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2015 ASME Design Competition - Group III Final Report

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MEMS 411 Design Report Title

ASME III
Paper Cannon

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Contained here are the details concerning the conceptualization, design, prototyping and final product for the American Society of Mechanical Engineering design competition for group three.

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Selecting the Right Tool

 - 5.6.2 Risk Prioritization (Write a short description of how your team prioritized risk for your project. Include any tables or diagrams that support your prioritization).
 - 5.6.2.1 Risk Prioritization in the Systems Engineering Program

(Source:
<http://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/risk-management/risk-impact-assessment-and-prioritization>)
- 6 Working prototype

- 6.1 A preliminary demonstration of the working prototype (this section may be left blank).
- 6.2 A final demonstration of the working prototype (this section may be left blank).
- 6.3 At least two digital photographs showing the prototype
- 6.4 A short videoclip that shows the final prototype performing
- 6.5 At least four (4) additional digital photographs and their explanations
- 7 Design documentation
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1 Introduction

1.1 Problem statement

The American Society of Mechanical Engineers sponsors an annual competition which tasks students with designing and building a machine to perform a specified function. The 2015 challenge focused on the field of manufacturing, which receives a majority of private research and development spending and also employs a number of engineers from all fields. More specifically, the challenge was to construct a device which manufactures a projectile from a piece of copy paper then launches it as far as possible. At the competition, each team has five minutes to assemble their machine, craft three projectiles and fire them for a cumulative distance. In addition to launching paper projectiles as far as possible, the machines must also be designed to take up as little space as possible while still performing its main function effectively. A team's final score is the ratio of the cumulative distance of all three projectiles to the volume of a box used to transport their machine.

1.2 List of team members

The team members for ASME III are Nick DiVincenzo, Matt Yurescko, Sean Cole-Jansen, and Sam Johnson.

2 Background Information Study

2.1 A short design brief description that defines and describes the design problem

From the design brief, it is clear that the two main challenges facing our group were developing a design that effectively shot paper while at the same time keeping it as small as possible. These metrics relate to the field of manufacturing in that a machine must perform its function as precisely as possible in a reasonable amount of time. The machine must be as small as possible because space on a factory floor is at a premium. If many smaller machines can be fit into the same space as a single large one that performs the same function, that increases the potential number of units that can be produced at a given location. For our project, this means producing

fairly uniform paper projectiles that are fired a maximum distance while working to ensure the machine can be fit into as small a box as possible when disassembled.

2.2 Summary of relevant background information

The two chief problems that came up in early design meetings were which methods to use in making the projectile and how it should be fired. The group was in agreement from the beginning that a machine which produced paper airplanes was not feasible, especially when considering the amount of parts that would be involved as well as the volume constraint. Rolling the paper into an arrow or spear-like projectile was considered. This was inspired by a patent (patent number: US4357140 A) for an electronic device which rolls newspapers into a compact log which is then used for fire kindling. Another projectile idea was to tightly crush the paper into a ball. This idea was inspired by the design of trash compactors and car crushers used in scrap yards, which basically use brute force to squeeze their contents into a smaller volume. A variety of methods were considered for launching the projectile. Compressed air was briefly considered, however it was determined that this actually violated one of the more specific rules of the competition that the machine was to end up at the same energy level as it started. So unless the machine continually compressed air on its own for use, we would be in violation of the competition rules. Pitching machines, which are used in sports to “throw” balls at high speeds, use two counter spinning wheels to generate energy and were also considered. This design is pictured below in Fig. 1.



Figure 1: A pitching machine showing the two spinning wheels which would fire the paper projectile.

A more simple idea based on the design of a slingshot came up as well and would have used elastic bands to generate energy. This idea eventually moved towards a catapult design which would use springs as an energy source and evolved over time into a more simple cannon-like design which would also be spring powered.

3 Concept Design and Specification

3.1 User needs, metrics, and quantified needs equations. This will include three main parts:

3.1.1 Record of the User Needs Interview

Since our project was developed to compete in a design competition, there was not an actual customer to interview. Instead, we answered our questions based on the competition's rules and the advice of our academic advisor Professor Mark Jakiela.

Table 1: Results of Customer Interview to Determine Design Needs

Question	Customer Statement	Interpreted Need	Importance
How large should the device be?	See guidelines	The volume should be as small as possible.	5
How quickly should it fire projectiles?	See guidelines	The device must fire three projectiles within 300 sec	5
How far should it shoot projectiles?	See guidelines	The device should shoot the projectiles as far as possible.	5
How many fasteners should we use for assembly?	As few as possible	Very few fasteners	3

How accurate should it be?	See guidelines	The projectiles should land within the 3 m competition course	2
How reliable should the device be?	See guidelines	The device should fire three projectiles every time.	4
How long should the device take to set up?	See guidelines	The device should take less than a minute to set up.	3
How much should the device cost.	As little as possible	The device should cost less than \$200 dollars	4
Should the device be fully automated?	See guidelines	Yes, except for inserting paper.	5

Table 2: Design Needs and Importances

Need Number	Need	Importance
1	Box volume should be minimized.	5
2	The device must fire three projectiles within 300 sec.	5
3	The device should shoot projectiles as far as possible.	5
4	The projectiles should land within the 3 m wide competition track.	2
5	The device should shoot 3 projectiles every time.	4
6		3
7	The device should take less than 1 minute to set up.	4
8		5
9	The device should cost less than \$200	
	The device should be fully automated.	4
	Device should be easily manufacturable	

3.1.2 List of identified metrics

Table 3: Identified Metrics Affecting Design Quality

Design Metrics: Paper Launcher (BB)					
Metric Number	Associated Needs	Metric	Units	Min Value	Max Value
1	3	Length	m	0	50
2					
3	1	Volume	cm ³	4,800	1,000,000
4					
5	4	Theta	degrees	45*	0*
6	2, 6	Time	Seconds	0	300
7	5	Projectiles Fired	Integer	0	3
8	7	Cost	Dollars	0	300
9	8	Automation	Binary	0	1
10	9	# of Drill Operations	integer	0	100
11	9	Tolerances	integer	1	5
12	9	# of Long Parts	integer	0	10
	9	# of Fasteners	integer	0	20
	9	# of adjustments	integer	0	20

3.1.3 Table/list of quantified needs equations

Table 4: Quantified Needs and Happiness Valuation

Paper Launcher		Metrics																	
		Length	Volume	Theta	Time	Projectiles Fired	Cost	# of Drill Operations	# of Long Parts	# of Fasteners	# of Adjustments	Need Happiness 1	Need Happiness 2	Need Happiness 3	Need Happiness 4	Importance Weight	Happiness Value 1	Happiness Value 2	Happiness Value 3
1	Minimal Volume		1												0.25	0.175743	0.24505	0.200495	0.200495
2	Firing Speed				1										0.025	0.01	0.01375	0.008333	0.008333
3	Range	1													0.25	0.125	0.125	0.166667	0.166667
4	Accuracy			1											0.02	0.015556	0.013333	0.015556	0.013333
5	Reliability					1									0.1	0.1	0.1	0.1	0.1
6	Set Up Time				1										0.025	0.01	0.01375	0.008333	0.008333
7	Cost						1								0.1	0.016667	0.033333	0.05	0.033333
8	Manufacturability							0.1	0.2	0.5	0.2				0.23	0.15295	0.18055	0.1896	0.19665
	Units	m	cm ³	degrees	seconds	Integer	Dollars	Integer	Integer	Integer	Integer					Total Happiness			
	Best Value	30	10,000	0	0	3	0	0	0	0	0					0.605915	0.724766	0.737984	0.727145
	Worst Value	0	1,000,000	45	300	0	300	20	10	50	20								

3.2 Four Concept Drawings

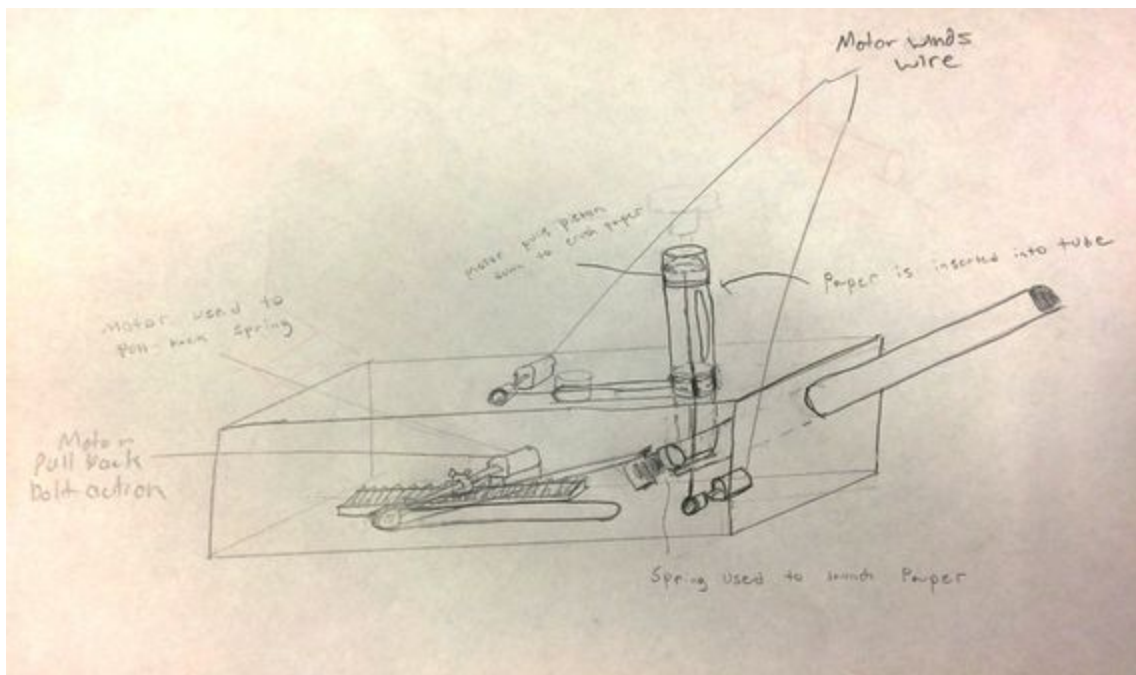


Figure 2: Rubber Band Bolt Action Concept Design

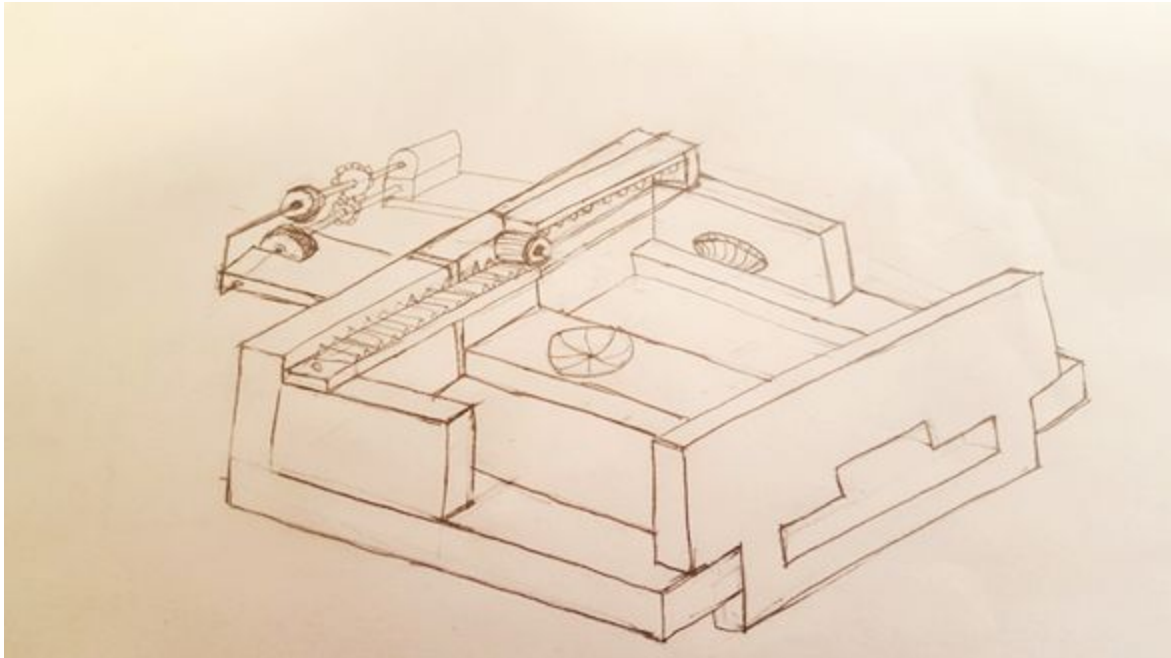


Figure 3: Disc Compactor Concept Design

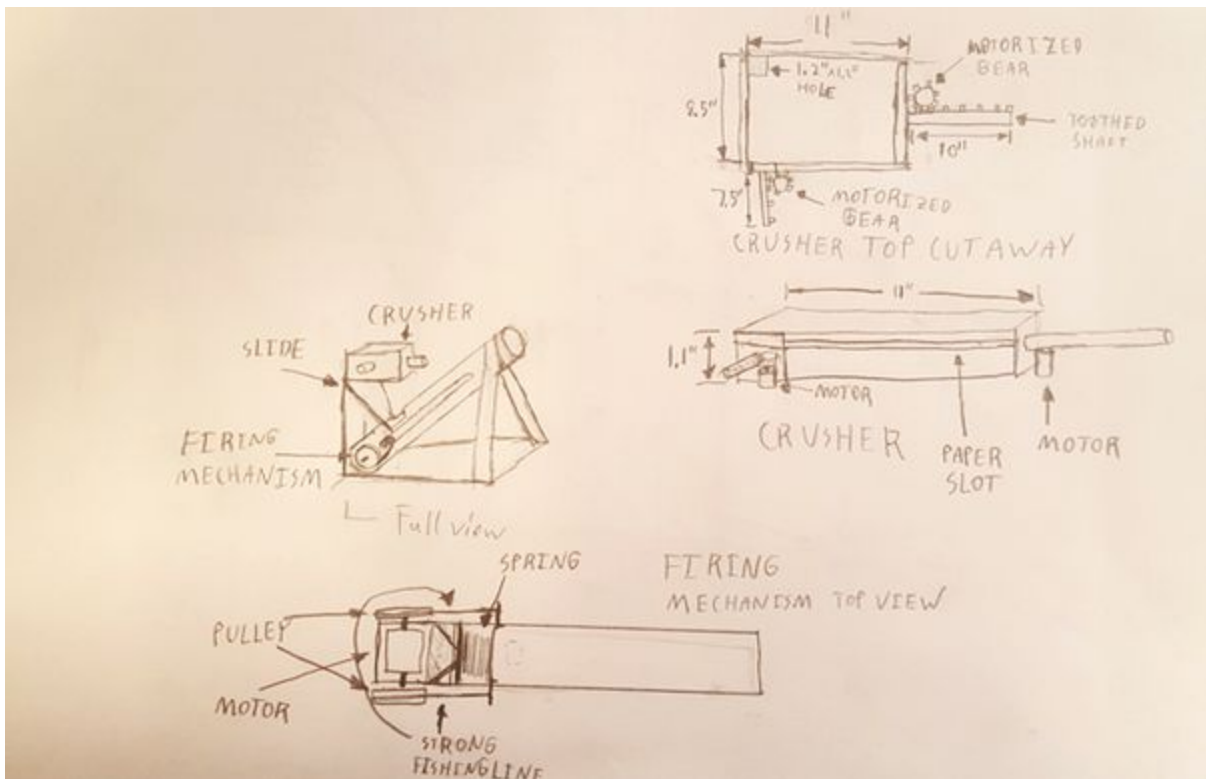


Figure 4: Spring Cannon Concept Design

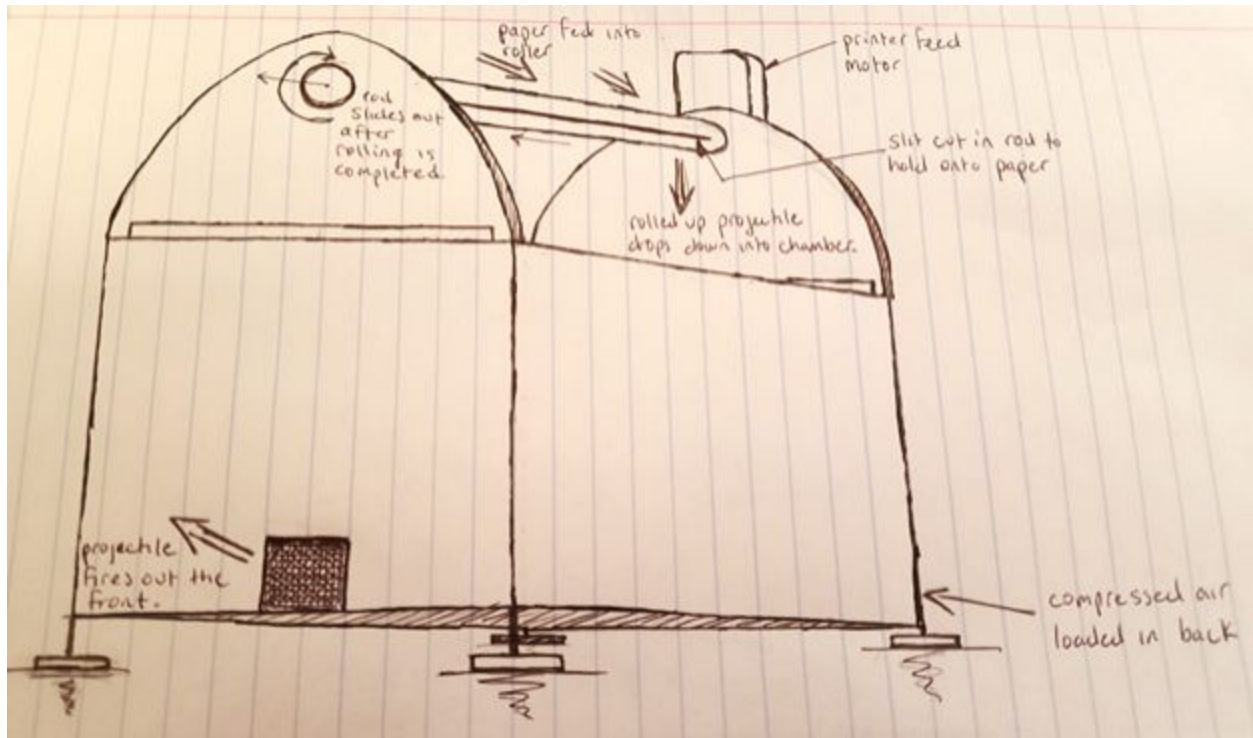


Figure 5: Compressed Air Log Cannon Concept Design

3.3 Concept Selection Process. This will have three parts:

3.3.1 Concept Scoring

Table 5: Concept Scoring

		Metrics																		
Paper Launcher		Length	Volume	Theta	Time	Propellets / Feat	Cost	# of Drill Operations	# of Long Parts	# of Fasteners	# of Adjustments	Need Happiness 1	Need Happiness 2	Need Happiness 3	Need Happiness 4	Importance Weight	Happiness Value 1	Happiness Value 2	Happiness Value 3	Happiness Value 4
1	Minimal Volume		1									0.7	0.98	0.8	0.8	0.25	0.175743	0.24505	0.20049505	0.200495
2	Firing Speed				1							0.4	0.55	0.33	0.33	0.025	0.01	0.01375	0.00833333	0.008333
3	Range	1										0.5	0.5	0.67	0.67	0.25	0.125	0.125	0.16666667	0.166667
4	Accuracy			1								0.78	0.67	0.78	0.67	0.02	0.015556	0.013333	0.01555556	0.013333
5	Reliability					1						1	1	1	1	0.1	0.1	0.1	0.1	0.1
6	Set Up Time				1							0.4	0.55	0.33	0.33	0.025	0.01	0.01375	0.00833333	0.008333
7	Cost						1					0.17	0.33	0.5	0.33	0.1	0.016667	0.033333	0.05	0.033333
8	Manufacturability							0.1	0.2	0.5	0.2	0.665	0.785	0.82	0.855	0.23	0.15295	0.18055	0.1886	0.19665
	Units	m	cm^3	degrees	seconds	integer	Dollars	Integer	Integer	Integer	Integer	Total Happiness					0.605915	0.724766	0.73798394	0.727145
	Best Value	30	10,000	0	0	3	0	0	0	0	0									
	Worst Value	0	1,000,000	45	300	0	300	20	10	50	20									
Bolt-action Rubber	Actual Value 1	15	300,000	10	180	3	250	5	2	25	2									
	Metric Happiness 1	0.5	0.7	0.78	0.4	1	0.17	0.75	0.8	0.5	0.9									
Disc Compactor	Actual Value 2	15	20,000	15	135	3	200	5	3	12	1									
	Metric Happiness 2	0.5	0.98	0.67	0.55	1	0.33	0.75	0.7	0.76	0.95									
Spring Cannon	Actual Value 3	20	200,000	10	200	3	150	6	4	5	2									
	Metric Happiness 3	0.67	0.8	0.78	0.33	1	0.5	0.7	0.6	0.9	0.9									
Compressed Air	Actual Value 4	20	200000	15	200	3	200	5	1	5	5									
	Metric Happiness 4	0.67	0.8	0.67	0.33	1	0.33	0.75	0.9	0.9	0.75									

3.3.2 Preliminary analysis of each concept's physical feasibility

Concept 1: Bolt Action Rubber Band

Difficulties in this design include ensuring that the tolerances on the tubings are correct so that the motors can wind the spring and crush the paper inserted into the tube. The rough shape of the crushed paper may also pose a difficulty because a protruding edge may get caught on a piece of tubing or rattle when it is being fired from the main tube, causing it to lose energy and slow launching speed. The number of moving parts is minimal in this design: there are only two motors and a spring. The cylinders should be easy to make out of pvc pipe or a similar type of plastic. The vertical tubing will need to be very rigid in order to withstand the forces involved with crushing the paper into a ball. The motor pulling back the spring will also need to output a high torque in order to compress the stiff spring. Slits will be cut into the pvc pipe using a jig-saw or some type of sharp knife, and then sand or ground smooth, so no rough edges interrupt the launching process. A clutch would also have to be developed to successfully launch, since the motor won't allow free spinning. This design should be reliable because the paper does not need to be a specific shape to be launched, it just needs to be slightly crushed. This concept will probably not get a very high score because the projectile will not be very aerodynamic.

Concept 2: Disc Compactor

Like the other concepts, much of the difficulty of this design comes from the precision needed to crush the paper into the desired shape, which is a disc in this case. The compactor portion of the machine is run by racks and pinions that close the walls in on the paper. The motors that drive these pinions will need to be able to handle a large torque to effectively crush the paper to as compact of a disc as possible. The walls will have a disc mold cutout, to manipulate the crushed paper into a disc. The cutouts will make manufacturing the walls difficult, so we will probably have to carve them out of wood or another material that's easier to machine than metal, such as 3D printing plastic. The disc is supposed to be launched by 2 fast rotating wheels, much like a pitching machine. The motor that drives these rollers should be moving as fast as possible to create the maximum initial velocity possible. The complications of this design lie in that it would have to be fairly large, which goes against our primary design focus of making a compact machine. It would also require a conveyor belt to move the compacted disk to the firing station. The multistep process would also require a well tuned control system. With many moving parts, this design would probably be the most expensive and difficult to manufacture, but also has the potential to have the farthest launch.

Concept 3: Spring Cannon

This design uses a motor-driven spring to fire cubes of paper crushed into an aerodynamic shape by a compactor box, the ‘crusher’ whose walls are pushed by a pair of motor-driven rack and pinion systems. The main difficulty in this design is making the device finish each step before beginning the next step. After slotting the paper into the crusher the crusher has to compact the paper lengthwise down to an inch, then crush it widthwise while holding its height and length at an inch, and then release pressure in all three dimensions so that the now-compacted cube can fall down the slide and into the firing chamber as well as return the crusher to its starting state so that it can receive the next sheet of paper. Once the cube is in the firing chamber the launcher has to release the spring to fire the cube and then recompress the spring before the crusher has finished the next cube. While this is possible with a purely mechanical design it would likely be easier to do so with a simple program and a circuit board. This design would be reliable and its range can be readily increased by using a stronger spring and motor in the firing mechanism.

Concept 4: Compressed Air Log Cannon

This concept uses a printer feed motor to roll pieces of paper into a cylinder projectile. The roller is then pulled out allowing the projectile to drop down into a firing chamber. Before being loaded it can also be forced through a narrow channel to further compress it. This design has a great potential for shooting the projectile a maximum distance by using compressed air, however the design prompt states that the system must end at the same energy as it began so there would be difficulties in implementing a compressed air system that recharges itself within the given time constraints. This design has a simple layout however, so implementing a different means of firing the projectile may not be too hard. There wouldn’t be too many moving parts either which would make assembly and manufacturing less difficult. Another pro of this design is its small size, which directly factors into our overall score.

3.3.3 Final summary

Winner: Concept 3 (Spring Cannon)

Concept 3 has several advantages over the other designs. It is more compact than concept 1 and 4, and it will more reliably crush the sheet of paper into a usable projectile than concept 2. The design has only three moving parts and all should be easy to machine. The design minimizes the number of parts and fasteners needed. The cannon in concept 3 should also launch the projectile straight and accurately, more so than the other designs. The design itself is flexible,

with launching speed being directly based on the stiffness of the spring and the torque of the motor winding it, while the height of the firing arc can be adjusted by changing the angle of the cannon.

Though Concept 3 is the superior design compared to the others, we will likely implement some of the other designs' mechanisms, such as the crusher in concept 2, into the final embodiment.

3.4 Proposed performance measures for the design

Performance Goals

1. Can be easily disassembled into a 50 cm x 50 cm x 50 cm box
2. Fire a sheet of paper at least 10 meters
3. Fires at least 90% of the time
4. Always hits within 3 m strip
5. Can assemble and fire three times in under 5 minutes
6. Costs less than \$200

3.5 Design constraints

3.5.1 Functional

The finished machine is judged considering the size of the rectangular box that it is stored in. The machine must also be assembled and complete three launches within five minutes of being taken out of the box, which means the design must be as modular as possible and allow for quick assembly. The assembly time can be eliminated by having the fully assembled or almost fully assembled machine in the box, but that, in all likelihood, would increase the necessary box size.

Vibration from motors could cause the machine to vibrate or wobble. Including a damping system would increase the size of the design, so to keep vibrations low, motor speeds should be kept to a minimum. Since the motors in the chosen design are all high torque, speed should not be an important factor. Wobbling in the machine can be negated by increased

structural support, but making additional supports would mean increasing the size of the machine.

The chosen design required that multiple motors work together to perform a multistep crushing and launching process. The control system organizing the motors will have to be programmed to be precise, which will require a long debugging design stage. We also need to supply the system with enough electricity to power all needed motors.

3.5.2 Safety

The design poses little to no environmental or health risks. The only safety concern is the operational risk involved with launching the projectile. Before using the machine to launch anything, the path trajectory should be cleared of any humans or valuables. However, this risk is still small if the machine is used properly to launch paper, which shouldn't reach high enough velocities to hurt anyone.

3.5.3 Quality

There are no standards, regulations, or codes that need be met for this machine. The reliability, however is very important. For the competition, we need to successfully launch three pieces of paper within five minutes. If any part of the multi-step crushing and launching operation fails, then it would be detrimental to our competition score. A paper jam on any throw would take us out of consideration, to the machine we design should be able to perform reliability and not get jammed.

3.5.4 Manufacturing

The manufacturing processes used in this machine fabrication have to be simple above all else. Of the group members, none of us are particularly talented machinists, and hiring a machinist to make professional quality parts is unrealistic for our budget. We also do not have the ability, given our tools and expertise, to make parts that require too critical of tolerances. Simple parts with loose tolerances are most ideal for this project.

The finished assembly should have a few permanent links (welds, glue) as possible. A modular design that can be easily assembled and torn down is our primary focus, since we want to minimize box size. By competition rules, that box must be rectangular, so we cannot form fit a custom box around any other shape.

For any hard to manufacture parts, we could use 3D printing, but 3D printed parts are not very strong and could be prone to breaking.

3.5.5 Timing

For many of the approved part vendors, it takes around four to five days after ordering to receive the parts, so any online ordered parts should be placed over a week before any key deadlines. The deadlines of this project were:

November 4, 2015 - Initial Prototype demo for our academic instructors needs to show proof of concepts.

December 2, 2015 - Final Prototype needs to be ready to present to judges

The actual ASME competition date has not been determined, but it will be sometime in the Spring of 2016.

3.5.6 Economic

There is no foreseeable market for a paper cannon, so we don't expect to try to sell our work or see any return on our research and development costs. However, since ASME is sponsoring the design competition, they could end up paying for a large chunk of our costs.

Our budget for the entire project was \$400, which could be spent entirely on design and manufacturing, since there are no marketing or distribution costs. While the time of the students working on this project is considered to be quite valuable, it does not actually cost us anything or affect our budget. We planned on making all the machined parts ourselves, which greatly cuts down on our manufacturing costs, since we only had to pay for some raw materials. We also found many raw materials available in Washington University's machine shop and other mechanical engineering labs.

The biggest cost for this project will be the parts that need to be ordered. These parts, such as gears, racks, and pinions, are much more expensive than the ones we manufacture ourselves, but they should also be of much higher quality. The most expensive parts we had to order were motors. We had to make sure the motors we ordered had the necessary torque to

power our machine, because we could not afford to buy expensive motors that don't perform as needed.

3.5.7 Ergonomic

There were no specific constraints in the design competition rules that puts any limits on the That being said, the system should be comfortable and easy to transport and reposition, so we don't have to worry about running into transportation and setup issues during the prototype presentations and competition.

3.5.8 Ecological

There are no plausible ecological risks from this project. Our project is small scale, and uses common, non-toxic materials, so there are essentially no potential environmental, commercial, or political consequences.

3.5.9 Aesthetic

The were no aesthetic constraints pertaining to our design. Aesthetics is not considered as part of the competition, and there are no consumers to market an aesthetic design to.

3.5.10 Life cycle

Our machine shouldn't have any significant life cycle constraints, because our machine only will be in operation for a few months. The only significant life cycle constraint we have to abide by is that we need to tear down our project when finished and try to salvage parts for future senior design classes.

3.5.11 Legal

4.2 Parts List

Table 6

	Part	#	Location	Part #	Cost (\$)
1	Base Block	1	Scrap		Nil
2	Base	1	Scrap		Nil
3	Cannon Spring Shaft	2	Scrap		Nil
4	Clutch Engaging Motor	1	Basement		Nil
5	Clutch Shaft and Driver Motor	2	Amazon	B00B1KZ8UU	23.98
6	Clutch Side	2	Scrap		Nil
7	Crusher Motor Shaft	1	Scrap		Nil
8	Crusher Motor Mount	1	Scrap		Nil
9	Crushing Tube	1	Basement		Nil
10	Firing Barrel	1	Basement		Nil
11	Crusher Head	1	3D Printed		Nil
12	Lower Crusher Base	1	Scrap		Nil
13	Firing Cup	1	3D Printed		Nil
14	Steel Extension Springs	2	McMaster	9654K305	7.50
15	3/16" mounted bearings	2	McMaster	8600N2	30.28
16	¼" mounted bearing	2	McMaster	8600N3	30.28
17	Rack	1	McMaster	6295K14	25.39
18	Pinion	1	McMaster	6867K38	22.82
19	40 lb fishing line	60"	Amazon	B0036DS6Q8	6.79

20	3/16 bearings	2	McMaster	6383K11	6.56
21	Arduino Uno Rev3	1	Arduino	A000066	24.95
22	12V battery cases	2	Amazon	700724502308	13.00
23	3 1/2" Split Ring Pipe Hanger	1	McMaster	3023T16	13.89
24	1 7/8" Split Ring Pipe Hanger	1	McMaster	3023T73	5.98

4.3 Draft detail drawings for each manufactured part

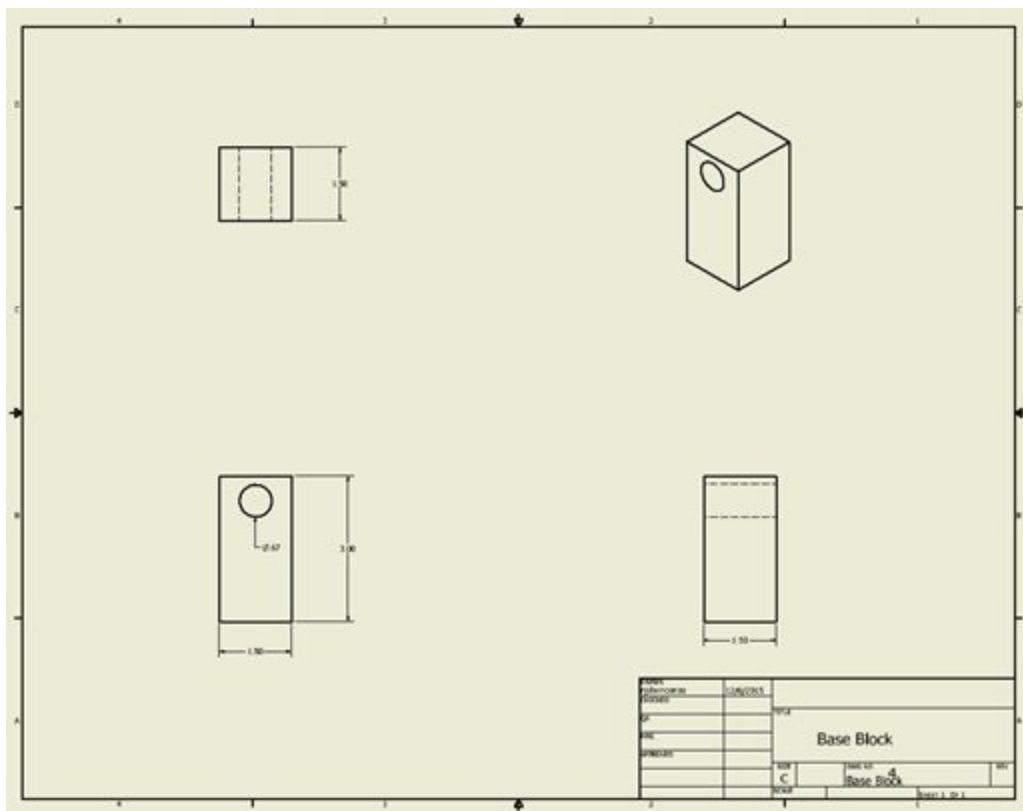


Figure 7: Base Block

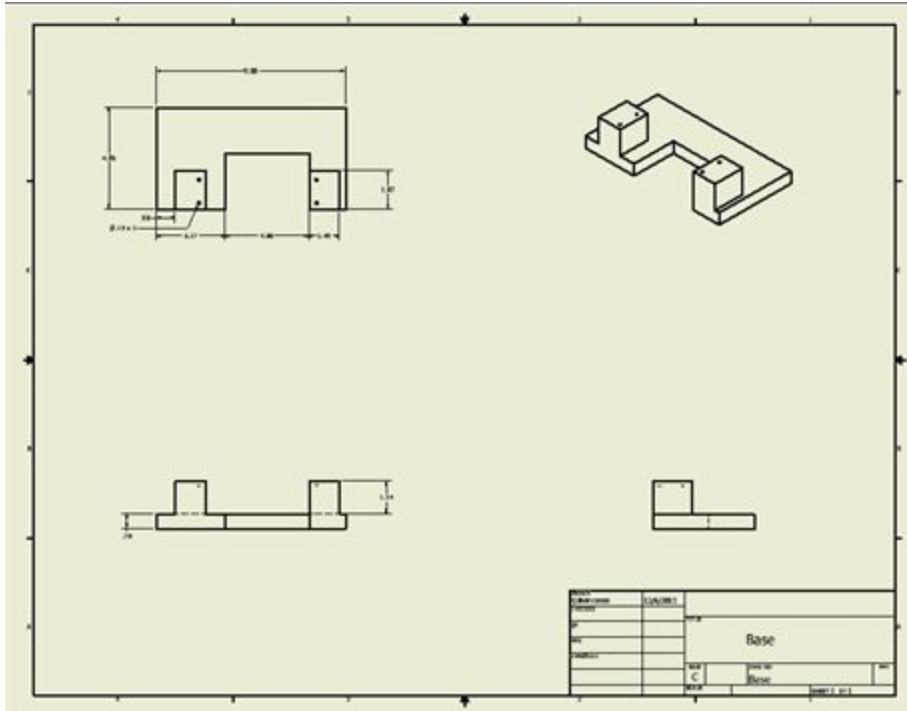


Figure 8: Base

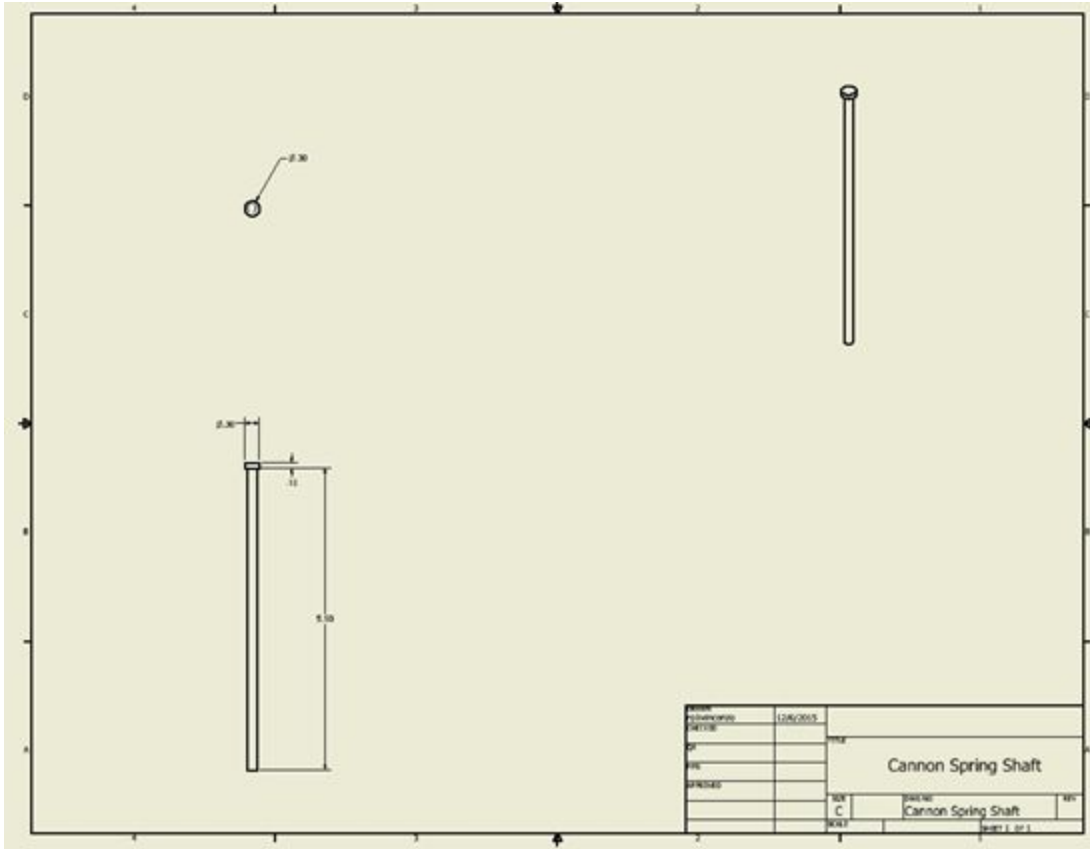


Figure 9: Cannon Spring Shaft

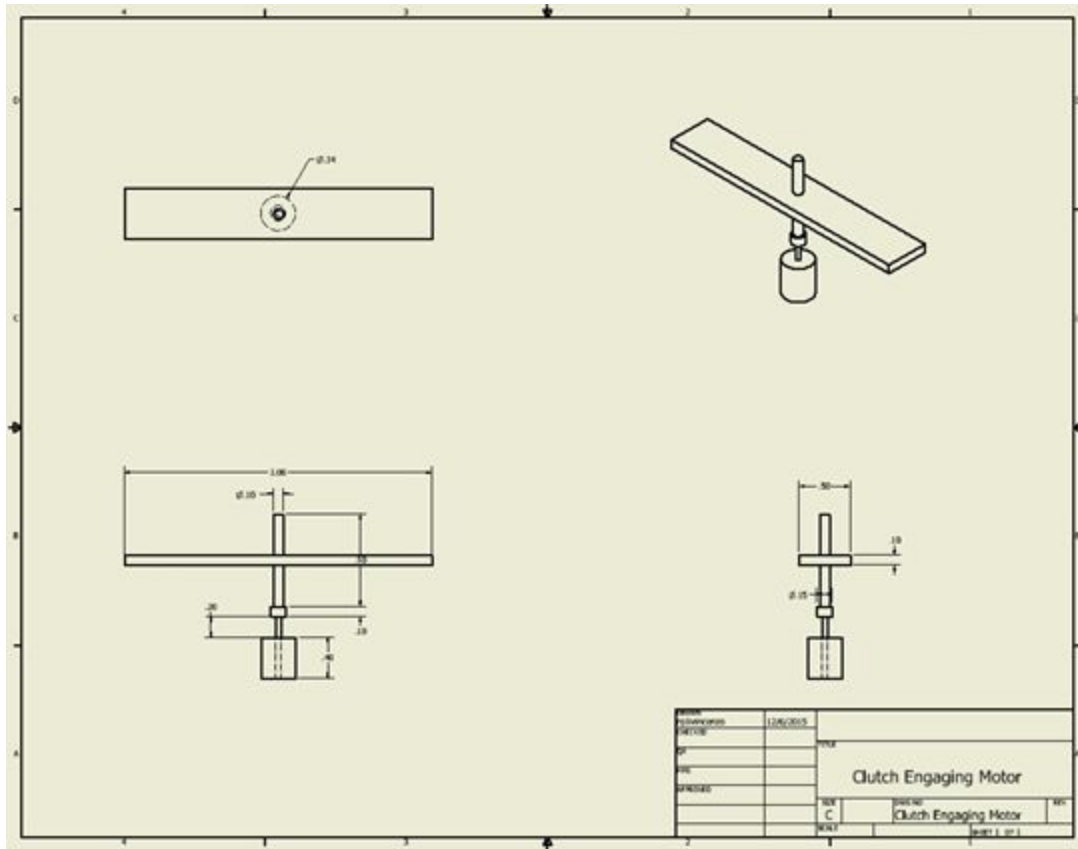


Figure 10: Clutch Engaging Motor

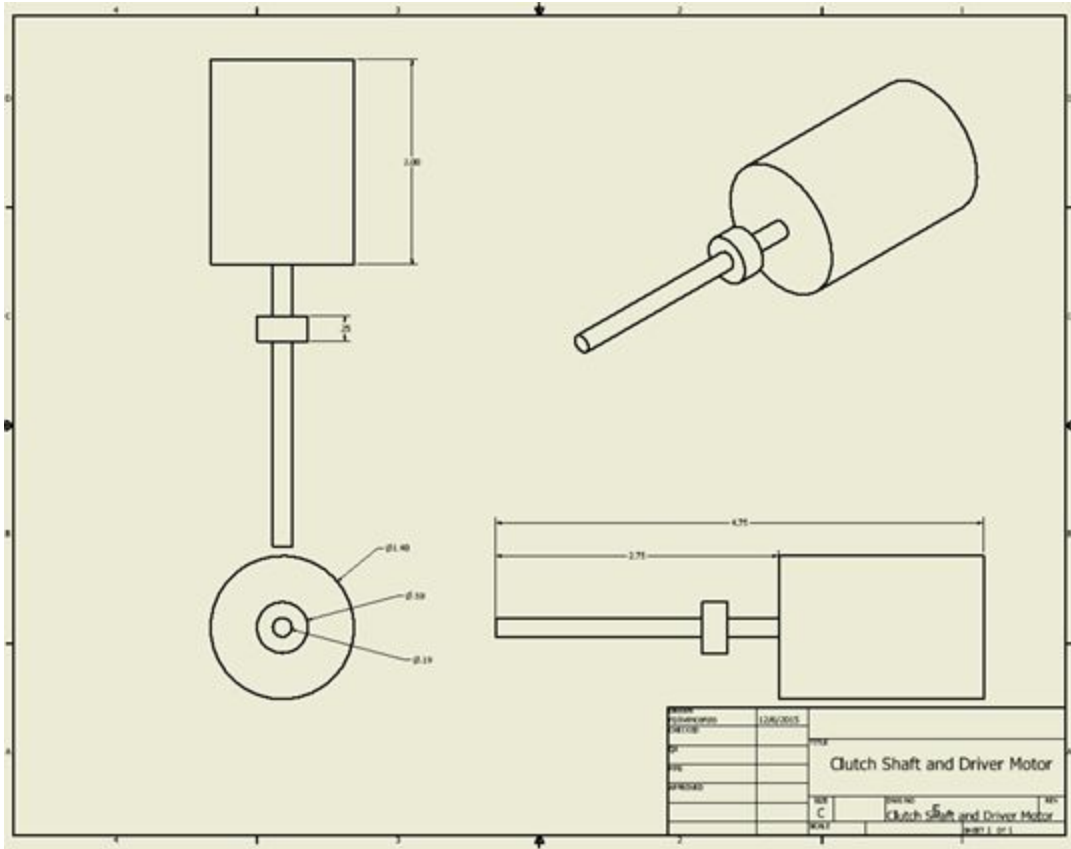


Figure 11: Clutch Shaft and Driver Motor

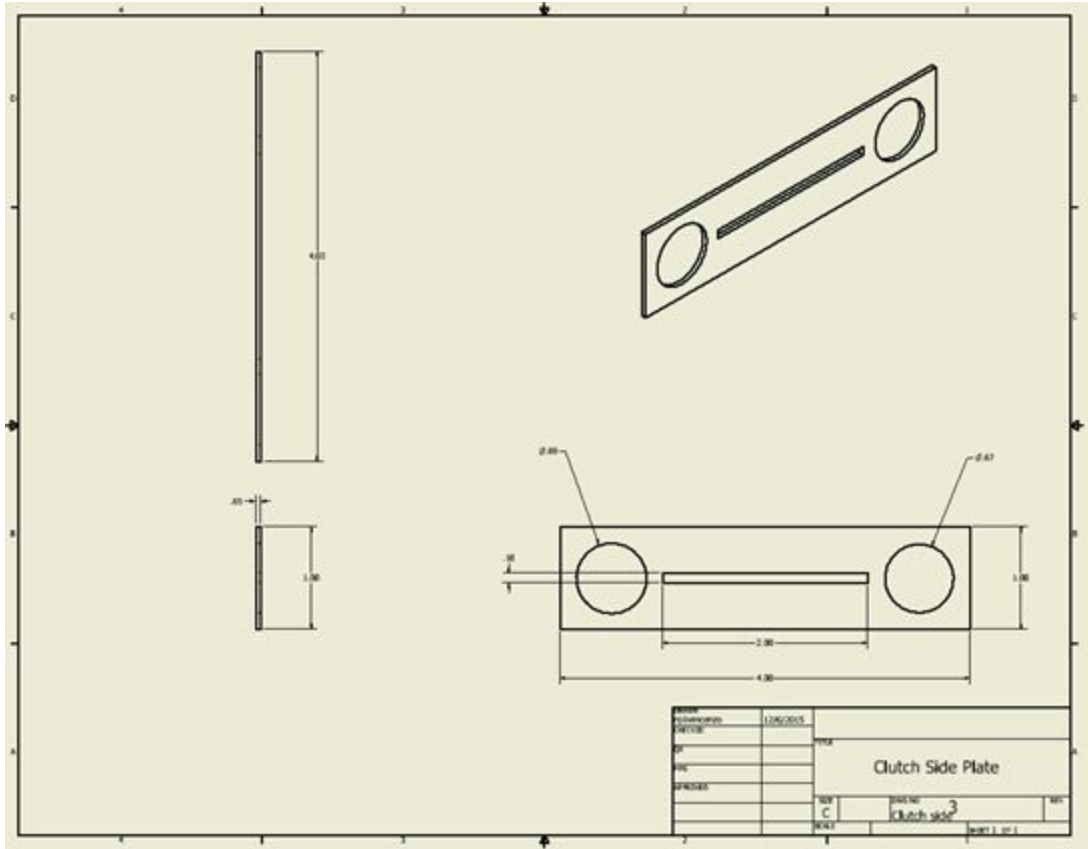


Figure 12: Clutch Side

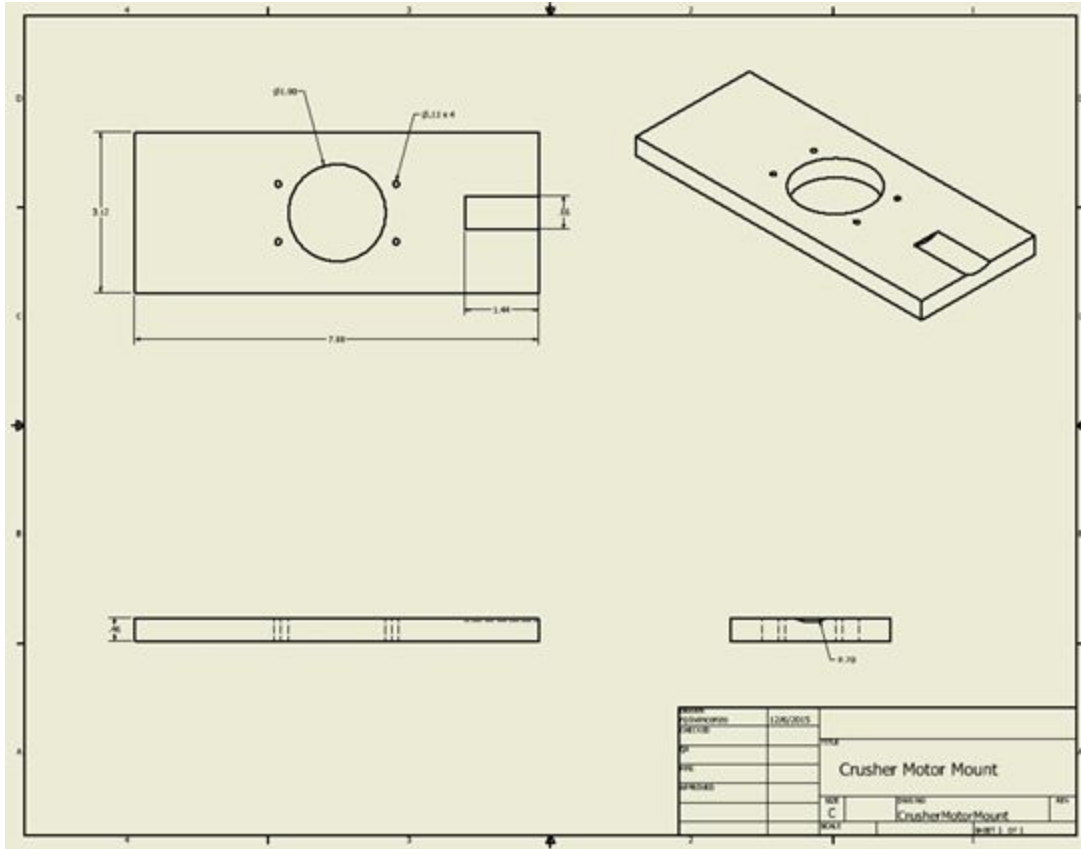


Figure 14: Crusher Motor Mount

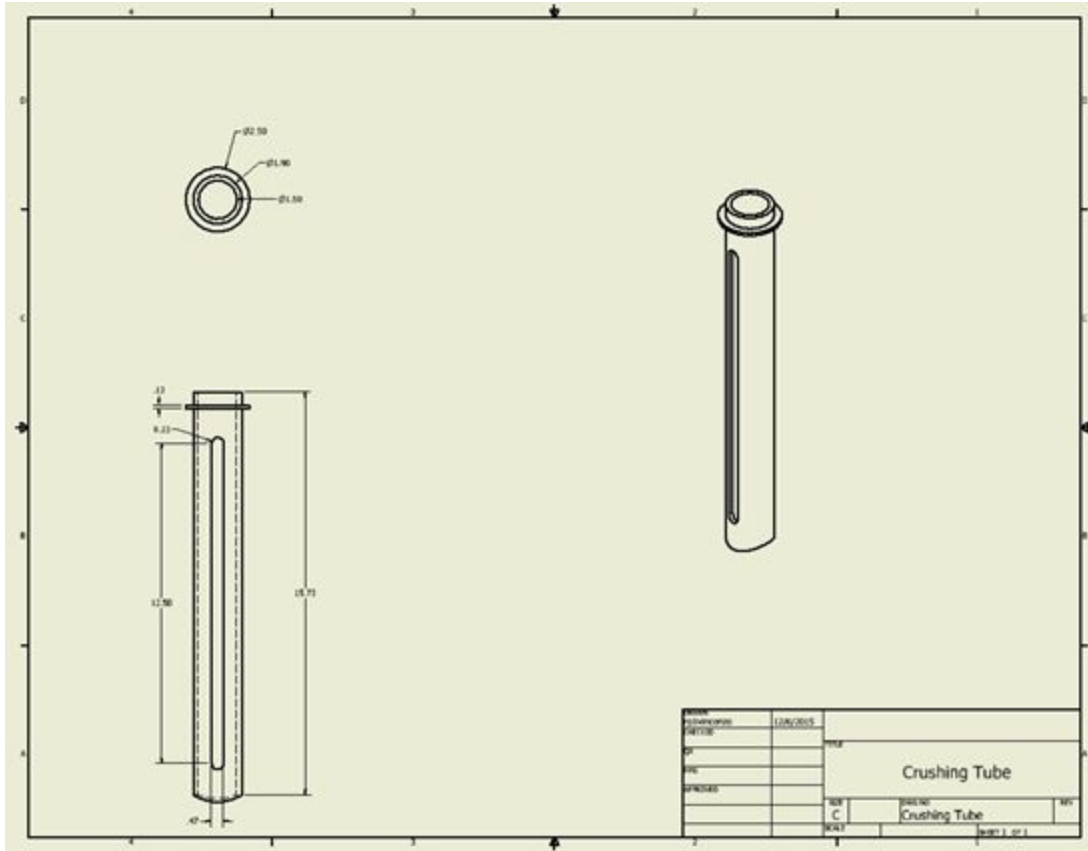


Figure 15: Crushing Tube

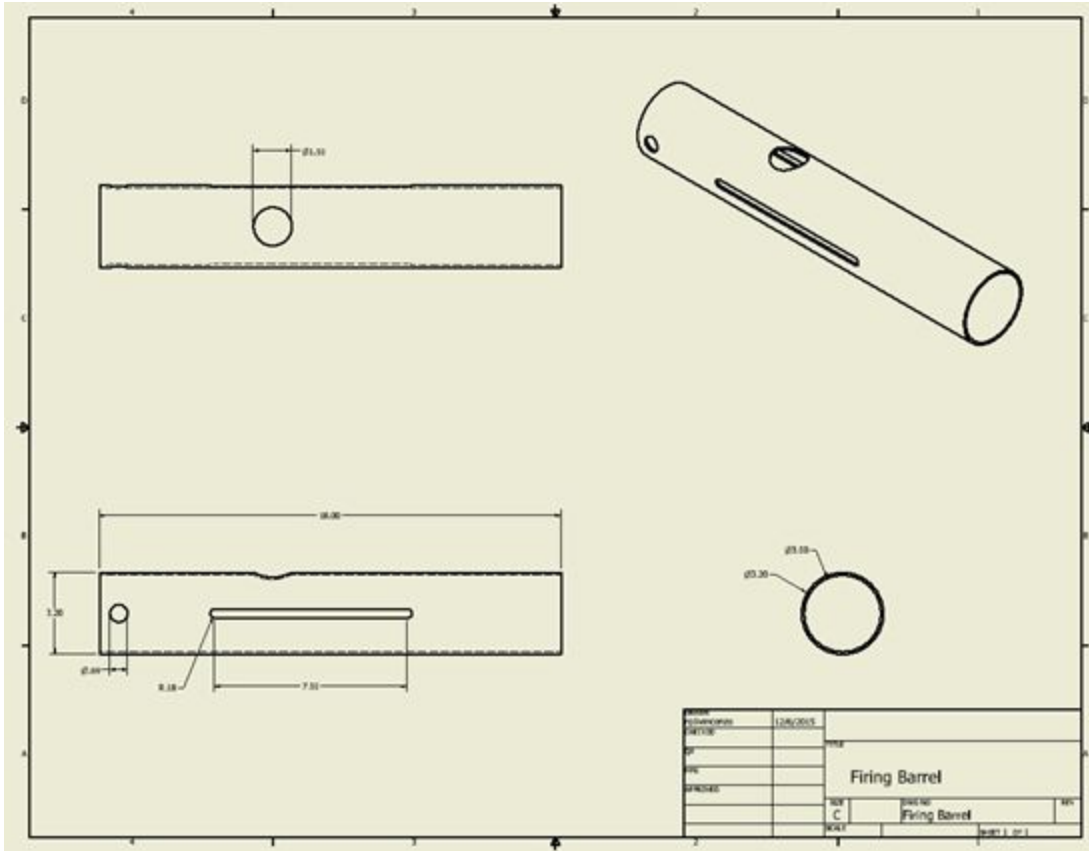


Figure 16: Firing Barrel

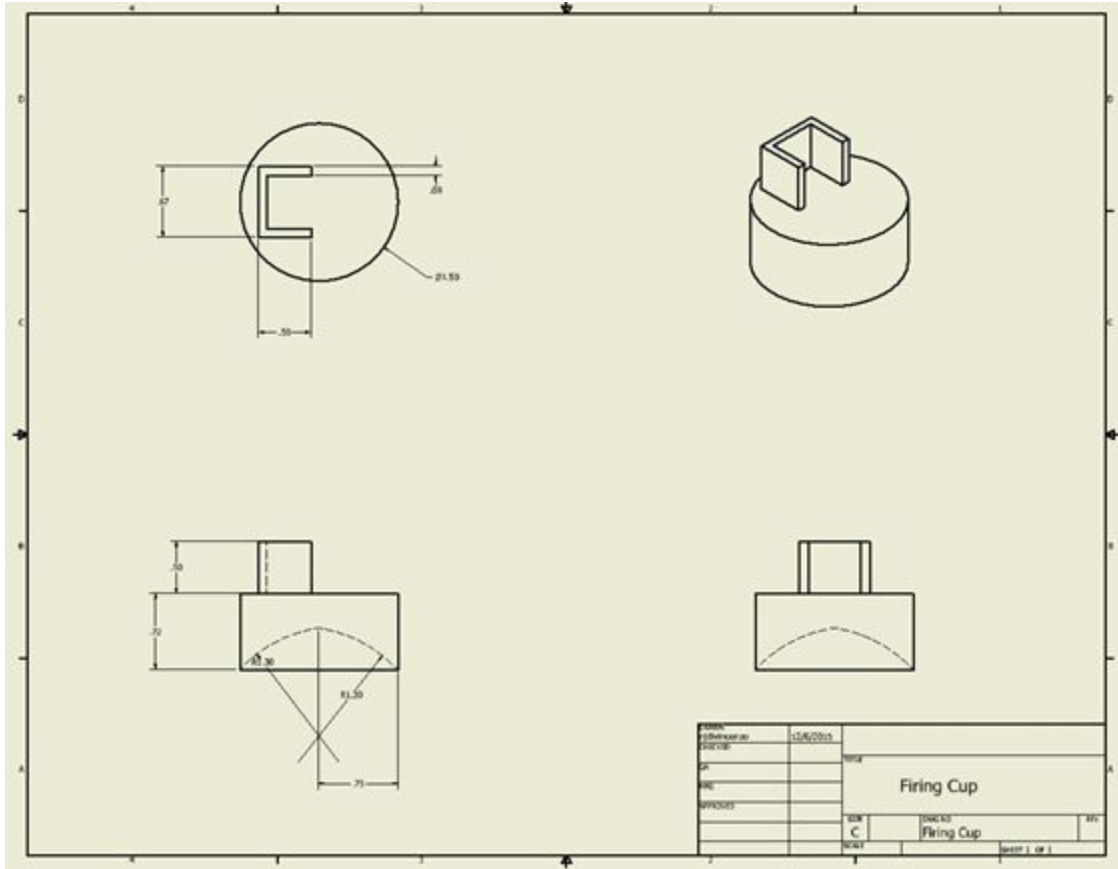


Figure 17: Crushing Head

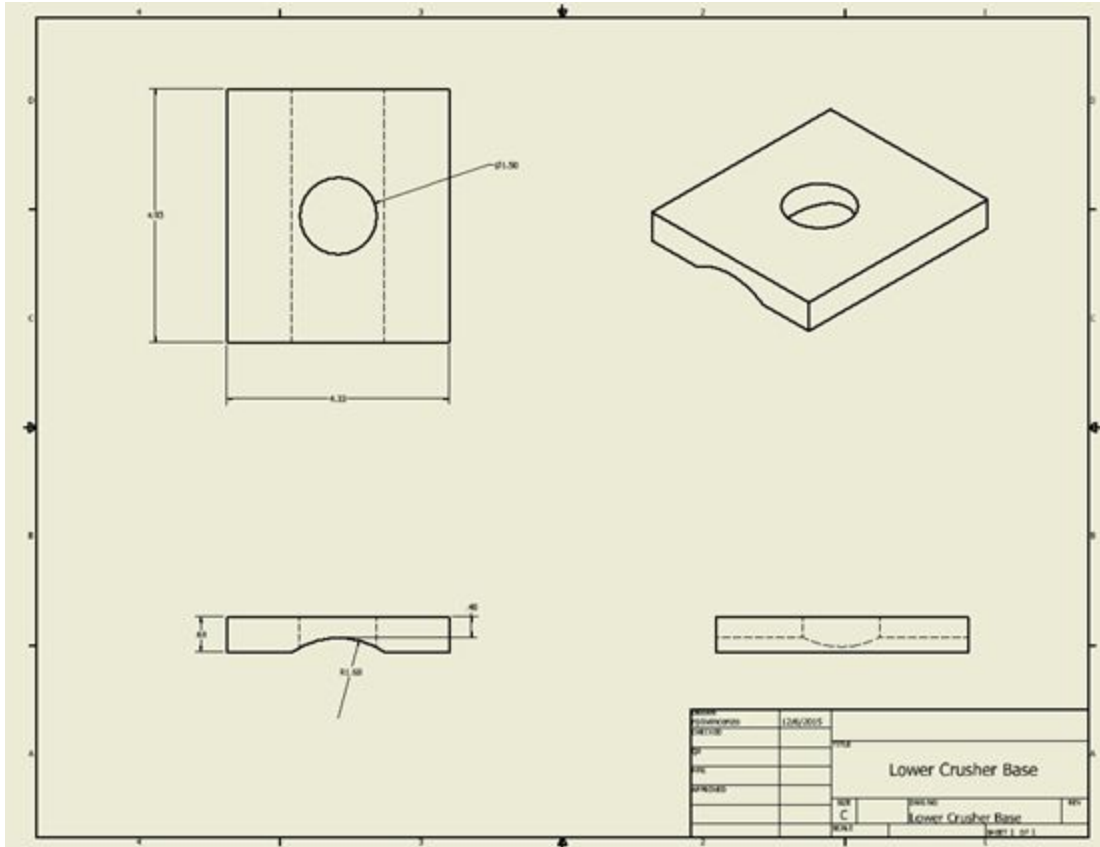


Figure 18: Lower Crusher Base

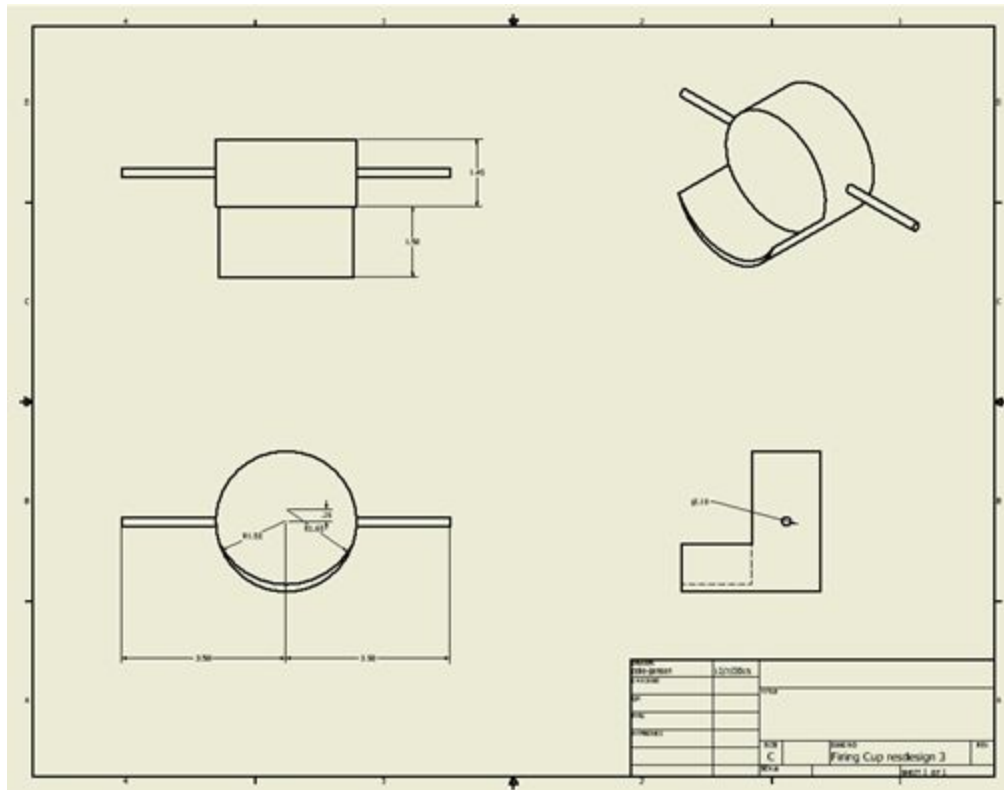


Figure 19: Firing Cup

4.4 Description of the design rationale for the choice/size/shape of each part

The Base Block is thick enough to not split and yet still fit the clutch around it.

The Base is the minimum size necessary to hold the clutch and cannon barrel.

The Cannon Spring Shaft is the minimum length necessary to fit around the barrel and still have room for the fishing line to wind around it. The nub at one end is wide enough to stop it from passing through the 3/16" mounted bearing, fixing it in that dimension.

The Clutch Engaging Motor is a rough model of the motor we chose with the lead screw and plate already attached. The plate is slightly thinner than the corresponding slits in the Clutch Sides so it has some give, allowing the clutch to engage and disengage. As we found this motor

in the basement we've unsure of the voltage its rated for, but it seems to be adequate for our purposes.

Likewise the Clutch Shaft and Driver Motor is a rough model of the motor we chose already attached to the shaft. The shaft and motor will be held together by a shaft collar. This motor is rated for 12V and can, with difficulty, draw back the springs to their full extension. If the springs are upgraded then this motor will likewise have to be upgraded. It is face mounted to one of the side plated, eliminating the need for a second bearing there and keeping it stable.

The Clutch Side has holes large enough to fit the linear bearing on one side and attach to the Base Block on the other via a thick shaft. Its slit is slightly wider than the Clutch Engaging Motor plate as mentioned above.

Like the other motors, the Crusher Motor Shaft is a rough model of the motor we chose already attached to the shaft. The shaft and motor will be held together by a shaft collar. This motor is rated for 12V and can easily crush the paper into the barrel and draw the Crusher Head out again.

The Crusher Motor Mount is symmetrical about the hole to keep the Crusher balanced. The hole is a tight fit around the Crushing Tube to help hold it on. There is a small indentation cut on the side the motor will rest on in order to better fit the motor in place.

The diameter of the Crushing Tube was chosen to minimize the size of the projectile while still allowing for easy loading and maintaining stiffness of the tube. The ring near the top is a rough model of the 1 7/8" split ring hanger which is there to ensure that the Crusher Motor Mount doesn't slip down the barrel. The bottom of the tube is cut to fit on top of the Firing Barrel without interfering with it.

The diameter of the Firing Barrel was chosen to ensure that the projectile wouldn't get caught on the Crushing Tube hole. The Crushing Tube hole diameter is just wide enough to permit the Crusher Head so that the Crushing Tube doesn't slip inside. The slit width doesn't particularly matter, it just needs to be a little larger than the shaft that runs through the Firing Cup. The two holes cut at the bottom end of the barrel are a tight fit for the 3/16" bearings. The 3 1/2" split ring hanger is attached to the firing to provide the springs with an attachment point.

The Crushing Head should be a close fit to the Crushing Tube without being a tight fit. The structure atop the Head is a tight fit for the rack, helping holding it in place. The divet cut out of the bottom of the Head helps draw the paper into the center of the Head instead of being caught along the edges, leading to an improper crushing and failed firing.

The Lower Crusher Base is wide enough to allow for square brackets to hold the Crushing Tube in place. Its hole is a tight fit for the Crushing Tube to help stabilize it. This is screwed and glued onto the Firing Barrel

The Firing Cup has a shovel scoop in front into which the projectile is crushed. This ensures that the projectile feels little to no friction as the cannon fires. It is thick enough to prevent it from pivoting inside the barrel, potentially damaging it and interfering with the firing. The rod sticks out several inches to either side to insure that the fishing line doesn't fall off. The diameter of the cup is slightly smaller than the inner diameter of the Firing Barrel to minimize friction between the cup and the barrel whilst firing.

The springs chosen for this prototype were so picked because a smaller spring constant would allow us to find any serious problems with the mechanism without damaging the prototype. Larger spring constant springs will allow for a greater firing distance, though they will also necessitate a stronger Clutch Shaft and Driver Motor.

All bearings chosen were picked because they fit the shafts we chose.

The Rack and Pinion were chosen for their strength and mass ensured maximum crushing potential for the price.

40 lb Fishing Line was chosen because of its high tensile strength and flexibility. If we upgrade the motor and springs we will have to likewise upgrade the line to 60 lb or double up on the fishing line used.

12V battery cases were chosen because our chosen motors were rated for 12V and a great deal of torque is needed to draw back the firing cup. For the Clutch motor, where high voltage is undesirable, the Arduino would allow for fine control of the voltage.

The Arduino was chosen for its low price and functionality. It will control the precise timing needed to coordinate each separate part of the cannon moving in turn. It also allows for control of the amount of voltage provided to specific motors to be varied, important in the case of the clutch.

4.5 Gantt chart

MEMS 411 Senior Project

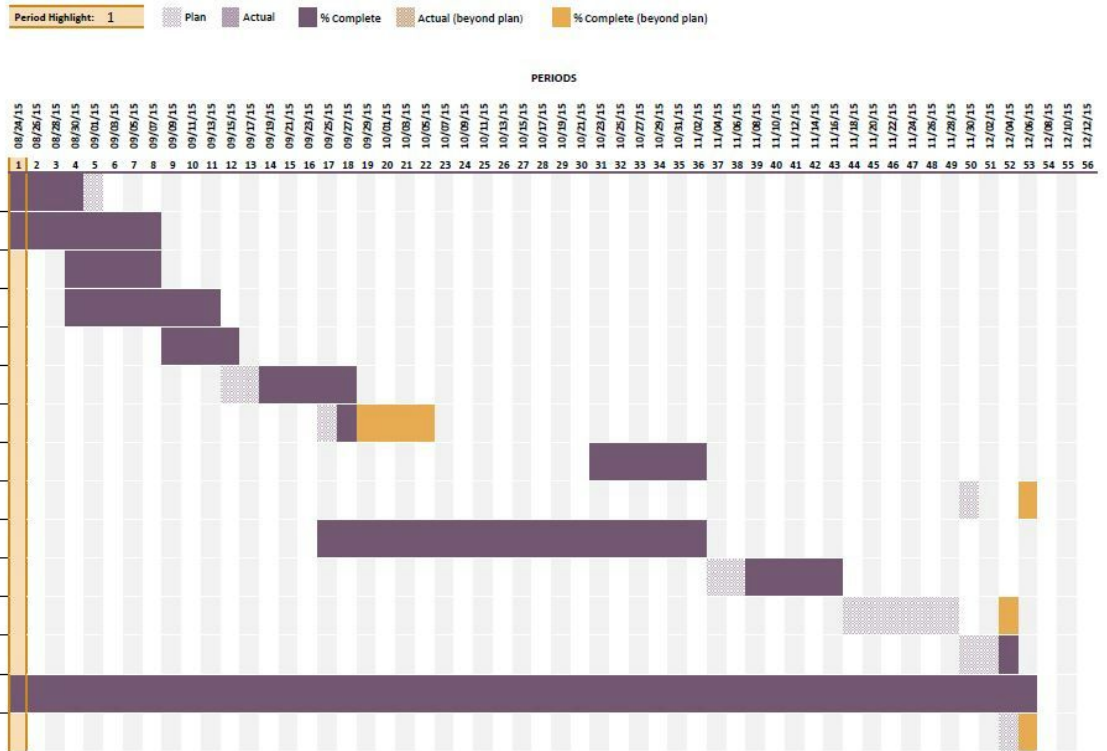


Figure 20: Gantt Chart

5 Engineering analysis

5.1 Engineering analysis proposal

ANALYSIS TASKS AGREEMENT

PROJECT: ASME Challenge NAMES: Nick DiVincenzo

Matt Yurescko

Sam Johnson

Sean Cole-Jansen

I. Before we began construction on our prototype we decided to analyze several different components of the system. We calculated the power required to draw back the launching spring, the power output of the launching motor, the power output of the crushing motor, and the distance traveled by the launched paper.

II. After we finish the first prototype we will measure the actual launch distance and compare it with our calculated value. We will also measure the time required to compress the spring, how stable the prototype is while firing, and how quickly the prototype can fire.

8400 RPM
 Gear ratios (71.4:1, 149.9:1, 319.9:1, 6612:1)
 3mm per shaft

SECOND MOTOR
 HIGH TORQUE DC MOTOR
 16 RPM 12V .125" diameter L: 1 $\frac{11}{16}$ " W, H 1"

SPRING = $K = 221,000 \text{ lbs/in}$ Max Compression = .69 in

$$W = \frac{1}{2} K X^2 = \frac{1}{2} (221,000 \text{ lbs/in}) (.69 \text{ in})^2 = 52.6 \text{ lbs-in}$$

$$P = \frac{W}{t} = \frac{52.6}{5} = 10.52 \text{ lbs-in/s}$$

$$2.78 \left(\frac{.125}{16} \right) \text{ in / rev} \times 11 \text{ rev/s} = .69 \text{ in rev} = .978$$

Figure 21: Spring Calculations

8400 RPM
 Gear ratios (71.4:1, 149.9:1, 314.9:1, 6612:1)
 3mm per shaft

Fe

SECOND MOTOR
 High TORQUE DC MOTOR
 16 RPM 2V, .125" diameter L: 1 $\frac{18}{16}$ " W, H 1"

SPRING: $K = 221,000 \text{ lbs/in}$ Max Compression = .69 in

$$W = \frac{1}{2} k x^2 = \frac{1}{2} (221,000 \text{ lbs/in}) (.69 \text{ in})^2 = 52.6 \text{ lbs-in}$$

$$P \uparrow t = 5 \text{ sec} = \frac{10 \cdot 52 \text{ lbs-in}}{5}$$

$$2.7 \pi \left(\frac{.125}{2} \right) \text{ in/rev} \times \pi \text{ revs} = .69 \text{ in} \quad \pi \text{ rev} = .978$$

Figure 22: Launcher Motor Calculations

Requirement

MOTOR

$T = 120 \text{ N-cm}$ In order to compress spring
 $\omega = 30 \text{ RPM}$ in 5 seconds $P \geq \frac{10 \cdot 52 \text{ lb-in}}{5}$

$$P = T \times \omega$$

$$= 120 \text{ N-cm} \cdot \frac{.0895 \text{ lb-in}}{1 \text{ N-cm}} \times \frac{30 \text{ rev}}{\text{min}} \cdot \frac{2\pi}{\text{rev}} \cdot \frac{1 \text{ min}}{60 \text{ s}}$$

$$P = 33.36 \frac{\text{lb-in}}{\text{s}} \text{ which } > \frac{10 \cdot 52 \text{ lb-in}}{5}$$

Figure 23a: Crusher Power Calculations

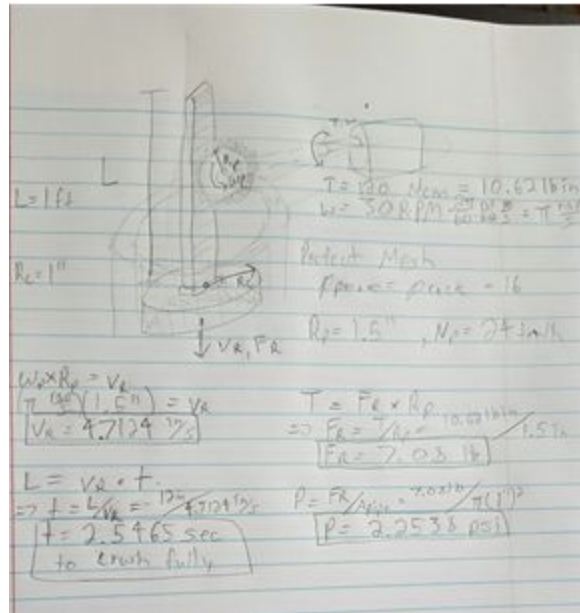


Figure 23b: Crusher Power Calculations

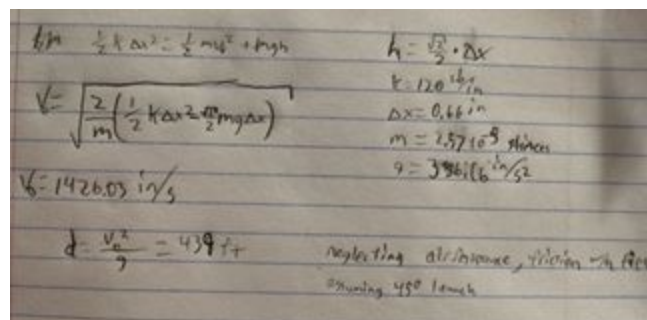


Figure 24: Projectile Motion Calculations

5.2 Engineering analysis results

5.2.1 Motivation

Engineering analysis at this point is vital as the need for further improvements are derived from any problems discovered during the analysis.

5.2.2 Summary statement of analysis done

The results were found using the same equations listed in 2.1 with the latest prototype. The sum of the times required for each process is 27 seconds and launched the projectile 1.2 meters with little recoil.

5.2.3 Methodology

The analysis was done using a timer and a meter stick with the final prototype.

5.2.4 Results

It took 10 seconds to load the crusher. The firing motor took 7 seconds to wind back the firing cup. The crusher took 9 seconds to crush the paper into the firing cup and return to the fully upright position. The clutch took less than a second to disengage. The projectile fired 1.22 m across a flat surface at a 10° angle from forward. There was no noticeable recoil. Yes these results make sense.

5.2.5 Significance

Given the low recoil and low distance we will switch out the springs and the firing motor for stronger ones. This will not result in changes in the dimensions of most of the structures outside of minor adjustments to the Cannon Base to accommodate the larger motor, however these changes can't be made until a new motor is chosen

5.2.6 Summary of code and standards and their influence

There were no necessary codes or standards to follow because of the nature of the ASME design competition.

5.3 Risk Assessment

5.4 Context

Risk management lies at the intersection of project functions performed by the systems engineer and the project manager [3]. Historically, risk management focused more on management elements such as schedule and cost, and less on technical risks for well-defined or smaller projects. However, larger and more complex projects and environments have increased the

uncertainty for the technical aspects of many projects. To increase the likelihood of successful project and program outcomes, the systems engineer and project manager must be actively involved in all aspects of risk management.

A substantial body of knowledge has developed around risk management. In general, risk management includes development of a risk management approach and plan, identification of components of the risk management process, and guidance on activities, effective practices, and tools for executing each component. One characterization of the risk management process is shown in Figure 1 [1].

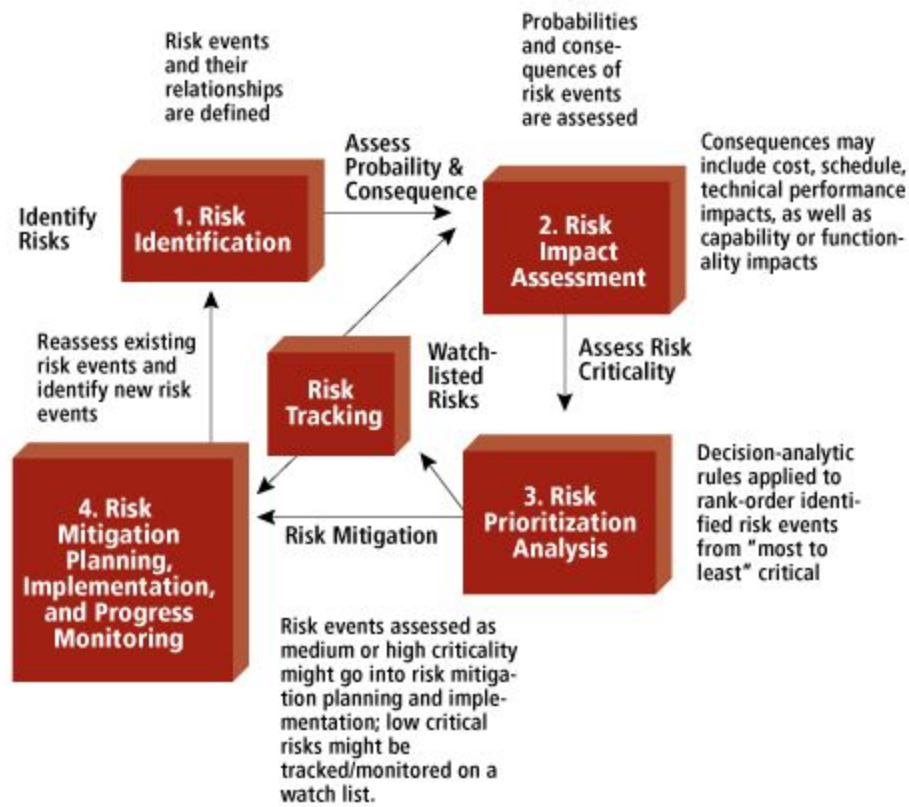


Figure 1. Fundamental Steps of Risk Management

5.4.1 Risk Identification

Risk	Probability of Occurrence	Order of Importance
------	---------------------------	---------------------

Not meeting performance goals	Medium	1
Cost	Low	2
Scheduling (finishing on time)	Low	3
Safety	Low	4

Table 7: Risk Identification

5.5 Background

(Source:

<http://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/risk-management/risk-identification>)

Risk identification is the critical first step of the risk management process depicted in Figure 1.

The objective of risk identification is the early and continuous identification of events that, if they occur, will have negative impacts on the project's ability to achieve performance or capability outcome goals. They may come from within the project or from external sources.

There are multiple types of risk assessments, including program risk assessments, risk assessments to support an investment decision, analysis of alternatives, and assessments of operational or cost uncertainty. Risk identification needs to match the type of assessment required to support risk-informed decision making.

Identifying Risks in the Systems Engineering Program

There are multiple sources of risk. For risk identification, the project team should review the program scope, cost estimates, schedule (to include evaluation of the critical path), technical maturity, key performance parameters, performance challenges, stakeholder expectations vs. current plan, external and internal dependencies, implementation challenges, integration, interoperability, supportability, supply-chain vulnerabilities, ability to handle threats, cost deviations, test event expectations, safety, security, and more. In addition, historical data from similar projects, stakeholder interviews, and risk lists provide valuable insight into areas for consideration of risk.

Risk identification is an iterative process. As the program progresses, more information will be gained about the program (e.g., specific design), and the risk statement will be adjusted to reflect the current understanding. New risks will be identified as the project progresses through the life cycle.

5.6 Best Practices and Lessons Learned

Operational Risk. Understand the operational nature of the capabilities you are supporting and the risk to the end users, their missions, and their operations of the capabilities. Understanding of the operational need/mission (see the [Concept Development](#) topic of the Systems Engineering Guide) will help you appreciate the gravity of risks and the impact they could have to the end users. This is a critical part of risk analysis, realizing the real-world impact that can occur if a risk arises during operational use. Typically operational users are willing to accept some level of risk if they are able to accomplish their mission (e.g., mission assurance), but you need to help users to understand the risks they are accepting and to assess the options, balances, and alternatives available.

Technical maturity. Work with and leverage industry and academia to understand the technologies being considered for an effort and the likely transition of the technology over time. One approach is to work with vendors under a non-disclosure agreement to understand the capabilities and where they are going, so that the risk can be assessed.

5.6.1 Risk Analysis

Calculations were performed to determine how much power it would require to pull back our springs. We used this calculation to determine how powerful of a motor we would need to reliably operate the firing mechanism. Because not meeting our performance goals was our number one source of risk, these calculations were important for mitigating risk.

3900 RPM
 Gear ratio (71.4:1, 49.9:1, 314.9:1, 4412:1)
 3mm per slot

Fe
 SECOND MOTOR
 HIGH TORQUE DC MOTOR
 10 RPM 12V, 125" diameter, L: 1 3/8" W, H

SPRING $K=22100 \text{ lbs/in}$ Max Compression = 0.69 in

$$U = \frac{1}{2} kx^2 = \frac{1}{2} (22100 \text{ lbs/in}) (0.69 \text{ in})^2 = 52.6 \text{ lbs-in}$$

$$P = \frac{U}{t} = \frac{52.6 \text{ lbs-in}}{5 \text{ sec}} = 10.52 \text{ lbs-in/s}$$

$$\left(\frac{2\pi (125)}{60} \right) \text{ in/rev} \times 10 \text{ rev/s} = 129 \text{ in/s} \quad \text{rev} = 0.78$$

Figure 25: Spring Calculations

After determining how much power we would need to pull back the springs we were able to select a motor. We determined that the motor we had chosen would be able to output 33.36 lb-in/s of power, which was three times as much power as we needed. This factor of safety helped mitigate the risk that the motor would not be powerful enough to draw back the springs.

MOTOR

$T = 120 \text{ N-cm}$ In order to compress spring
 $\omega = 30 \text{ RPM}$ in 5 seconds $P \geq \frac{10.52 \text{ lb-in}}{5}$

$$P = T \times \omega$$

$$= 120 \text{ N-cm} \cdot \frac{0.085 \text{ lb-in}}{1 \text{ N-cm}} \times 30 \frac{\text{rev}}{\text{min}} \cdot \frac{2\pi}{60} \frac{\text{rad}}{\text{rev}} = 33.36 \frac{\text{lb-in}}{\text{s}}$$

$P = 33.36 \frac{\text{lb-in}}{\text{s}}$ Which $\geq \frac{10.52 \text{ lb-in}}{5}$

Figure 26: Motor Calculations

Background

(Source:

<http://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/risk-management/risk-management-tools>)

Risk analysis and management tools serve multiple purposes and come in many shapes and sizes. Some risk analysis and management tools include those used for:

- Strategic and Capability Risk Analysis—Focuses on identifying, analyzing, and prioritizing risks to achieve strategic goals, objectives, and capabilities.
- Program Risk Management—Focuses on identifying, analyzing, prioritizing, and managing risks to eliminate or minimize their impact on a program's objectives and probability of success.
- Cost Risk Analysis—Focuses on quantifying how technological and economic risks may affect a system's cost. Applies probability methods to model, measure, and manage risk in the cost of engineering advanced systems.

Each specialized risk analysis and management area has developed tools to support its objectives with various levels of maturity. This article focuses on tools that support the implementation and execution of program risk management.

Selecting the Right Tool

It is important that the organization defines the risk analysis and management process before selecting a tool. Ultimately, the tool must support the process. Below are criteria to consider when selecting a risk analysis and management tool:

- Aligned to risk analysis objectives—Does the tool support the analysis that the organization is trying to accomplish? Is the organization attempting to implement an ongoing risk management process or conduct a one-time risk analysis?
- Supports decision making—Does the tool provide the necessary information to support decision making?
- Accessibility—Is the tool accessible to all users and key stakeholders? Can the tool be located/hosted where all necessary personnel can access it?
- Availability of data—Is data available for the tool's analysis?

- Level of detail——Is the tool detailed enough to support decision making?
- Integration with other program management/system engineering processes——Does the tool support integration with other program management/system engineering processes?

5.6.2 Risk Prioritization

Our group identified several important areas of risk when discussing our risk management process. They are, in descending order of importance, performance challenges, cost, scheduling, and safety. Our system needs to operate continuously and without maintenance or modification for five minutes. If any part of the system were to come out of alignment, or if a part were to break, we would receive a very low score at the ASME competition. It is imperative that the system operates smoothly and as intended.

Cost was our second largest source of risk. We were given a budget of \$400 dollars and asked to stay within that operating budget. Several of the parts that we needed to buy were very expensive. If the part was damaged while we were assembling our prototype, or if a part was ordered that doesn't end up meeting our needs, we would incur a large loss in our available funds. We had to modify several of the parts that we ordered by machining them. If the machining was done incorrectly and we ruined the part, we would be hard pressed to get enough money together to buy another one.

Scheduling was our third largest source of risk. We had a rigid schedule for when we needed to deliver our product by. It was important that we continuously looked at our progress so that we could make any necessary adjustments so that we finished our product on time.

Safety was our smallest source of risk. No combustion components or pressurized gas components were allowed in the competition, which would have made our design much more dangerous. Our design used springs and electric motors; there was very little danger associated with those components. The only safety issue that we would imagine would be getting a finger tangled up with the springs while the system is firing.

6 Working prototype

6.1 A preliminary demonstration of the working prototype (this section may be left blank).

6.2 A final demonstration of the working prototype (this section may be left blank).

6.3 At least two digital photographs showing the prototype



Figure 27: Isometric View

The first photograph shows the entire Paper Launcher assembly. It consists of three main components: A firing tube, a crushing tube, and a clutch. The paper is inserted into the

cylindrical crushing tube through a narrow slit and is then crushed by a plastic crushing head. The crushing head is driven by a rack and pinion, which is powered by a motor mounted on a wood support at the top of the crushing tube. The firing tube has a long shaft running through it near the bottom end of the barrel. Two pieces of fishing line connect this shaft to a rod which is attached to two springs. The springs are pulled back by a motor which winds the fishing line around the firing tube shaft. The projectile is fired when the clutch disengages the spring tension is released.



Figure 28: Side View

The second figure shows a side view of the system. The bearing seen near the bottom end of the firing tube allows the shaft running through the barrel to be driven by a motor and stretch the springs. The fishing line is tied onto the shaft running through the slit connecting the springs and is threaded through a hole drilled in the firing shaft.

6.4 A short videoclip that shows the final prototype performing

<https://www.youtube.com/watch?v=MsrBP-ok5Qs>

6.5 At least four (4) additional digital photographs and their explanations

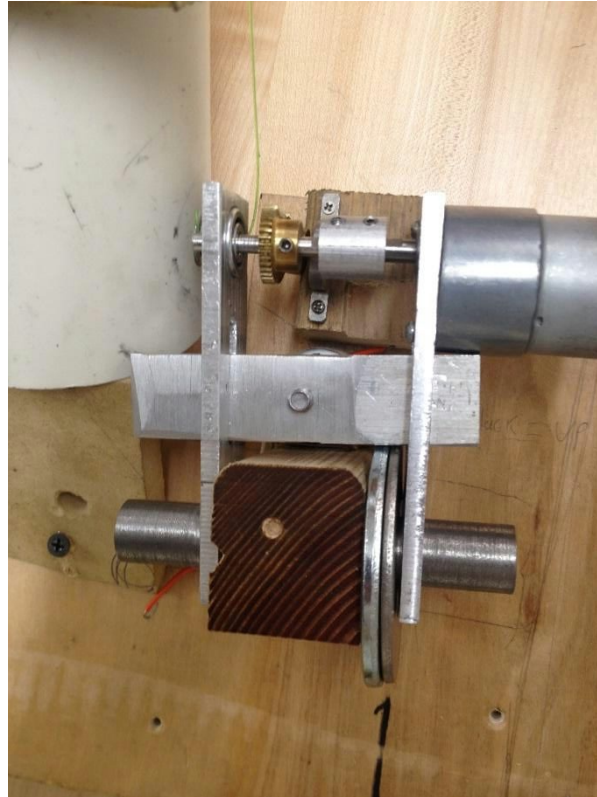


Figure 29: Clutch

This figure shows the top view of the clutch. A shaft with a brass gear affixed to it runs between two aluminum plates called arms. A small motor attached to the underside of the flat aluminum plate in the middle pushes the clutch up and down, allowing the gear to engage and disengage from the firing shaft.

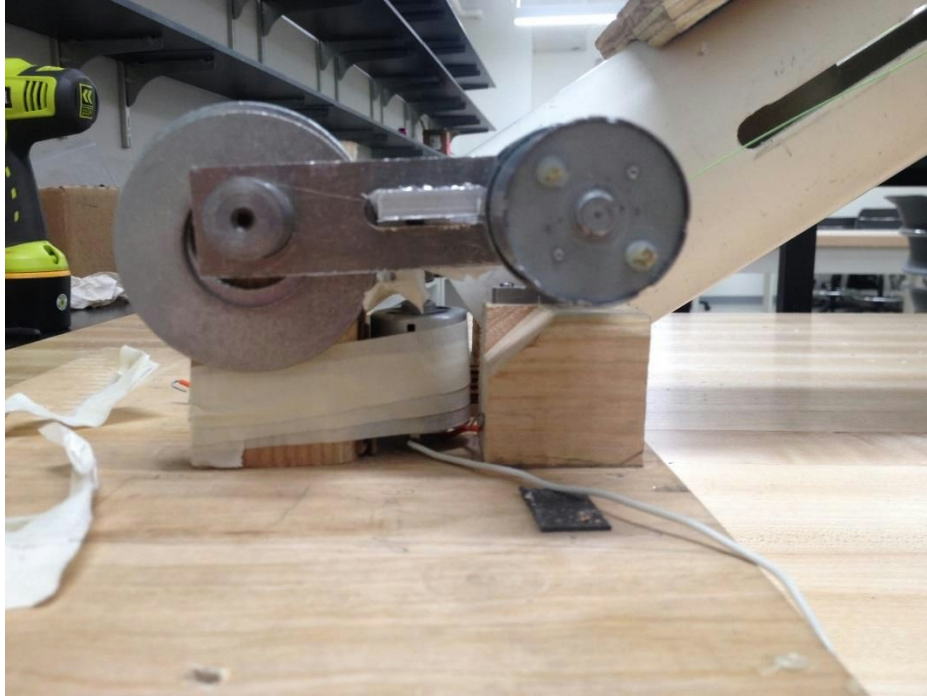


Figure 30: Clutch, Side View

This figure shows a side view of the clutch. The motor driving the clutch up and down can be clearly seen. This motor drives a lead screw, which is screwed into a threaded hole in the metal plate that connects the two arms of the clutch. The arms rotate about the axle on the left side of the picture. The motor and shaft on the other end of the arms rotates about that axle, but for small angle approximation the motor essentially moves vertically a small distance. When the lead screw is turned, it forces the the arms and motor to move up or down. At the beginning of the launching process, the lead screw holds the arms in a position so that the gears that are winding the springs stay engaged. When the springs are fully wound and the projectile is crushed completely in the firing tube, the lead screw rotates in the opposite direction, which pushes the clutch upward, thereby releasing the spring.

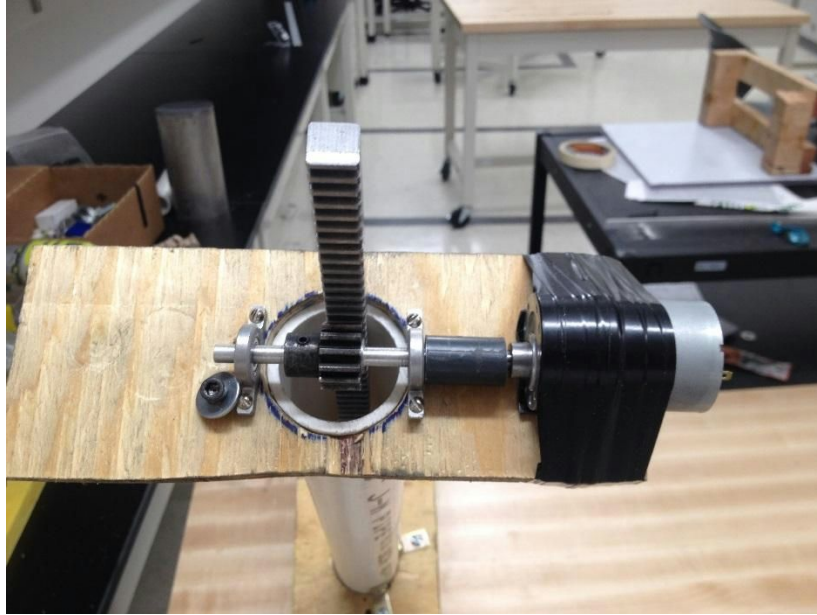


Figure 31: Down Barrel

This figure shows the top of the crushing mechanism. A motor turns a shaft which has a pinion mounted on it. The pinion engages with the rack and moves it upwards or downwards depending on which direction the motor shaft is rotating. Two bearings support the shaft and a black shaft collar connects the motor shaft to the crushing shaft.



Figure 32: Crusher Rack and Head

This figure shows the crushing mechanism. It consists of a rack and pinion gear and a 3-d printed crusher head. The head is covered in order to ensure a tight fit between the crusher head and the crushing tube, so that the paper is unable to slip between the crusher head and the crusher tube. The crusher head is designed to have a length longer than the diameter of the firing barrel in order to constrain it axially within the crushing tube. The face of the crusher head is concave so that it shapes the paper into a ball as it crushes.

7 Design documentation

7.1 Final Drawings and Documentation

7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models. *Include units on all CAD drawings. See Appendix C for the CAD models.*

See Appendix C for CAD models and drawings

7.1.2 Sourcing instructions

See Appendix A for part-by-part breakdown on part sources.

7.2 Final Presentation

7.2.1 A live presentation in front of the entire class and the instructors (this section may be left blank)

7.2.2 A link to a video clip version of 1

<https://youtu.be/J53L5ufg1aA>

7.3 Teardown

TEARDOWN TASKS AGREEMENT

PROJECT: ASME III NAMES: Nick D. INSTRUCTOR: Malast

Matt Y.

Sam C-J

Sam J.

The following teardown/cleanup tasks will be performed:

- project completely disassembled.
- recyclable materials recycled
- raw materials repurposed
- motors, etc. put in basement for future reuse.

All work areas cleaned.

Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: Mary Mahst; Print instructor name: Mary Mahst

Date: 12/7/15

SJ GET N.D. M.Y.
(Group members should initial near their name above.)

8 Discussion

8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met? Discuss the result.

Our final score would be 0.09 in^{-2} or 0.581 cm^{-2} . This doesn't do particularly well on the happiness equations, mostly due to its small distance fired, but it does do extremely well in both the volume and the firing time metrics. In retrospect we severely overestimated its ability to fire long distances and underestimated its ultimate cost, though we remained within our budget. It failed the number of projectiles metric by default as that is only applicable when the machine is automated, which our prototype was not.

8.2 Discuss any significant parts sourcing issues? Did it make sense to scrounge parts? Did any vendor have an unreasonably long part delivery time? What would be your recommendations for future projects?

Our group had some trouble sourcing parts from Amazon. We initially ordered our electric motors from amazon.com, but the motors were unable to be delivered in a timely fashion, so we needed to find another vendor to buy our electric motors from. We scrounged our PVC and wood from the basement and also scrounged one of our electric motors. McMaster Carr was an excellent vendor and delivered our order within two business days. I would recommend that groups avoid buying motors and electrical components from amazon because they take a long time to ship and are often not high quality parts. We also encountered problems with poor quality battery cases from Amazon, making testing the motor-driven parts needlessly frustrating and difficult.

8.3 Discuss the overall experience:

8.3.1 Was the project more or less difficult than you had expected?

It was more difficult than we expected because our initially simple design grew more and more complicated as we discovered new problems that had to be solved. The biggest example of this was the creation of the clutch mechanism midway through the construction of the Initial Prototype; we also needed to make a larger firing tube when we realized that the diameter of the

crushed paper ball was the same as the diameter of the firing tube. This led to the paper getting wedged stuck in the tube. There were many additional problems that arose which needed new mechanism and more complex parts to solve.

8.3.2 Does your final project result align with the project description?

It currently fulfills most of the requirements of the competition. The only requirement that is currently not satisfied is the automation of the system, something that could be done relatively quickly once we learn how to run Arduino and acquire a reliable power source.

8.3.3 Did your team function well as a group?

For the most part. Once we began to work in the shop and had clear objectives things went smoothly and pieces were finished quickly and efficiently. Finding times where we all could meet was difficult and so we generally ended up meeting in the evenings and on weekends.

8.4.4 Were your team member's skills complementary?

Some of our team member's skills were complementary. One of our group members was an excellent drawer and designer, so he did a lot of work on our concept drawings and initial prototype drawings, and other group members had good writing skills and were able to spend a lot of time writing our reports. We had a decent amount of skill overlap in areas like engineering analysis and fabrication.

8.4.5 Did your team share the workload equally?

Yes. We split up the manufacturing work equally. Two of our group members had more experience on the lathe so they fabricated any parts which needed to be made on a lathe, and the other two group members had more experience on the mill, so they fabricated any parts which needed to be milled. The design work was not split up as evenly, but to compensate for this the group members who did not work as much on the design did more work on finding and ordering the required parts and completing the required write-ups.

8.4.6 Was any needed skill missing from the group?

No one in our group had previous experience with Arduino which made it very difficult to automate our prototype. We struggled to learn the programming language and then build the circuits needed to autonomously control our system. If one of us had previous experience at programming Arduino we likely would have been more successful.

8.4.7 Did you have to consult with your customer during the process, or did you work to the original design brief?

Outside of the User Needs Interview, we worked exclusively from the ASME design brief.

8.4.8 Did the design brief (as provided by the customer) seem to change during the process?

No. There were set competition guidelines from the beginning and throughout.

8.4.9 Has the project enhanced your design skills?

We are all more comfortable machining parts in a machine shop, and we learned a lot about the difficulties involved with part fabrication. Throughout the process, we had to constantly adjust our design to meet the problems that were coming up, especially with the clutch. Through that experience, we developed our problem solving skills needed to meet unforeseen challenges.

8.4.10 Would you now feel more comfortable accepting a design project assignment at a job?

Yes. While the machining/building of a project would be a standard process no matter where you are, the conceptualization and design process taught in Machine Elements and stressed in Senior Design is very helpful in organizing your thoughts as a group and recognizing top priorities/deliverables of any project you are tasked with completing. We feel more confident in being able to break down a problem, analyse possible solutions, choose a solution, and to write and create deliverables for our customer.

8.4.11 Are there projects that you would attempt now that you would not attempt before?

Yes. There were some projects we had as our second options that seemed very challenging, which made us hesitate to put them as our primary choice, namely the moped and combustion chamber projects. Now that we've gone through the entire design and build process and have seen the success other groups who did those projects had, they do not seem as daunting.

9 Appendix A - Parts List

	Part	#	Location	Part #	Cost (\$)
1	Base Block	1	Scrap		Nil
2	Base	1	Scrap		Nil
3	Cannon Spring Shaft	2	Scrap		Nil
4	Clutch Engaging Motor	1	Basement		Nil
5	Clutch Shaft and Driver Motor	2	Amazon	B00B1KZ8UU	23.98
6	Clutch Side	2	Scrap		Nil
7	Crusher Motor Shaft	1	Scrap		Nil
8	Crusher Motor Mount	1	Scrap		Nil
9	Crushing Tube	1	Basement		Nil
10	Firing Barrel	1	Basement		Nil
11	Crusher Head	1	3D Printed		Nil
12	Lower Crusher Base	1	Scrap		Nil
13	Firing Cup	1	3D Printed		Nil
14	Steel Extension Springs	2	McMaster	9654K305	7.50
15	3/16" mounted bearings	2	McMaster	8600N2	30.28
16	1/4" mounted bearing	2	McMaster	8600N3	30.28
17	Rack	1	McMaster	6295K14	25.39
18	Pinion	1	McMaster	6867K38	22.82

19	40 lb fishing line	60''	Amazon	B0036DS6Q8	6.79
20	3/16 bearings	2	McMaster	6383K11	6.56
21	Arduino Uno Rev3	1	Arduino	A000066	24.95
22	12V battery cases	2	Amazon	700724502308	13.00
23	3 1/2'' Split Ring Pipe Hanger	1	McMaster	3023T16	13.89
24	1 7/8'' Split Ring Pipe Hanger	1	McMaster	3023T73	5.98
Total Cost:					\$188.60

Table 6: Parts List

10 Appendix B - Bill of Materials

See above

11 Appendix C - CAD Models

See attached folder labeled Appendix C

12 Annotated Bibliography (limited to 150 words per entry)

The picture of the pitching machine shown in Fig. 1 in Section 2.2 was obtained from this source:

Curveball Pitching Machine. JugsSports, *Jugssports.com*. Accessed From:

<<http://jugssports.com/pitching-machines/curveball-pitching-machine/>>. 4 Dec. 2015.

Phillips, D. Curtis. "Patent US4357140A - Electric Newspaper log Roller Machine." *Google Books*. N.p., 2

November 1982. Web. 13 Oct. 2015. <http://www.google.com/patents/US4357140>

For our background information study, we were hoping to find a method of making paper into projectiles that was both simple and compact. The paper log rolling machine patent referenced in Section 2.2 was considered as a possible way to roll the paper into arrows, which would be an aerodynamic and fairly balance projectile.