The Medusa

Final Project Report

Engineering 339/340
Calvin College 2016/2017 Senior Design Team 25

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Executive Summary

Nerf is a toy line known for its blasters. However, unlike its competitors such as airsoft or paintball, Nerf has not significantly diversified its products with more novel projectile systems. Team 25 feels that, due to this lack of diversity, Nerf is lacking in dynamic forms of play offered by other product lines. Therefore, it has become the team's overarching guideline to "change the way the game of Nerf is played." This change will come about by providing the market with a stationary, single-volley, mass projectile toy designed to tag a large group of players at once that can be remotely triggered by the user. From market and precedent research, safety analysis, and rapid prototyping, Team 25 concluded this was a feasible project worth pursuing, and has developed a preliminary system to meet this goal through analysis of spring driven launch systems, pressure vessels, electronic controls, and user interface. *The Medusa* currently utilizes a small, onboard air compressor for energy storage, and a series of quick exhaust valves that launch a considerable barrage of foam projectiles, with safety and deployment controlled by an Arduino board and associated sensors. The following report details the evolution of these systems over the course of the 2016/2017 academic year, and how Team 25 integrated them into a cohesive, functioning prototype.

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Introduction

Disclaimer

Due to the product nature of Nerf toys and, therefore, the nature of this project, language that draws upon firearm and ammunition technology will be used throughout this report. This terminology is meant to simply and easily convey operation and deployment means. It must be noted outright that Team 25's project and the real-world product line it represents are non-lethal and meant for play.

A Narrative (An Example of Play)

The only light in the long corridor came from the dim emergency light that had been triggered. Jimmy ducked behind a column, catching his breath. He clutched his rifle close to his chest, sporadically peering around the corner of his temporary shelter to gauge just how far the walking dead were behind him; a mob of shambling, moaning figures darkened the far end of the way he came, and the way he was going led to a dead end. He knew he didn't have enough rounds left in his clip to put down the herd chasing him. If Jimmy wanted to make it out of this death trap, he only had one option left.

Setting aside his rifle, he reached into his pack and removed what he hoped would be his savior; an explosive device he had been holding onto for a while. He looked over his shoulder; the zombies were halfway to him, now, the chorus of moans now distinctly calling for "Braaaaiiiiiins…" Jimmy wiped a bead of sweat from his forehead and opened the device's loading doors and dumped all the ammunition for it he had for it into the cavity. He slammed the trap door shut, primed the firing mechanism, and moved the switch on the side from "SAFE" to "FIRE." Eyes wide and heart racing, Jimmy dropped the charge in the corner he had hidden himself, grabbed his gun, and stumbled forward in a mad dash.

He couldn't go far, though, before his back was to the wall at the end of the corridor. The mass of dead were maybe ten meters in front of him, lurching ever closer, groaning louder as they closed in on their prey. Jimmy whispered a prayer as he pulled the remote detonator from his pocket, and, once the walkers were almost upon him, he pressed the button.

The device clicked, and with a loud bang, shrapnel flew through the air.

"Aw, man…" one of the zombies grumbled as he was tagged out.

"Where did that even come from?" another chimed in.

"I'm out, are you?"

"Yeah… Start counting."

Almost two thirds of the group that had been chasing Jimmy were tagged out of the game by the barrage of foam balls he triggered. Anyone else who was still standing were quickly tagged out by a NERF dart from his blaster. Jimmy laughed impishly as he gathered up as many of the darts and balls he could and shoved them back into his bag. He picked up the spring-loaded plastic box he had set in the corner, and quickly made his way down the cleared hallway to rejoin the other "uninfected" in this game of "Zombie Walk."

Project Goal

Nerf, a brand of the Hasbro company, is ubiquitous with childhood play. For its history, the company's defining product has been its line of blasters; toy guns that shoot foam darts singularly or in rapid succession. Essentially, this beloved product has remained unchanged for twenty years.

Nerf's competitors, those who market to a more mature age demographic, have long since diversified their product lines. Games like airsoft and paintball offer not just guns, but landmines, grenades, and claymores. These games have also been incredibly team-oriented since their inception. It is these advantages in play to which Nerf has yet to fully catch up.

However, Nerf has begun to redefine its product lines. The *Rival* line of blasters is the most recent, and while it continues the long tradition of singular, handheld blasters, the main marketing push of this line is team-based play—red versus blue.

In addition to this shift, Nerf has also unveiled an unprecedented toy for Holiday 2016: the *Terrascout*, a tank-like drone with remote control and video streaming capabilities. The MSRP value for this new product is two hundred dollars USD with pre-release consumer reactions being universally positive. This shows that Nerf is not only now not afraid to diversify its products, but that it is willing to market at much higher price points than before.

Therefore, it is Team 25's goal to enter into this fledging sub-market and change the way the game of Nerf is played. The team desires to facilitate this newfound team-based organization found in the *Rival* line, and augment this toy line with more unconventional arms.

The Medusa is being put forth as a claymore-like toy that appeals to both a pre-teen and young adult demographic. It is an easily transportable and deployable launcher able to rapidly fire a single volley of multiple projectiles from a stationary position. Team 25 has taken design cues from existing systems in other toys, along with developing novel ideas of its own, in order to develop this product.

The Team

Team 25 is comprised of four mechanical engineers with a wide range of talents and interests. The team was selected to provide a wide range of solution diversity in an attempt to mitigate risks in the project.

Scott Bokach's primary strengths include advanced CAD techniques and rapid prototyping knowledge, primarily associated with 3D printing technologies. He is able to quickly and efficiently bring designs from thought to reality. He perseveres through a problem and maintains focus until a task is complete. His deliverables provide a clear, physical model for the team to analyze and test.

Ian McClaskie's strengths lie in his deep knowledge of munition mechanisms and quality of work. Ian has a deep patience that, when he is tasked to build or learn something new, drives him to get it done right the first time. Though a mechanical engineer, Ian has a strong interest and aptitude in electronic systems, and has therefore tasked himself with managing the onboard electronic systems and coding.

Scott Stamper, while obtaining a degree in mechanical engineering, is also pursuing a biochemistry degree with a focus on pre-professional medicine. This double major dynamic brings with it a mind not just for the technical performance of the project, but the “human element” of the design, and safety precautions for both the potential user and the designers. With experience in research writing and journalistic methods, Scott brings his strengths to the documentation and communication functions of the group.

Nate Zylstra's strengths revolve around the theoretical side of this project, making predictive models and analyzing test data. He has a wide variety of skills that include machining skills and system construction, data recording and analysis, and web design. Nate is the team's webmaster and in charge of media presence; he quantifies the team’s progress and guides the testing phases forward in order to more fully and effectively develop the project.

Preliminaries

Communication

Data records, documentation, and 3D CAD models were all stored on associated cloud servers: Google Drive was utilized to conveniently create and store word documents and data sheets, while *AutoDesk Fusion 360* offered a cloud-based storage system for designs and models that could be shared between users and accessed from any computer with the same software. Any changes to any file in either of these systems would be logged and able to be accessed by any team member at any time.

It is here that Team 25 would recommend the use of AutoDesk Fusion for future teams not just re-evaluating this project, but undertaking any other project that may be heavy in 3D design work; Fusion has all the same features as AutoDesk Inventor, arguably laid out in an even more usable manner; it is free for students to use and download to their own personal computers; and the cloud-based storage and servers enable users to access and edit files from anywhere, not just university computers with the software package. All of the design renderings of the Medusa that follow hereafter were generated using AutoDesk Fusion.

Financial records were also kept up to date in a shared document, letting each member know who purchased what, for what amount, and where it was obtained. These records were kept primarily as a parts list for future reference, and for reimbursement records from the school for budgetary reasons.

Budget Plans

Calvin College allots an initial budget of five hundred dollars to each design team; Team 25 initially elected to remain within this budget for the foreseeable project. The team felt comfortable with the allotted amount, since a small portion of needed materials for this project can be found in house; with the machine shop, wood shop, and electronics shop at the team’s disposal, several raw components and needed tools were found on hand or readily provided by advisors: basic sensors, wire, fixtures, et cetera. It was decided that approximately three hundred dollars of the budget would be focused into “research and development,” the building processes during the first semester. A larger portion of the budget was spent on the rapid prototyping and development of ideas during the fall, to effectively develop ideas and workable models, testing their viability. The remaining two-fifths of the budget was allocated for second semester, where refinement of the project would take place. Since the second semester is focused primarily on the refinement of one system developed in the first semester, the team planned on not having to spend nearly as much money on material costs; the major components would already be in place by then, and many of the remaining pieces from other developments have the potential to be reused. This view adjusted once the spring semester started, however.

During the spring, it became necessary to replace or rework parts that fell into the more expensive end of useful materials; an entirely new Arduino needed to be purchased for the electronics system, several quick exhaust valves were faulty and needed to be replaced, and some parts that were thought to be reusable from previous iterations simply were not so. In addition to replacing components, the scope of the project also expanded to include several auxiliary devices, two additional builds requiring many of the same components; therefore, the initial budget provided by the college needed to be expanded. It was now that Team 25 sought out an increase to an overall budget of eight hundred dollars, instead of the initial five hundred. This influx allowed all parts necessary to achieve the new project scope to be easily acquired.

Most of this budget went to acquiring parts from various distributors like Lowe's, Home Depot, and Amazon, mostly being specific PVC fixtures and assorted electronic components. What parts could not be found in-house were purchased on an as-needed basis. Digital documentation of purchase records and physical receipts were kept for reimbursement purposes. This record can also be seen in **Appendix II**.

Custom parts were also able to be made with both the engineering department's 3D printers, and the 3D printer of team member Scott Bokach; the availability and cost effectiveness of 3D printing technology has been an invaluable aid in the rapid prototyping process.

Research

Market Precedence

As stated above, Nerf does not have the diversity of its competitors. Airsoft produces its own claymore-style device which uses a torsion spring system to catapult its payload. Paintball grenades have existed for some time now, where a player throws a small canister that, upon striking the ground, releases a wide spray of paint in every direction. The soon-to-be-released, as of this writing, *Terrascout* is the closest thing Nerf has produced to match these other armaments.

Nerf did, however, once produce a viral marketing campaign that at least appealed to the desire for such a product, if not fulfilling it. The Nerf *Nuke* was a 2014 April Fool's Day joke put out by ThinkGeek, advertised as a large, cartoonish missile that could be launched into the middle of a group. Upon striking the ground, a large payload of darts would fire in every direction, in the hopes of tagging out as many opposing team members as possible. To date, the video on YouTube has over ten and a half million views, with commenters still asking, "Is this a real thing? Where can I get one?" This obviously shows that the Nerf community wants devices in Hasbro's product lines that perform like its competitors.

Safety

First and foremost, safety is the main concern of the team, which would be accomplished through the adoption of the same standards for safety as seen in existing Nerf product lines. Hasbro recommends using safety glasses during play; therefore, safety standards assumed by this team were set for the impact safety standard from the OSHA accepted ANSI Z87.1-2010 impact rated testing.

The requirements from ANSI outline two methods of tests: a high mass impact and a high velocity impact. A pair of safety glasses must pass both tests without failure, which is defined as: any piece fully fractures, device fracture, penetration of the rear surface, and/or the lens is not retained. Impact rated testing for the high velocity test dictates a 0.25-inch diameter steel ball that is fired at 150 feet per second at the lens, and the high mass impact requires a pointed projectile that weighs 500 grams be dropped from a height of 50 inches. The results of these tests were then adapted to a safety factor of four, and it was then determined that the maximum muzzle velocity for the product would be 464 ft/s. This is obviously much, faster than any product Nerf produces. Team 25's project will perform nowhere near this threshold (in fact, on the scale the team is building, this speed is unachievable, anyway). Because of this, there is a large margin for safety already inherent in the system; the Nerf Rival line operates at a muzzle velocity of 150 ft/s, and it is the team's goal to come within 15% of that value. The final test considerations can be seen in **Appendix III**.

Target Market Ergonomics

Team 25's intent was to design a product for children ages ten and up that could be used comfortably and safely. Academic research was initially sought out in order to create clear specifications for ergonomic use and safety. After thorough research, no directly relevant studies were found. The following sources were used as a reference for the development of our specifications.

According to Nemours Health System, the average ten-year-old should carry no more than ten and a half pounds. This is given for a child carrying a standard school backpack. The maximum size of the product must be an appropriate for an average child. According to the CDC, the wingspan is 50 in. The ideal carrying width and depth of the product is to not exceed 25% of the average wingspan. The height of the object is to not exceed the normal claymore dimension of 8 in tall.

Specifications

The final requirements the team determined were created according to the SMART design model. SMART design specifications are ones which are specific, measurable, assignable, realistic, and timely.

1. Safety
   1.1. Eye protection: impact will not exceed 50% of the standard rating for impact on safety glasses
   1.2. No bruising from impact
   1.3. No pinch points greater than 1/8in
2. Light weight, less than 10 pounds
3. Portable, less than one cubic foot in volume
4. Repeatability, spread of fire will be 15 +/- 2 ft.

5. Spread will be 120 degrees +/- 30 degrees
6. Muzzle velocity (average) is 55 +/- 10 ft/s
7. Safety switch (on/off) emergency deactivation
8. 12 projectile minimum

The development of these specifications over time, with an outline of basic, desired, and reach goals the team considered can be found in **Appendix I**.

Development

Brainstorming

The first major hurdle the team encountered in development was energy storage: how will the Medusa be primed and fire its payload?

The initial design process for the project began with a team-driven creative brainstorming session. This was modelled on a method used by the engineering company, Disher. Disher is a product development company based out of Zeeland, Michigan, for whom Scott Bokach interned this past summer. The method used by the team was based on Disher's Whiteboard Wednesday (hereafter referred to as "WBW") sessions. In these structured brainstorming sessions, team members are given a set of boundaries and boosters, which help aid in the creative process. Every idea presented is valid and open for consideration, but never criticized. The aim of this process is pure, massive idea generation through the process of drawing and writing.

After the preliminary WBW session, the team moved forward by selecting the most promising ideas presented and moved to rapid iteration of proofs of concepts. The following proofs of concepts were deemed by the team as the most feasible options moving forward:

1. *Spring Action Pressurized Piston (Hasbro's Current Method)*. Resembling a bolt action lever, this system uses a spring mechanism to pressurize a single piston. When triggered, it fires a single projectile from the attached barrel. This is the system currently in use in every modern Nerf toy. The Medusa would employ an array of these pistons, all primed and triggered simultaneously. This system would allow for uniform launching distance, speed, and density every deployment.
2. *Momentum Spring System.* This system would eschew the piston mechanism and simply use the force of a spring driven hammer to strike the projectile itself, imparting the stored energy directly to the projectile. This could be accomplished with an array of individual hammers for each projectile, or one single hammer used to propel a mass of projectiles.
3. *Torsion Spring with Sling.* This system is one present in airsoft and paintball applications of this design. The projectiles are packed into a sling, which is anchored at opposite ends to two torsion springs. Similar to a mousetrap, the spring mechanisms are triggered simultaneously, drawing the sling taught, and propelling its contents outward.
4. *Manually primed pressure tank.* This system would use a pressurized vessel that would be pumped by the user. Air pressure would then be rapidly released and used to launch the projectiles from their storage area. Nerf has used pressure vessels in their blasters in years past to varying degrees of success, so precedence for this system exists in the product line.

Risks and Rewards

It is here that one must stop and consider what may happen in undertaking this project. What risks are associated with the proposed ideas found above? First and foremost, none of them could work, and the project would be a failure. However, the fact that the proposed systems are already implemented in other markets begins to negate that specific concern for risk. For the team's purposes, however, these systems may not scale appropriately or transfer to the specific projectile desired to be used here: what works for paintball and airsoft may not necessarily work for Nerf projectiles.

Another major risk of this project has to do with cultural appropriateness. With past teams and current peers working on projects geared towards sustainability and renewability to further human flourishing, it is a very valid to question why this team would undertake a project that centers around a children's toy, let alone one that simulates violent combat.

This team admires and celebrates the other teams working with communities and companies to find solutions to resource usage, sustainable production, and environmental impact. Something that is just as important as these endeavors to human flourishing, though, is the concept of recreation; rest, relaxation, and entertainment are necessary to healthy living.

Team-based gameplay fosters healthy competition, community, and cooperation. Just one example is the semiannual game of "Zombies," a capture-the-flag type event hosted by members of the Calvin College Computer Sciences Department, a Nerf game involving teams of "survivors" and "zombies" spending the evening running and chasing each other through the science building, boosted by their imaginations and sharing an evening of fun, laughter, and competition.

Many Christians have argued against simulated violence, whether it be in toys, paintball, airsoft guns, or, more recently, video games. Many would argue that the virtual shooting of someone else only makes light of the violent act it represents: an actual gunshot. Yes, violence is a terrible and wicked thing, but, the depiction of violence, in and of itself, is not necessarily the same thing. Depictions of violence can be a matters-of-life representation; a portrayal of struggle, real or symbolic; or it can even be a call to action. It may be argued that games such as Nerf, paintball, or airsoft are merely more complex versions of tag or capture the flag. While this can be a contentious subject amongst the believing community, and a discourse on the condemnation or defense of such is too long and not necessarily relevant to this paper, it is this team's opinion that the game of Nerf and other similar concepts, if they are performed with a healthy attitude and respect for other players, are acceptable in which to engage for the Christian. Strategic thinking, team dynamics, and imagination all come into play when people come together in these games. To quote Dr. Renard Tubergen, the advisor of this team, "We model conflict so that we can model resolution."

Despite these potential risks, the team feels that pursuing a testable system is worth the expenditure. The reward would be a new toy, a new product associated with the Nerf brand. Nerf is ubiquitous with play and being able to bring about a new, unique toy and product line would be a worthy endeavor. The creation of the Medusa will facilitate an understanding of energy storage and delivery in a small, mechanical projectile system. Even with the risks of failing, cultural insensitivity, and potential misuse, the reward of understanding, the creation of new product line, and the potential to positively influence and inspire children in play are reasons to pursue this project.

Prototyping

The team began researching into not only existing products, but literature associated with the mechanisms, as well. It was quickly discovered, however, that to fully understand what it was exactly the team was trying to accomplish, the above systems had to be immediately taken to the real-world; physical, testable models were quickly developed.

The first avenue explored involved the torsion spring system. In mimicking airsoft’s claymore design, the team used standard mousetraps connected to a cloth sling to model the propulsion system; when the traps were triggered simultaneously with a lever arm, the cloth sling was snapped taught, launching the Nerf balls. This system had the benefit of being the potentially simplest and easiest to fire mechanism, however, it did not provide initial considerations for consistent launches: there was no control over launch distance or velocity of any given projectile.

The team moved on to the pressurized piston and momentum spring system. It is obvious from picking up any current Nerf product that the pressurized piston system works exceedingly well, so the team first delved into the momentum spring, since it is a very similar mechanic that simply removes the pressure vessel aspect and physically strikes the projectile with a plunger head, rather than using the plunger to prime a small air piston that then acts on the projectile. This proved promising at first; parts were easily created from PVC tubing, springs, and 3D printed parts. Complications arose when multiple firing mechanisms were chained together; pulling back one spring was easy enough, but the force to pull back four at the same time was far more considerable, almost impossible to do by hand, let alone for the desired twenty shots at a time. It was reasoned that the piston version would encounter similar priming issues, and the team moved on.

Next, the use of pressurized air was considered. Nerf has used air tanks in their blasters before, and continue to do so in their Super Soaker line, but it is a now rare system in the dart blasters. The team found that attempting to manifold one small air tank into twenty separate barrels would result in substantial pressure loss throughout the system, and would not be able to perform up to specifications, so a more novel system had to be implemented.

Further research led the team to consider piston valves as a mechanism for storage and firing; this is a system common in potato guns and similar, larger projectile projects. Piston valves use a free-floating piston inside the pressure chamber to seal off the barrel containing the projectile, which interacts with pressure differentials created on either side of the piston to allow the pressurized air to escape the vessel and launch the projectile. Several configurations exist for this system, notably one using a chamber separate from the barrel, and one having the barrel mounted in line with the pressure chamber, the latter also known as a coaxial piston valve.

Below, **Figure 1** details the team’s decision matrix when it came to evaluating the systems under consideration. As can be seen, many of the systems scored very close to one another; again, this can be contributed to the fact that these are already marketable solutions that exist in other applications; they work, and they work well in their given products. However, as is shown in the decision matrix, according to the team’s criteria, the coaxial piston valve more consistently met the desired specifications and was therefore the model pursued further in testing and analysis.

Criteria	Weight of Importance	Launch Mechanism				
		Torsion Sling	Spring Momentum	Spring Compressed Air	Compressed air tank pull valve	Compressed air tank piston valve
Weight	8	8	8	6	6	6
Ease of Loading	9	10	6	6	5	5
Failure Potential	8	1	6	4	4	7
Volume	6	6	8	8	6	4
Moving Parts	10	2	2	2	10	7
Total Potential Energy Storage	10	6	7	5	10	10
Ease of Priming	8	2	4	4	5	5
Safety of Design	10	3	3	3	7	7
Ease of Triggering	8	4	6	6	3	8
Hasbro Precedence	6	1	4	8	3	3
Ability to Manipulate Trajectory	7	1	5	5	5	5
Muzzel Velocity	8	7	5	3	8	8
Usable at Partial Capacity	9	9	9	9	5	5
	Final Desirability	506	594	550	657	679

Figure 1: Energy Storage System Decision Matrix

Progression

Air Storage and Release

The largest and most overarching design decision for the project became how to store and release energy to fire a large volume of projectiles simultaneously. Preliminary testing as discussed above led to the exploration of piston valves and compressed air as the most feasible means to accomplish this. Throughout the end of the Fall semester, the team built, tested, and refined a coaxial piston valve (**Figure 2**). This system performed remarkably according to the testing parameters of desired muzzle velocity (60-80 ft/s) and operating pressure (25-35 psi) for a single projectile. How a coaxial piston valve works is demonstrated in **Appendix IV**.

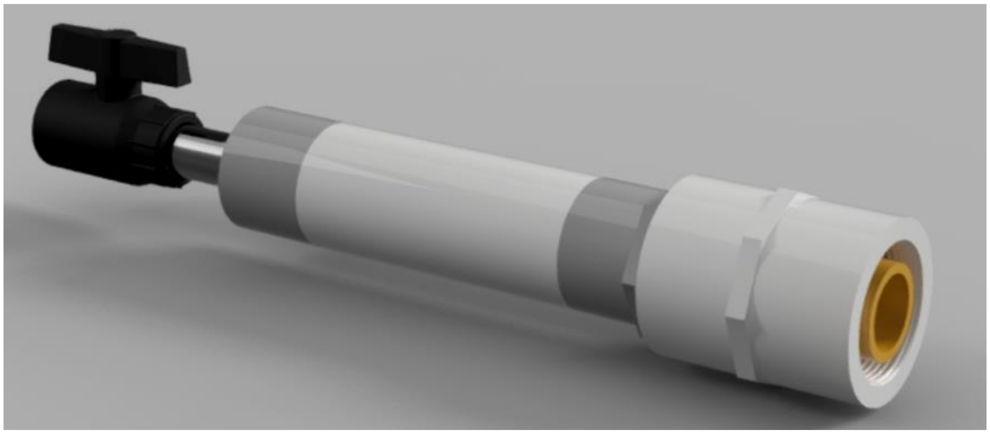


Figure 2: 3D Rendering of Coaxial Piston Valve Assembly.

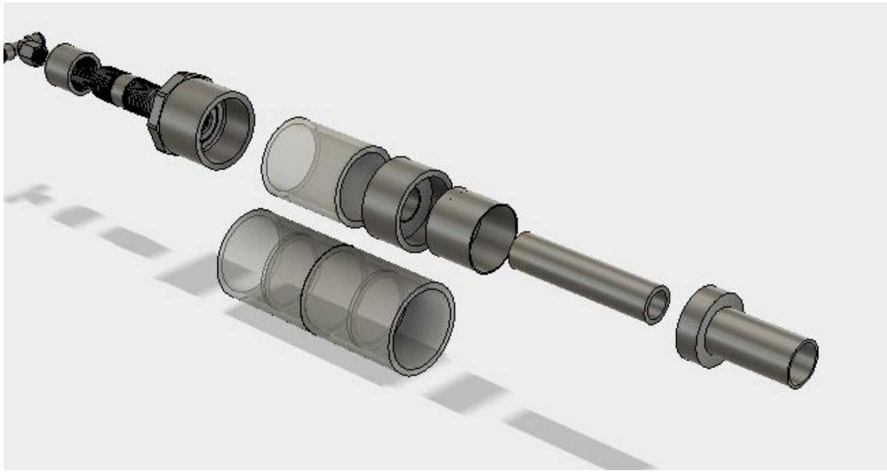


Figure 3: Exploded View of Coaxial Piston Valve Assembly

Once the coaxial piston valve was constructed, the team immediately began testing performance criteria. The primary consideration was system pressure, and how that affects projectile velocity. A theoretical model was constructed in Excel that took the input of final air pressure in the system and provided a calculation of muzzle velocity through volume, pressure, and fluid dynamic equations, which can be found in **Appendix V**.

In tandem with the theoretical calculations, the physical piston valve began to be tested. Time gates were used to measure the exit velocity of the Nerf dart after the system was pressurized at increasing values. **Figure 4** showcases averaged raw data of the system compared to the theoretical model produced in Excel.

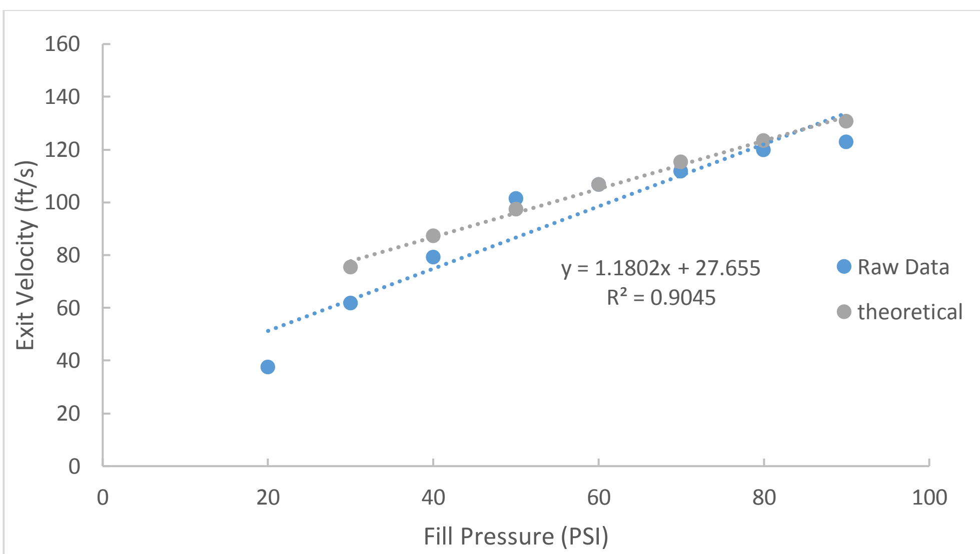


Figure 4: Average of Raw Data compared to the Theoretical Model

The experimental data corresponds well to the theoretical model; discrepancies can be contributed to a failure to fully consider losses due to friction in the physical apparatus, and also to human error. The latter is most likely the largest contributor to discrepancy in the data, since the release valve thus far has been turned by a team member every time, which contributes a lack of consistency to the speed at which the system depressurizes. It is for that reason the team has been developing an electronic triggering mechanism, to remove the human element in testing, as well as move towards a final product. This has been initially accomplished by replacing the manually turned ball valve with a solenoid. **Figure 5** below shows the collected data using a solenoid in which the results highlighted the fact that the orifice of the solenoid acted as a velocity cap due to flow restriction through the orifice.

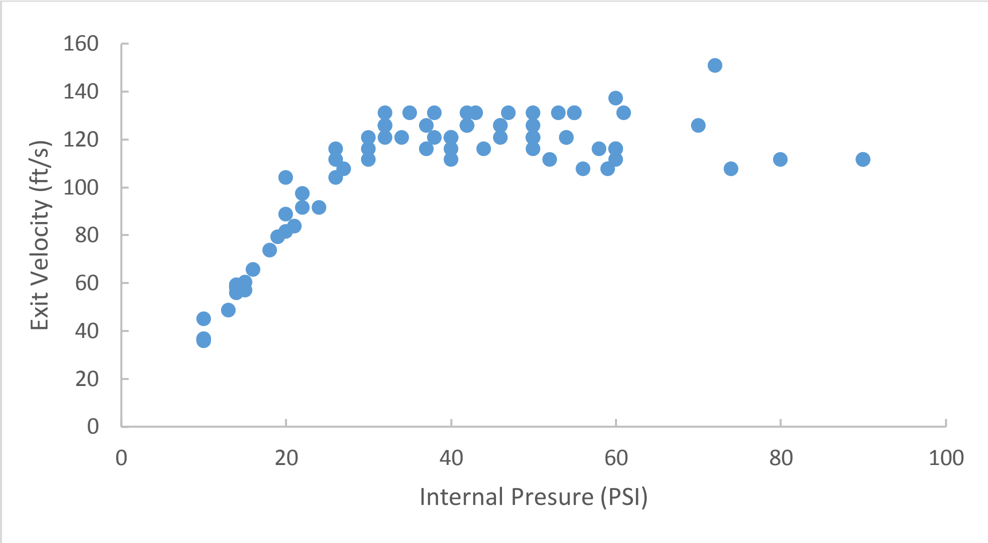


Figure 5: Exit Velocity as a Function of Internal Pressure

Encouraged by this, the system was expanded to begin accommodating for the desired projectile volume, as well as being more compacted to meet size constraints. Three smaller piston valves were connected to a single exhaust output that was piloted by one ball valve (**Figure 6**).

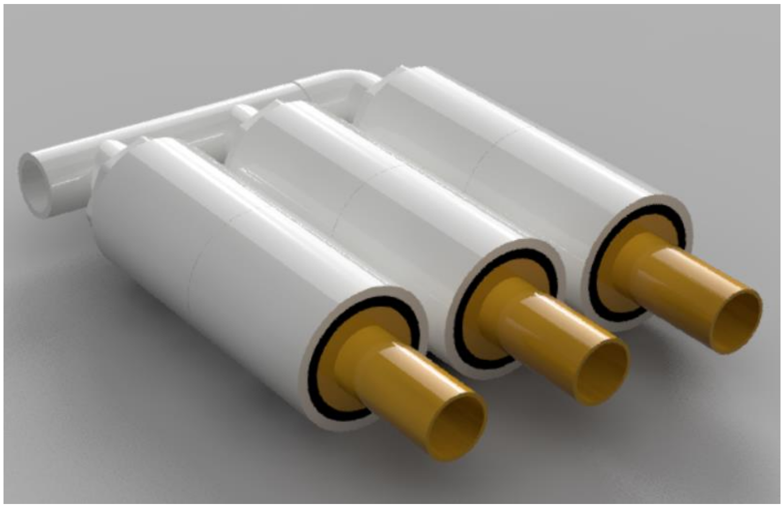


Figure 6:Three Coaxial Piston Valves with One Exhaust Line.

Once the system was daisy-chained in this manner, however, the team had to tackle a new challenge. Due to the reduced capacity of each piston, the introduction of several more pistons to the same exhaust line, the small orifice diameter of the exhaust line, and the slow deployment speed of the exhaust ball valve, a sufficiently large volume of air could not be evacuated from the system fast enough to fire all projectiles adequately and uniformly: projectile velocity was either severely reduced below the desired 60 ft/s, or they simply did not exit the barrel. The team approached several solutions to this, with varying degrees of success.

First, it was thought that the ball valve simply needed to be turned faster. For testing purposes, the design used a manual valve turned by hand to trigger the system. It was decided early on that the system would be remotely controlled, so this manual system would be replaced with an electronic one eventually, so the problem could disappear on its own once that was accomplished. However, as it was then designed, a servo motor strong enough to turn that ball valve quickly enough to trigger the system, with its larger size and internal friction, would be both too large for the final product and not budgetarily feasible.

The next approach was to fabricate a custom piloting valve. Shown in **Figure 7**, the team designed a custom valve that used a small servo to move a cam that locked a small piston in place inside the exhaust line; when the cam was moved, the internal pressure would drive the piston back and open the valve to atmosphere, allowing the system to quickly evacuate.

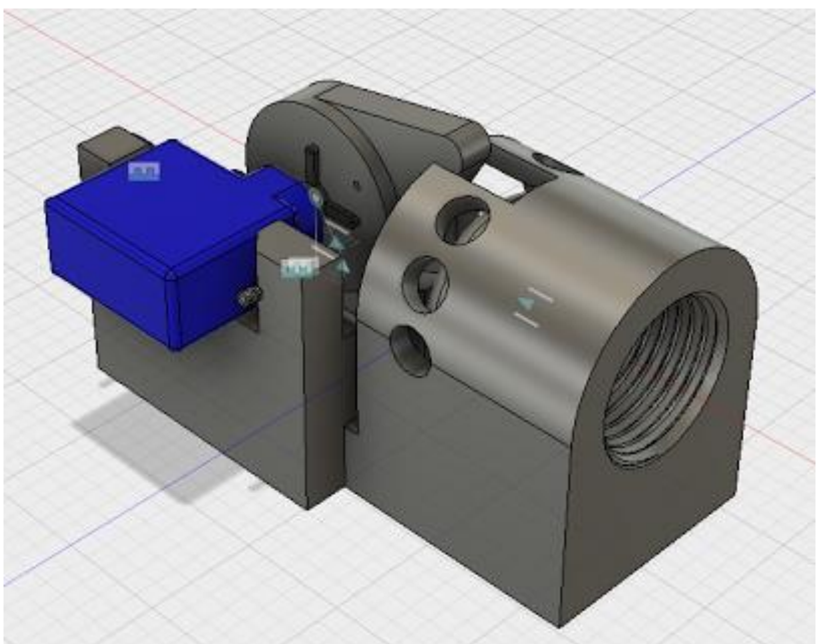


Figure 7: Rendering of Custom Piloting Valve

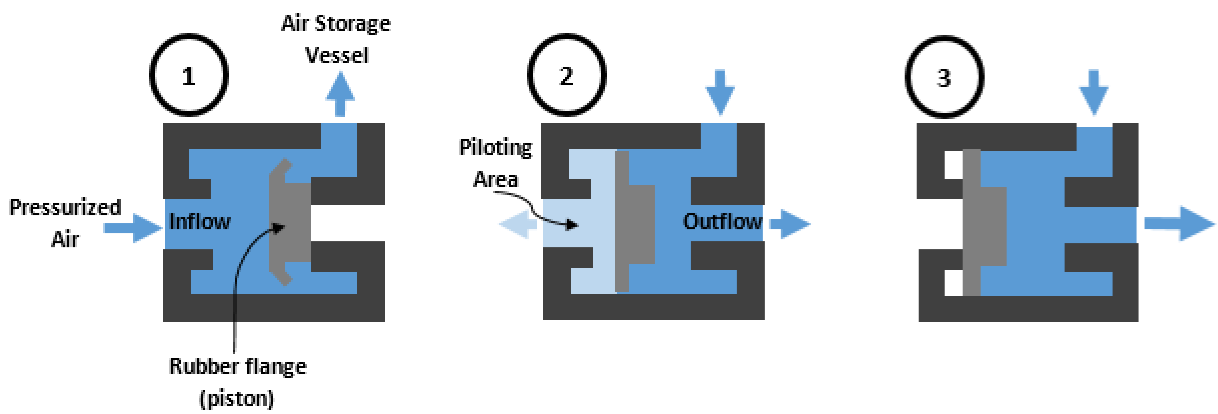
The custom valve was printed out of ABS plastic and bathed in acetone vapor to ensure a strong and airtight mechanism was crafted. Due to tolerances on the 3D printer used and the strength of the cam on the servo, a reliable and consistent fixture to contain the internal pressure could not be maintained. In addition to this, torsional stresses on the servo assembly created by the internal pressure load on the piston head caused the material to yield and leak; the shaft was not strong enough to hold as designed.

Figure 8: Water Solenoid

A water solenoid (**Figure 8**) was considered next. The advantage to this pre-manufactured component was that it already was compatible with existing PVC components, it could be run from the same 12V source as the Arduino controlling other safety features, and the solenoid fired virtually instantaneously, allowing for the desired rapid evacuation. This water solenoid met the speed and sizing requirements for the system, but the problem of a too small orifice diameter was still present. To solve this lingering issue, the team intensely researched options over Interim.

The resulting new solution was found in Quick Exhaust Valves (**Figure 9**). These are small mechanisms used in air cannons such as “spud guns” or t-shirt cannons to pilot the system and move a large air volume very quickly. The team integrated one of these QEVs in between the water solenoid and the main piston valve assembly; the idea behind this was to pilot the QEV with the solenoid, which would then pilot the coaxial piston valve. Before this entire assembly could be tested, however, it was found that the QEV could move a large enough amount of air for the project’s purposes very quickly in and of itself.

Figure 9: Quick Exhaust Valve (QEV)



(1) System is pressurized, sealing rubber flange against exhaust opening.
(2) Piloted Area creates pressure difference that removes rubber flange from exhaust port.
(3) Remaining pressurized air exits through open outlet.

Figure 10: Quick Exhaust Valve Operation

A quick exhaust valve is, essentially, a small piston valve, operating in the same fashion (**Figure 10**), so the team postulated that the QEV alone could be used as the firing mechanism. A small air reservoir was attached to the QEV, and the new apparatus could meet the system specifications laid out for the larger piston valve. With this manufactured part, the team could substantially reduce cost and size, match and even improve performance, and increase capacity. Below, **Figure 11** shows the size comparison between the original piston valve created by the team, and the QEV subassembly currently present inside the Medusa.

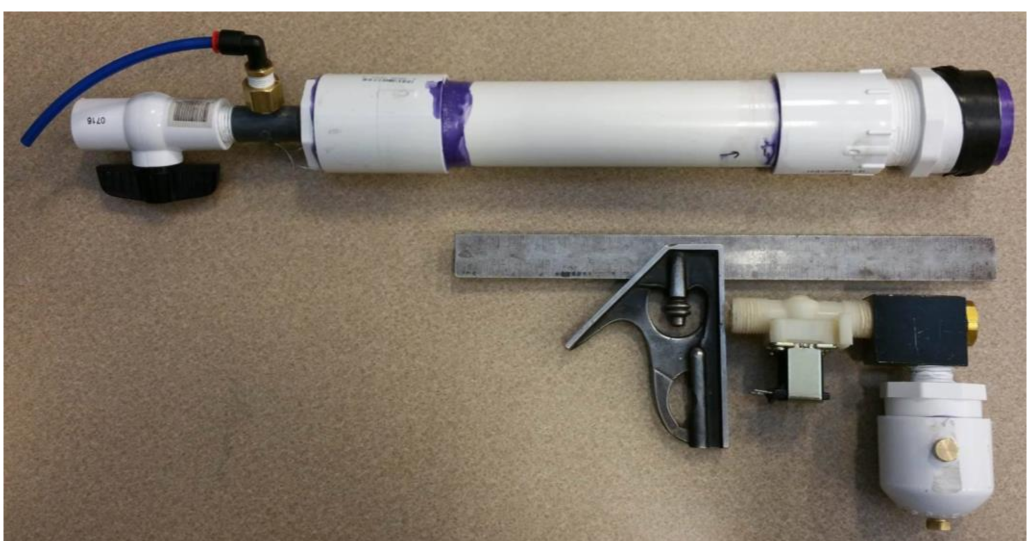


Figure 11: Size Comparison of Built Coaxial Piston Valve and QEV Subassembly (Combination Square set to 6 inches for Scale).

By chaining several of these QEV subassemblies together with a common exhaust line, the firing capacity for the main system could be increased without loss of airflow due to piloting. Four QEVs were used in the final assembly, with the exhaust line triggered by a water solenoid also acting as a barrel to fire projectiles, allowing for the Medusa to have five ports total to release air and propel the foam balls at the desired speed. Figure XX below shows the QEV assembly.

One final challenge with piloting remained, even with the introduction and use of the QEVs. While the new design worked great at storing and releasing air, a problem with consistently priming all QEVs persisted; approximately one in every five attempts at pressurizing resulted in at least one QEV misfiring, or not firing at all. It was quickly discovered that the rubber piston inside the QEV would sometimes not seal correctly when the system was pressurized, and therefore that QEV would not trigger. This was attributed to the inexpensive overseas manufacturing of the valves, affecting their quality and reliability. This was overcome with the introduction of another solenoid and small air tank; this tank would be initially filled by the compressor before the solenoid was fired, releasing a quick burst of pressurized air that would close all the QEVs before the entire system continued to pressurize.

Figure 12: Final Air Storage and Release Assembly

Barrels and Projectile Model

Given that the QEVs now being used within the system had a threaded port through which the air was released, this presented an opportunity for the team to design and use a variety of barrels to hold projectiles and distribute air that could be easily interchangeable and tested for efficacy. **Figure 13** below shows the designs for single, double, and triple barrels that could be attached to the QEVs and muzzle loaded with projectiles.

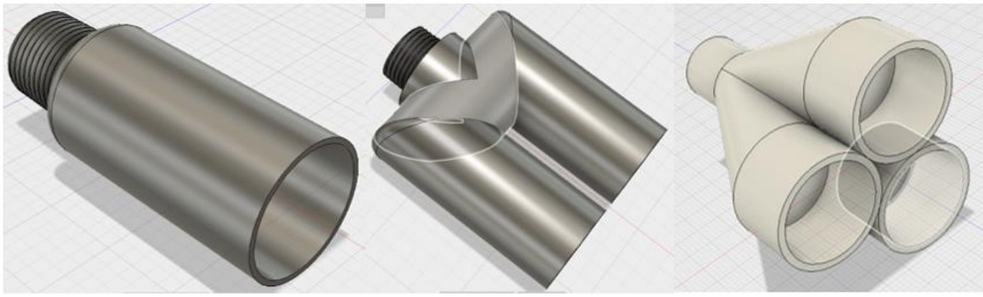


Figure 13: Proposed Barrel Designs

A model to predict projectile speed based on air pressure, number of barrels, and number of projectiles was desired. To create this model, a mathematical derivation was performed and empirical data was collected.

The exit velocity of the projectiles fired from a single QEV at a designated pressure was recorded. It was obvious that one projectile in a single barrel worked excellently. The question progressed: What about two projectiles in one barrel per QEV? Two barrels with one or two projectiles each? Three barrels? Each scenario was tested, and the resulting data can be seen in **Figure 14** below.

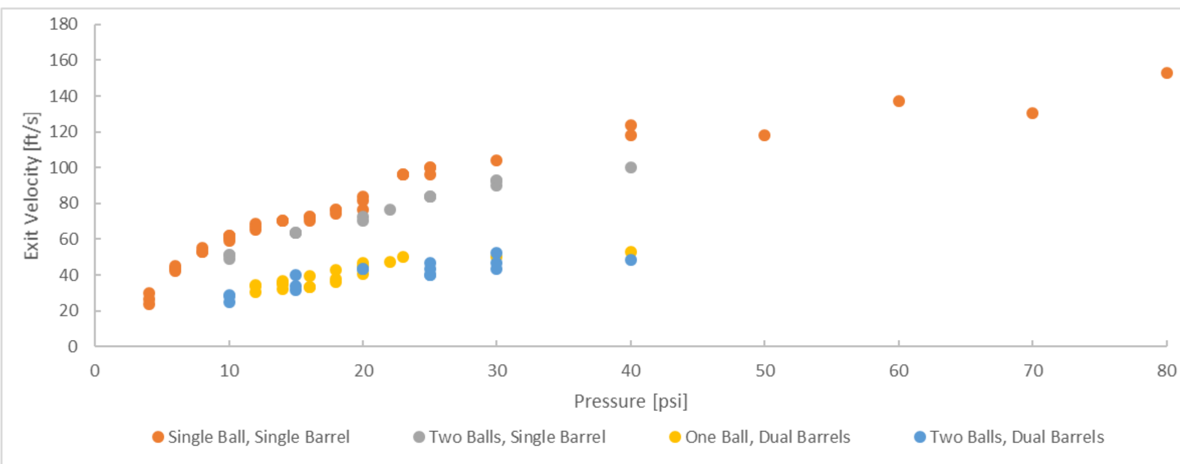


Figure 14: Collected Muzzle Velocity Data as a function of Number of Barrels and Number of Projectiles

Mathematically, Newton's Second Law and the kinetic energy equation were combined and manipulated to yield **Equation 3**, which would calculate projectile velocity based on the volume of air in the system, the mass of the projectiles, the number of projectiles in a barrel, and the number of barrels attached to a QEV. The accuracy of this equation was tracked against the data collected given specific parameters, examples of which can be seen in **Figures 15 and 16**.

$$Velocity = \sqrt{\frac{2*Volume}{m}\frac{P}{(\#\ of\ barrels)}\sqrt{\#\ of\ projectiles}} \qquad \textbf{(Eq. 3)}$$

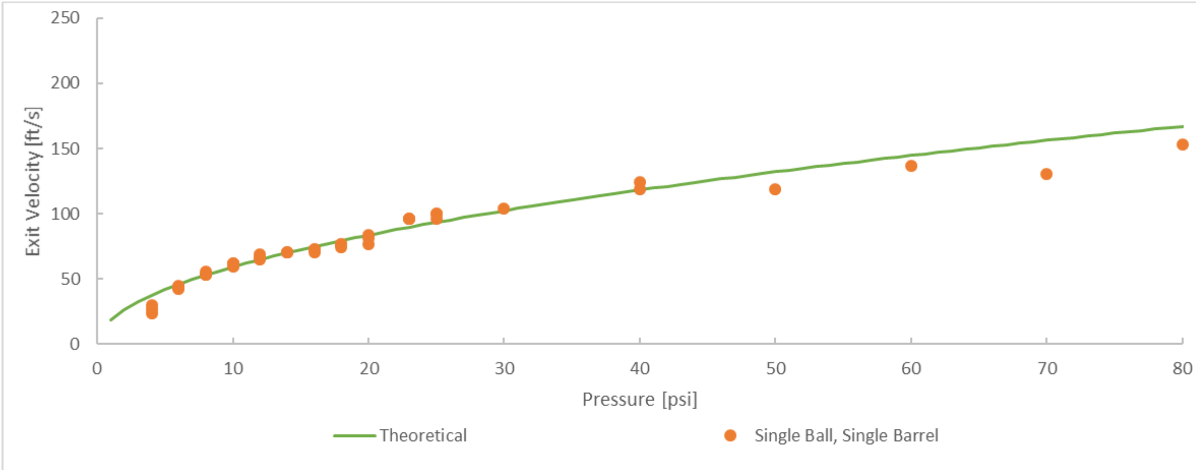


Figure 15: Theoretical Model (Equation 3) with input parameters of One Barrel and One Projectile Plotted Against Comparable Collected Data

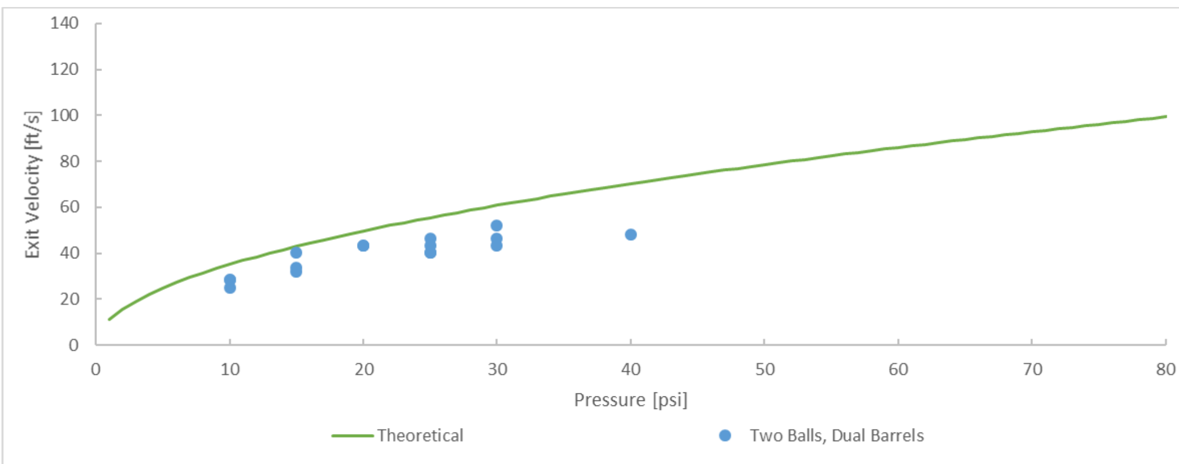


Figure 16: Theoretical Model (Equation 3) with input parameters of Two Barrels and Two Projectiles Plotted Against Comparable Collected Data

As can be seen, the simple mathematical model follows a similar trend as the data collected. The complexity of air flow around the projectiles, air resistance, and the interaction between several projectiles with each other and the barrel walls due to friction can be largely ignored or folded into the square root term of the number of projectiles within **Equation 3**, without a significant sacrifice of accuracy in prediction. The data collected across all testing scenarios can be seen in **Appendix VI**.

From these tests and mathematical model, it was found that a bifurcating barrel on each QEV along with a single barrel attached to the exhaust port, loaded with two projectiles in each barrel, operating between 20-25 psi, would meet the system requirements of velocity of 60-80 ft/s (65 ft/s), safe pressure operation below 40 psi (23 psi average), and capacity of 15-20 projectiles (18 projectiles total).

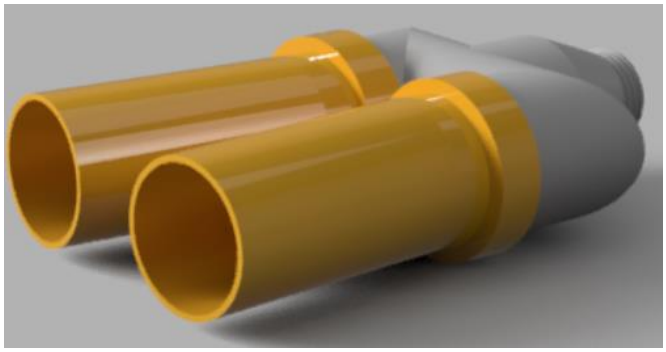


Figure 17: Render of Final Barrel Design

Air Pressurization

Once it was decided that an air-powered system would be used to fire the projectiles, it was obvious that a way to generate compressed air was needed. Early on and for testing purposes, a typical bike pump was used to fill the system. For ease and convenience, the team eventually began using a portable air compressor and car battery to load and test the system.

As user interfacing and usability during play was further considered, though, it was reasoned that expecting a child to pump up a system that continued to grow was unreasonable and impractical; the effort and time required to manually pressurize the system took away from play experience. Nor could a lead-acid battery and machine shop compressor be integrated into the system, not only for practical reasons, but also for safety.

To address this, the team began considering smaller compressors that could be operated with smaller batteries. The solenoids and Arduino were already in place with a power source, so it was decided to add in a small on board compressor to also draw from the electronics system and pressurize the air tanks. Since some components used 5V and others, like the new compressor, 12V power supplies, several voltage dividers and a rechargeable 12V, 3-cell Lithium Polymer battery were integrated into the system. Now, the entire package could be electronically controlled, triggered, and transported with ease.

Final Mechanical System

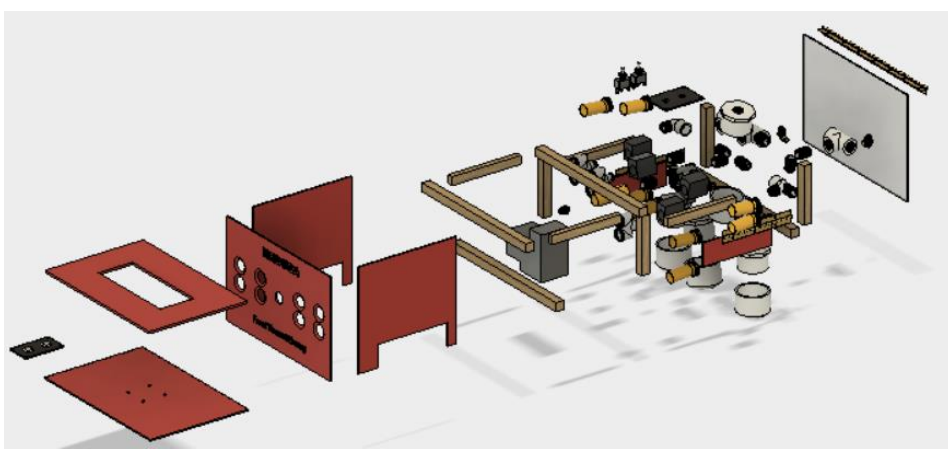


Figure 18: Exploded View of Entire Mechanical Build

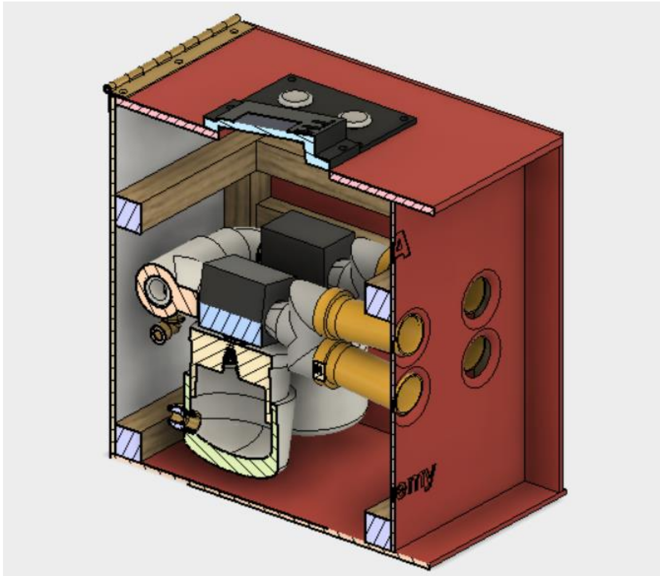


Figure 19:Cross-Sectional View of Mechanical Internals

Final Electronic Control System

The mechanical system is controlled using an onboard electrical system to dictate safety features as well as a user interface. The electrical system can be triggered via a remote control or a pyroelectric infrared sensor. Integrated in the electrical system is a variety of safety features to stop the device from firing and start the deactivation of the system (depressurizing). This system, or rather, the need for this system, developed over time with this project.

One of the goals laid out at the inception of this project was to have a motion detection device to trigger the firing mechanism. This goal evolved to also include a remote triggering option. These desires for an electrical based triggering control quickly grew into a system geared towards safety that has become just as vital, if not more so, than the physical, mechanical firing mechanism.

What started out as a desired feature for the final product became a necessary system in order to control and define safety parameters. The electrical components and the system controlling and monitoring has developed separately as its own entity in tandem with the mechanical firing system; essentially, the team has two separate working systems designed to work together, yet were not fully integrated with each other at first. Once that package was developed, the entire project was refined, calibrated, and, in some cases for specific components, reworked entirely. The actual electronics package on board The Medusa can be seen in **Figure 20**, and the final circuit diagram for the unit can be seen in **Figure 21**, with that figure elaborated on with the bill of materials listed in **Appendix IX**. The entirety of the code programmed into the Arduino board can be seen in **Appendix VIII**. This is the brains of the Medusa; the designation between remote control and motion detection firing modes, the control of which solenoids trigger and when to do so, and the monitoring and maintaining of safe pressures are all coordinated by this microprocessor. Since safety has been the largest concern throughout this project, many redundancies within this digital control system were integrated: the compressor is controlled by the Arduino to shut off when the digital pressure sensor reads a pre-coded value, which, if exceeded, triggers a relief valve to be opened by a solenoid. The User interface is set up in such a way that an operator is walked through instructions step by step through an LCD display to safely use, prime, and deploy the system. Should the electronics fail, a manual relief valve calibrated to approximately 30 psi would be released should the system reach unsafe levels of pressure.

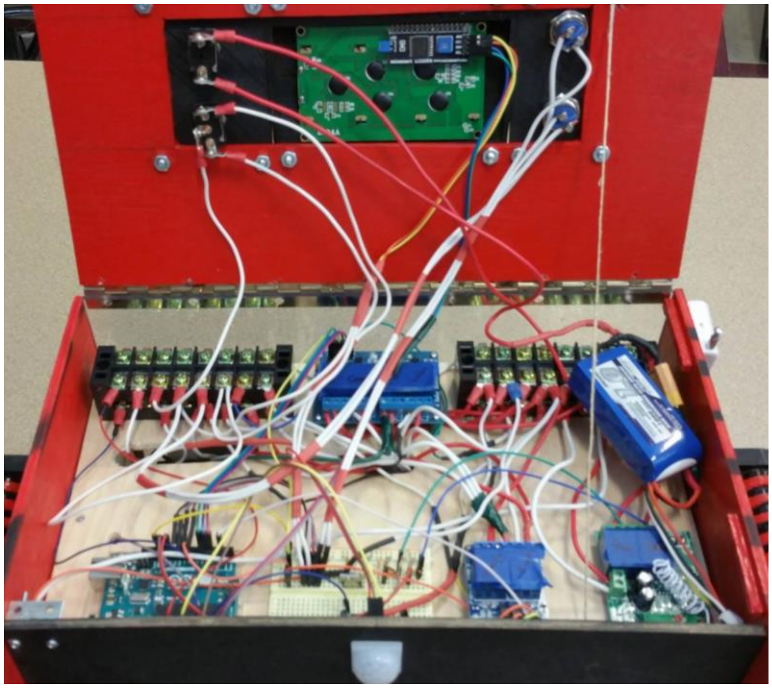


Figure 20: Internal Electronic Components

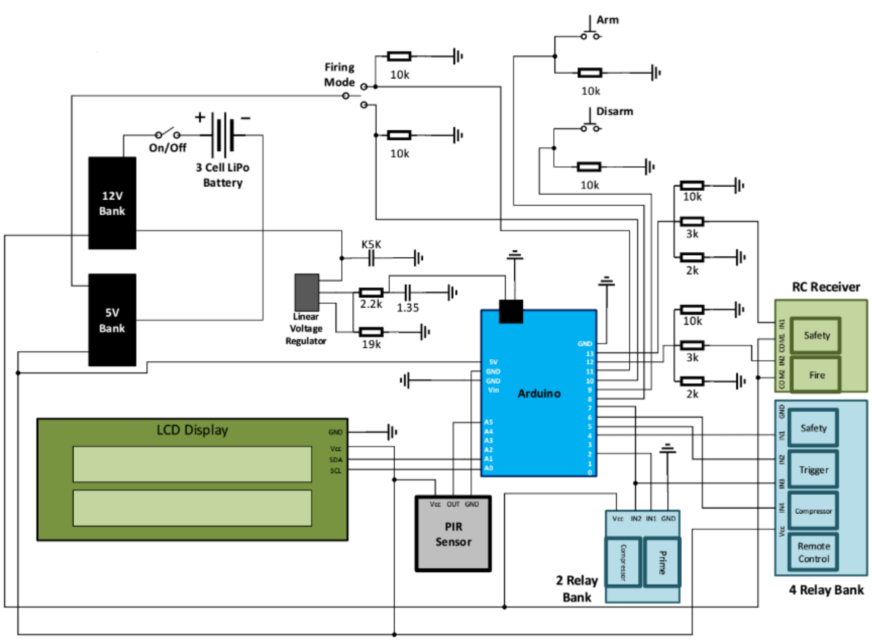


Figure 21: Circuit Diagram

FMEA

As the systems being developed for this project grew more complex, the potential for failure in any of these components also grew. Therefore, from a not just a documentation standpoint, but a safety standpoint, a Failure Mode and Effects Analysis became one of the more pertinent aspects of this project. Since this project will be marketed as a toy, planning for any and all ways each component could fail is vitally important. The analyses of potential failure modes of the Medusa can be seen in **Appendix VII**, outlined according to various subsystems.

Final Prototype

Once the mechanical firing system and electronics control system were united, it did not take much longer for the entire prototype to take a more complete shape. There were some timing and coding issues to work out at first, certainly, but by the beginning of March, troubleshooting had reached its conclusion, and a robust, working model was finished. Team 25 could have finished there with a strong project considerably ahead of schedule. The Medusa at the time fired eighteen projectiles at 65 ft/s, with an operating pressure of 22 psi, along with motion sensing and remote control capabilities. It worked, and it did so beautifully.

There is that whole "idle hands" idiom, though, and with so much time to spare, scope creep began to, well, creep its way into Team 25. It was asked, "What's better than shooting about twenty darts?" The answer, obviously, was, "Sixty darts." With that, two auxiliary systems, or daughter units, affectionately named "Scope" and "Creep" were born.

These daughter units are constructed in the same exact manner as the initial Medusa model: each one contains its own onboard compressor, four QEVs in series, mechanical and digital safety valves, and each one fires eighteen projectiles on its own. However, the daughter systems lack the complex electronic controls present in the main model; instead, the two auxiliary units connect to the main unit through a pneumatic hose connection and a four-prong wire connector, which allows all three systems to be controlled from the sole Arduino, LCD display, and switches on the main unit. These auxiliary units triple the Medusa's capacity to 54 darts, and allows all units to be positioned in any way the user may desire in order to cover a diverse area of spread and targeting.

Once *The Medusa* has been set in place, all the user must do is turn the power switch to "On," press the "Arm" button when prompted by the LCD display, and then, finally, when prompted, select the firing mode, either "Motion Sensing" via the PIR sensor, or "Remote Control" via the radio receiver. The pressurized system will then, when triggered by either of these mechanisms, unleash a barrage of Nerf Rival balls in one powerful blast. The graphic shown in **Figure 26** below visually relates *The Medusa's* specifications and capabilities.

With that, it is with great pleasure that Team 25 presents the finished prototype of The Medusa.

Figure 22: Front View of Loaded Medusa

Figure 23: Isometric View of Loaded Medusa

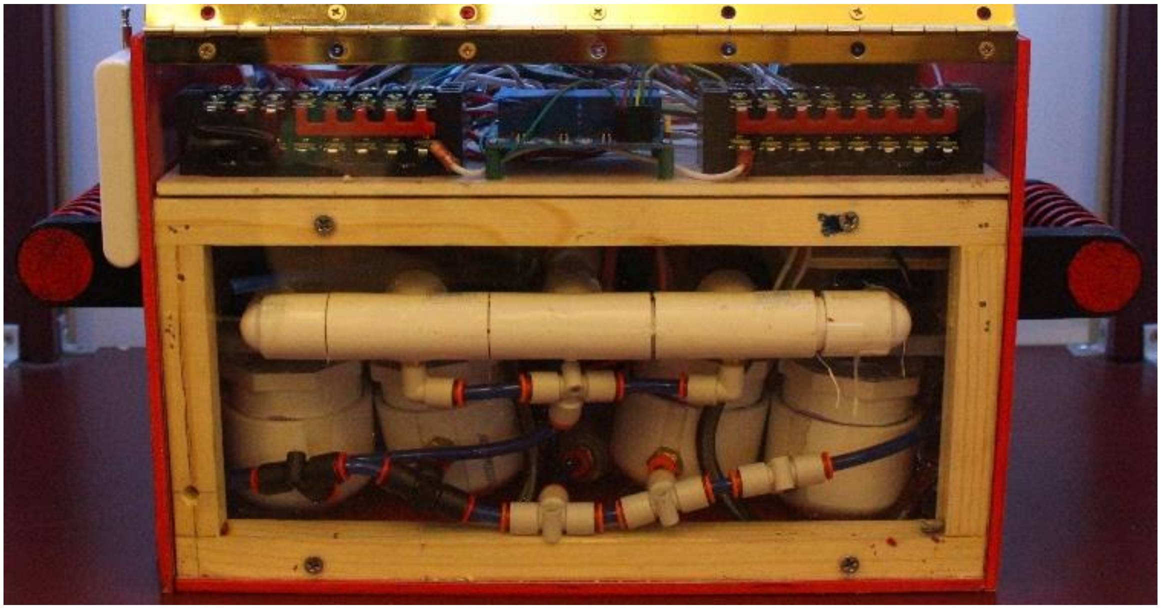


Figure 24: Rear View of Medusa, Showcasing Inner Mechanisms

Figure 25: User Interface of The Medusa

Figure 26: Auxiliary Units, "Scope" and "Creep"

Figure 27: Entire Connected System

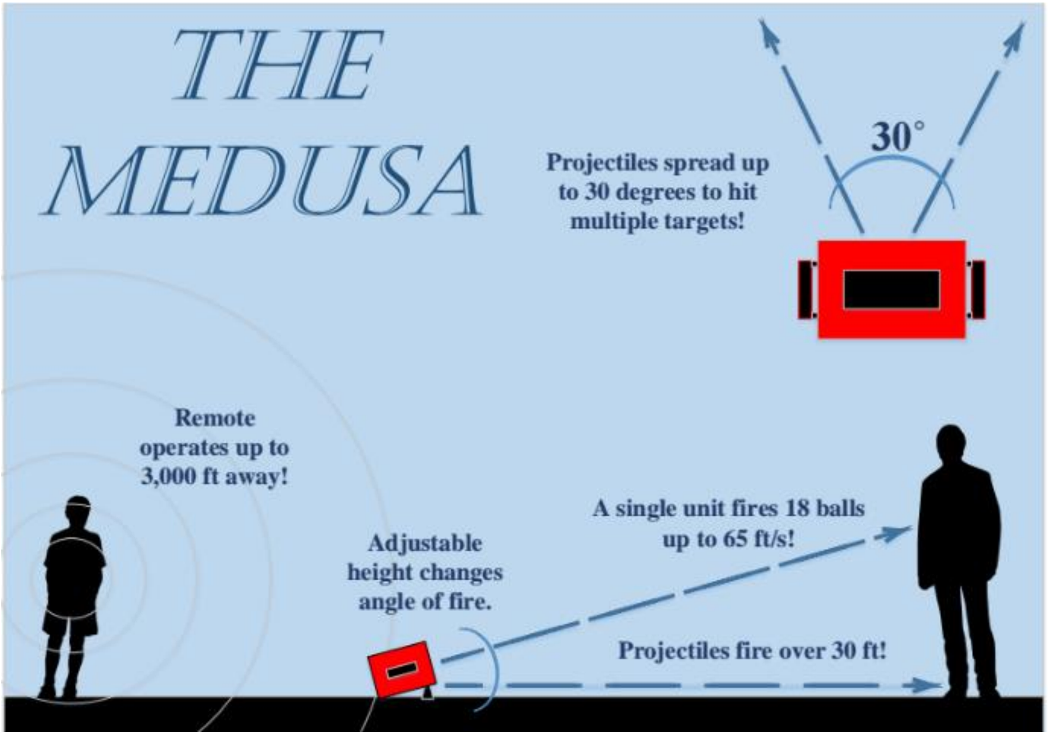


Figure 28: Medusa Infographic

Acknowledgements

There are many people Team 25 would like to thank:

Professor Ren Tubergen for his knowledge, guidance, love of fun, and advising over the course of this project; and his son, Boyd Tubergen, for his involvement in testing and marketing of The Medusa.

Mr. Phil Jasperse, an invaluable wealth of experience and teaching in the machine shop.

Mr. Bob DeKraker and Mr. Chuck Holwerda, for purchasing and providing many necessary components during the build.

Wes Richards was the industrial consultant to this team, and he provided a great deal of guidance and encouragement throughout.

Jessica Zylstra provided artistic renderings and logos for potential final product looks.

Alex Guinn provided contact information to Hasbro engineers.

Kirk Driesenga created promotional videos showcasing The Medusa that the team hopes to send to Hasbro.

And, finally, our friends and family for their love and support, not just during this project, but throughout these past four years as we have pursued an education in engineering.

Thank you, all.

Appendices

Appendix I: Initial Goals and Specifications

Required Features

The required category contains design features in the final product the team felt must be holistically integrated into the design. All following design features are intended to be included in the final design of the Medusa. The required design features are as follows:

- Safe (Does not exceed Hasbro's own guidelines)
- Must shoot something (Elite dart, Mega dart, Rival ball).
- Light and portable (< 5lbs.)
- Repeatability
- Uniform projectile velocity
- Single high volume discharge
- Pre-existing ammunition
- 6 projectile minimum
- Energy storage
- User friendly
- Time delay triggering
- Motion sensing

Desired Features

The desired category contains design features which the team feels are within scope of the project, but are secondary to the required design features. The desired design features are as follows:

- Omni-directional firing
- Light and portable
- (<3lbs.)
- Purely mechanical
- 15 projectile minimum
- Quiet
- Discrete (Not heavily realistic, but also not cartoonish)
- Simultaneous/rapid cascade triggering
- Stable mounting
- Uniform spread
- Compact
- Adjustability of projectile volume/Operation

Reach Features

The reach category is design features the team believes would allow the product to be of a higher intricacy, but are potentially outside the scope of the project. The reach design features are as follows:

- 35 Projectile Minimum
- Multi-surface mounting (Horizontal and Vertical)
- Motion sensing

- Camouflage
- Design for manufacturing
- Use of psychological gameplay (noisemakers)
- Elegance

Preliminary Product Specifications

By organizing our design features in the above categories, a clear framework was developed to aid in the creation of the products specifications. Using the design framework as guiderails, product specifications were created that adhere to the SMART design model. All specifications are specific, measurable, assignable, realistic, and time related. The final product specifications are as followed:

1. Safety
    1.1. Eye protection: impact will not exceed 50% of the standard rating for impact on safety glasses
    1.2. No bruising from impact
    1.3. No pinch points greater than 1/8in
2. Light weight, less than 5 lbs
3. Portable, less than 1 ft^3
4. Repeatability, spread of fire will be 15 +/- 2 ft.
5. Spread will be 120 degrees +/- 30 degrees
6. Life Cycle will be 5 hours of continuous dry fire
7. Muzzle velocity (average) is 32 +/- 2 ft/s
8. Safety switch (on/off)
9. 12 projectile minimum
10. Requires less than 5 lbs of force to prime the triggering mechanism (mechanical spring system) OR operates below 40 psi (compressed air system).

Appendix II: Expenditures

Table 1: Fall Semester Personal Expenditures

Responsible Party	Date	Establishment	Number of Items	Store Transaction #	Price	Balance
						$800.00
Ian	10/15/2016	Lowe's	1	76561518	$4.87	$795.13
Ian	10/25/2016	AutoZone	1	994433	$3.49	$791.64
Ian	10/25/2016	Lowe's	3	74416211	$9.86	$781.78
Scott B.	10/30/2016	Ebay	2	172150755621	$6.52	$775.26
Ian	11/5/2016	Lowe's	13	73365889	$17.42	$757.84
Ian	11/7/2016	The Home Depot	8	27150005617337	$1.02	$756.82
Ian	11/7/2016	Riders of Grand Rapids	1	MDJGH9XG81107	$16.95	$739.87
Ian	11/7/2016	O'Reilly Auto Parts	1	2353-254572	$1.79	$738.08
Scott B.	11/10/2016	Lowe's	1	75808952	$1.67	$736.41
Scott B.	11/10/2016	The Home Depot	9	27150005895966	$11.46	$724.95
Ian	11/11/2016	Radioshack	4	35000	$21.69	$703.26
Scott B.	11/12/2016	Lowe's	5	73976750	$4.75	$698.51
Scott B.	11/17/2016	Lowe's	9	75397168	$11.11	$687.40
Scott B.	11/18/2016	Lowe's	9	12494131	$14.10	$673.30
Ian	11/19/2016	Amazon	2	114-4197790-4089023	$21.04	$652.26
Scott B.	11/27/2016	Lowe's	2	73274534	$2.06	$650.20
Scott B.	11/29/2016	Lowes	8	12446378	$12.18	$638.02
Ian	11/30/2016	Amazon	1	106-5899942-4899465	$8.23	$629.79
Scott S.	11/30/2016	Lowe's	2	75535477	$3.56	$626.23
Scott S.	11/30/2016	Jo-Ann Fabric and Craft	1	5DA04916C1DD89C7	$1.05	$625.18
Ian	12/1/2016	O'Reilly Auto Parts	1	2353-256140	$1.69	$623.49
Ian	12/1/2016	Lowe's	13	74605106	$13.10	$610.39
Scott S.	12/2/2016	Lowe's	4	71716577	$4.39	$606.00
Ian	12/4/2016	Amazon	2	103-0479252-9952268	$28.21	$577.79
Ian	12/4/2016	Amazon	2	103-3489194-7363456	$11.78	$566.01
Ian	12/5/2016	GetFPV	1	100240919	$6.98	$559.03
Nate	12/10/2016	Lowe's	14	73400314	$25.76	$533.27
Ian	12/10/2016	Amazon	2	107-8626120-7545003	$23.38	$509.89
Ian	12/10/2016	Amazon	2	107-8588897-3498628	$13.58	$496.31
Ian	12/12/2016	AutoZone	2	45434	$10.58	$485.73
				Fall Expenditures:	$314.27	

Table 2: Spring Semester Personal Expenditures

Responsible Party	Date	Establishment	Number of Items	Store Transaction #	Price	Balance
						$485.73
Ian	2/6/2017	O'Reilly Auto Parts	2	2353-260795	$3.58	$482.15
Ian	2/7/2017	Lowe's	5	74500662	$10.53	$471.62
Ian	2/7/2017	Amazon	2	11079457509802600	$16.60	$455.02
Ian	2/10/2017	Amazon	1	10763378580725000	$8.22	$446.80
Ian	2/13/2017	Amazon	1	10713816938676200	$8.29	$438.51
Ian	2/14/2017	Amazon	1	10737812836390600	$12.99	$425.52
Ian	2/17/2017	O'Reilly Auto Parts	2	2353-261341	$6.76	$418.76
Ian	2/21/2017	Lowe's	52	73718253	$64.30	$354.46
Ian	2/21/2017	Amazon	2	10721816207029000	$16.91	$337.55
Ian	2/21/2017	Amazon	1	10771380219478600	$21.95	$315.60
Ian	2/21/2017	Amazon	5	10742849308405800	$41.60	$274.00
Scott S.	2/22/2017	Ebay	4	71G91848FS1712105	$22.64	$251.36
Ian	2/25/2017	Amazon	2	102-6110300-8841008	$16.91	$234.45
Scott S.	2/26/2017	Amazon	1	002-8176024-0191425	$25.99	$208.46
Ian	3/27/2017	Amazon	2	114-2925508-3276231	$41.02	$167.44
Nate	3/3/2017	Professor Haan	1	--	$10.00	$157.44
Ian	3/3/2017	Lowe's	7	70564595	$16.03	$141.41
Ian	3/4/2017	O'Reilly Auto Parts	2	2353-262330	$6.76	$134.65
Ian	3/6/2017	O'Reilly Auto Parts	1	2353-262487	$6.03	$128.62
Ian	3/6/2017	Lowe's	4	73846209	$2.50	$126.12
Ian	3/7/2017	Lowe's	1	73888429	$4.01	$122.11
Scott S.	3/11/2017	Lowe's	4	76274342	$13.96	$108.15
Scott S.	3/16/2017	Lowe's	4	74705267	$19.84	$88.31
Ian	3/27/2017	Amazon	2	114-2925508-3276231	$41.02	$47.29
Scott S.	3/31/2017	Lowe's	3	76987013	$10.09	$37.20
Scott S.	4/2/2017	Lowe's	1	75172499	$4.11	$33.09
				Spring Expenditures:	$452.64	

Table 3: Total Personal Expenditures for Project

Total Expenditure:	**$766.91**

Appendix III: Safety Calculations

Table 4: Calculations of Dart Velocity Based on Blaster Used

Blaster:	Slingfire	**Dart Type:**	Elite			
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0084	0.0000084	5	0.41666667	49.6031746	33.7301587
2	0.0068	0.00000068	5	0.41666667	61.2745098	41.6666667
3	0.0063	0.00000063	5	0.41666667	66.1375661	44.973545
4	0.0055	0.00000055	5	0.41666667	75.7575758	51.5151515
5	0.0064	0.00000064	5	0.41666667	65.1041667	44.2708333
6	0.0066	0.00000066	5	0.41666667	63.1313131	42.9292929
7	0.0045	0.00000045	5	0.41666667	92.5925926	62.962963
8	0.0068	0.00000068	5	0.41666667	61.2745098	41.6666667
9	0.007	0.0000007	5	0.41666667	59.5238095	40.4761905
10	0.0069	0.00000069	5	0.41666667	60.3864734	41.0628019
11	0.0075	0.00000075	5	0.41666667	55.5555556	37.7777778
12	0.0079	0.00000079	5	0.41666667	52.742616	35.8649789
Avg	0.006716667				63.5903219	43.2414189

Blaster	Apollo	**Dart Type**	Rival			
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0043	0.0000043	5	0.41666667	96.8992248	65.8914729
2	0.0041	0.00000041	5	0.41666667	101.626016	69.1056911
3	0.0042	0.00000042	5	0.41666667	99.2063492	67.4603175
4	0.0041	0.00000041	5	0.41666667	101.626016	69.1056911
5	0.0041	0.00000041	5	0.41666667	101.626016	69.1056911
6	0.0042	0.00000042	5	0.41666667	99.2063492	67.4603175
7	0.0041	0.00000041	5	0.41666667	101.626016	69.1056911
8	0.0042	0.00000042	5	0.41666667	99.2063492	67.4603175
9	0.0042	0.00000042	5	0.41666667	99.2063492	67.4603175
10	0.0042	0.00000042	5	0.41666667	99.2063492	67.4603175
11	0.0044	0.00000044	5	0.41666667	94.6969697	64.3939394
12	0.0043	0.00000043	5	0.41666667	96.8992248	65.8914729
Avg	0.0042				99.2526025	67.4917697

Blaster	SuperMax [six pumps loose head]			**Dart Type**	1 Rival	
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0087	0.0000087	5	0.41666667	47.8927203	32.5670498
2	0.0231	0.00000231	5	0.41666667	18.037518	12.2655123
3	0.0108	0.00000108	5	0.41666667	38.5802469	26.2345679
4	0.0096	0.00000096	5	0.41666667	43.4027778	29.5138889
5	0.0092	0.00000092	5	0.41666667	45.2898551	30.7971015
6	0.0075	0.00000075	5	0.41666667	55.5555556	37.7777778
7	0.0082	0.00000082	5	0.41666667	50.8130081	34.5528455
8	0.0077	0.00000077	5	0.41666667	54.1125541	36.7965368
Avg	0.0106	2.0388E-06	5	0.41666667	44.2105295	30.0631601

Blaster	SuperMax(six pump, loose head)			**Dart Type**	2 Rival	
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0051	0.0000051	5	0.41666667	81.6993464	55.5555556
2	0.0061	0.0000061	5	0.41666667	68.3060109	46.4480874
3	0.0059	0.0000059	5	0.41666667	70.6214689	48.0225989
4	0.0036	0.0000036	5	0.41666667	115.740741	78.7037037
5	0.0049	0.0000049	5	0.41666667	85.0340136	57.8231293
6	0.0061	0.0000061	5	0.41666667	68.3060109	46.4480874
7	0.0075	0.0000075	5	0.41666667	55.5555556	37.7777778
8	0.0086	0.0000086	5	0.41666667	48.4496124	32.9457364
Avg	0.005975	5.975E-06	5	0.41666667	74.2140949	50.4655846

Blaster	SuperMax (six pump, tight head)			**Dart Type**	1 Rival	
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.006859	6.86E-06	5	0.416667	60.74744	41.30826
2	0.0049	4.9E-06	5	0.416667	85.03401	57.82313
3	0.0056	5.6E-06	5	0.416667	74.40476	50.59524
4	0.0039	3.9E-06	5	0.416667	106.8376	72.64957
5	0.0047	4.7E-06	5	0.416667	88.65248	60.28369
6	0.006	0.000006	5	0.416667	69.44444	47.22222
7	0.0054	5.4E-06	5	0.416667	77.16049	52.46914
8	0.0056	5.6E-06	5	0.416667	74.40476	50.59524
Avg	0.005369875	5.37E-06	5	0.416667	77.59336	52.76349

Blaster	SuperMax (six pump, tight head)			**Dart Type**	2 Rival	
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0079	7.9E-06	5	0.416667	52.74262	35.86498
2	0.0063	6.3E-06	5	0.416667	66.13757	44.97354
3	0.0069	6.9E-06	5	0.416667	60.38647	41.0628
4	0.004	0.000004	5	0.416667	104.1667	70.83333
5	0.0066	6.6E-06	5	0.416667	63.13131	42.92929
6	0.0086	8.6E-06	5	0.416667	48.44961	32.94574
7	0.0056	5.6E-06	5	0.416667	74.40476	50.59524
8		0	5	0.416667	#DIV/0!	#DIV/0!
Avg	0.006557143	5.74E-06	5	0.416667	63.54394	43.20988

Blaster	SuperMax (six pump, long barrel 3 shot)			**Dart Type**	2 Rival	
Trial	**Time [ms]**	**Time [sec]**	**Distance [in]**	**Distance [ft]**	**V [ft/s]**	**V [mph]**
1	0.0067	6.7E-06	5	0.416667	62.18905	42.28856
2	0.0073	7.3E-06	5	0.416667	57.07763	38.81279
3	0.0047	4.7E-06	5	0.416667	88.65248	60.28369
4	0.0063	6.3E-06	5	0.416667	66.13757	44.97354
5	0.0058	5.8E-06	5	0.416667	71.83908	48.85057
6		0	5	0.416667	#DIV/0!	#DIV/0!
7		0	5	0.416667	#DIV/0!	#DIV/0!
8		0	5	0.416667	#DIV/0!	#DIV/0!
Avg	0.00616	3.85E-06	5	0.416667	67.64069	45.99567

Table 5: Energy Calculations for Various Projectile Types

				Nerf Projectile Properties							
				Nerf Dart		Nerf Rival Ball					
ABSI High Velocity Test				**L**	2.8125	NA					
Density	7850			**D**	0.5	1	1				
Velocity [m/s]	45.72			**Volume [in^3]**	0.55223308	0.52	0.23				
Velocity [ft/s]	150			**Volume [m^3]**	9.05E-06	0.00000852	3.76903E-06				
Pressure [Mpa]	8.2			**mass**	0.001	0.00175	0.00661387	0.007848			
	Nerf Elite Dart	**Nerf Rival Ball**		**density [kg/m^3]**	111.0	205.3679184	1754.792277	11360			
Density	110.5	205.4									
Pressure 25%[MPa]	2.1	2.1									
Max Velocity [m/s]	192.7	141.3									
Max Velocity [ft/s]	632.1	463.7									
				weight	0.00661387						
				Volume	0.16						
Calculated pressure											
	Nerf Bullet	**Nerf Rival**						**Bullet**	**Paintball**	**Nerf Dart**	**Nerf Rival**
Density	110.5036006	205.3679184	1754.792	11360			**Mass [kg]**	0.00356	0.003	0.000454	0.000794
Velocity [ft/s]	60	100	300	2500			**Velocity [m/s]**	762	18.288	18.288	30.48
Velocity [m/s]	18.288	30.48	91.44	762			**Joules**	1033.546	0.501676	0.075852	0.368726
Pressure [MPa]	0.018479017	0.09539652	7.336149	3298.05792							

Table 6: Final Values of Initial Safety Considerations

	ABSI High Velocity Test	
Density [kg/m^3]	7850	
Velocity [m/s]	45.7	
Velocity [ft/s]	150	
Pressure [MPa]	8.20	
	Nerf Elite Dart	**Nerf Rival Ball**
Density	111	205
Pressure 25% [MPa]	2.05	2.05
Max Velocity [m/s]	193	141
Max Velocity [ft/s]	632	464

Appendix IV: Piston Valve Operation

The following figures illustrate the priming and firing phases of a coaxial piston valve. These images were taken from an animation that can be found at this source[1].

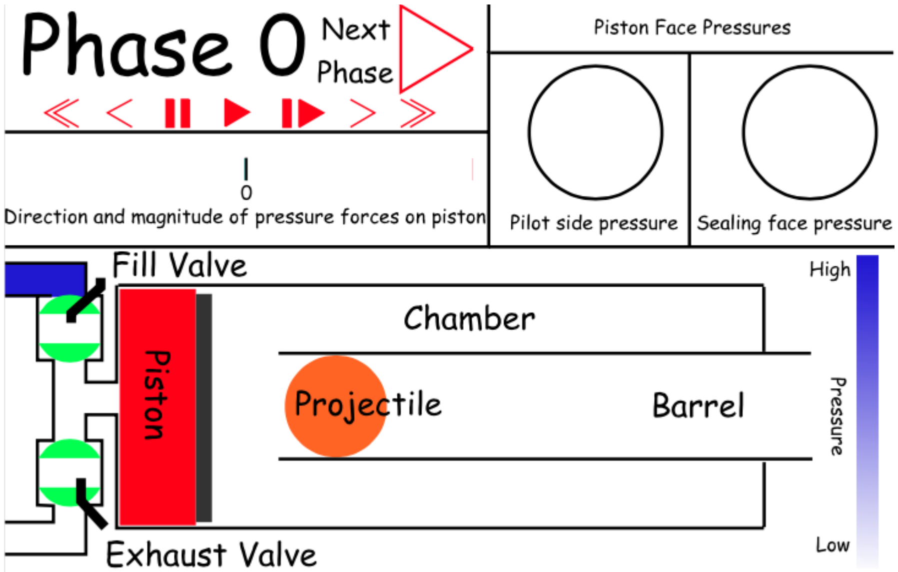


Figure 29: Phase Zero, The Neutral State of the Piston Valve

The projectile is loaded into the barrel before the fill valve is opened.

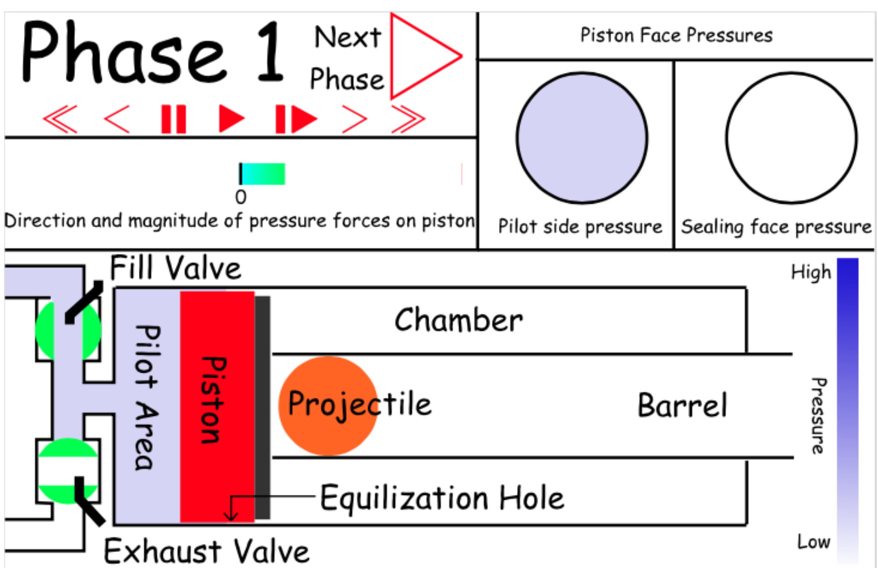


Figure 30: Phase One, When the Fill Valve is Opened

[1] Bell, Bryce. "Coaxial Piston Valve Concept." GBCannon, 6 Jan. 2009, gbcannon.com/concepts/coaxial.html.

The free-floating piston is moved by the inflow of pressurized air that creates the pilot area and seals the piston against the interior opening of the barrel; air begins to flow through the equalization hole around the outside of the piston and fill the rest of the chamber.

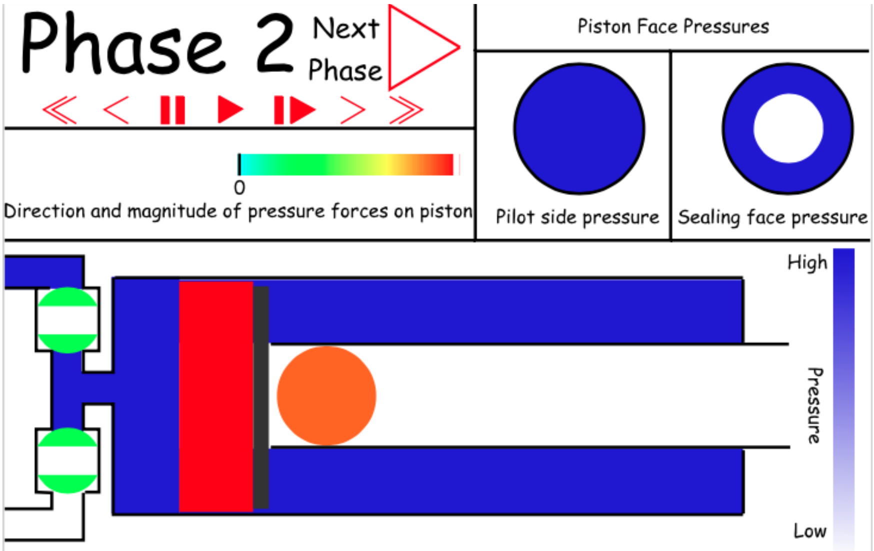


Figure 31: Phase Two, The Fully Primed System

The fill valve is closed when the chamber reaches the desired pressure.

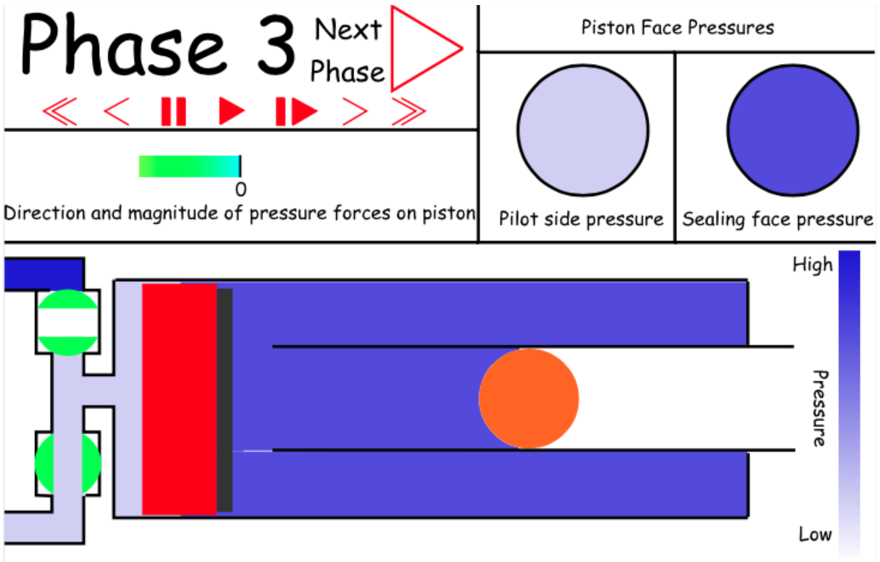


Figure 32: Phase Three, The Discharge of the System

When the exit valve is open, the pilot area initially created depressurizes first, creating a pressure differential that quickly sucks the piston away from the barrel and blocks the exit valve. The system then continues to depressurize through the barrel, launching the projectile.

Appendix V: Piston Valve Testing

Table 7: Piston Valve Muzzle Velocity as a Function of Internal Pressure

	Distance Between Gates [ft]	0.301666667			
PSI	Time [s]	Velocity [ft/s]	PSI	Time [s]	Velocity [ft/s]
60	0.0026	116.025641	47	0.0023	131.1594203
50	0.0024	125.6944444	46	0.0024	125.6944444
40	0.0026	116.025641	44	0.0026	116.025641
90	0.0027	111.7283951	46	0.0024	125.6944444
90	0.0027	111.7283951	46	0.0025	120.6666667
74	0.0028	107.7380952	40	0.0025	120.6666667
80	0.0027	111.7283951	43	0.0023	131.1594203
70	0.0024	125.6944444	42	0.0023	131.1594203
72	0.002	150.8333333	42	0.0024	125.6944444
60	0.0027	111.7283951	42	0.0024	125.6944444
60	0.0022	137.1212121	35	0.0023	131.1594203
50	0.0023	131.1594203	38	0.0025	120.6666667
50	0.0026	116.025641	37	0.0024	125.6944444
40	0.0027	111.7283951	37	0.0026	116.025641
40	0.0025	120.6666667	38	0.0023	131.1594203
40	0.0025	120.6666667	32	0.0024	125.6944444
30	0.0027	111.7283951	32	0.0025	120.6666667
30	0.0025	120.6666667	32	0.0024	125.6944444
20	0.0034	88.7254902	34	0.0025	120.6666667
20	0.0029	104.0229885	32	0.0023	131.1594203
10	0.0082	36.78861789	30	0.0026	116.025641
10	0.0067	45.02487562	26	0.0026	116.025641
18	0.0041	73.57723577	27	0.0028	107.7380952
16	0.0046	65.57971014	26	0.0029	104.0229885
61	0.0023	131.1594203	26	0.0027	111.7283951
60	0.0026	116.025641	24	0.0033	91.41414141
60	0.0026	116.025641	19	0.0038	79.38596491
58	0.0026	116.025641	21	0.0036	83.7962963
59	0.0028	107.7380952	22	0.0031	97.31182796
55	0.0023	131.1594203	20	0.0037	81.53153153
55	0.0023	131.1594203	22	0.0033	91.41414141
54	0.0025	120.6666667	15	0.005	60.33333333
56	0.0028	107.7380952	14	0.0051	59.1503268
54	0.0025	120.6666667	14	0.0052	58.01282051
52	0.0027	111.7283951	15	0.0053	56.91823899
50	0.0025	120.6666667	14	0.0054	55.86419753
50	0.0025	120.6666667	13	0.0062	48.65591398
50	0.0025	120.6666667	10	0.0082	36.78861789
53	0.0023	131.1594203	10	0.0084	35.91269841
			10	0.0083	36.34538153

Table 8: Piloting Tests for Releasing Piston Valve Manually

						Test compressor speed					
	Small Gun					50psi max?					
								0.666666667			
		ft	0.398333	4.78				79.79938419			
						psi	velocity 1b	velocity 2b linear		1 ball theoretical	
Psia	time	release	Velocity (ft/s)			90	122.8984788	81.93231922	90	130.6691	
79	0.0059	med	67.51412			80	119.6990763	79.79938419	80	123.196	
79	0.0083	slow	47.99197			70	111.7728641	74.51524276	70	115.2393	
79	0.0052	med	76.60256	Bad		60	106.6164342	71.07762283	60	106.6909	
79	0.0045	fast	88.51852			50	101.3229425	67.54862834	50	97.39501	
79	0.0041	fast	97.15447			40	79.05334206	52.70222804	40	87.11275	
80	0.0034	fast	117.1569			30	61.63408034	41.08938689	30	75.44185	
80	0.0033	fast	120.7071			20	37.52817553	25.01878369	20	61.59801	
80	0.0032	fast	124.4792								
80	0.0031	fast	128.4946								
80	0.0037	med	107.6577								
70	0.0036	fast	110.6481								
70	0.0105	heela slov	37.93651								
70	0.0039	fast	102.1368	Crooked							
70	0.009	slow	44.25926								
70	0.006	med	66.38889								
70	0.0043	fast	92.63566								
70	0.0033	fast	120.7071								
70	0.0033	fast	120.7071								
70	0.0037	fast	107.6577								
70	0.0034	fast	117.1569								
60	0.0052	fast	76.60256								
60	0.0054	med	73.76543								
60	0.0053	med	75.15723	Bad							
60	0.0081	slow	49.17695								
60	0.0047	fast	84.75177								
60	0.0036	fast	110.6481								
60	0.0038	fast	104.8246								
60	0.0036	fast	110.6481								
60	0.0038	fast	104.8246								
60	0.0039	fast	102.1368								
50	0.0055	fast	72.42424								
50	0.0078	med	51.06838								
50	0.0052	fast	76.60256	Bad							
50	0.0057	fast	69.88304								
50	0.0048	fast	82.98611								
50	0.0038	fast	104.8246								
50	0.0037	fast	107.6577								
50	0.0042	fast	94.84127								
50	0.0039	fast	102.1368								
50	0.0041	fast	97.15447								
40	0.0053	fast	75.15723								
40	0.0061	med	65.30055								
40	0.0049	fast	81.29252								
40	0.0048	fast	82.98611								
40	0.0044	fast	90.5303								
30	0.0063	fast	63.22751								
30	0.0056	fast	71.13095								
30	0.0073	med	54.56621								
30	0.0059	fast	67.51412								
30	0.0077	slow	51.7316								
20	0.0107	fast	37.22741								
20	0.0136	slow	29.28922								
20	0.0107	fast	37.22741								
20	0.0093	fast	42.83154								
20	0.0097	fast	41.06529								
90	0.003	fast	132.7778								
90	0.0032	fast	124.4792								
90	0.0035	med	113.8095								
90	0.003	fast	132.7778								
90	0.0036	med	110.6481								

Table 9:Energy Calculations for Projectile Fired from Piston Valve

				psi	20	6894.76						
				pa	137895.2							
1	0.785398											
Diameter	Area	Length	Volume				0.058928					
1.5	1.178097	1.88	2.214823								22	78.61635
1.75	1.374447	2.23	3.065016								30	80.12821
0.84	0.659734	3.88	2.55977								37	119.0476
		in^3	2.720069	0.0254	1.64E-05						39	115.7407
		m^3	4.46E-05								41	78.61635
		energy=	6.15	J			1.133917028	1.86E-05			50	115.7407
		energy ball	0.104583				1.335566435	2.19E-05			65	126.2626
		Energy remaining=	6.04				vol of barrel	4.05E-05			66	126.2626
		P_pa	7.10E+04				new vol=	8.50E-05			102	198.4127
		Psi	1.03E+01								117	198.4127
		rho	403.1									
			18.77507	3.28084								
			61.59801				90	130.6691				
							80	123.196				
		v	70				70	115.2393				
			5.0225				60	106.6909				
							50	97.39501				
							40	87.11275				
							30	75.44185				
							20	61.59801				

Appendix VI: Analytical and Mathematical Models for Barrel Study

Equation 1: our device converts pressurized potential energy into kinetic energy

$$PV = 0.5 * m * Velocity^2$$

Equation 1.1: solve this equation for velocity terms

$$Velocity^2 = \frac{P * Volume}{0.5 * m}$$

Equation 1.2: Equation for solving velocity for pressure, volume, and mass

$$Velocity = \sqrt{\frac{2 * P * Volume}{m}}$$

Equation 2: taking Equation 1.1 and accounting for multiple barrels

$$Velocity = \sqrt{\frac{2 * Volume}{m} * \frac{P}{(\# \; of \; barrels)}}$$

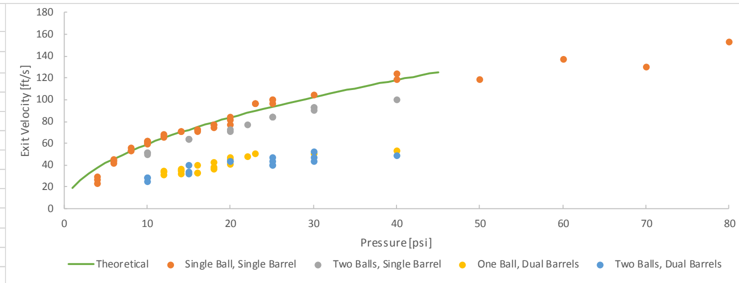
Equation 3: Final predictive model equation which accounts for multiple barrels and the number of projectiles based on relationships determined analytically.

$$Velocity = \sqrt{\frac{2 * Volume}{m} * \frac{P}{(\# \; of \; barrels)} * \sqrt{\# \; of \; projectiles}}$$

Table 10: Barrel Study Predictive Model

Predictive Model

Parameters	
psi-pa	6894.76
in^3-m^3	1.64E-05
m/s-ft/s	3.28
fudge	4.00
m [kg]	0.00185
Vol [m^3]	6.96E-05
P [psi]	20
Vel [ft/s]	83.54748632



Theoretical Model						Single Fire Single Barrel		Double Fire Single Barrel		Single Fire Double Barrel		Double Fire Double Barrel	
Projectiles	1					Projectiles	1	Projectiles	2	Projectiles	2	Projectiles	4
Barrels	1					Barrels	1	Barrels	1	Barrels	2	Barrels	2
Fill Pressure [PSI	Velocity [ft/s]	ll Pressure [PS	Velocity [ft/s]	ll Pressure [PS	Velocity [ft/s]	Fill Pressure [PSI	Velocity [ft/s]	Fill Pressure [PSI	Velocity [ft/s]	Fill Pressure [PSI	Velocity [ft/s]	Fill Pressure [PSI	Velocity [ft/s]
1	18.7	46	126.7	91	178.2	20	84.0	40	100.1602564	20	46.5	40	48.22530864
2	26.4	47	128.1	92	179.2	20	76.6	30	93.00595238	20	40.7	30	52.08333333
3	32.4	48	129.4	93	180.2	20	81.4	30	89.79885057	20	44.9	30	43.40277778
4	37.4	49	130.8	94	181.1	18	76.6	30	93.00595238	18	36.2	30	46.50297619
5	41.8	50	132.1	95	182.1	18	76.6	25	84.00537634	18	37.7	25	40.06410256
6	45.8	51	133.4	96	183.0	18	74.4	25	84.00537634	18	42.7	25	46.50297619
7	49.4	52	134.7	97	184.0	16	72.3	25	84.00537634	16	39.5	25	40.06410256
8	52.8	53	136.0	98	184.9	16	70.4	20	72.33796296	16	33.0	25	43.40277778
9	56.0	54	137.3	99	185.9	16	72.3	22	76.59313725	16	33.0	20	43.40277778
10	59.1	55	138.5	100	186.8	14	70.4	20	70.38288288	14	34.7	20	43.40277778
11	62.0	56	139.8	101	187.7	14	70.4	15	63.51626016	14	36.7	15	31.75813008
12	64.7	57	141.0	102	188.7	14	70.4	15	63.51626016	14	32.2	15	40.06410256
13	67.4	58	142.3	103	189.6	12	66.8	15	63.51626016	14	35.7	15	33.82034632
14	69.9	59	143.5	104	190.5	12	68.5	10	49.13522013	12	30.6	10	28.61721612
15	72.4	60	144.7	105	191.4	12	65.1	10	51.0620915	12	33.8	10	28.30615942
16	74.7	61	145.9	106	192.3	10	60.6	10	51.0620915	12	34.3	10	25.0400641
17	77.0	62	147.1	107	193.2	10	59.2			22	47.3		
18	79.3	63	148.3	108	194.1	10	62.0			23	50.1		
19	81.4	64	149.5	109	195.0	25	100.2			30	50.1		
20	83.5	65	150.6	110	195.9	25	96.5			40	53.1		
21	85.6	66	151.8	111	196.8	25	100.2						
22	87.6	67	152.9	112	197.7	30	104.2						
23	89.6	68	154.1	113	198.6	23	96.5						
24	91.5	69	155.2	114	199.5	40	124.0						
25	93.4	70	156.3	115	200.3	40	118.4						
26	95.3	71	157.4			23	96.5						
27	97.1	72	158.5			23	96.5						
28	98.9	73	159.6			10	62.0						
29	100.6	74	160.7			10	62.0						
30	102.3	75	161.8			10	60.6						
31	104.0	76	162.9			8	55.4						
32	105.7	77	163.9			8	53.1						
33	107.3	78	165.0			8	53.1						
34	108.9	79	166.0			6	44.1						
35	110.5	80	167.1			6	42.0						
36	112.1	81	168.1			6	43.4						
37	113.6	82	169.2			6	44.9						
38	115.2	83	170.2			4	29.6						
39	116.7	84	171.2			4	26.3						
40	118.2	85	172.2			4	23.5						
41	119.6	86	173.2			70	130.2						
42	121.1	87	174.3			50	118.4						
43	122.5	88	175.3			60	137.1						
44	123.9	89	176.2			80	153.2						
45	125.3	90	177.2			91	162.8						

In the excel file containing the actual model, the lighter green cells below the Theoretical Model heading are variable, able to change the curve to reflect the scatter plot data.

Appendix VII: Failure Mode Effects Analysis

Table 11: FMEA Severity Rating Scale

Severity Rating Scale

Rating	Description	Definition (Severity of Effect)
10	Dangerously high	Failure could injure the customer or an employee.
9	Extremely high	Failure would create noncompliance with federal regulations.
8	Very high	Failure renders the unit inoperable or unfit for use.
7	High	Failure causes a high degree of customer dissatisfaction.
6	Moderate	Failure results in a subsystem or partial malfunction of the product.
5	Low	Failure creates enough of a performance loss to cause the customer to complain.
4	Very Low	Failure can be overcome with modifications to the customer's process or product, but there is minor performance loss.
3	Minor	Failure would create a minor nuisance to the customer, but the customer can overcome it without performance loss.
2	Very Minor	Failure may not be readily apparent to the customer, but would have minor effects on the customer's process or product.
1	None	Failure would not be noticeable to the customer and would not affect the customer's process or product.

Table 12: FMEA Detection Rating Scale

Detection Rating Scale		
Rating	Description	Definition
10	Absolute Uncertainty	The product is not inspected or the defect caused by failure is not detectable.
9	Very Remote	Product is sampled, inspected, and released based on Acceptable Quality Level (AQL) sampling plans.
8	Remote	Product is accepted based on no defectives in a sample.
7	Very Low	Product is 100% manually inspected in the process.
6	Low	Product is 100% manually inspected using go/no-go or other mistake-proofing gages.
5	Moderate	Some Statistical Process Control (SPC) is used in process and product is final inspected off-line.
4	Moderately High	SPC is used and there is immediate reaction to out-of-control conditions.
3	High	An effective SPC program is in place with process capabilities (C_{pk}) greater than 1.33.
2	Very High	All product is 100% automatically inspected.
1	Almost Certain	The defect is obvious or there is 100% automatic inspection with regular calibration and preventive maintenance of the inspection equipment.

Table 13: FMEA Occurrence Rating Scale

Occurrence Rating Scale		
Rating	**Description**	**Potential Failure Rate**
10	Very High: Failure is almost inevitable.	More than one occurrence per day or a probability of more than three occurrences in 10 events ($C_{pk} < 0.33$).
9	High: Failures occur almost as often as not.	One occurrence every three to four days or a probability of three occurrences in 10 events (Cpk ≈ 0.33).
8	High: Repeated failures.	One occurrence per week or a probability of 5 occurrences in 100 events ($C_{pk} \approx 0.67$).
7	High: Failures occur often.	One occurrence every month or one occurrence in 100 events ($C_{pk} \approx 0.83$).
6	Moderately High: Frequent failures.	One occurrence every three months or three occurrences in 1,000 events ($C_{pk} \approx 1.00$).
5	Moderate: Occasional failures.	One occurrence every six months to one year or five occurrences in 10,000 events ($C_{pk} \approx 1.17$).
4	Moderately Low: Infrequent failures.	One occurrence per year or six occurrences in 100,000 events ($C_{pk} \approx 1.33$).
3	Low: Relatively few failures.	One occurrence every one to three years or six occurrences in ten million events ($C_{pk} \approx 1.67$).
2	Low: Failures are few and far between.	One occurrence every three to five years or 2 occurrences in one billion events ($C_{pk} \approx 2.00$).
1	Remote: Failure is unlikely.	One occurrence in greater than five years or less than two occurrences in one billion events ($C_{pk} > 2.00$).

Table 14: Upper Barrel Subsystem FMEA

System	Upper barrel							
Cause	Occurance	Severity	Detection	Score		Solution	To be fixed by:	Aprrox Time to Fix:
Seal Failure Female Threads	6	5	5	150				Quick Fix
Seal Failure at 1.5" Slip	3	7	6	126				Quick Fix
Barrel Ejects	1	9	1	9				.5 Day
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Table 15: Main Barrel Subsystem FMEA

System	Main Air Tank Housing							
Cause	Occurance	Severity	Detection	Score		Solution	To be fixed by:	Aprrox Time to Fix:
Seal Failure at Male Thread Slip	6	5	5	150				1 Day
Seal Failure at PVC Coupling either End	3	7	6	126				1 Day
Seal Failure at .5"Threaded Spigot	6	5	5	150				1 Day
Any PVC Crack	1	10	9	90				2 Days
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Table 16: Piston Subsystem FMEA

System	Piston							
Cause	Occurance	Severity	Detection	Score		Solution	To be fixed by:	Aprrox Time to Fix:
Foam Comes Loose	4	10	2	80				Quick Fix
Piston Shatters	1	10	2	20				.5 Day
Chip in .5" Barrel cause leak	1	10	8	80				1 Day
Foam Chips/ Is cut cause leak	2	10	2	40				Quick Fix
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Table 17: Firing Mechanism Subsystem FMEA

System	Trigger Mechanism							
Cause	Occurance	Severity	Detection	Score		Solution	To be fixed by:	Aprrox Time to Fix:
Motor Dies	2	10	5	100				1 Day
Loose Wire	4	7	2	56				Quick Fix
Solinoid Jam	1	8	7	56				1 Day
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Table 18: Manifold Subsystem FMEA

System	Manifold Connectors							
Cause	**Occurance**	**Severity**	**Detection**	**Score**		**Solution**	**To be fixed by:**	**Aprrox Time to Fix:**
Seal Failure at any Joint	3	6	6	108				.5 Day
Seal Failure at Schrader Valve	3	6	6	108				1 Day
Seal Failure Pressure Gauge	3	6	6	108				.5 Day
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Table 19: Arduino Subsystem FMEA

System	Arduino							
Cause	**Occurance**	**Severity**	**Detection**	**Score**		**Solution**	**To be fixed by:**	**Aprrox Time to Fix:**
Fried Board	2	10	2	40				1 Day
Loose Wire	10	1	4	40				Quick Fix
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				
				0				

Appendix VIII: Arduino Code

```
#include <Wire.h>  // Comes with Arduino IDE

#include <LiquidCrystal_I2C.h>

// set the LCD address to 0x20 for a 20 chars 4 line display
// Set the pins on the I2C chip used for LCD connections:
//                    addr, en,rw,rs,d4,d5,d6,d7,bl,blpol
LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);  // Set the LCD I2C address

// constants won't change. They're used here to
// set pin numbers:
const int Fillbutton = 8;   // compressor fill signal
const int compressor =  7; // compressor relay signal
const int RFpower =  6; // RC relay signal
const int Killbutton = 9; // Safety button signal
const int SafetyS = 4;  //  Depressurization solenoid
const int pirinput = A0; //  PIR sensor's output
const int PIR = 11;  //  PIR selection from switch
const int RFsafety = 12; //  input from reciever safety
const int RFswitch = 10;  //  RF selection from switch
const int RFfire = 13; //  input from reciever fire
const int Trigger = 5; // output for triggering solenoid
const int Prime = 2; // priming solenoid

float sensorValue = A3;
float voltage = 0;
float actualvoltage = 0;

// variables will change:
int buttonState = LOW;  // variable for reading the pushbutton status
int buttonState1 = LOW; // variable for reading the pushbutton status
int buttonState2 = LOW; // variable for reading the pushbutton status
int buttonState3 = LOW; // variable for reading the pushbutton status
int buttonState4 = LOW;
int buttonState5 = LOW;
int buttonState6 = LOW;


//VARS
//the time we give the sensor to calibrate (10-60 secs according to the datasheet)
int calibrationTime = 7;
//the time when the sensor outputs a low impulse
long unsigned int lowIn;
//the amount of milliseconds the sensor has to be low
//before we assume all motion has stopped
long unsigned int pause = 2000;
```

```
boolean lockLow = true;
boolean takeLowTime;

int count;

unsigned long start;

boolean pear = false;
boolean apple = false;
boolean pineapple = false;
boolean filled = false;
boolean peach = false;
boolean a = false;
boolean b = false;
boolean c = false;
boolean d = false;
boolean e = false;
boolean f = false;
boolean g = false;



void setup() {
Serial.begin(19200);
 pinMode(compressor, OUTPUT);  // initialize the compressor pin as an output:
 pinMode(SafetyS, OUTPUT);
 pinMode(Killbutton, INPUT); // initialize the Killbutton pin as an output:
 pinMode(Fillbutton, INPUT); // initialize the pushbutton pin as an input:
 pinMode(PIR, INPUT);
 pinMode(pirinput, INPUT);
 pinMode(RFsafety, INPUT);
 pinMode(RFswitch, INPUT);
 pinMode(RFfire, INPUT);
 pinMode(RFpower, OUTPUT);
 pinMode(Trigger, OUTPUT);
 pinMode(Prime, OUTPUT);


 digitalWrite(Trigger, HIGH);
 digitalWrite(compressor, HIGH);
 digitalWrite(RFpower, HIGH);
 digitalWrite(SafetyS, HIGH);
 digitalWrite(Prime, HIGH);




lcd.begin(20,4); // initialize the lcd for 20 chars 4 lines and turn on backlight
```

```
// ------- Quick 3 blinks of backlight  -------------
 for(int i = 0; i< 1; i++){
   lcd.backlight();
   delay(250);
   lcd.noBacklight();
   delay(250);
 }

 lcd.backlight(); // finish with backlight on
}//



void loop() {
 if(pear == false){
   lcd.setCursor(0,0);
   lcd.print("    INITIALIZING    ");
   lcd.setCursor(0,1);
   lcd.print("     THE MEDUSA      ");
   delay(2000);
   pear = true;
 }

 int sensorValue = analogRead(A2); // tells which to plug in the signal output into
 int Pressure = (sensorValue*0.2683-44);  // modifier to tell what pressure is in PSI

 //Battery Voltage Check
 if(peach == false){
   float sensorValue2 = A3;
   float voltage = 0;
   float actualvoltage = 0;
   voltage = analogRead(sensorValue2);
   actualvoltage = ((voltage*0.0131)-0.9563+0.47);
   lcd.clear();
   lcd.setCursor(0,0);
   lcd.print("   BATTERY LEVEL:   ");
   lcd.setCursor(7,1);
   lcd.print(actualvoltage);
   lcd.setCursor(12,1);
   lcd.print("V");
   delay(3000);
   peach = true;
 }



 buttonState = digitalRead(Fillbutton); // read the state of the pushbutton value:
 buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
 buttonState2 = digitalRead(PIR);
```

```
buttonState3 = digitalRead(RFswitch);
buttonState4 = digitalRead(RFfire);
buttonState5 = digitalRead(RFsafety);



if(Pressure > 10 && d == false && f == false){
   digitalWrite(SafetyS, LOW);   // activate safety solenoid
   digitalWrite(Prime, LOW);
   lcd.clear();
   lcd.setCursor(0,0);
   lcd.print("   DEPRESSURIZING");
   lcd.setCursor(0,1);
   lcd.print("    RESET SYSTEM    ");
   Serial.println("#1");
   delay(5000);
   digitalWrite(SafetyS, HIGH);   // activate safety solenoid
   digitalWrite(Prime, HIGH);
   delay(100000);
   a = true;
}

if(buttonState1 == HIGH){   // if KILL button is pressed
    digitalWrite(compressor, HIGH);  // kill compressor
    digitalWrite(SafetyS, LOW);   // activate safety solenoid
    digitalWrite(Prime, LOW);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("   DEPRESSURIZING");
    lcd.setCursor(0,1);
    lcd.print("    RESET SYSTEM    ");
    Serial.println("#2");
    delay(5000);
    digitalWrite(SafetyS, HIGH);   // activate safety solenoid
    digitalWrite(Prime, HIGH);
    delay(100000);
    a = true;
  }

//SELECTOR SWITCH START
if((buttonState2 == HIGH or buttonState3 == HIGH) && f == false){
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("TURN SELECTOR SWITCH");
  lcd.setCursor(0,1);
  lcd.print("      TO PRIME      ");
  delay(500);
  apple = true;
}
```

```
 if(buttonState2 == LOW and buttonState3 == LOW){
   apple = false;
   lcd.clear();
 }


 //SELECTOR SWITCH START
 if(buttonState == LOW && a == false && apple == false && f == false){
   digitalWrite(compressor, HIGH);  // turn off compressor:
   lcd.clear();
   lcd.setCursor(0,0);
   lcd.print("PUSH BUTTON TO FILL");
   delay(500);
 }

 if (buttonState == HIGH && a == false && apple == false) {   // check if the pushbutton is
pressed, if it is, the buttonState is HIGH:
   lcd.clear();
   int sensorValue = analogRead(A2); // tells which to plug in the signal output into
   int Pressure = (sensorValue*0.2683-44);  //modifier to tell what pressure is in PSI
   Serial.println(Pressure);
     while(Pressure < 10 && a == false && filled == false){
     buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
     buttonState2 = digitalRead(PIR);
     buttonState3 = digitalRead(RFswitch);
     int sensorValue = analogRead(A2); // tells which to plug in the signal output into
     int Pressure = (sensorValue*0.2683-44);  //modifier to tell what pressure is in PSI
     digitalWrite(compressor, LOW);  // turn compressor on
     delay(750);
     digitalWrite(Prime, LOW);
     lcd.setCursor(0,0);
     lcd.print("PRESSURIZING      ");

     if(buttonState1 == HIGH){   // if KILL button is pressed
       digitalWrite(compressor, HIGH);  // kill compressor
       digitalWrite(SafetyS, LOW);   // activate safety solenoid
       digitalWrite(Prime, LOW);
       lcd.clear();
       lcd.setCursor(0,0);
       lcd.print("   DEPRESSURIZING");
       lcd.setCursor(0,1);
       lcd.print("    RESET SYSTEM    ");
       Serial.println("#3");
       delay(5000);
       digitalWrite(SafetyS, HIGH);   // activate safety solenoid
       digitalWrite(Prime, HIGH);
       delay(100000);
       a = true;
```

```
   }

   digitalRead(Pressure);
   if(Pressure > 15){
     digitalWrite(compressor, HIGH);
     digitalWrite(Prime, HIGH);
     delay(1000);
     lcd.clear();
     lcd.setCursor(0,0);
     lcd.print("   SYSTEM ARMED    ");
     lcd.setCursor(0,1);
     lcd.print("  SELECT FIRE MODE  ");
     filled = true;
     //break;
   }
}

  while(filled == true){
    buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
    buttonState2 = digitalRead(PIR);
    buttonState3 = digitalRead(RFswitch);
    if(buttonState1 == HIGH){   // if KILL button is pressed
     digitalWrite(compressor, HIGH);  // kill compressor
     digitalWrite(SafetyS, LOW);   // activate safety solenoid
     digitalWrite(Prime, LOW);
     lcd.clear();
     lcd.setCursor(0,0);
     lcd.print("   DEPRESSURIZING");
     lcd.setCursor(0,1);
     lcd.print("    RESET SYSTEM    ");
     delay(5000);
     digitalWrite(SafetyS, HIGH);   // activate safety solenoid
     digitalWrite(Prime, HIGH);
     Serial.println("#4");
     delay(100000);
     a = true;
   }
    // PIR
    if(buttonState2 == HIGH){
      buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
      c = true;
      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("MOTION SENSING ON");
      if(buttonState1 == HIGH){   // if KILL button is pressed
        digitalWrite(compressor, HIGH);  // kill compressor
        digitalWrite(SafetyS, LOW);   // activate safety solenoid
        digitalWrite(Prime, LOW);
        lcd.clear();
```

```
      lcd.setCursor(0,0);
      lcd.print("   DEPRESSURIZING");
      lcd.setCursor(0,1);
      lcd.print("    RESET SYSTEM    ");
      delay(5000);
      digitalWrite(SafetyS, HIGH);   // activate safety solenoid
      digitalWrite(Prime, HIGH);
      Serial.println("#5");
      delay(100000);
      a = true;
    }
    delay(1000);
    break;
  }

  // RFswitch
  if(buttonState3 == HIGH){
    buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("REMOTE CONTROL ON");
    b = true;
    delay(1000);
    digitalWrite(RFpower, LOW);
    if(buttonState1 == HIGH){   // if KILL button is pressed
      digitalWrite(compressor, HIGH);  // kill compressor
      digitalWrite(SafetyS, LOW);   // activate safety solenoid
      digitalWrite(Prime, LOW);
      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("   DEPRESSURIZING");
      lcd.setCursor(0,1);
      lcd.print("    RESET SYSTEM    ");
      delay(5000);
      digitalWrite(SafetyS, HIGH);   // activate safety solenoid
      digitalWrite(Prime, HIGH);
      Serial.println("#6");
      delay(100000);
      a = true;
    }
    break;
  }
 }
}

if(a == false && c == true && f == false){ // add final if for switch selection pirinput as required
   int y = 2; // time variable for countdown pre calibration
   int z = 7; // time variable for countdown calibration
  for(int k = 0; k < 7; k++) {
```

```
  buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("      RUN!! ");
  lcd.setCursor(0,1);
  lcd.print("TIME TO START:");
  lcd.setCursor(16,1);
  lcd.print(y);
  y--;  //reduces y by 1
  delay(1000);
  if(buttonState1 == HIGH){   // if KILL button is pressed
    digitalWrite(compressor, HIGH);  // kill compressor
    digitalWrite(SafetyS, LOW);   // activate safety solenoid
    digitalWrite(Prime, LOW);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("   DEPRESSURIZING");
    lcd.setCursor(0,1);
    lcd.print("    RESET SYSTEM    ");
    Serial.println("#6");
    delay(5000);
    digitalWrite(SafetyS, HIGH);   // activate safety solenoid
    digitalWrite(Prime, HIGH);
    delay(100000);
    a = true;
  }
}
for(int i = 0; i < calibrationTime; i++){
 buttonState1 = digitalRead(Killbutton); // read the state of the pushbutton value:
  f = true;
  if(buttonState1 == HIGH){   // if KILL button is pressed
    digitalWrite(compressor, HIGH);  // kill compressor
    digitalWrite(SafetyS, LOW);   // activate safety solenoid
    digitalWrite(Prime, LOW);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("   DEPRESSURIZING");
    lcd.setCursor(0,1);
    lcd.print("    RESET SYSTEM    ");
    delay(5000);
    digitalWrite(SafetyS, HIGH);   // activate safety solenoid
    digitalWrite(Prime, HIGH);
    Serial.println("#6");
    delay(100000);
    a = true;
  }
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("CALIBRATING:");
```

```
    lcd.setCursor(14,0);
    lcd.print(z);
    z--;  //reduces z by 1
    delay(1000);
    if(buttonState1 == HIGH){   // if KILL button is pressed
      digitalWrite(compressor, HIGH);  // kill compressor
      digitalWrite(SafetyS, LOW);   // activate safety solenoid
      digitalWrite(Prime, LOW);
      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("   DEPRESSURIZING");
      lcd.setCursor(0,1);
      lcd.print("    RESET SYSTEM    ");
      delay(5000);
      digitalWrite(SafetyS, HIGH);   // activate safety solenoid
      digitalWrite(Prime, HIGH);
      Serial.println("#6");
      delay(100000);
      a = true;
    }
  }
  while (digitalRead(pirinput) == HIGH) {
    delay(500);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("x");
  }
    delay(20);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(" MOTION TRIGGER SET");
    lcd.setCursor(0,1);
    lcd.print("  TO KILL ZOMBIES ");

}

if(digitalRead(pirinput) == HIGH && f == true && g == false){
   //digitalWrite(TRIGGER, HIGH);  // if motion detected activate trigger

   //ADD MOTION SENSING CONTROLL

  tone(9,1900,130); // sound sequence before firing
  delay(160);
  noTone(9);
  delay(50);
  tone(9,150,375);
  digitalWrite(Trigger, LOW);
  digitalWrite(Prime, LOW);
  delay(375);
```

```
  noTone(9);
  delay(1500);
  digitalWrite(Trigger, HIGH);
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("  CONGRATULATIONS");
  lcd.setCursor(0,1);
  lcd.print("  YOU HAVE KILLED");
  lcd.setCursor(0,2);
  lcd.print("    THE ZOMBIES");
  delay(5000);
  lcd.clear();
  digitalWrite(RFpower, HIGH);
  g = true;
}



while(a == false && b == true && d == false){
  buttonState4 = digitalRead(RFfire);
  buttonState5 = digitalRead(RFsafety);
  if(buttonState5 == HIGH){
    digitalWrite(SafetyS, LOW);   // activate safety solenoid
    digitalWrite(Prime, LOW);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("   DEPRESSURIZING");
    lcd.setCursor(0,1);
    lcd.print("    RESET SYSTEM    ");
    delay(5000);
    digitalWrite(SafetyS, HIGH);
    delay(5000);
    digitalWrite(SafetyS, HIGH);   // activate safety solenoid
    digitalWrite(Prime, HIGH);
    delay(100000);
    a = true;
  }


  if(buttonState4 == HIGH && a == false){

    tone(9,1900,130); // sound sequence before firing
    delay(160);
    noTone(9);
    delay(50);
    tone(9,150,375);
    digitalWrite(Trigger, LOW);
    digitalWrite(Prime, LOW);
    delay(375);
```

```
    noTone(9);
    delay(1500);
    digitalWrite(Trigger, HIGH);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("  CONGRATULATIONS");
    lcd.setCursor(0,1);
    lcd.print("  YOU HAVE KILLED");
    lcd.setCursor(0,2);
    lcd.print("    THE ZOMBIES");
    delay(5000);
    digitalWrite(Trigger, HIGH);
    lcd.clear();
    d = true;
  }
 }



}//
```

Appendix IX: Bill of Materials

Table 20: BOM for Large Mechanical Parts

Complex Parts				
Part Name	**Number**	**Amazon # (ASIN)**	**Unit Price**	**Cost**
Water Solenoid Valve	2	B00K0TKJCU	$ 8.29	$ 16.58
uxcell Pneumatic QE-04 3/4" Inlet Port Air Quick Exhaust Valve	4	B007Q82RAU	$ 8.22	$ 32.88
Kole Imports GW314 Portable Tire-Shaped Auto Air Compressor	1	B015ZXGGKY	$ 12.25	$ 12.25
			Subtotal:	$ 61.71

Table 21: BOM for PVC Components

PVC Components				
Part Name	**Number**	**Grainger (McMaster-Carr)**	**Unit Price**	**Cost**
Threaded Inline Tee Adapters	3	22FL01	$ 1.60	$ 4.80
Street Elbow, 90 Degrees	2	22FJ87	$ 1.05	$ 2.10
Thick-Wall Dark Gray PVC Threaded Pipe Nipple	10	(4882K13)	$ 0.67	$ 6.70
PVC Cap, Socket, 2" Pipe Size	5	22FJ37	$ 1.10	$ 5.50
PVC Reducing Bushing, Spigot x FNPT, 2" x 1/2" Pipe Size	5	22FK59	$ 2.19	$ 10.95
			Subtotal:	$ 30.05

Table 22:BOM for Tube Fittings

Tubing				
Part Name	**Number**	**Grainger (McMaster-Carr)**	**Unit Price**	**Cost**
1/4" Brass Male Adapter, Brass	4	36X027	$ 2.56	$ 10.24
1/4" Plastic Male Elbow, 90°, White/Gray	4	36X117	$ 3.13	$ 12.52
1/4" Plastic Union Tee, White/Gray	1	36W764	$ 4.78	$ 4.78
			Subtotal:	$ 27.54

Table 23: BOM for Electronic Components

Electronics				
Part Name	**Number**	**Amazon # (ASIN)**	**Unit Price**	**Cost**
XLX 12pcs (6 Set) 600V 15A 8 Positions Double Row Screw Terminal Strip and 400V 15A 8 Positions Red / Black Pre-Insulated Terminal Barrier Strip	1	B01M995LI0	$ 12.99	$ 12.99
SunFounder Mega 2560 R3 ATmega2560-16AU Board (compatible with Arduino)	1	B00D9NA4CY	$ 17.99	$ 17.99
JBtek 4 Channel DC 5V Relay Module for Arduino Raspberry Pi DSP AVR PIC ARM	1	B00KTEN3TM	$ 7.59	$ 7.59
Adafruit ADXL335 - 5V ready triple-axis accelerometer (+-3g analog out) [ADA163]	1	B00NAY2TUC	$ 19.95	$ 19.95
1000M DC 12V 2CH Wireless Remote Control Switch System Receiver + Transmitters for Garage Door Window Lamp	1	B01G5BEMVA	$ 12.99	$ 12.99
HC-SR501 PIR Pyroelectric IR Infrared Motion Sensor for Arduino, Raspberry Pi, and other microcontrollers	1	B017HOA9KW	$ 5.79	$ 5.79
SainSmart IIC/I2C/TWI Serial 2004 20x4 LCD Module Shield For Arduino UNO MEGA R3	1	B0080DYTZQ	$ 12.99	$ 12.99
DIGITEN G1/4" inch 5V 0-1.2 MPa Pressure Transducer Sensor Oil Fuel Diesel Gas Water Air	1	B00YPA6V9U	$ 17.99	$ 17.99
HQ 10*16cm Double Side Prototype Board Perforated 2.54mm Plated Breadboard	1	B01980GWU4	$ 3.88	$ 3.88
Yueton DC 36V 2A 16mm High Round Cap Waterproof Metal Momentary Push Button Switch High Flush Reactable Screw Terminals	2	B0131XF9KS	$ 5.89	$ 11.78
Turnigy 1000mAh 3S 20C Lipo Pack	1	B00MVQ8T6I	$ 6.82	$ 6.82
Heavy Duty Toggle Switch - SPST On/Off Type	1	B0002ZPBRA	$ 2.09	$ 2.09
uxcell 12V DC 25A Off Road Car 3 Pin 3 Position On/Off/On Toggle Switch	1	B00E1JNAC6	$ 7.15	$ 7.15
DC 9-15V HYD-4218 Active Piezo Electronic Alarm Buzzer	1	B00HG7H2TM	$ 2.21	$ 2.21
Resistors, assorted	12			
LEDs, assorted	3			
Wire/Terminal Connectors, assorted				
			Subtotal:	$ 142.21

Table 24: Total Cost of Materials for The Medusa

Total:	$ 261.51

Appendix X: Drawings and Schematics

The following pages showcase some of the technical drawings and schematics that detail the construction of The Medusa.