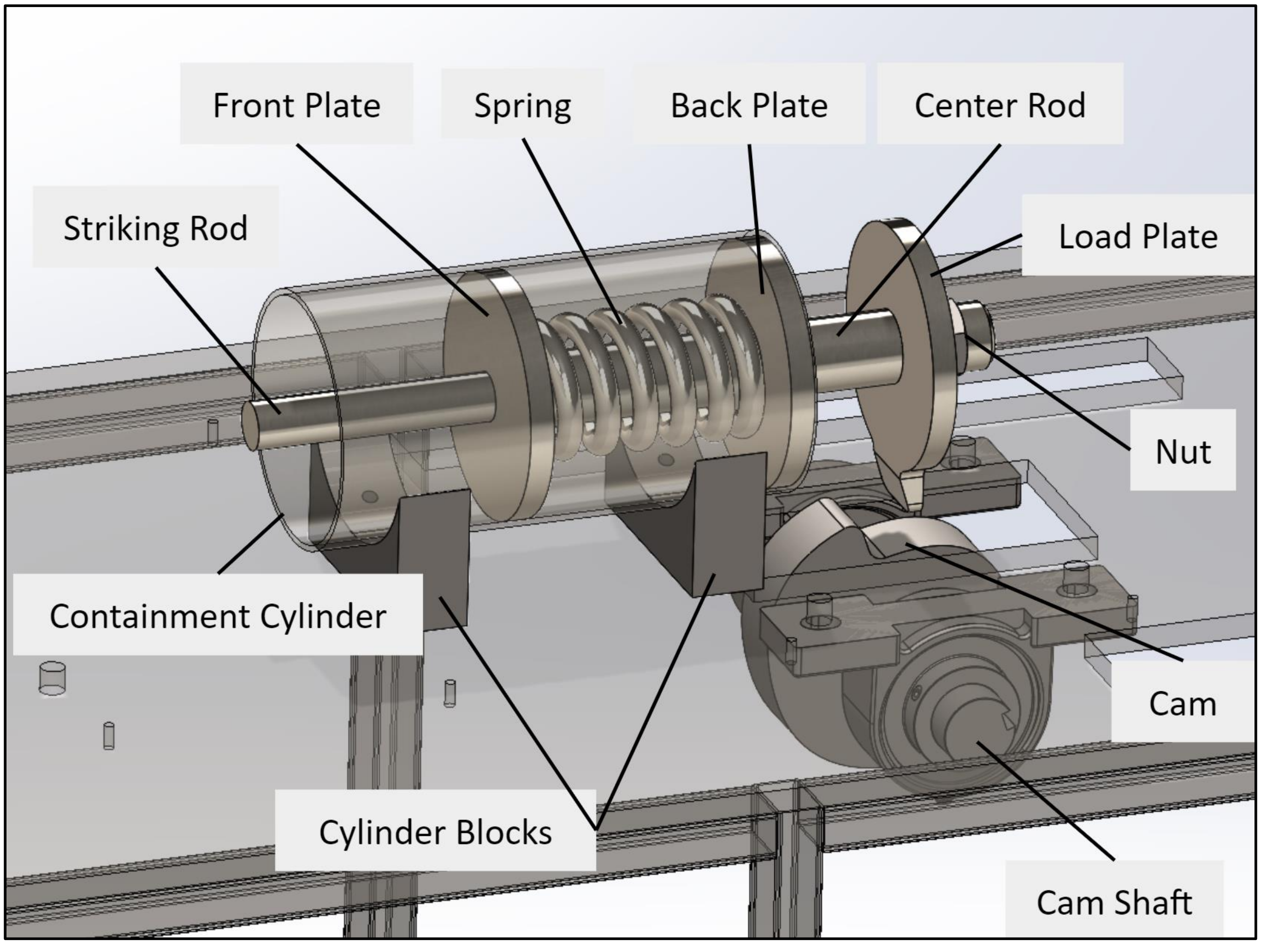

Figure 9: Spring Compression/Striking Assembly

Construction

When beginning the manufacturing for the force generation subsystem, the first decision that had to be made was determining how the team wanted to manufacture the plates of the assembly, the cam, and the cylinder blocks. Ultimately, the team determined that all these parts would be water jetted. During the process of getting the cam water jetted, the FEDC decided that the fabrication of the cam would be best if they used a CNC rather than using the waterjet due to the desired thickness of the cam.

During the manufacturing, there were a few issues that occurred. One of the first issues that the team had to resolve was an oversight in the design. The design had the back plate made of steel which was then welded to the aluminum containment cylinder. To solve this issue, the team determined that it would be best to make the back plate out of aluminum as well, and then to TIG weld it to the cylinder to ensure a strong connection.

The oversight of the material interfaces with the force generation subsystem impacted another portion of the force generation assembly. More specifically, connecting the aluminum cylinder to the steel cylinder blocks. The team's initial plan was to weld the cylinder to its supports, but this could not be done due to the different materials. To mitigate this issue, the team decided to drill and tap holes in the cylinder blocks, then drill thru holes in the cylinder, so that they could be attached using bolts.

Another issue that arose when fabricating the force generation subsystem, was threading the center rod. After removing the appropriate amount of material at the end of the rod it was discovered that the Zachry machine shop did not have the necessary equipment to make the 1-1/8' thread on the center rod. To solve this problem a team member took a lathe course in the mechanical engineering department machine shop and was able to manually create the thread pattern on the rod using the lathe. Specific settings, speeds, and tolerances were used in the lathe to be able to get the correct pattern and have the nuts sit flush with the rod. The threading procedure was a success despite initial setbacks.

Table

Function

The table's main goals are to house the other subsystems and to withstand all forces felt during the device's lifetime. The frame is constructed with six legs, a tabletop, a motor shelf, supports, and lockable casters. The casters were added to help move the system for testing and manufacturing due to the size. These were attached with bolts and nuts. The rest of the table is welded together for structural integrity through the testing. Because stability and strength were important to the subsystem, these factors informed many design decisions.

Design Decisions

The table is made of A500 mild steel because the metal must be weldable, economical and strong. Other materials considered were stainless steel and 4140 steel. Due to the difficulty of welding stainless steel, it was not selected. After looking at the strength and cost of A500 and 4140 steel, A500 was selected. Though 4140 is stronger, A500 is cheaper and provides enough strength for the application.

The tabletop is 0.5" thick to reduce deformation failure probability. A thickness of 0.25" was initially considered for a cost reduction, but after speaking with professors it was determined this was too thin for the table's intended purpose. It has a footprint of 24" x 42". The initial design was 48”, but it was reduced by 6” to avoid unused space. This also reduced the cost and weight of the subsystem. The legs are made of 1” x 1.5” rectangular tubing with a wall thickness of 0.12”. They are 30” long. 24” and 36” were also considered, but 36” was too costly and 24” was not ergonomic for the user’s back long-term.

Construction

The entire table was welded together to have a strong resistance to shear fractures caused by the horizontal spring impact. Four of the legs were welded to the corners of the tabletop, while the other two were placed in the middle of the ling sides of the top. At the top and middle of the legs, the metal tubing used for the legs was welded between the legs for additional structural support.

During the procurement process, the team forgot to shorten the structural supports to match the 42” length. This problem was not caught until after the entire table frame had been welded together. Because of this, the team had to cut the table at both sides of the middle legs, take off 3” on each side, and reweld the sides to the middle legs.

The team also chose casters that had a wider footprint than the bottom of the legs did. The team requested scrap steel from the FEDC and cut six rectangles that were slightly larger than the footprint of the casters, drilled holes for bolts to attach the casters to the legs, then welded these six rectangles to act as the feet of the table.

Usage

The only knowledge of usage necessary is how to lock and unlock the casters for transportation. To lock, the user simply hits the on switch with their foot on each caster, resulting in the two switches separating. To unlock it, the user hits the off switch with their foot on each caster, resulting in the two switches coming back together in the horizontal position.

Electronics

Function

The electrical subsystem fulfills several roles in the PRS system. Firstly, the subsystem supplies and controls power to the motor, preventing the motor from running when the system should not be active. The subsystem is also connected to several switches to allow for user operation, and a radial encoder for counting the number of cycles completed by the system.

Design Decisions

In order to meet the specification of Sellmark, the electrical subsystem was designed to be powered using standard household AC power (120VAC, 1-Phase, 60 Hz). Because of the high power usage of the system, an emergency off (E-OFF) button was added to the power cable between the source and the rest of the system. Thus, pressing the E-OFF cuts all power to the PRS system in an emergency.

For the control of the electrical subsystem, the team chose to use an Arduino Uno microcontroller. The Arduino is connected to every part of the electrical subsystem and is where the operational software of the system is hosted. To control the motor, a 5 HP Variable Frequency Drive was selected to be able to supply sufficient power to the large motor required for force generation. The VFD is controlled by the Arduino via MODBUS-RTU protocol. To accomplish this, the Arduino required an externally mounted “shield” for converting its standard communication protocol (RS-232) to the protocol required for MODBUS (RS-485).

A custom printed circuit board (PCB) was designed and implemented to add an additional layer of safety to the design. The board interrupts the wire path between the power cable and the VFD. On the board, the power cable wires are routed through a power relay that is controlled by the Arduino. This means that the VFD and motor are unpowered until the Arduino closes the relay and will lose power if the Arduino opens the relay or is disconnected from the system. The relay is normally open and the relay coil line has a pulldown resistor, so the relay will always be open unless the Arduino is actively supplying it power.

Two intended features of the electrical subsystem were unable to be implemented into the physical prototype due to time constraints. The first missing feature is the safety cover switch line, which would route two limit switches into the connection from the Arduino to the relay. The switches would have been positioned such that if the polycarbonate safety cover was not in place over the mounting and force generation components, the enable line would be interrupted. This would prevent the Arduino from closing the relay and allowing the VFD and motor to be powered unless the safety cover was closed. The other feature was the addition of a 4-digit 7-segment display that would display the number of cycles completed by the system. The number counted by the encoder would be written to the screen.

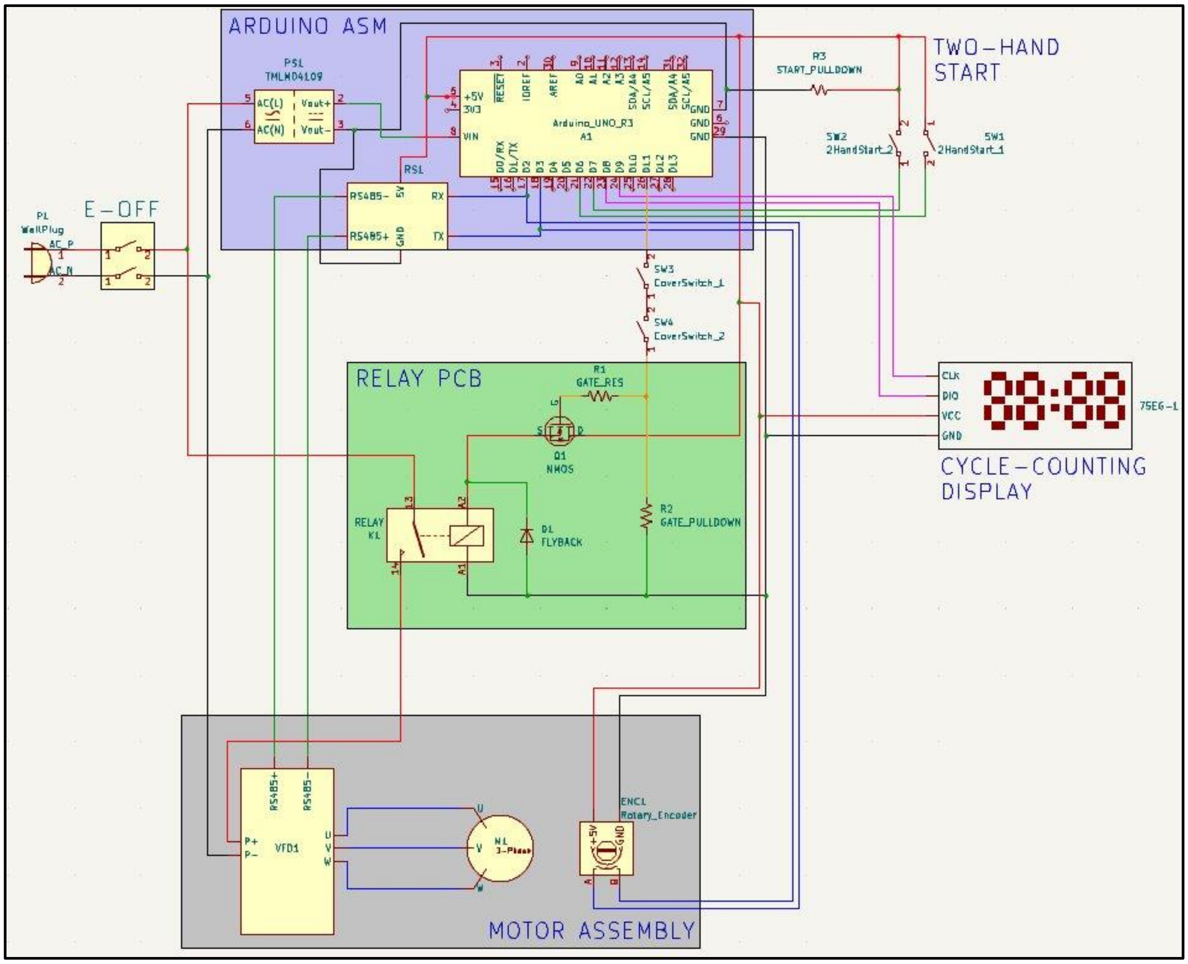

Figure 10: PRS Electrical Diagram

Figure 10 shows the complete electrical diagram of the electrical subsystem. The two missing features were not removed from the electrical diagram to allow easier implementation if development of the prototype continues.

Construction

Most of the construction of the electrical subsystem just involved soldering the various wires and components together as per the electrical diagram. The Arduino, RS-485 conversion shield, AC-DC converter, and relay PCB are all housed inside of a 3D-printed electrical box. On the outside of the box, the two-hand start switches are mounted far enough apart that they cannot both be pressed with the same hand. The E-OFF button was mounted by cutting out a rectangular portion of the expanded metal surrounding the motor and pulley system and bolting the button to the expanded metal.

The most complicated part of the electrical subsystem construction was the process of mounting the encoder to the camshaft. To accomplish this, a hole was drilled and tapped into the end of the shaft so that a 5/16” bolt could be threaded into the hole. That bolt ran through the center of the encoder, which was held in place in front of the end of the shaft by a 3D-printed mounting piece.

Usage

Nominal usage of the electrical subsystem is very straightforward. After the power cable is plugged into a standard wall outlet, the E-OFF button must be enabled. To do this, compress the red tab on the side of the main button, then pull open the cover on the front of the switch. Press the green button, then close the switch cover again. Power is now being supplied to the Arduino. Press both two-hand start switches simultaneously, and the relay will audibly click. This signifies power being supplied to the VFD and motor. After ten seconds, the Arduino will send a start signal to the VFD and the system will start running.

If the Arduino software needs to be updated, a USB cable and the Arduino IDE are required. The USB connection to the Arduino is accessible from the front of the electrical box. Connect a computer with the Arduino IDE to the Arduino, open the script file, and upload the updated script to the Arduino.

Risk Analysis

FMECA

The Failure Mode, Effects, and Criticality Analysis (FMECA) is a standardized method used to evaluate potential failure points of a design, the consequences of these failures, and the order of importance of them based on perceived impact. This method of analyzing risk combines the severity of the failure with its rate of occurrence and ease of detection to create a Risk Priority Number (RPN), which is the product of these three factors. According to SAE standards, recommended actions should be taken to address the failure if the RPN is greater than 125 [12]

Process

To successfully analyze the failure methods of the overall design, the team broke down the system into its subcomponents and their respective failures. The design was split into frame, force generation, mount, and electrical subsystems. These were then analyzed individually to identify their failure points, their effects on the system, and their severity regarding the function of the design and danger to the users, as seen in Appendix A. 5

Results

In the Pistol Recoil Simulator’s FMECA, four main modes of failure were determined to need a recommended action due to having an RPN greater than 125. The first of these was for the frame. If the welds connecting the structure together are weak then it is likely the table will have a critical fracture in a weak point. If this occurs, it will not be able to hold the other subsystems properly, causing inaccurate or misaligned acceleration and increasing risk of injury to the operator. To mitigate the potential, team members have undergone welding training in Texas

A&M's Fischer Engineering and Design Center and the welding process will be supervised and checked by the professional employees.

The failure mode with the highest RPN had a score of 384. This would occur when the cam pushes upwards on the load plate, causing the middle plate to have friction with the containment cylinder, hindering the movement of the shaft. This failure has a high likelihood of occurrence since the cam force will be mostly translated into the vertical axis. This vertical movement is due to the geometry and interface between the load plate and the cam tip. If this failure were to occur then the striking rod would not be able to transfer the instantaneous force onto the mount subsystem, failing to create the necessary acceleration as stated in the needs. To prevent this failure from occurring, the load plate interface with the cam was machined to have an angle.

Another potential failure point from the force generation subsystem is the cam failing to compress the spring by an inch. This could occur due to frictional losses or a part fracture. This failure could have severe consequence, potentially causing the system to fail its requirement of the expected acceleration. Possible solutions are to alter the cam placement in the shaft and how it interacts with the load plate to ensure the correct compression length.

A potentially detrimental failure mode regarding the mounting sub-system is the possibility of the slide and body not resetting promptly. This would lead to the slide being in a suboptimal position when the striking rod actuates. The effects of this could be the striking rod completely missing or incorrectly striking the mount, causing a failure to create the necessary acceleration on the test optic. At worst, this could cause critical damage to the system due to the striking force not being absorbed. A recommended action for this failure mode is to thoroughly test both the torsion and tension springs to ensure they are tight enough. Different springs can be chosen if necessary to ensure timely reset for the correct function of the mechanisms.

Fishbone

The Fishbone Analysis Method is a model used to help teams find the root cause of a problem. The defining characteristic of a Fishbone Analysis is its ability to identify systemic. Because of this, actions can be taken to correct the deeper cause rather than implementing a symptomatic solution that only fixes the surface issue.

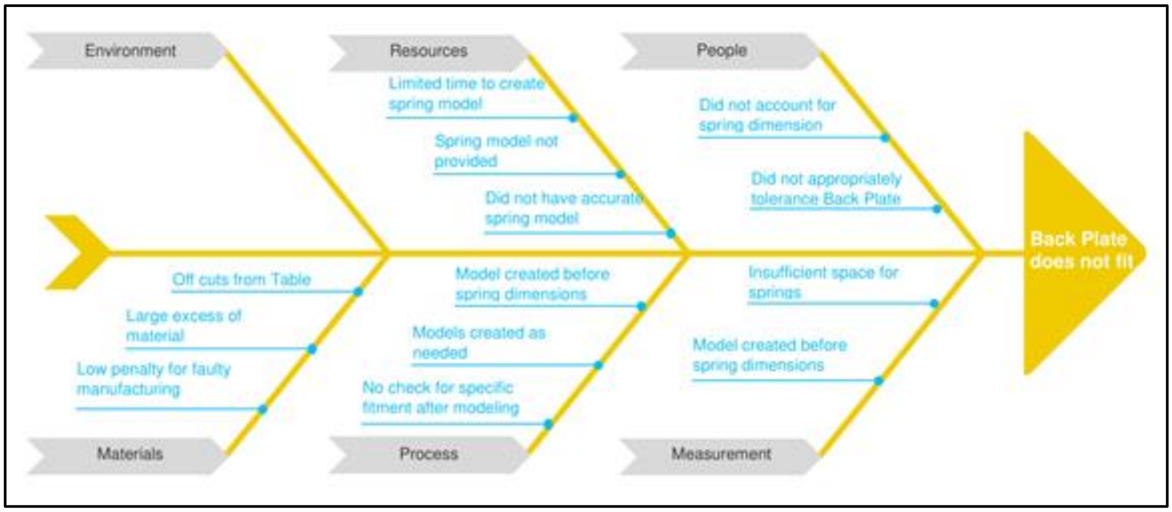

Figure 11: Fishbone Diagram for Incorrect Fit of the Back Plate onto the Actuating Slide

Process
During the design process, the team created a 3D printed prototype of the mount system to determine if the movement would be as expected. The back plate is meant to provide a mounting point for the extension springs by interfacing with the actuating slide, as seen in Figure 5. Upon completing the initial prototype, however, the team found that there were issues with parts fitting together, specifically the Back Plate. The plate was unable to be secured to the actuating slide without excessive force due to the protrusion of the extension springs. To determine the root cause of this issue, the team utilized a Fishbone Analysis model. The six main categories selected were environment, resource, people, materials, process, and measurement.

Results
As indicated by causes listed in the process category in Figure 11, there was no implemented standard for checking the tolerancing of the mounting subassembly before manufacturing, leading to improper fitments. Furthermore, the materials category indicates that the low penalty for faulty manufacturing on the back plate led to a failure to check the fitment of the back plate before manufacturing, leading to a potential for low-quality parts. Ultimately, the root cause was a lack of attention to the design of the back plate, leading to its improper interface with the actuating slide. To address this root cause, the team carefully redesigned the mount to have the necessary tolerances and reprinted the prototype. They also created a quality assurance procedure for when any redesigns were made and before manufacturing. By implementing this system for each part's fitment before machining, this issue was less of a problem in the manufacturing phase.

5 Whys

The Five Whys risk analysis method is based on solving problems that have occurred during the prototyping stage and determining the causes. This is based on the theory that, for every issue found, 5 questions are able to determine the root cause. The procedure is to ask questions about the root causes of higher-level issues to determine actions that can be taken.

Table 3: Five Whys Analysis

Why does the Mount Reset Too Slowly?	Cause
Why is there too much friction in the slide?	Tolerances too tight, Slide not aligned properly
Why is there too much friction on the shaft?	Tolerances too tight
Why don't the springs attach properly?	Holes in the front are too small
Why are the tolerances too tight?	Base and slide are the same width in CAD, same for shaft and hole
Do the springs absorb too much force?	If the springs are too strong, then the mount will not fully slide back

Process

When assembling the prototype, the team ran into friction during both the rotation and sliding motions, which caused problems with the mount's resetting capabilities. To find the problem, the team ran a 5 Why's analysis, as shown in Table 3. The first step was determining potential root causes, such as the friction between moving parts and the springs not attaching properly. By thinking about why these issues occurred, the team could find solutions to solve the higher-level problem of the reset speed being too slow.

Results

The first problem was that it took significant force to move the slide back and forth. This would lead to a very slow reset upon impact without intervention. After looking at why the problem occurred, two causes were identified: The tolerances for the slide were too tight, and the linear rail was slightly misaligned, also due to tolerancing. The team then asked why the tolerances were too tight. Before manufacturing the final product, the tolerances were implemented in CAD.

Fault Tree Analysis

An FTA is a top-down approach to finding causes of failures. It starts with a high-level failure and finds various combinations of faults that could lead to it. This orientation to specific failure modes makes it ideal for focusing on the most complicated parts of a design, such as failure modes that received a high RPN in the FMECA.

Process

When assembling the prototype, it was found that the slide had significantly more friction than designed for despite the addition of a linear rail. As a result, this was one of the two problems chosen for a fault tree analysis, as seen in Appendix A. 6. Additionally, the presence of higher friction than expected, combined with the high RPN score given to the reset time of the mount, led to the team running an FTA on the potential failure, shown in Appendix

A. 7.

Results

The first fault tree analysis was performed on the slide friction. This revealed several potential problems that were rectified for the slide to perform as expected. One of the potential issues found was metal on metal contact, in which the slide and base are rubbing against each other during each cycle. Further down the tree, it was identified that this could be caused by either poor tolerances, or poor alignment of the slide. The tolerances were fixed in the CAD stage, by slightly widening the slide before sending the part to be manufactured. The poor alignment of the slide was also avoided by including the correct hole locations in the CAD. This helped determine placement for the manufacturers and allowed the team to avoid the hand drilling that was done during the prototype assembly.

Design Validation

Validation Techniques

The PRS team created tests of two different categories to determine whether or not the Pistol Recoil Simulator could meet the defined needs. These two categories are validation and verification tests. Verification tests do not directly address design requirements. However, they verify that parts of the system function as intended. These tests all occur before integration. Validation tests are meant to demonstrate the customer needs have been achieved. These tests all require at least partial integration.

Verification Tests

Frame Test Plan

The frame test was a simple loading test to ensure that the table was sturdily constructed. To accomplish this, a large weight was placed on the center of the table and the table was visually examined to ensure that there was no visible deformation and no damage caused by the loading. Since no standalone weights were available to complete this test, two members of the team stood on the top surface of the table near the center. The test was successful, as the table did not visibly deform at all and no damage occurred.

Mounting Test Plan

The mounting test was created to confirm that the mounting system functioned as expected. This included a fit-check where the test performer moved the mounting system through its intended full range of motion. The test was to be considered passed if the motions were smooth and there were no unintended collisions between the slide and other subsystem components.

The test was completed successfully. During this test, the mount moved backwards before turning. It resisted movement and reset itself with the springs. It was, however, noted that there could be potential complications due to the strength of the tension springs.

Force Generation Test Plan

The force generation test was created to confirm that the subsystem was capable of moving as intended without the spring. This was done by using the motor to turn the camshaft to pull the cylinder back. The test was to be considered passed if the subsystem moved smoothly and as expected.

The test was initially failed. When the back plate was pulled on at the bottom, it created an upward force. After addressing this problem with the addition of the threaded rod, the test was run again. The second test showed greatly improved movement, meaning it was considered passed.

Electrical Test Plan

The electrical test was designed to verify that the Arduino, VFD, and motor were all wired correctly, operating nominally, and properly communicating. A custom Arduino script was used to input a motor output speed as a percentage, and test performers used the script to adjust the speed and confirm that the motor reacts as commanded.

This test was fully successful. The motor responded quickly to the commands and set to the commanded percentage. No commands were unsuccessful or needed to be resent. Using the test script, the performance variables on the VFD like ramp-up and ramp-down speed were adjusted to appropriate values.

Validation Tests

Sensor Functionality

The sensor functionality test was intended to validate that the system could count the number of completed cycles and stop after the desired number (3000). The motor would be run slowly, and the test performer would count the number of cycles and compare it to the number counted by the Arduino and encoder.

This test was not successful. As discussed in the Limitations of Current Solution section, the encoder was not functional while integrated with the entire system. Thus, the number of cycles could not be counted. If the issue with the encoder could have been resolved, the test would have been attempted again.

Safety System Test Plan

This test was focused on the safety features of the PRS system, including the E-OFF button, two-hand start switches, and the safety cover switches. Each component would be tested as part of the system to confirm that they were functioning nominally.

This test was partially successful: the E-OFF and two-hand start switches were functional and passed the test, but the safety cover switches were unable to pass the test because they were not able to be implemented into the system due to time constraints.

Full Integration Test Plan

This test was the final validation of the entire system. The system would run for a full 3000 cycles with an accelerometer attached to the mounting subsystem. This would allow for the acceleration requirements to be validated and would show that the system was fully functional and ready for use.

Only part of the full integration test could be completed, and it was only partially successful. The full motion of the force generation and mounting subsystems could not be obtained, so the system was stopped after around twenty cycles.

Final Validation Map

The completed validation map for the PRS system can be found in

Table 4. The requirements that were not able to be satisfied are the two acceleration values and the number of continuous cycles. Much of the reason that the acceleration values were not met was because of the issues with the cam. Because the cam was not able to compress the spring as much as it was intended to, the force generation was not able to produce the desired force. The number of continuous cycles could have been reached, but the system would not have stopped at 3000 cycles because of the issues with the encoder. These failures could be solved by replacing or troubleshooting the cam and encoder, but they could not be addressed in the delivered prototype.

Table 4: Final PRS Validation Map

Functional Requirement	Quantitative Requirement	Design Feature	Validation Test	Actual Value	Satisfied?
Footprint	<24"x57"	Table Base	Measure external frame with measuring tape	24"X42.25"	Yes
Height	<36"	Table Base	Measure from floor to highest point with measuring tape	34.75"	Yes
Cycle Time	>=1 Hz	Pulley system and Motor	Measure cycles per second with a tachometer	1 Hz	Yes
Acceleration X	>700 g +10% unc	Spring and Mount	Measure on the mount with a tri-axial accelerometer	300	No
Acceleration Y	>420 g +10% unc	Spring and Mount	Measure on the mount with a tri-axial accelerometer	300	No
# of Continuous Cycles	3,000	Motor and cam	Measure cam rotations with arduino and encoder	N/A	No
External Temperature Rating	>100F	System	Based off manufacturing documentation	130	Yes
External Humidity Rating	>75%	System	Based off manufacturing documentation	90	Yes
Safety Start	0V unless started	Electrical	Measure Volts to system with multimeter	0V	Yes
E-Stop	0V	Electrical	Measure Volts to system with multimeter	0V	Yes

Budget and Cost Model

Budget

After selecting the raw materials and COTS items, the expected final cost of the system was $4,483.00. However, because there were still uncertainties in the design and there was potential for error in manufacturing and testing phases, a margin of 21% was added. This led to a total requested budget of $5,274.00. The full breakdown of the budget by subsystem and individual category can be seen in Appendix A. 8.

The final cost used from the university, after returns, was $4,504.96. The budget went slightly over due to a last minute need for electronic components being shipped overnight. Despite this, the team only had to use $21.96 of their margins. The final bill of materials can be seen in Appendix A. 9.

Cost Model

The final cost model, seen in Appendix A. 10, gives an estimate of how much it would cost to reproduce this machine. The cost includes all COTS and raw materials, manufacturing cost, and integration cost. To determine the cost of manual labor for manufacturing and integration, the team multiplied the time it took to manufacture or integrate each component and multiplied it by $15. Therefore, this cost would increase if the person recreating the system were to choose a company that charges more than $15/hr.

Table 5: System and Subsystem Level Cost Model Breakdown

	Force Generation	Mount	Table	Electrical	Safety Cage	Connectors and Maintenance	Total
Manufacturing & COTS	2339.79	690.86	662.40	582.86	310.72	124.74	4711.37
Integration	375.00	75.00	300.00	150.00	150.00	150.00	1200
Total	2714.79	765.86	962.40	732.86	460.72	274.74	**5911.37**

Table 5 shows the total expected price a manufacturer would expect to pay to build each system, as well as a breakdown of how much each subsystem costs. Overall, the manufacturer should expect to spend $5,911.37. This cost is more than what is seen in the bill of materials because the PRS team provided the manufacturing and integration labor for free. It should also be noted that this model does not reflect the design, documentation, and testing time.

The system was broken down into six categories for this model: Force Generation, Mount, Table, Electrical, Safety Cage, and Connectors and Maintenance. The subsystems vary greatly in the categories of COTS, manufacturing, and integration due to the variance in difficulty and customization.

The most expensive subsystem is Force Generation. This is because this subsystem contains the motor and pulley system. It also required the most integration, with a calculated time of 25 hours. The Mount subsystem, however, required the most time for manufacturing, with 15.5 hours dedicated to manufacturing. This is due to the subsystem requiring nine custom metal parts. During part selection, the team was unable to find anything that could fulfil the requirements of the subsystem that fit within the given budget.

Broader Impact of Design

Lifecycle Design

This system was designed to be capable of long-term use. Because of this, the lifecycle was closely considered. Lifecycle design encompasses the system from the procurement of raw materials to the disposal of materials at the end of its lifetime.

The first design choice was minimizing specialized parts that are difficult to replace. If the team was able to find a COTS item that remained in budget, that item was selected. This included any springs, connectors, motors, and electronic parts. Unfortunately, due to budgetary constraints, certain parts that had potential COTS counterparts, such as the mount, had to be custom designed. Because of this constraint, priority was given to items that may need to be replaced frequently. For custom made parts, the manufacturing drawings and .STL files were provided for the sponsors so they can easily replace any parts.

Additionally, the team emphasized repairability. Because of the high accelerations the system will experience cyclically, many parts are likely to be broken. During the design, the team ensured that all parts could be reached if needed. For example, the cylindrical tube was originally intended to be completely welded, preventing the spring from being removed. However, after reevaluation, the team determined it would be best to weld the back plate to the cylinder and the front plate to the striking rod, which would then be connected to the back plate with a nut and bearing. This allows for the spring to be removed and replaced with stronger springs or in case of a spring failure. The team also wanted any disassembly to be capable with simple tools. All bolts selected use Allen keys, and nuts can be removed with wrenches.

For the disposal aspect, most of the parts are made from steel and aluminum. These materials are both recyclable. Additionally, the overall system was designed to have a long lifecycle to reduce waste. As an example, the Actuating Slide on the mount was initially intended to be reset with recoil springs, similar to a pistol. However, the recoil springs would need to be replaced every 3,000 rounds, which is a single test. The team redesigned the system to reset with tension springs instead. These need to be replaced approximately every 10,000 rounds, reducing the waste caused by the springs by 300%.

Intellectual Property

Intellectual property is any creation a person comes up with. Though there is not much intellectual property found within the design, certain IP was a part of the product realization process. The mount was initially inspired by a fake gun that was seen on *Mythbusters*, though the one seen on the PRS varies greatly. For instance, the pivot point is lower on the one designed by the team, and the *Mythbusters* one could not reset itself nor could it simulate the pistol slide.

The team also found inspiration from the rifle recoil simulator that Sellmark currently owns. This machine also utilizes a compressed spring system to strike a surface. However, the current machine does not have the rotating optics mount. It also uses two springs instead of one to create the force needed.

Liability Considerations

Liability can be considered the legal and moral responsibility of us as engineers to be accountable for our designs and products. As engineers it is our responsibility to prioritize safety for the public and environmental awareness when designing, building, operating, and disposing of our product. For the safety aspect, many considerations were made to prioritize the well-being of the operator. The most dangerous component of the design is the spring itself since it is being compressed thousands of times repeatedly and since it has a high spring coefficient any explosion or rupture would cause shrapnel to be sent to its surroundings, putting the operator or anyone near the test rig at risk of great bodily harm. To prevent any injuries the spring is housed inside of an aluminum cylinder, this housing unit would contain any shrapnel in the case that the spring ruptures, preventing any metal pieces from escaping and impacting anything around the test rig.

The second safety measure implemented for the test rig is the use of a polycarbonate box surrounding the mounting, striking mechanism, spring, cam, and pulley. This polycarbonate box is bolted onto the table itself and has a latch at the top for easy access to the components previously mentioned. The plastic is there because many metal pieces are moving with high forces and repeatedly in both the mounting and force generation subsystems. There is a very real possibility of metal chipping or a piece coming loose due to the repeated impacts and cycles, the consequences of this occurring would be very serious to anyone around the test rig, so the polycarbonate shielding is put in place to prevent any parts from hitting a human in the case of a failure.

The third safety feature is expanded metal covering the underside of the table. This includes the motor, pulleys, and partially the cam. The decision to add expanded metal was taken because the rotating pulleys are a very serious hazard when the machine is operating. If a body extremity were to be caught in one of the pulleys, then the consequences would be severe. Another thing that went into consideration is that the v belts will be under a lot of tension, and this will eventually cause them to fail, a failure of these belts under tension could cause them to create a whipping effect, causing them to be a danger for anyone near the test rig. The expanded metal keeps any limbs from interacting with the pulleys and any ruptured belt from harming the operator.

The fourth and final safety feature employed is an emergency stop button. In the case that there is any failure with either the pulleys, spring or mounting it is imperative that the motor rotation can be stopped immediately to prevent further damage to the test rig itself or any operators. The emergency stop was wired so that it cuts power off directly to the motor, bypassing the Arduino and controller so that if something goes wrong with the Arduino power can still be cut off from the motor and function can be ceased.

Ethical Considerations

The purpose of this machine is to be able to test the durability of an optic. This machine itself will have an impact on the specifications, marketing, and warranty of the product. Any miscalculation or mistake in the assessment of the acceleration and cycles reached will cause the sponsor to give inaccurate guarantees of the durability of the product to the customer. This would be unethical since it is imperative to be honest and truthful about the quality of your product. Furthermore, the biggest ethical concern arises from the safety aspect of the test rig itself. The machine has the capacity to cause serious physical harm or death to an operator if improperly used. This is why all the safety features mentioned in the previous segment have been employed. On top of this, a user manual has been given to the sponsors so they can follow the correct procedure when operating the machine and prevent any injuries.

Conclusions

Work Breakdown Structure

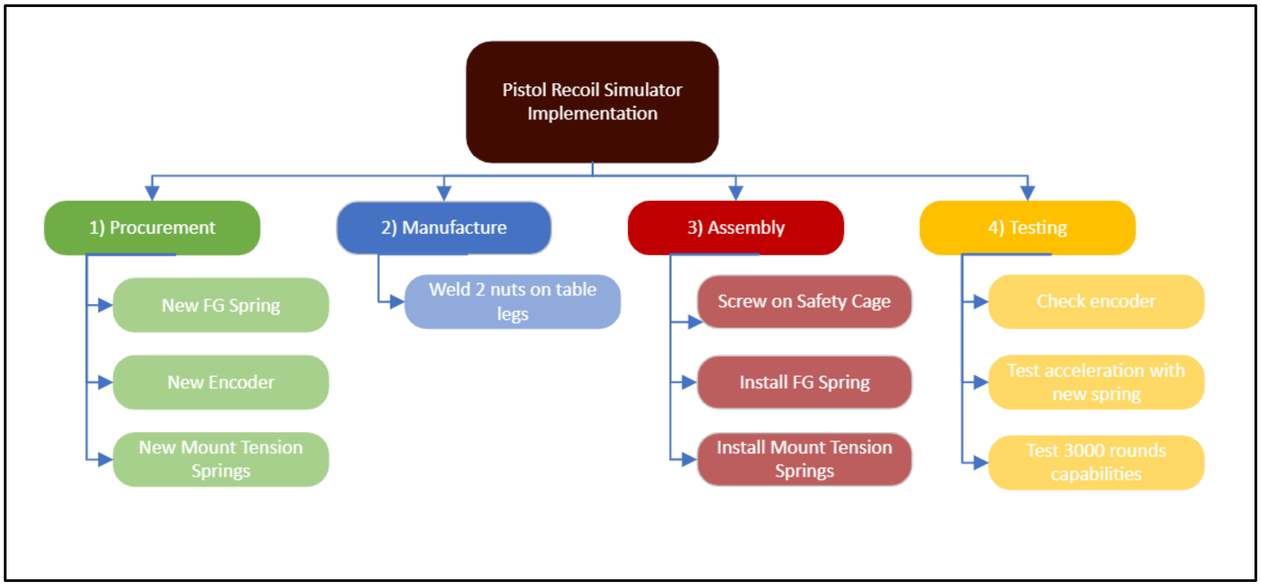

Figure 12: Work Breakdown Structure

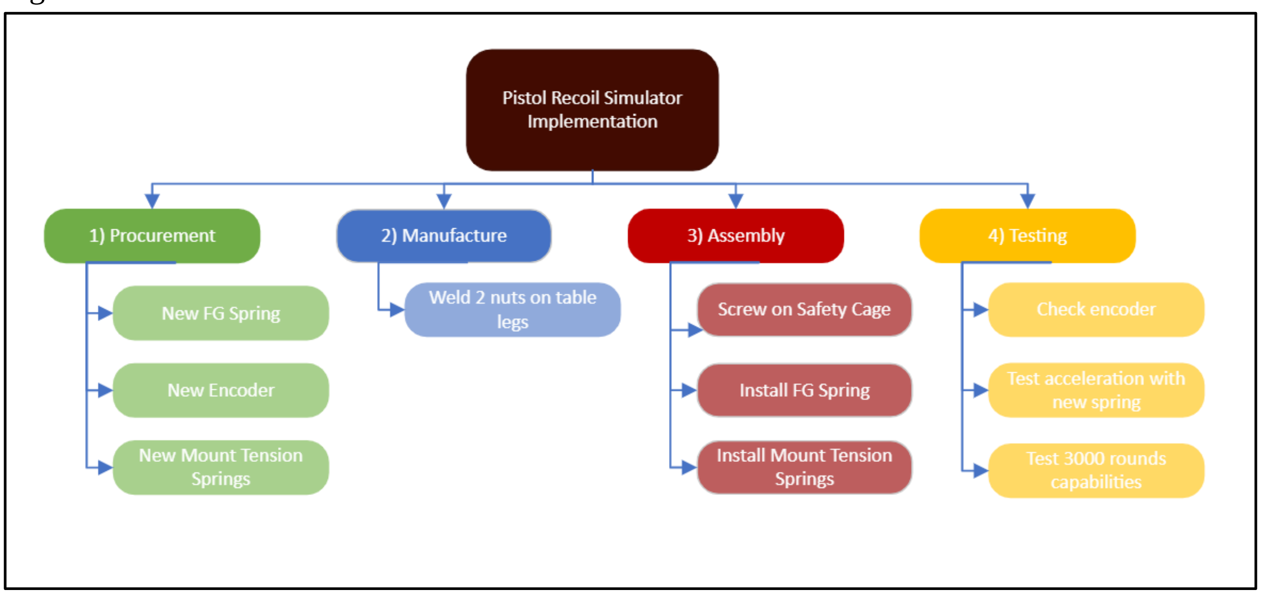

Figure 12 shows the work breakdown required for the sponsors to implement the design into their intended use. To implement the PRS, Sellmark must complete 10 tasks. These tasks are divided into four categories: Procurement, Manufacture, Assembly, and Testing.

Procurement only consists of purchasing and receiving new items. There are three items needed for this. These items include a spring that can reach the maximum desired forces, a new encoder, and potentially weaker tension springs if the sponsors would like the rotational movement.

For the manufacturing phase, the team will need to find someone to weld two nuts onto the table legs. During testing, the ones placed by the PRS team fell off. These nuts are necessary to keep the safety cage on.

There are a few assembly items that need to be taken care of. They first will need to screw on the safety cage. Then, they can take apart the FG cylinder to install the new spring. This just requires unscrewing the nut, taking the shaft out, replacing the springs, realigning the shaft in the sleeve bearing, and re-tightening the nut. Finally, if they choose to purchase them, they will install the new mount tension springs. This process involves unscrewing the plates, swapping the springs, and screwing the plates back in place.

The final, and arguably most important category, is testing. The Sellmark team will need to complete three tests to ensure correct functionality before implementing the simulator. First, the team should check that the encoder is working properly. This involves plugging the encoder in and seeing if it is counting the rotations properly. Next, they will test the acceleration of the new spring. This can be done by installing the 3D printed accelerometer mount given to them, plugging it into the DAQ, and seeing if they are reaching their expected acceleration of 3000gs in the x-direction and 1800 in the y-direction. Finally, they will need to check that the test shuts off after 3000 rounds. If they have implemented the encoder properly, this just involves starting the machine and counting how many rounds it completes before stopping.

Project Plan

To create a timeline to follow, the team utilized a Gantt chart. The Gantt chart was updated as tasks got pushed back to reflect the actual schedule. Because of unexpected procurement and manufacturing issues, the team had to move back many tasks to take place from mid-March to the end of April. The final Gantt chart can be seen in Appendix A. 11.

Due to the previously mentioned problems, as well as decreasing motivation in the team, the project began to fell behind. To combat this, manufacturing breakdowns were made for the Table, Force Generation, and Mount subsystems. These detailed what parts were being manufactured, whether the team was in charge of manufacturing or the FEDC staff, and the progress of each part. These can be found in Appendices A. 12, A. 13, and A. 14. These breakdowns greatly increased the speed at which the items were being completed and integrated.

Limitations of Current Solution

As it stands right now, the test rig does not meet multiple of the design requirements stated at the beginning of this document. There are a couple of reasons for these failures that can be addressed by modifying the current system or designing a new one to meet the requirements.

Cam Issues

The cam does not push the load plate one inch as planned. Due to having a thicker tabletop, the cam displaces the load plate approximately half an inch. This reduction in displacement of the load plate causes a reduction in the compression of the spring, thus reducing the force the spring produces and resulting in a 50% decrease in acceleration in the mounting mechanism. To combat this, the team recommends selecting a spring with a higher spring constant. During testing, it was found that the collision lasts $2.5727*10^{-4}$. Using Equation 2, the recommended spring constant is 28,728 lb/in.

Equation 2

$$k = \frac{(m_m a_m \Delta t)^2}{m_s x^2}$$

Encoder Issues

Another limitation is the fact that the encoder does not function properly. The purpose of the encoder isa to track the amount of cycles or impacts onto the mounting mechanism. This value is important for several reasons: during nominal operation, the system will be able to stop after exactly 3000 cycles, allowing easy validation of optic warranties. Additionally, if a failure occurs on the optic, the operator can stop the machine and see the number of cycles it took to induce this failure. However, during final system testing, the encoder was not successfully counting cycles. The exact reason for this could not be determined during troubleshooting, but it meant that the system would run indefinitely unless the operator manually stopped it.

The two most likely sources of failure are either a flaw in the software or a damaged encoder. However, during troubleshooting, the team ran the testing script that was used to verify the encoder functionality before it was integrated into the system. The encoder was not responding at all, which seems to imply that the component was damaged at some point during the assembly or transportation process.

To fix the issue, the best course of action would be to first remove the encoder from the system and re-test it as an individual unit. If the encoder remains unresponsive, it can simply be replaced with a new encoder. If not, further troubleshooting will be required to determine the exact issue causing it to not function when integrated into the model.

Future Work

Over the next week, the team will continue corresponding with Sellmark to ensure they have all the information necessary to run and maintain the test rig. This includes having a final meeting with Sellmark, creating any additional manufacturing drawings, and being available to answer any questions. In addition, the team will finish a user's manual to ensure the sponsors can use the machine efficiently, as well as how to install the final parts.

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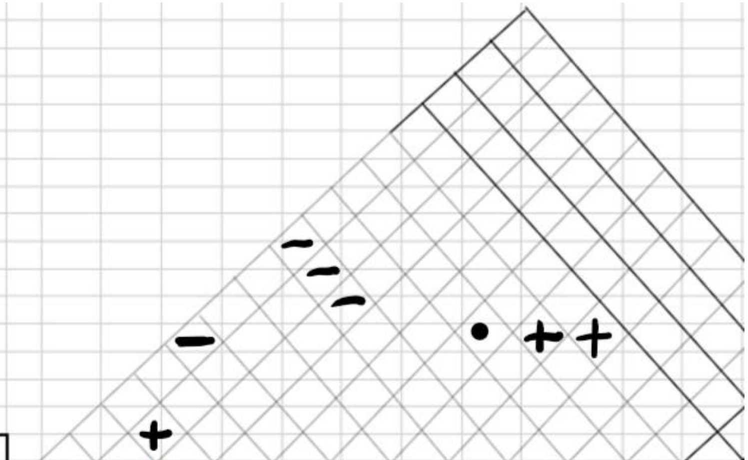
Appendices

A. 1: First Iteration of Customer Needs Table

Customer Need	Importance (Appreciated [1] – Necessary [5])
Can simulate pistol recoil	5
Can simulate both horizontal and vertical recoil	5
Hits the minimum force requirement (3,000 G's)	5
Can simulate rifles or other firearm recoil	2
Is 24" W x 57" L x 36" H	3
Has easily replaceable components	4
Can operate in temperatures up to 100F	5
Is powered by 120V, 60Hz, 1 Phase input	3
Can be partially disassembled/reassembled to move	4
Is quiet	1
Is designed with safety features to minimize risk	5
Can simulate a high number of impacts	5
Fast operation between impacts	4
Can be bolted into a concrete slab	5
Inexpensive to operate	4
Is safe to operate	5
Can attach various types of specimens	5

A. 2: House of Quality



THE CHAMBER OF QUALITY												
Test Rig	Importance	Shock	Maximum Operating Humidity	Maximum Operating Temp	Number of Pinch Points	Size	Time between cycles	Required Voltage	Number of Custom Parts	Cycles per Test	Cost per Test	Two button start
min (-), max(+), nom(*)		*	+	+	-	-	-	-	-	+	-	*
Simulates Pistol Recoil	5	9	1	1	1	1	1	1	1	3	1	1
Can Operate in Texas Humidity	5	1	9	3	1	1	1	1	1	1	1	1
Can Operate in Texas Temperature	5	1	3	9	1	1	1	1	1	1	1	1
Safe to operate	3	3	1	1	9	3	3	3	1	1	1	9
Fits within a desk's volume	3	1	1	1	1	9	1	1	1	1	1	1
Rapid Cycling	3	9	1	1	1	1	9	3	1	9	1	1
Can power by wall plug	2	1	1	1	1	1	1	9	1	1	3	1
Has easily replaceable components	4	1	1	1	1	1	1	1	9	1	3	1
Can be disassembled and reassembled	4	1	1	1	1	1	1	1	3	1	3	1
Can simulate a high number of impacts	5	9	1	1	1	1	1	3	1	9	1	1
Inexpensive to operate	4	1	1	1	1	1	1	1	3	1	9	1
Holds all standard gun accessories	5	3	1	1	1	1	1	1	1	1	1	1
Units		g-force	% Relative	°F	#	ft^3	sec	V	#	#	$	Y/N
Absolute importance		168	98	98	72	78	78	86	96	122	100	
Relative importance		16.9	9.8	9.8	7.2	7.8	7.8	8.6	9.6	12.2	10.0	
Technical difficulty		5	2	2	1	1	4	3	2	1	3	
Existing Test Rig												
Targets			0.75	100	5		1	120	5	3000		Y

A. 3: Force Generation Hand Calculations

m_s — mass of the striking shaft

m_m — mass of the mount

δ_t — Impulse time of the impact

k — spring constant

V_s

V_m

a_s

a_m

X – Compression distance

Desired output: a_m Input: k

Momentum transfer (assuming Coefficient of Rest. = 1)

$$m_s V_s = m_m V_m \qquad V = a\,\delta_t$$

$$m_s V_s = m_m a_m \delta_t$$

$$V_s = \frac{m_m a_m \delta_t}{m_s}$$ Required impact velocity of the striking shaft

Energy analysis of the striking shaft

$$\underbrace{\tfrac{1}{2} k x^2}_{\text{spring potential}} = \underbrace{\tfrac{1}{2} m_s V_s^2}_{\text{kinetic}}$$

$$k = \frac{m_s V_s^2}{X^2} = \frac{m_s \left(\frac{m_m a_m \delta_t}{m_s}\right)^2}{X^2} = \frac{m_s \frac{m_m^2 a_m^2 \delta_t^2}{m_s^2}}{X^2}$$

$$k = \frac{m_m^2 a_m^2 \delta_t^2}{m_s X^2}$$ Required spring constant

Required compression force F_c

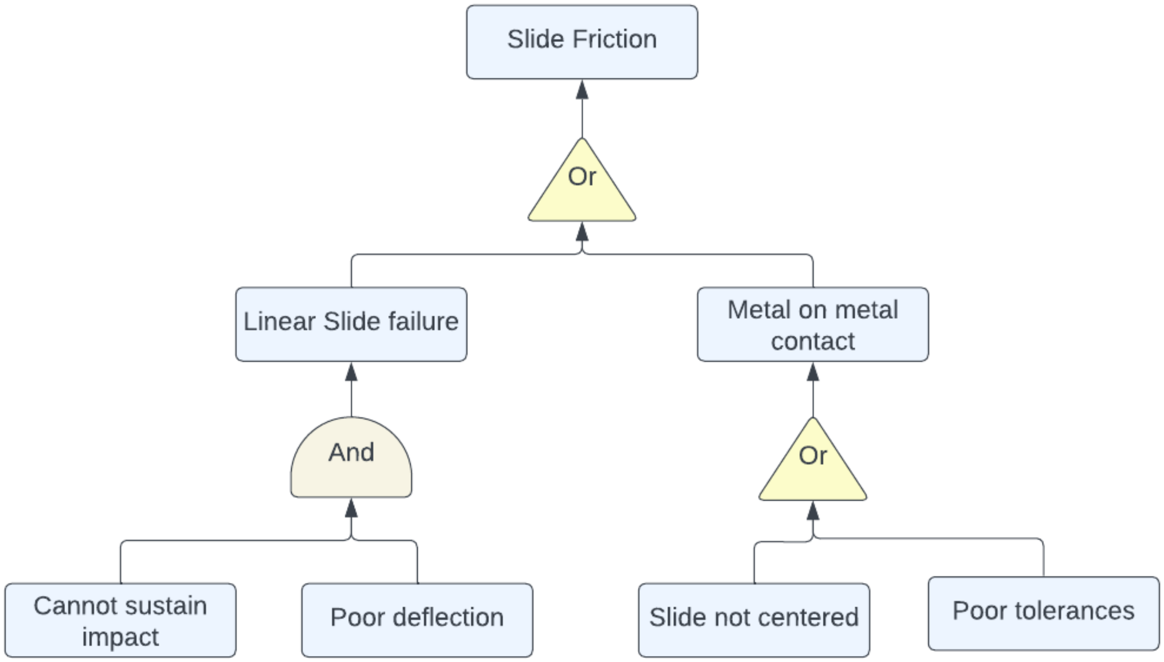
$$F_c = kX = \frac{m_m^2 a_m^2 \delta_t^2}{m_s X^2} X = \boxed{\frac{m_m^2 a_m^2 \delta_t^2}{m_s X}} = \frac{m_m^2 V_m^2}{m_s X}$$

A. 4: Black Box Model

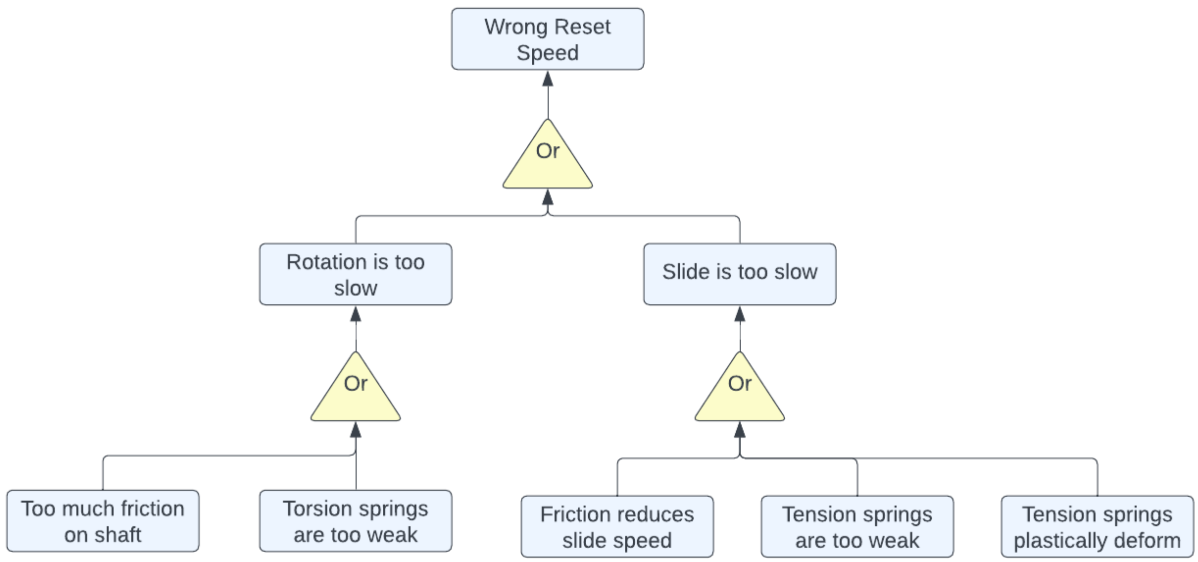
A. 5: FMECA

Part # and Functions	Potential Failure Mode	Assessment							Recommended Actions	
		Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurence (O)	Current Design Controls Test	Detection (D)	RPN	Description of Action	Responsibility & Target Completion Date
Frame; welded table to hold/mount the rest of the assembly	Poor welds	Cause frame to break	9	Bad welds	5	Test welds	5	225	Practice welds before, multiple people inspect welds, advised by FEDC professionals	Megan, 3/1/24
	Deformation of top	Causes misalignment of mount and hammer	8	Too much weight for thickness	4	Calculations	3	96	Add supports to the bottom of the table top	Megan, 3/1/23
	Warping of metal	Cause uneven legs	5	Poor welds	3	Use welding table to minimize warping	4	60	Use welding table to minimize warping	Megan, 3/1/24
Pulley/belt system; converts motor output to the proper torque needed for the system to rotate a cam to compress a spring	Belt looses tension	Will not rotate cam	8	Wrong belt size	4	motor mount	3	96	Utilize motor mount/ change in location of pulley's rod	Gabe, 3/3/24
	Belt snaps	Will not rotate cam	8	Too much tension	2	quality of belts	3	48	Using 2-groove pulleys so 2 belts per pulley	Gabe, 3/3/24
Cam Interface; Cam rotates to compress the spring which is used to generate the necessary force	Cam pushes upwards on load plate	Jams the center plate into the cylinder	8	Design	6	orientation of cam	8	384	Will not know till we test. May have to rotate cam, or alter the load plate	Megan, 3/3/24
	Cam eats at load plate	Does not compress the spring 1". May chip	5	Friction/ gouging	3	Material of Cam and Load plate	2	30	May need to add a polymer cushion	Megan, 3/1/24
load plate/canister assembly; encloses the spring and compresses the spring 1"	Center plate and cylinder have a lot of friction	Jams the center plate into the cylinder	8	Friction/ gouging	4	Material/ tolerances	5	160	May need to add a cushion material	Megan, 3/3/24
	Screw securing plate to rod shears	CAM unable to load spring	8	Excess shock/Fatuige	3	Material/Size	4	96	Use two bolts with opposite threading	Gabe, 3/3/24
	Spring does not compress 1"	Incorrect force	6	Cam interface, frictional losses, cant withstand the force	4	System tests	6	144	May need to alter cam placement	Megan, 3/3/24
Mount; Houses the optic and is hit by the force generation mechanism then pivots to create the x and y acceleration that is needed	Too much friction for the top slide to slide properly	incorrect acceleration	7	Friction	4	Linear rail	4	112	Linear rail implemented into design	Alan, 3/3/24
	Will not reset in a timely manner	increases cycle time	9	Could cause FG to hit nothing causing catrostrophic failure of the simulator	6	Springs in design	3	162	Springs in design, testing, then altering accordingly	Alan, 3/3/24
	Springs absorb too much energy	incorrect acceleration	7	incorrect calculations	4	testing	4	112	Springs in design, testing, then altering accordingly	Alan, 3/3/24
	Where FG strikes, deforms mounting plate	incorrect acceleration, limits lifetime	4	material selection	3	material selection	4	48	Looked into material interaction, may add polymer at interface	Alan, 3/3/24
	Misalignment between slide and rail interface	Incorrect acceleration, increases posibility of detachment or deformation of slide	6	Incorrect machining	3	Tolerancing	3	54	Ensured design has correct tolerancing and alignments. Assembly must be done carefully	Jarrett, 3/3/24
	Tension spring detaches from either slide or body	Failure to cycle slide movement correctly	8	Excess shock	3	Small containment rings	2	48	Use two tension springs and have small retianment rings	Jarrett, 3/3/24
	Tension Spring ruptures	Failure to cycle slide movement correctly	8	Excess use	4	Easy to replace springs	2	64	Springs are expected to fail at some point. Low cost to replace	Jarrett, 3/3/24
	Torsion Spring mechanical failure	Failure to absorb shock and return to resting position in a timely manner	8	Excess use, over rotation	4	Easy to replace springs	2	64	Springs are expected to fail at some point. Low cost to replace	Jarrett, 3/3/24
	Torsion spring too weak	Failure to strike slide in correct position, incorrect acceleration	8	Incorrect calculations	3	Strong spring was selected	6	144	Over estimate the force necessary to reset the slide	Jarrett, 3/3/24
Electrical	Cover switch fails	Force generation does not stop when the safety cover is opened	7	Mechanical/ wiring failure	2	Safety system testing	4	56	Two switches for redundancy	James, 3/3/24
	Start switch fails	System cannot be started	1	Mechanical/wiring failure	2	Safety system testing	1	2	Simple switch mechanism, low chance of failure	James, 3/3/24
	Arduino fails to stop VFD	System continues cycling indefinitely until power is directly cut	6	Software error	9	Robust software testing and E-Stop button	2	108	Implement N/O relay controlled by Arduino/cover switches	James, 3/3/24
	E-Stop button fails	System continues cyling after button is pressed	9	Mechanical Failure / overcurrent	2	Switch is rated for intended current and physically separates power line	4	72	Test E-Stop button before full system integration	James, 3/3/24
	Arduino sends erroneous start command to VFD	System begins cycling before it is supposed to; operators not clear of force generation system	9	Software error	1	System must send specific command to start, and switch configuration must be correct	1	9	Carefully defined software to prevent any chance of erroneous commands	James, 3/3/24

A. 6: Fault Tree Analysis for Slide Friction



A. 7: Fault Tree Analysis for Incorrect Speed of Mounting Assembly



A. 8: Requested Budget Breakdown

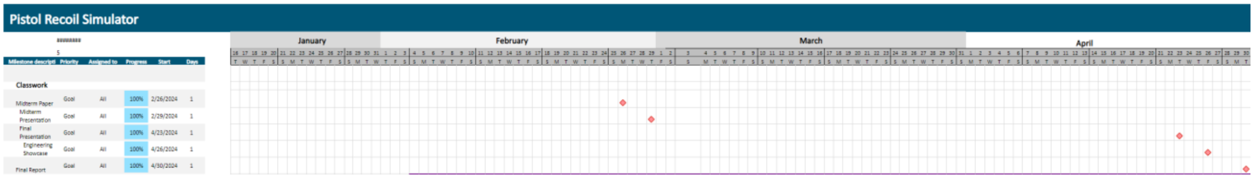
Category	Item	Predicted Cost	Cost Margin	Estimated with Margin
Mounting	Aluminum	$171.00	25%	$214.00
	Pillow Blocks	$21.00	10%	$24.00
	Keyed Shaft	$19.00	10%	$21.00
	Linear Slide	$184.00	25%	$230.00
	Spring	$26.00	50%	$39.00
	Shaft Collar	$23.00	10%	$26.00
	Rubber	$7.00	10%	$8.00
Force Generation	Steel	$470.00	25%	$588.00
	Spring	$29.00	100%	$58.00
	Aluminum	$106.00	25%	$133.00
	Pulleys	$278.00	10%	$306.00
	Belts	$127.00	25%	$159.00
	Motor	$676.00	10%	$744.00
	Bearings	$333.00	10%	$367.00
	shaft collar/nut	$51.00	10%	$57.00
	Motor mount	$181.00	10%	$200.00
Table	Steel Tube	$252.00	25%	$315.00
	Steel Plate	$250.00	10%	$275.00
	Table Feet/casters	$68.00	10%	$75.00
Electrical	VFD	$393.00	10%	$433.00
	Arduino	$36.00	25%	$45.00
	Encoder	$24.00	25%	$30.00
	Switches/buttons	$47.00	25%	$59.00
	Wiring	$20.00	25%	$25.00
Miscellaneous	Fasteners	$63.00	0%	$63.00
	Paint	$97.00	50%	$146.00
	Lubrication	$18.00	25%	$23.00
	Safety Polycarbonate	$36.00	10%	$40.00
	Brackets and Hinges	$33.00	10%	$37.00
	Safety Metal	$144.00	10%	$159.00
Shipping	Shipping cost of materials	$300.00	25%	$375.00
Average Margin		$4,483.00	20.97%	$5,274.00

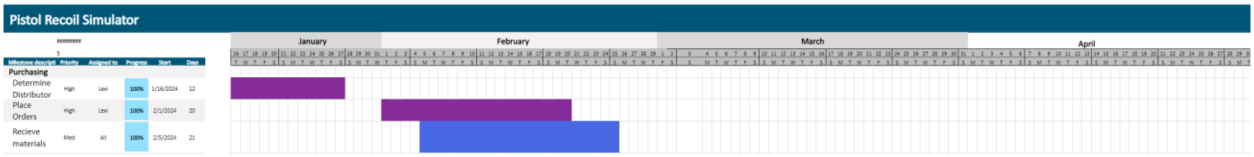
A. 9: Bill of Materials

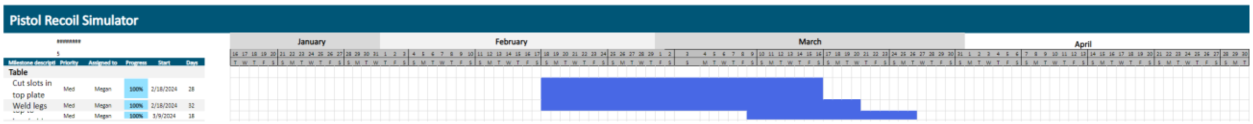
Manufacturer	Date of Purchase	Item	Quantity	Cost	Sub-total	Manufacturer Total
		4140 Alloy Steel Bar	3	$ 39.00		
		1018 Carbon Steel Rod 1" x 12"	1	$ 13.78		
		1018 Carbon Steel Rod 1.5" x 12"	1	$ 27.15		
	2/12/2024	1018 Carbon Steel Bar	3	$ 40.54	$ 596.20	
Grainger		Adjustible Slide Rail	1	$ 133.34		$ 760.98
		7075 Aluminum Flat Bar	1	$ 87.94		
		6061 Aluminum Flat Bar	1	$ 95.37		
	4/4/2024	1018 Carbon Steel Rectangular Bar: 1.5 in Thick, -0.004 in, 5 1/2 in x	1	$ 79.22	$ 79.22	
	4/11/2024	DAYTON V-Belt: A71, 76 in Outside Lg, 0.5 in Top Wd, 5/16 in Thick	2	$ 19.73	$ 39.46	
	4/23/2024	DAYTON V-Belt: A82, 84 in Outside Lg, 0.5 in Top Wd, 5/16 in Thick`	2	$ 23.05	$ 46.10	
		1045 Carbon Steel Keyed Rotary Shaft 1" dia 6" long	1	$ 18.49		
		Extension Spring	2	$ 10.35		
		Linear Slide Carriage	1	$ 127.27		
		15mm x 160mm Linear Slide Rail	1	$ 56.00		
		Shaft Collar 1" diameter	2	$ 11.26		
		1,220 lb/in Spring	1	$ 32.66		
		391.5 lb/in Spring	1	$ 28.72		
		1045 Carbon Steel Keyed Rotary Shaft 1-3/16" dia 24" long	1	$ 55.44		
		1045 Carbon Steel Keyed Rotary Shaft 1-7/16" dia 12" long	1	$ 55.80		
		Mounted Ball Bearing 1-1/8" dia	1	$ 145.03		
	2/12/2024	Mounted Ball Bearing 1-3/16" dia	1	$ 145.03	$1,010.71	
		Mounted Ball Bearing 1-7/16" dia	2	$ 48.59		
McMaster-Carr		Set Screw Shaft Collar 1-1/2" dia	2	$ 16.86		$ 1,029.21
		Sleeve Bearing	1	$ 20.55		
		Steel Hex Nut 1" 8 thread	1	$ 17.15		
		Pack of 25 316 Stainless Steel Washer	1	$ 9.72		
		Pack of 10 High-Strength Steel Hex Head Screw 1/2" #13 1" long	3	$ 13.47		
		Zinc-Plated Steel Corner Bracket 7/8" x 7/8" x 5/8"	12	$ 0.93		
		Plastic Hinges with Holes	2	$ 6.75		
		Zinc-Plated Steel Corner Bracket 1" x 1" x 1/2"	12	$ 0.68		
		1045 Steel Machine Key 3/8" x 3/8", 1-1/2" long	1	$ 11.63		
		Shipping	1	$ 39.87		
		Torsion Spring Right Hand	1	$ 3.82		
	2/29/2024	Torsion Spring Left Hand	1	$ 3.82	$ 18.50	
		Shipping	1	$ 10.86		
Bearings Direct	2/19/2024	1" Pillow Block UCP205-16 Ball Bearing YAS-1	2	$ 9.99	$ 19.98	$ 19.98
Home Depot	2/12/2024	EPDM Rubber Sheet- 1/4 in. Thick x 2 in. Width x 36 in. Length	1	$ 6.07	$ 6.07	$ 6.07
		6061 Aluminum Round Tube 5" dia, .25" thick, 12" long	1	$ 135.78		
		A500 Hot Rolled Steel 24" x 42" x .5"	1	$ 250.00		
		A500 Welded Rectangular Tube 1.5" x 1" x 22.5" .12" thick	8	$ 12.40		
Metal Supermarkets	2/20/2024	A500 Welded Rectangular Tube 1.5" x 1" x 21" .12" thick	4	$ 12.67	$ 901.23	$ 901.23
		A500 Welded Rectangular Tube 1.5" x 1" x 30" .12" thick	6	$ 16.23		
		A500 Hot Rolled Steel 24" x 12" x 0.25"	1	$ 63.77		
		Carbon Steel Expanded, Flattened, 30" x 21", .5" x #13	4	$ 29.49		
		Carbon Steel Expanded, Flattened, 30" x 24", .5" x #14	2	$ 43.23		
		15.75 OD 1-7/16" Bore 2 Groove Pulley	1	$ 116.50		
		3.95 OD 1-1/8" Bore 2 Groove Pulley	1	$ 30.90		
Surplus Center	2/29/2024	3.75 OD 1-1/8" Bore 2 Groove Pulley	1	$ 28.30	$ 331.34	$ 331.34
		18.75 OD 1" Bore 2 Groove Pulley	1	$ 99.05		
		Shipping	1	$ 56.59		
ATO	2/12/2024	3 hp (2.2kW) 3 phase 6 pole AC Induction Motor	1	$ 675.06	$1,067.41	$ 1,067.41
		5 hp VFD, Single Phase 120V Input, 1ph/3ph 220V Output	1	$ 392.35		
		ELEGOO UNO R3 Controller Board ATmega328P with USB Cable	1	$ 15.99		
		RS232/RS485 Shield for Arduino	1	$ 19.95		
	2/12/2024	9V 1A AC DC 100V-240V Power Supply Adapter Cord for Arduino UN(	1	$ 9.98	$ 127.87	
Amazon		Emergency Stop Button Switches for Electric Power Tools	1	$ 29.99		$ 134.36
		3 inch Heavy Duty Casters Load 1500lbs	2	$ 25.98		
	4/23/2024	LED Display Board	1	$ 6.49	$ 6.49	
Lowe's	4/11/2024	Rust-Oleum Professional Gloss Black	1	$ 48.48	$ 48.48	$ 57.46
	4/22/2024	Threaded Rod	1	$ 8.98	$ 8.98	
		Rotary Encoder Incremental 1024 Quadrature with Index	1	$ 23.18		
		Switch SPST-NO Through Hole	2	$ 0.45		
DigiKey	2/12/2024	Pushbutton Switch SPST-NO Keyswitch Through Hole	2	$ 1.24	$ 53.89	$ 53.89
		Shipping	1	$ 27.33		
		.100" x 24" x 48" - Clear Polycarbonate	1	$ 23.99		
Estreet Plastics	3/18/2024	.100" x 18" x 24" - Clear Polycarbonate	1	$ 11.99	$ 82.52	$ 82.52
		Shipping	1	$ 46.54		
		Relays	1	2.35		
		Resistors	2	0.245		
		10 kOhm Resistor	3	0.22		
	4/12/2024	rectifiers	3	0.16333333	$ 35.31	
Mouser		terminal block small	1	1.14		60.51
		terminal block large	2	2.595		
		Shipping	1	24.99		
	4/13/2024	100 kOhm resistor	3	0.07	$ 25.20	
		Shipping	1	24.99		
					Final Total	4504.96

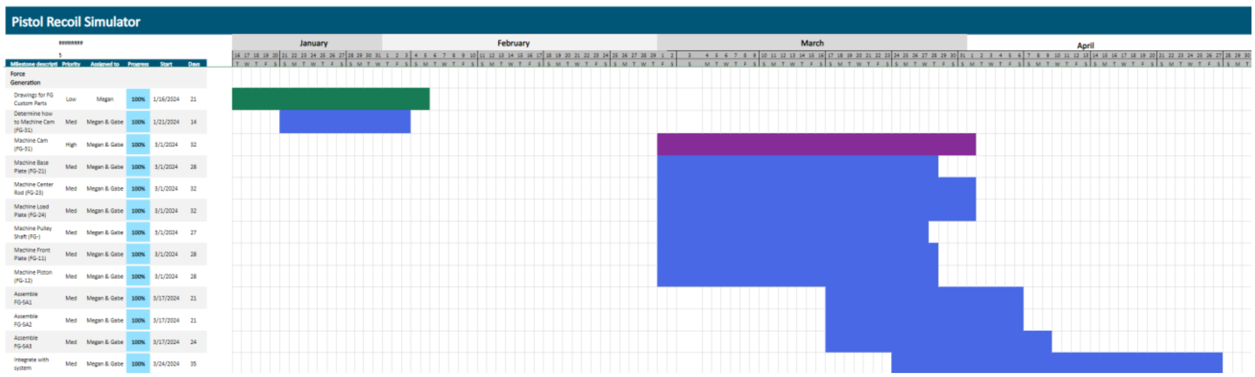
A. 10: Final Cost Model

A. 11: Final Gantt Chart









Pistol Recoil Simulator

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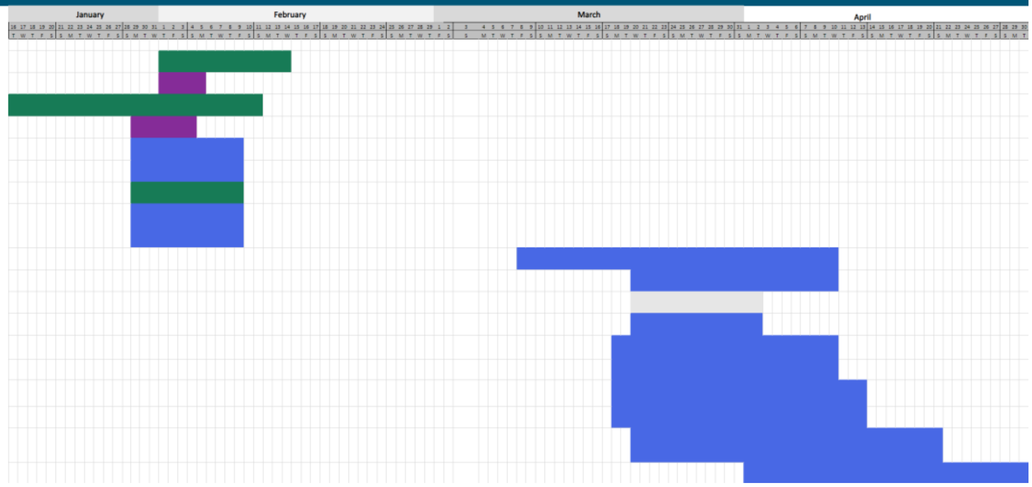
Milestone descripti	Priority	Assigned to	Progress	Start	Days
Mounting					
Drawings for Custom Parts	Low	Alan & Jarrett	100%	2/1/2024	14
Mounting plate design	High	Alan	100%	2/1/2024	5
Create Validation Plan	Low	Alan & Jarrett	100%	1/16/2024	27
Place Orders for critical parts	High	Alan & Jarrett	100%	1/29/2024	7
Bottom Slide Manufacturihg	Med	Alan & Jarrett	100%	1/29/2024	12
Slide Manufacturing	Med	Alan & Jarrett	100%	1/29/2024	12
Manufacturing Plan	Low	Alan & Jarrett	100%	1/29/2024	12
Determine Manufacturing Plan of Mounting Modules	Med	Alan & Jarrett	100%	1/29/2024	12
Machine Top Slide	Med	Alan & Jarrett	100%	3/8/2024	34
Machine Bottom Slide	Med	Alan & Jarrett	100%	3/20/2024	22
Machine Front Plate		Alan & Jarrett	100%	3/20/2024	14
Machine Back Plate	Med	Alan & Jarrett	100%	3/20/2024	14
Machine Hard Stop	Med	Alan & Jarrett	100%	3/18/2024	24
Machine Parallel Stop	Med	Alan & Jarrett	100%	3/18/2024	24
Machine Optic Mounting Plate	Med	Alan & Jarrett	100%	3/18/2024	27
Assemble Mount	Med	Alan & Jarrett	100%	3/18/2024	27
Validate Mounting Function	Med	Alan & Jarrett	100%	3/20/2024	33
Integrate with system	Med	Alan & Jarrett	100%	4/1/2024	50



Pistol Recoil Simulator

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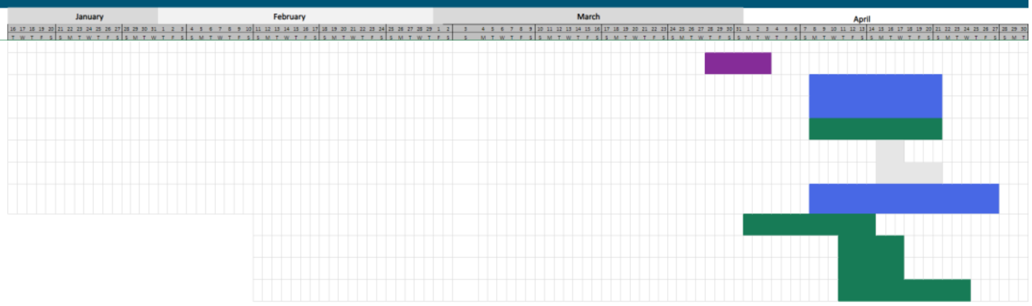
Milestone descripti	Priority	Assigned to	Progress	Start	Days
Electrical					
Motor/VFD functionalit	High	James	100%	3/28/2024	7
RS485 communica	Med	James	100%	4/8/2024	14
sensor test Arduino	Med	James	100%	4/8/2024	14
system Arduino	Low	James	100%	4/8/2024	14
Assembl e PCB		James	100%	4/15/2024	3
Relay PCB		James	100%	4/15/2024	7
Assemble full system wiring	Med	James	100%	4/8/2024	20
Complete electrical system	Low	James	100%	4/1/2024	14
Complete Sensor Test	Low	James	100%	4/11/2024	7
Complete Safety system test	Low	James	100%	4/11/2024	7
Complete Electrical system test	Low	James	100%	4/11/2024	14



A. 12: Mount Manufacturing Breakdown

y	Total Mount Assembly		
Fabricated	y	Actuating Slide	
		y	Recieve material
		y	Submit material to FEDC
		y	Recieved finished part from FEDC
		y	Add mounting holes
		y	Secure part to shaft
Fabricated	y	Slide Base	
		y	Recieve material
		y	Submit material to FEDC
		y	Recieved finished part from FEDC
		y	Add mounting holes
		y	Widen outter bore for springs
		y	drill through hole for springs
		y	Secure part to linear guide
Fabricated	y	Hard Stop	
		y	Recieve material
		y	Submit material to FEDC
		y	Recieved finished part from FEDC
		y	Drill holes for springs
		y	Add mounting holes
		y	Secure part to table top
Fabricated	y	Front Plate	
		y	Recieve material
		y	Cut to size
		y	Drill holes
		y	Paint
		y	Secure to slide base
Fabricated	y	Back Plate	
		y	Recieve material
		y	Cut to size
		y	Drill holes
		y	Paint
		y	Install on Actuating Slide
Fabricated	y	Parallel Stop	
		y	Recieve material
		y	Cut to size
		y	Drill holes
		y	Mount to table

	y	Interchangeable Mount	
		y	Receive material
		y	Cut to size
		y	Drill holes
Received	y	COTS Materials	
		y	Recieve Pillow Block Bearing
		y	Recieve Keyed Shaft
		y	Recieve Torsion Springs
		y	Receive Shaft Collars
		y	Recieve Tension Springs
		y	Recieve Linear Guide
		y	Install Pillow Block Bearing
		y	Install Keyed Shaft
		y	Install Shaft Collars
		y	Install Torsion Springs on Shaft
		y	Install Tension Springs
		y	Install Linear Guide

A. 13: Force Generation Manufacturing Breakdown

y	Total FG Assembly			
	y	SA 1 (Cam & shaft)		
		y	Cam	
			y	Recieve proper material
			y	Waterjet order
			y	give material
			y	Recieve cam
		y	Recieve shaft	
		y	Recieve bearings	
		y	Verify Bearing holes in table top	
		y	Attatch cam to shaft	
		y	Attatch shaft to bearings	
		y	Attatch Pulley to rod	
	y	Attatch SA 1 to table		
	y	SA 2 (spring housing)		
		y	Recieve cylinder	
		y	Recieve sleeve bearing	
		y	Recieve nut	
		y	Recieve spring	
		y	Cylinder Blocks	
		y	SA 2.1 (Striking rod assembly)	
			y	Weld center shaft to front plate
			y	Weld Striking rod to front plate
			y	Center Shaft
			y	Front plate
			y	Striking rod
		y	Back Plate	
		y	Load Plate	
		y	Weld back plate to cylinder	
		y	Place sleeve bearing in back plate	
		y	Attatch cylinder block to cylinder	
		y	put spring on SA2.1	
		y	Place SA2.1 through back plate	
		y	Add load plate to Center rod	
		y	Add nut	
	y	Attatch cylinder block to table		
	y	Long Pulley rod		

A. 14: Table Manufacturing Breakdown

y	Total Table Assembly			
	y	Table base		
		y	Vertical Legs	
			y	Recieve proper material
			y	cut to size
		y	Horizontal supports	
			y	Recieve proper material
			y	cut to size
		y	Recieve casters	
		y	Attatch horizontal supports to legs	
		y	attatch legs together	
		y	level	
		y	add casters	
		y	verify level	
	y	Table top		
		y	recieve material	
		y	submit waterjet request	
		y	drop off material	
		y	recieve waterjetted material	
	y	Weld to table base		
		Verify level		
		Motor shelf		
		y	recieve material	
		y	determine motor placement	
		y	drill holes for motor mount	
	y	weld shelf to table		