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ASME Design Challenge Final Report

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MEMS 4110 Senior Design

The American Society of Mechanical Engineers (ASME) 2016 Student Design Competition Challenge is to construct a compact system that can manufacture a projectile from a standard sheet of paper and propel it a maximum distance.

ASME Challenge
Group 1

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1 Introduction

1.1 Project Problem Statement

The American Society of Mechanical Engineers (ASME) 2016 Student Design Competition Challenge: "Manufacturing the Future" is to build a compact engineering system in order to manufacture a projectile from a standard sheet of paper and test it by propelling it a maximum distance. The testing will take place on a competition course that consists of a 3 meter wide strip along the length of the room, with a 1.5 m x 3 m setup area for the system at one end. The scoring for the device is the sum of the 3 throws divided by the volume of the device. (ASME)

1.2 List of Team Members

Charles "Chase" Ahrens Feldman, Julian Cecil, Maria Ferguson, Ashley Hosman

2 Background Information Study

2.1 Design Brief

The ASME-issued design constraints require the engineering system to fabricate three projectiles, each from a single sheet of unmodified 20-lb, A4 paper, and propel all three as far as possible down a course within a five minute time limit. The system cannot touch the floor outside the setup area and must have a height of less than 30 inches. It must be packed inside a rectangular box, be powered by batteries, and be automated such that the user only sets up the device and loads each sheet of paper without interfering with the device in any other way.

Scoring is based on the following equation:

$$s = \frac{d1 + d2 + d3}{V}$$

Thus, the most important design elements to optimize are the distance of the projectile and the rectangular volume of the device. (ASME)

2.2 Relevant Background Information

There exist several paper airplane-making machines, which we initially considered as one of our potential concept design, since paper airplanes generate lift.

- Paper Airplane Machine:
  - https://www.youtube.com/watch?v=7vCj2jDtyX4
- Paper Airplane flight of 266 feet, 10 inches
  - https://www.youtube.com/watch?v=wedcZp07raE

There are also patents for trash compactors, which could apply to crumpling the paper into a ball. Trash compactors are fairly simple: the main components are the receptacle and crusher. Our challenge was optimizing it for a single sheet of paper rather than assorted trash. These patents include cylindrical compactors, which provided the inspiration for our crumpler barrel.

- Vehicle litter compactor
  - US3929060A
  - Piston in Cylinder
- Solar powered compaction apparatus
  - US20050005785A1
  - Battery Powered, Ram
- Trash handling device
  - US5884556A
  - Rectangular Compactor

Several patents exist for ball pitching machine systems that operate with pitching wheels in a way similar to the launching system we selected.

- Baseball pitching device
  - US5865161 US Grant
  - Three drive wheels
- Baseball pitching machine
  - Patent US 4372284 A
  - Two drive wheels

3 Concept Design and Specification

3.1 User Needs, Metrics, and Quantified Needs Equations

3.1.1 User Needs Interview

Table 1: User Needs Interview

Customer: **Ethan Glassman** Address: Washington University in St. Louis Date: 16 September 2015			
Question	Customer Statement	Interpreted Need	Importance
How many projectiles must be manufactured and launched?	3	APC manufactures and launches 3 projectiles	5
What should the projectile consist of?	Each projectile must be made from one 20-lb, A4 sheet of paper, without adding any other materials.	Each APC projectile made from one sheet 20-lb A4 paper only	5
How quickly must the three projectiles be launched?	Within 5 minutes (300 sec), unload system from box, assemble, and feed in three sheets of paper	APC unloads, assembles, and launches three projectiles within 5 min	5
What safety considerations do you have? Are moving parts or electricity an issue?	Can't use batteries that would be difficult to transport to the event (lead-acid, jet engine, etc.). Use batteries that can be ordered online (shipped). Lithium batteries are fine.	APC must run on batteries that can be transported on a plane.	5
What are the constraints on the APC dimensions?	Height must be less than 30 inches, and device must not touch the floor outside the setup area	APC LxWxH : 1.5 m x 3 m x 0.762 m	5
Can the device's length and width extend outside the setup area as long as it does not touch the floor?	Yes, if we cantilevered an arm outside the setup area, that should be fine	APC length may exceed 1.5 m as long as it does not touch the ground	3
How should the APC be powered?	Zero on-board emissions, powered by battery or batteries	APC must be powered by batteries	5
What about using stored energy sources, like springs or other potential energy?	Only allowed if energy sources finish the competition at the same energy they started it	Stored energy sources must finish at the same energy they started	5

Can the paper be modified before loading?	No	Paper cannot be modified before loading	5
What modifications can the device make to the paper after loading?	Device can fold or cut the paper	APC can fold or cut the paper	5
How much is the user allowed to interfere with the device after assembly?	Papers are loaded manually, one at a time, after the prior sheet has been launched	Papers are loaded into the APC manually, one at a time, after the prior sheet has been launched	5
Are there constraints on the maximum height of the projectile?	Ceiling may be as low as 8 feet	APC must be adjustable to accommodate an 8-foot ceiling	4
What are the dimensions of competition course?	Competition space is 3-m wide. If the projectile lands outside the 3-m wide strip, the distance will be measured from the perpendicular point between the strip and where it first strikes the ground or any other object	APC projectile should fly straight	4
Does size of the APC matter?	The volume will be measured based on the size of the rectangular box in which the system is initially packaged	Volume of the box containing the APC must be minimized	5
What is the primary objective of the APC?	To launch the three projectiles as far as possible	Distance traveled must be maximized	5
Can heating elements be used, e.g., to iron the paper?	Yes, as long as it is electrically powered and does not exceed 450 degrees Fahrenheit or leave deposit on the paper	APC may incorporate a heating element	3
Any recommendations on materials?	Watch out for rubber melting with heating element, could use Teflon but it's hard to work with, Delrin is a good material	APC could be constructed from Delrin	3
What predictive design and simulation tools might we use?	Calculate air friction	The air friction of the APC projectile shall be calculated	3

What advanced manufacturing techniques can we use?	3D printing might count, could take advantage of it to make ridges. Waterjet cutting might or might not count. Laser-cutting might.	APC is 3D printed APC is made with waterjet cutting APC is made with laser cutting	3 1 1
Does the complexity of the final projectile matter?	No preference on planes vs. crumpled paper, lift might have better performance if done well	APC projectile utilizes lift	1
Does the complexity of the APC matter?	Less complexity might make for a more consistent score—won't have to worry about things breaking or jamming	APC device is simple	3
Does the APC need to be quiet?	Avoid unnecessary noise	Machine is quiet	1
Does the APC need to be easily transported?	Need to be able to transport it to the event, and into the setup area	APC is transportable	4
How easy does the assembly of the APC need to be?	Put it together and launch projectiles in less than 5 minutes	APC must assemble from box into full operation within 3 minutes	4
Is there a limit to the number of moving parts the APC can have?	Simpler is better to avoid breakdowns	APC device is simple	3
How long is the course?	Maybe 30 m? Unknown.		
Can part of our setup include guides outside the setup area (grappling hook, zip line, etc.), as long as it doesn't touch the ground?	In theory, but machine cannot exceed 30 inches in height, so only conceivable way to do that is to shoot a cable into the opposite wall without having it ever exceed 30 inches in height	External guides must not exceed 30 inches in height or touch the ground outside the setup area	5

3.1.2 Identified Metrics

Table 2: Identified Metrics

Design Metrics*: ASME Paper Crumpler (APC) ***Note: Every design must satisfy needs 1 and 8. If these needs are not met, the design will not be considered.**					
Metric Number	**Associated Needs**	**Metric**	**Units**	**Min Value**	**Max Value**
1	7	Height	m	0.1	0.7625
2	6	Width	m	0.1	3
3	5	Length	m	0.1	1.5
4	11	Initial Volume	m^3	0.001	3.4313
5	2, 3	Time	Sec	0	300
6	9, 10, 12, 14	Flight quality*	integer rank	0	10
7	15, 17, 4	Safety when packed**	integer rank	0	5
8	16	Number of moving parts	Integer	0	50

3.1.3 Quantified Needs Equations

Table 3: User Needs

Need Number	Need	Importance
1	APC manufactures and launches 3 projectiles from one sheet unmodified 20-lb A4 paper	5
2	APC assembles within 2 min	5
3	APC launches 3 projectiles within 3 min	5
4	APC runs on travel-safe batteries	5
5	APC length (touching ground) less than 1.5 m	5
6	APC width less than 3 m	5
7	APC height less than 0.762 m	5
8	Stored energy ends at same energy it started	5
9	APC projectile height adjustable to not exceed 8 ft	3
10	APC projectile flies straight	4
11	APC volume is minimized	5
12	APC projectile distance is maximized	5
13	APC manufacturing process uses 3D printing	3
14	APC projectiles utilize principles of aerodynamics	1
15	APC is not hazardous to transport	4
16	APC minimizes complexity and number of moving parts	3
17	APC can be easily lifted	4

The user needs were weighted and normalized in order to produce the following equation. The maximum score a design could get would be 1. Need #1 and Need #8 were ignored in the equation, as any design that did not fulfill these requirements would not qualify for the competition. We assumed that every design must fulfill these two needs in order to be scored with the equation.

$$\begin{aligned} Total\ Score = \ & 0.08065 * need2 + 0.08065 * need3 + 0.08065 * need4 \\ & + 0.08065 * need5 + 0.08065 * need6 + 0.08065 * need7 \\ & + 0.04839 * need9 + 0.06452 * need10 + 0.08065 * need11 \\ & + 0.08065 * need12 + 0.04839 * need13 + 0.01613 * need14 \\ & + 0.06452 * need15 + 0.04839 * need16 + 0.06542 * need17 \end{aligned}$$

3.2 Concept Drawings

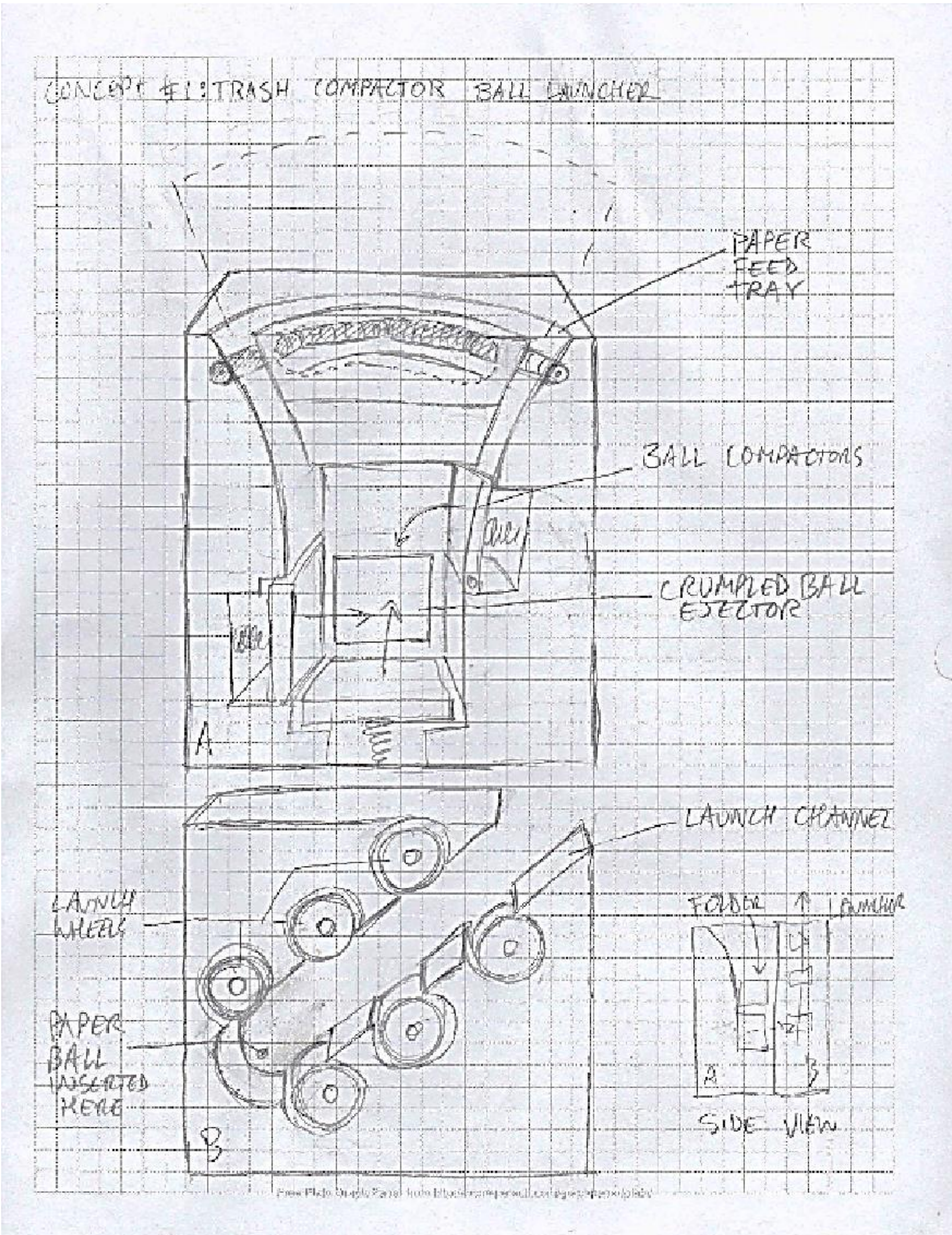


Figure 1: Trash Compactor Design Concept

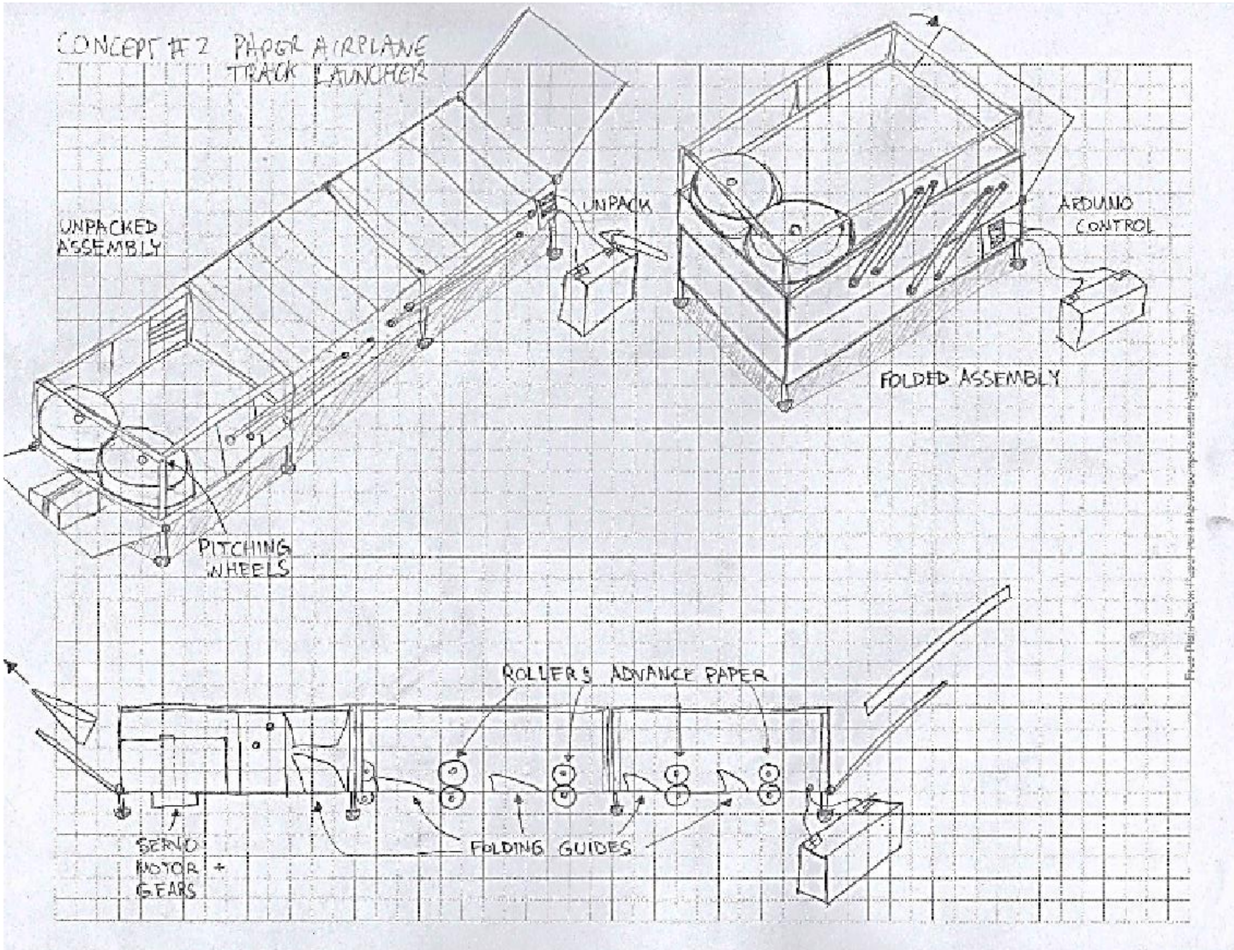


Figure 2: Paper Airplane Track Concept

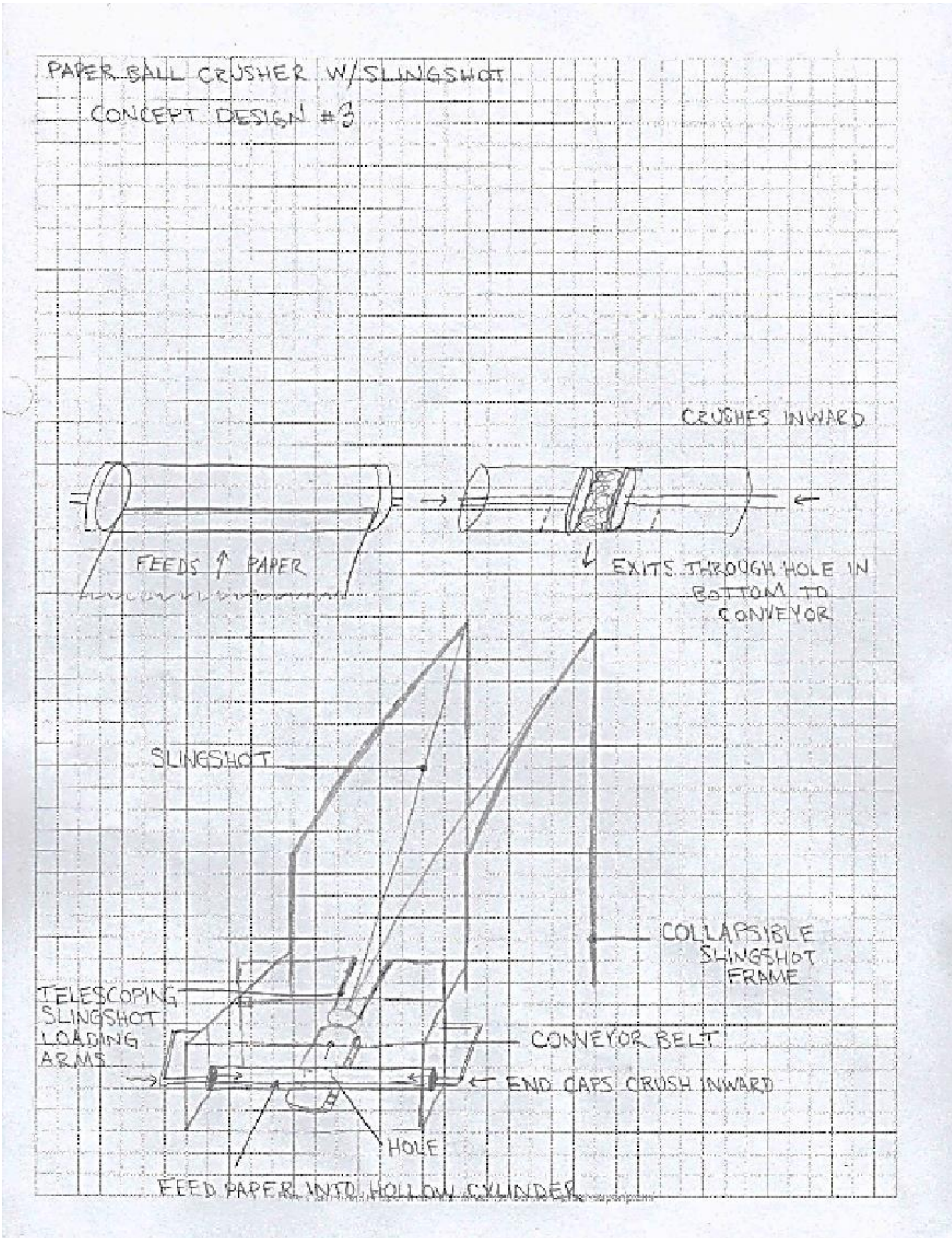


Figure 3: Paper Ball Slingshot Concept

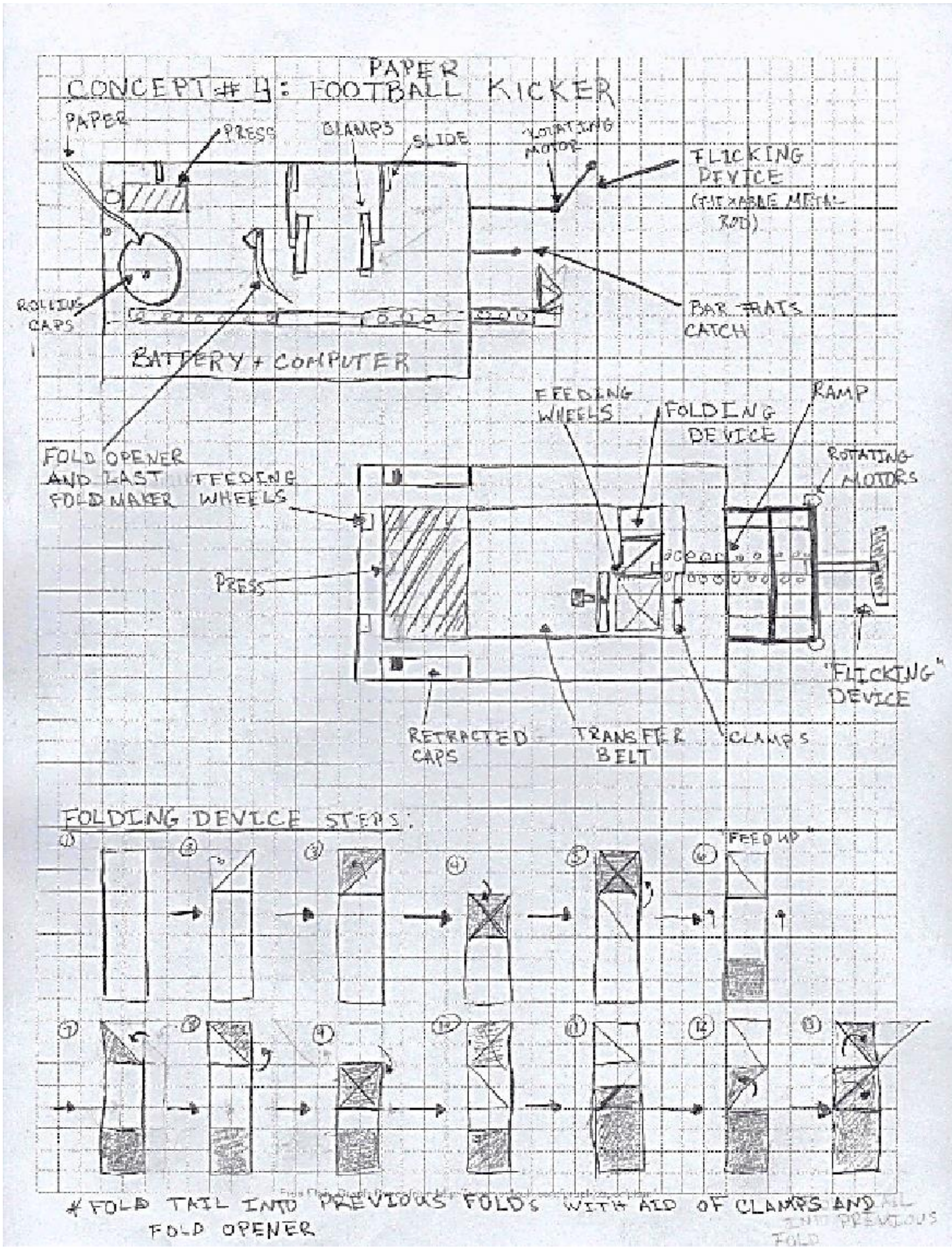


Figure 4: Paper Football Launcher Concept

3.3 Concept Selection Process

3.3.1 Concept scoring

Using the equation in Section 3.1.3, each of the four concepts was scored based on anticipated design characteristics. Concept 1 received a score of 0.825, Concept 2 received a score of 0.807, Concept 3 received the worst score, a score of 0.49, and Concept 4 received a score of 0.72.

3.3.2 Preliminary Analysis of Each Concept's Physical Feasibility

#1 - Paper Ball Launcher

The Paper Ball Launcher takes a standard sheet of A4 Paper through a curved feed tube with rollers around the outside edge of the guide and rolls the paper into a tube. Once the paper is rolled, the ball compacting plates crush the tube from the top and bottom simultaneously, then hold in place while the side compacts, then the process is repeated until the ball is a small cube. The ball ejector pushes the completed crumpled paper ball into the bottom of the firing mechanism, where the launch wheels spin the ball out of the launch tube. Each set of launch wheels is set to a higher speed, so that the first wheels spin at ~20 mph, the second set of wheels at ~50 mph, and the third set at ~100 mph in order to accelerate the ball in as short a distance as possible. Once the ball has entered the launch tube, the ball compactor arms are returned to the starting positions and the next sheet of paper is fed through the top for the cycle to continue.

This design received a 0.825 on the happiness equation, and was considered for the final design. The estimate of size was rather conservative, assuming a 1 cubic foot volume. All other metric estimates are close to the actual values once the device is complete.

#2 - Paper Airplane Track Launcher

The paper airplane track launcher design is initially 3 rectangular frames stacked upon each other, which then unfolds neatly into a continuous paper airplane assembly line. The frames swivel out with a jointed swinging arm, which minimizes the time needed to assemble the machine. Once unfolded, the machine is fed a standard A4 size piece of paper, which is provided in the competition, and is sent through a series of rollers. The rollers advance the paper into metal guides which force it to be folded into the desired shape. There will be anywhere from four to six metal guides: the number is determined by the desired shape of the finished airplane. Once finished, the final guide will smooth out the airplane and crease it, which will prepare it for launch. The launch mechanism is two rapidly spinning wheels moving in opposite directions, much like a pitching machine. When the airplane makes contact with the wheels, it is launched down a guide rail to make the desired trajectory. This machine is compliant to all ASME competition rules.

This concept achieved a 0.807 in the happiness equations, and is considered for a final design. This machine scored well for assembly time, launch time, and initial volume, because it is compact before unfolding and can fold an airplane continuously and rapidly. It would also be easy to power this machine with a travel save battery, as well lacks a need to be heavily programmed. It scored poorly on metrics for flight quality due to the nature of paper airplanes, which tend to make the flight path extremely sensitive to fold quality. The largest challenge in making this machine would be our ability to fine tune the airplane to have a straight and long flight path.

#3 - Paper Ball Crusher with Slingshot

The Paper Ball Crumpler with Slingshot takes a standard sheet of A4 Paper through a slit in a hollow tube and rolls the paper into a tube. Once the paper is rolled, two compressor discs press inward to crumple the paper, which then drops through a hole in the bottom of the tube. The projectile travels along the conveyor belt and drops into the slingshot sling. The slingshot is then cocked back with mechanical arms, released, and reset.

The paper ball crumpling mechanism will form a small, compact projectile, but might suffer from jamming when the paper is first loaded. The main problem with the slingshot design is that the crumpler will have trouble withstanding the moment generated by the long slingshot arms when the slingshot is pulled back and released. Though the design is compact, it is likely too flimsy to support the force of the slingshot. The number of telescoping arms and moving parts also make the design more difficult to assemble and more likely to break.

This design received a happiness equation score of 0.49 and was not chosen as the final concept design.

#4 - Paper Football Kicker

The Paper Football Kicker is a machine that will fold a paper football and then launch it forward with the aid of a bending rod. The device will first need to be fed a standard sheet of A4 Paper. This paper will then be guided into two round cylinder caps that will roll the paper into a tube. After the tube is formed, the caps retract and a press will push down on the tube to flatten it into a long rectangle. After the paper is flattened, it will then be moved with the aid of a conveyor belt onto a folding system. The folding system works with the aid of hinges that will fold the paper and a set of rollers that will move the paper into position between folds. The final fold of the football is done by using the soft clamps to help open the previous folds and a lever is used to tuck the paper into place and complete the football. The now completed football will be rolled outside of the device on its edge using a guide and wheels and then be launched using a bars elastic energy to “kick” it away from the device.

When scored using the happiness equation, this device earned a 0.72. Though this device is compacted, the fact that this device has a lot of moving components and a paper football will likely not launch more than 4 meters leaves these device will this low score and thus will not be used as the design for the prototype.

3.3.3 Final Summary

The clear winner is Concept 1, the trash compactor design.

Quantitatively, concept 1 had the highest score for the combined quantifiable needs test of the four designs. Concept 2 came in a close second, only 0.018 points behind. Concepts 3 and 4 did not score high enough to be considered. The trash compactor design was chosen because of its compact form, low number of moving parts, and ease of competition assembly. A paper ball projectile in concept 1 was chosen over a paper airplane projectile in concept 2 because it is easier to hurl the desired distance, has a predictable trajectory, and can be made with simpler mechanisms. Concept 3 was not chosen because it utilizes a flimsy slingshot arm, which makes it unstable and provides more room for catastrophic failure (i.e. flipping or misfiring). Concept 4 was not chosen because although it was compact, it had too many moving parts and threw a paper 'football' projectile. The football is predicted to fail at reaching the desired distance reliably. In the ASME challenge, concept 1: the trash compactor paper ball thrower, is expected to score the highest because of its compact form, ease of assembly on the competition floor, and the ability to hurl paper projectiles predictably and reliably.

3.4 Proposed Performance Measures for the Design

1. Device complies with standard ASME competition rules:
    a. Accepts A4 type paper
    b. Turns given paper into a paper projectile three times
    c. Device launches paper projectile into a 3 x 30 m scoring area
    d. Device cannot exceed 1.5 x 3 x 0.762 meters dimensions [LxWxH]
    e. Any stored energy must return to initial energy state following launch
    f. Max projectile trajectory height must not exceed 2.44 m
    g. Device must not take longer than 5 minutes to set up and launch projectiles
    h. Device may not touch the floor outside the set up area
    i. Device may not use human interaction other than initial paper feeding
2. Device is lightweight and easy to transport
3. Device runs on travel safe batteries
4. Device is not hazardous to transport

3.5 Design Constraints

3.5.1 Functional

- The machine must operate automatically after the sheet of paper is fed.
- The machine must not have any source of power other than mechanical or electrical.
- The machine must be less than 30 inches tall.

3.5.2 Safety

- The system cannot have a dangerous battery source that cannot be transported.
- The system cannot have any hazardous emissions from gasoline or explosives.

3.5.3 Quality

- The machine must be able to be transported, so must obey transportation restrictions and local laws for hazardous material.

3.5.4 Manufacturing

- The materials used in this machine must be easily found, sturdy, and easy to machine.
- The machine must be designed in such a way as to assemble within several minutes.

3.5.5 Timing

- The entire process of setup, taking a sheet of paper into the system, crumpling the paper into a projectile, and launching it on three separate tries must take less than 5 minutes total.
- The system must run autonomously so the timing between each step

3.5.6 Economic

- The only economic design constraints for this machine are the budget set by the class, at $400. The total cost of all the parts must be less than that value for the scope of this course.

3.5.7 Ergonomic

- Since the system must be transported and carried, it cannot be sharp and uncomfortable to transport.

3.5.8 Ecological

- The machine cannot have any source of energy except for batteries, but the batteries must be carefully handled in order to not have a dangerous leak or battery rupture. The batteries must be Lithium Polymer batteries in our design in order to handle the current needed by the motors, which require special consideration when disposing.

3.5.9 Aesthetic

- The machine must be as compact as possible, but does not need to be very aesthetically pleasing. The only aesthetic concern for the design of this machine was the choice of materials for the final design, where the wood frame looked much less professional than the remainder of the aluminum pieces.

3.5.10 Life Cycle

- The machine is meant to handle the competition, in which it will need to be operated for 5 straight minutes without breaking, as well as the testing phase of the design process, so the device only need to survive long enough to make it through the competition. After that, the machine can be safely disposed of.

3.5.11 Legal

- The machine does not have any sort of patent infringement or legal concern, as it is a unique machine meant for a competition and not for sale or production.

4 Embodiment and Fabrication Plan

4.1 Embodiment Drawing

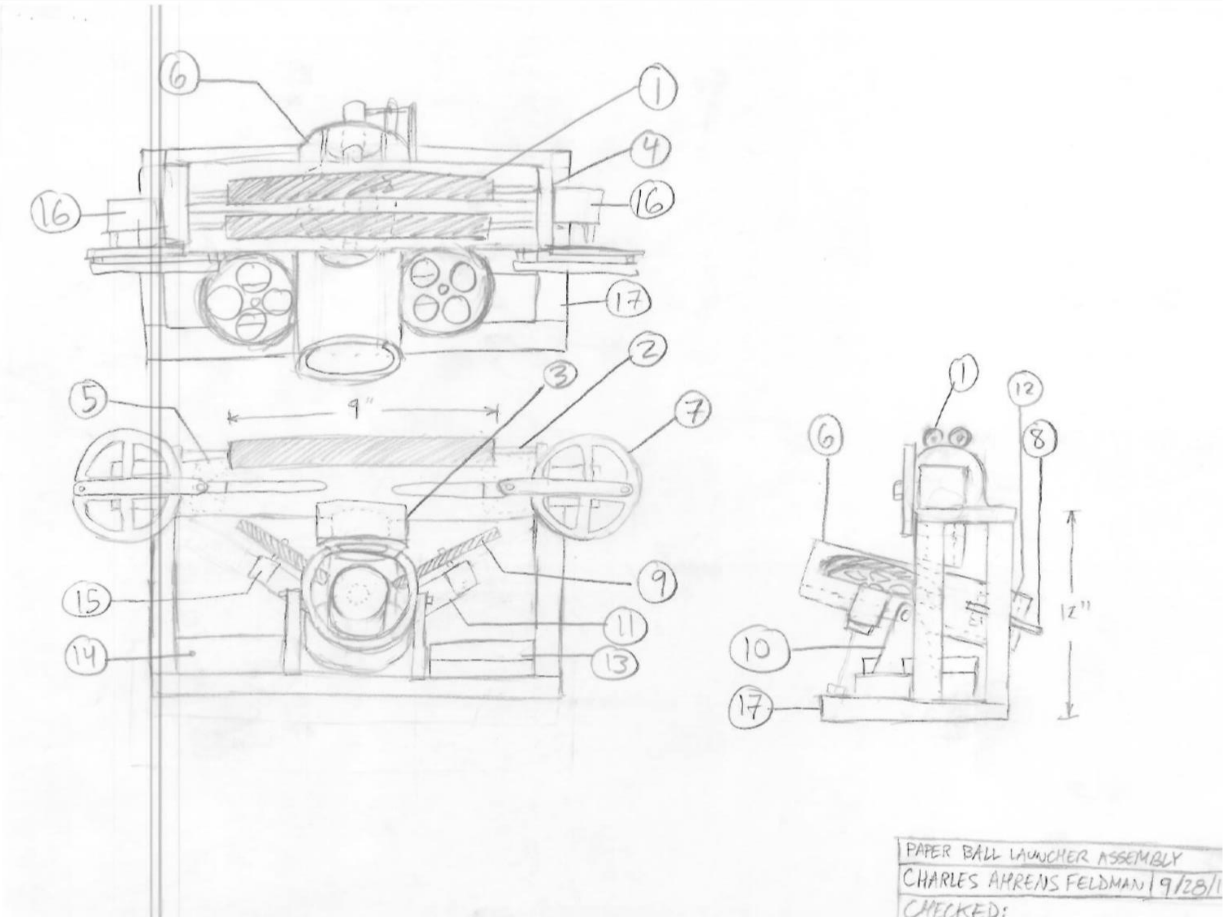


Figure 5: Embodiment Drawing

4.2 Parts List

Table 4: Proposed Parts List

Part No.	Part Name	No. of Parts	Material	Price Per Unit Stock	Quantity Stock Needed
1	Printer Rollers	1	Salvage from HP OfficeJet 4500	$0	1
2	Crumpler Barrel	1	Easy-to-Weld 4130 Alloy Steel Round Tube, 1.750" OD, .065" Wall Thickness, 3' Length	$40.07	1
3	Crumpler Guide	1	Multipurpose 6061 Aluminum Tube, 2-1/2" OD, 2" ID, .250" Wall Thickness, 6" Length	$20.59	1

4	Crumpler Holder	2	Multipurpose 6061 Aluminum, 3/4" Thick, 2" Width, 1/2' Length	$9.93	1
5	Crumpler Plunger	2	Multipurpose 6061 Aluminum Rod, 2" Diameter, 1/2' Length	$20.16	1
6	Launching Barrel	1	Multipurpose 6061 Aluminum Tube, 2-1/2" OD, 2" ID, .250" Wall Thickness, 1' Length	$34.32	1
7	Crank		0.375" Aluminum plate		
8	Launching Arm (8A)	1	Multipurpose 6061 Aluminum Rod, 3/8" Diameter, 1/2' Length	$1.99	1
8	Launching Plate (8B)	1	Multipurpose 6061 Aluminum, 2" Diameter	$4.03	1
9	Pitching Wheels	2	Black Delrin ® Acetal Resin Sheet, 1/2" Thick, 6" x 6"	$14.43	2
10	Angle Arms	1	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" x 1", 1' Length	$3.13	1
11	Motor Arms	1	Multipurpose 6061 Aluminum, 1/2" Thick, 1" Width, 1' Length	$5.14	1
12	Servo - Generic High Torque (Standard Size)	1	Servo Generic High Torque	$12.95	1
13	Arduino Uno - R3	1	Arduino Uno -R3	$24.95	1
14	Battery	4	Talentcell Rechargeable 6000mAh Li-Ion Battery Pack For LED Strip And CCTV Camera,12V DC Portable Lithium Ion Battery Bank With Charger,Black	$30	2
15	Motors for Pitching Wheels	2	Mabuchi RS-555 VD - 12V - 13500 RPM - High Torque Motor	$18.95	2
16	Motors for Crank Shaft	2	12Vdc 28rpm High-torque DC Turbo Worm Geared Motor With Dual Shaft	$60	2
17	Frame	1	Aluminum T-Slotted Framing Extrusion, Single Profile, 1" Size, Solid, 10' Length	$31.59	1
			Total Cost	$455.61	

4.3 Draft Detail Drawings for Each Manufactured Part

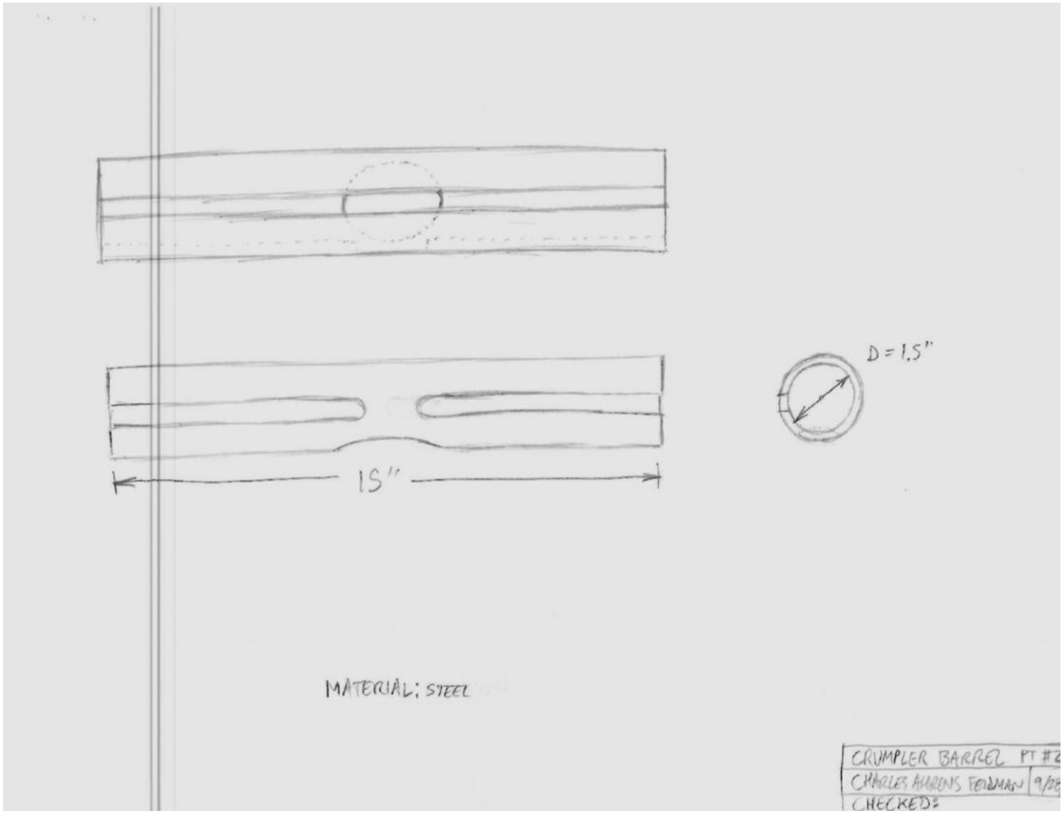


Figure 6: Crumpler Barrel Drawing

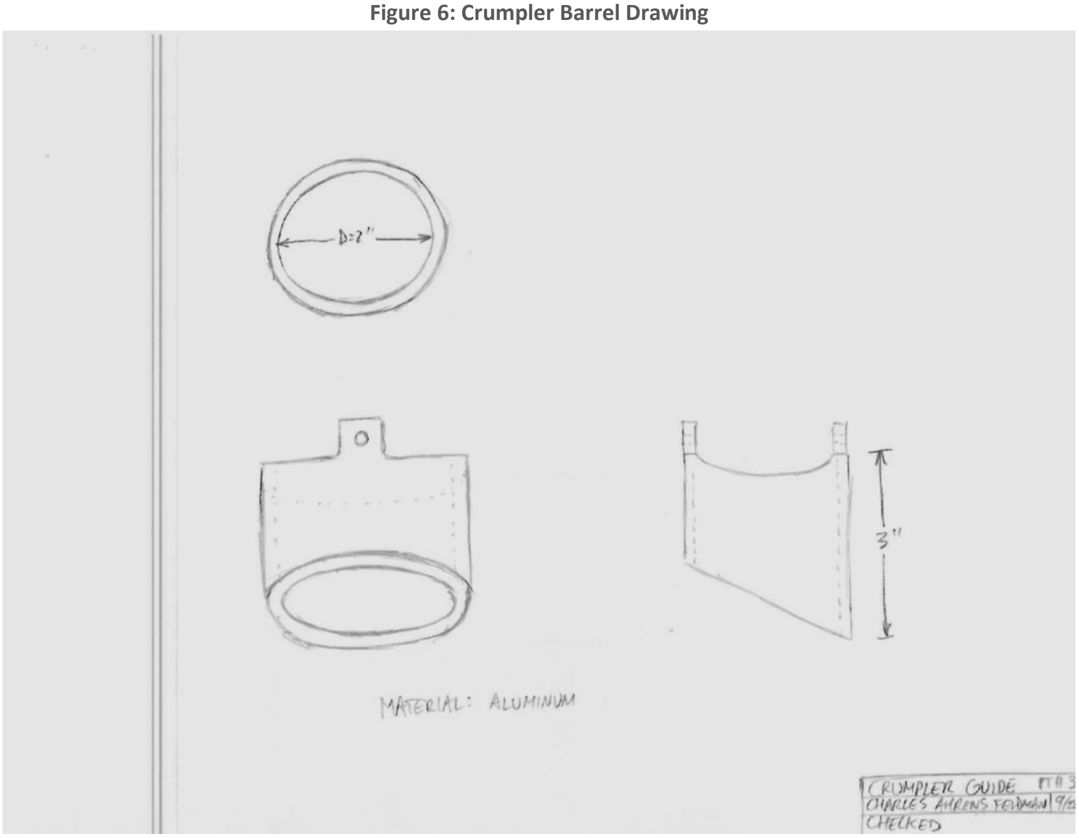


Figure 7: Crumpler Guide Drawing

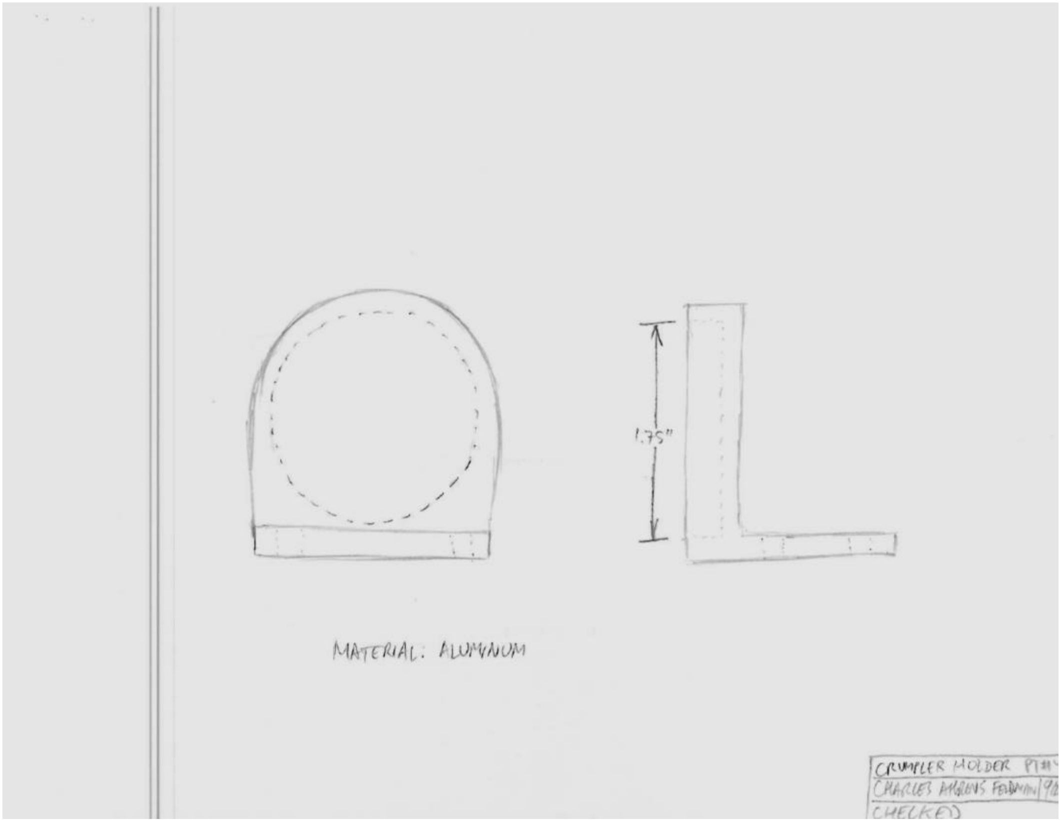


Figure 8: Crumpler Holder Drawing

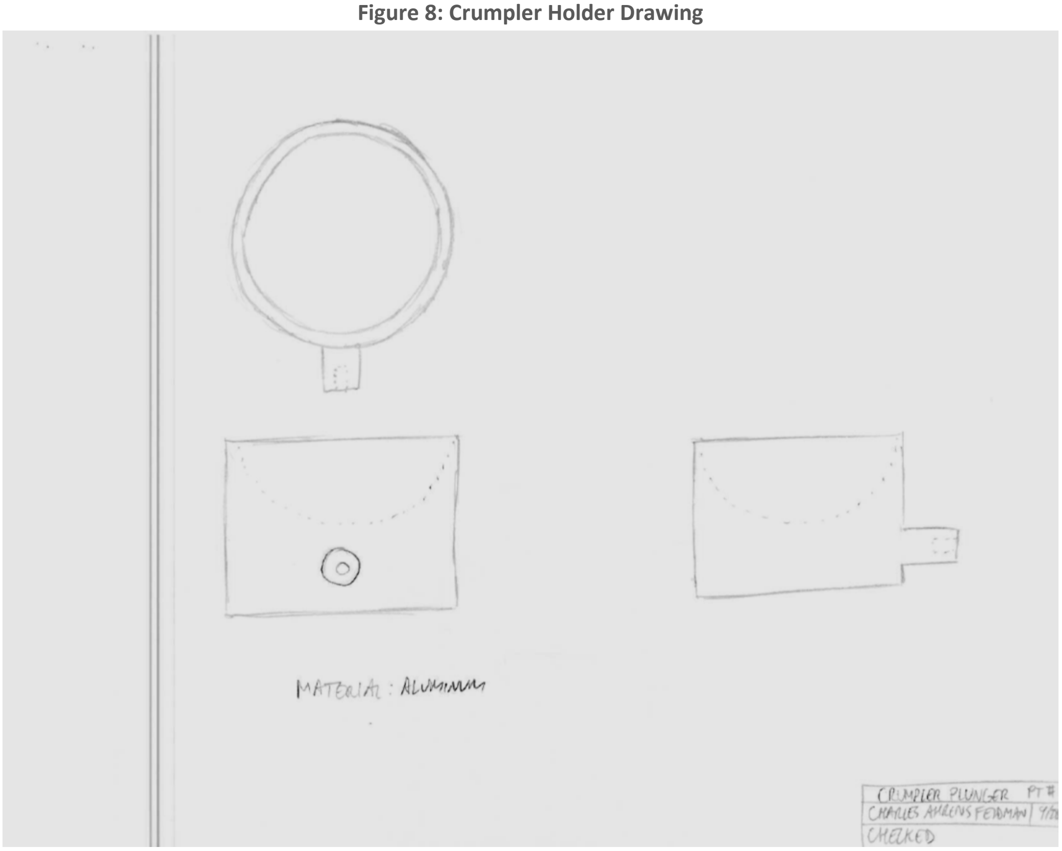


Figure 9: Crumpler Plunger Drawing

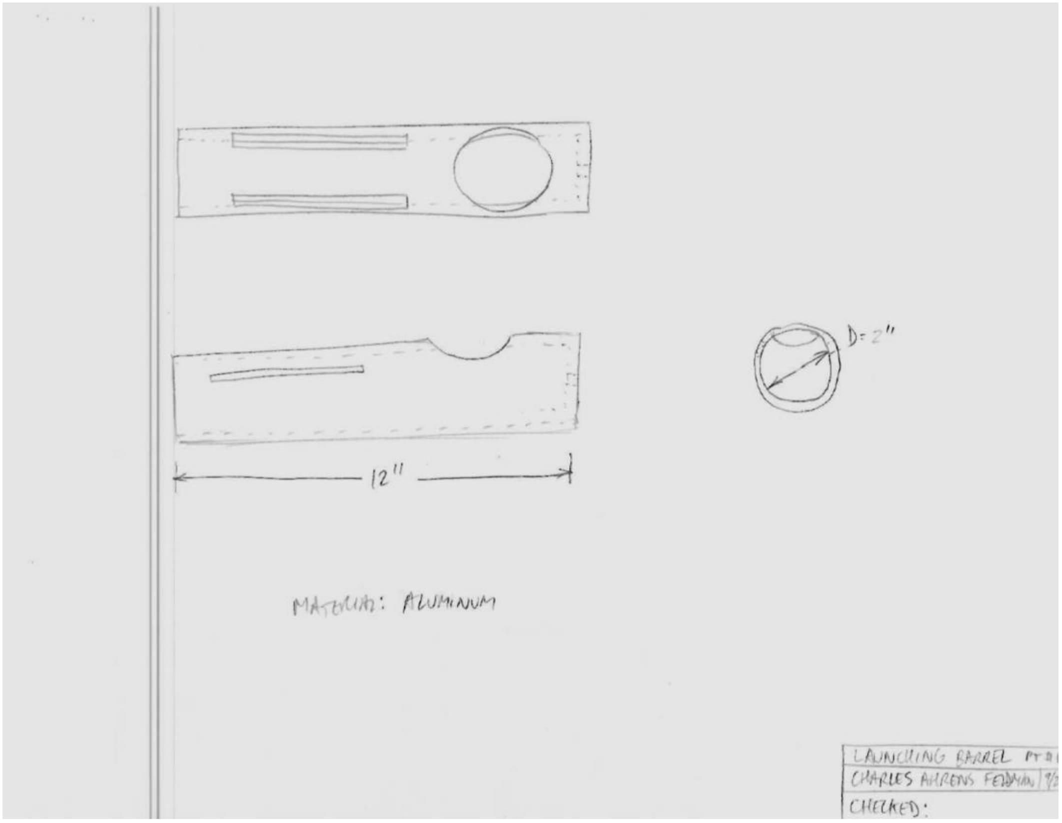


Figure 10: Launch Barrel Drawing

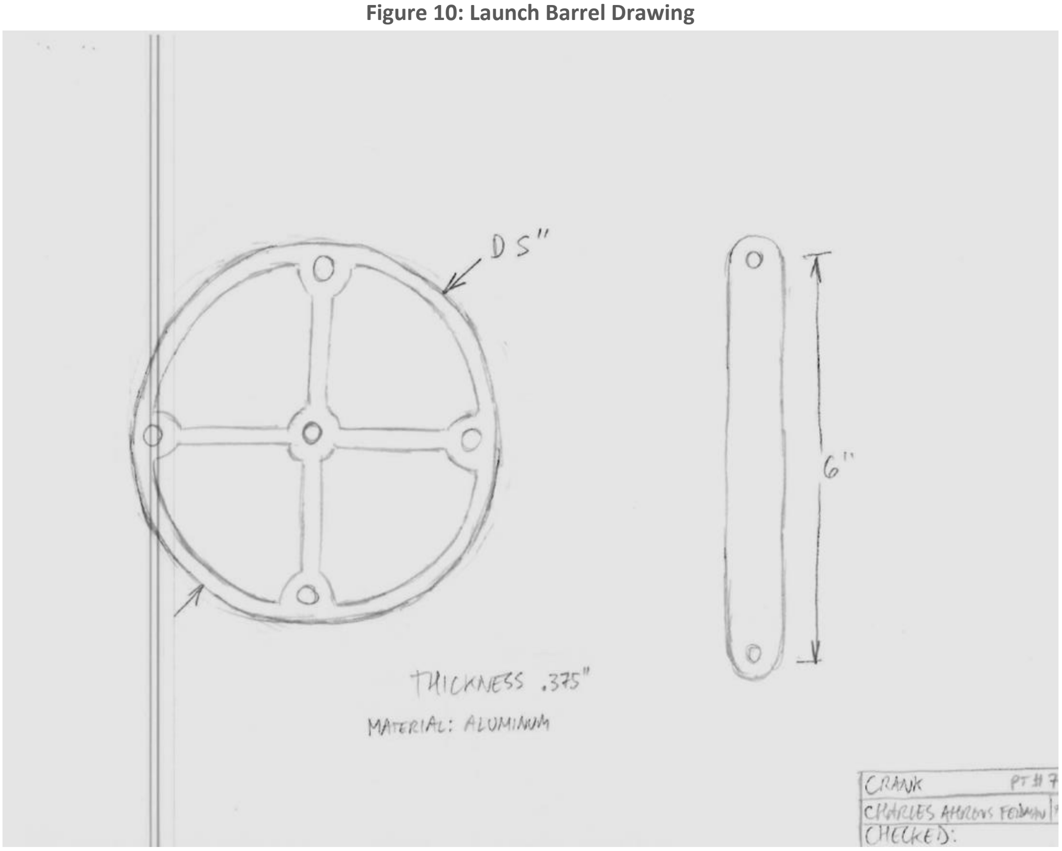


Figure 11: Crank Drawing

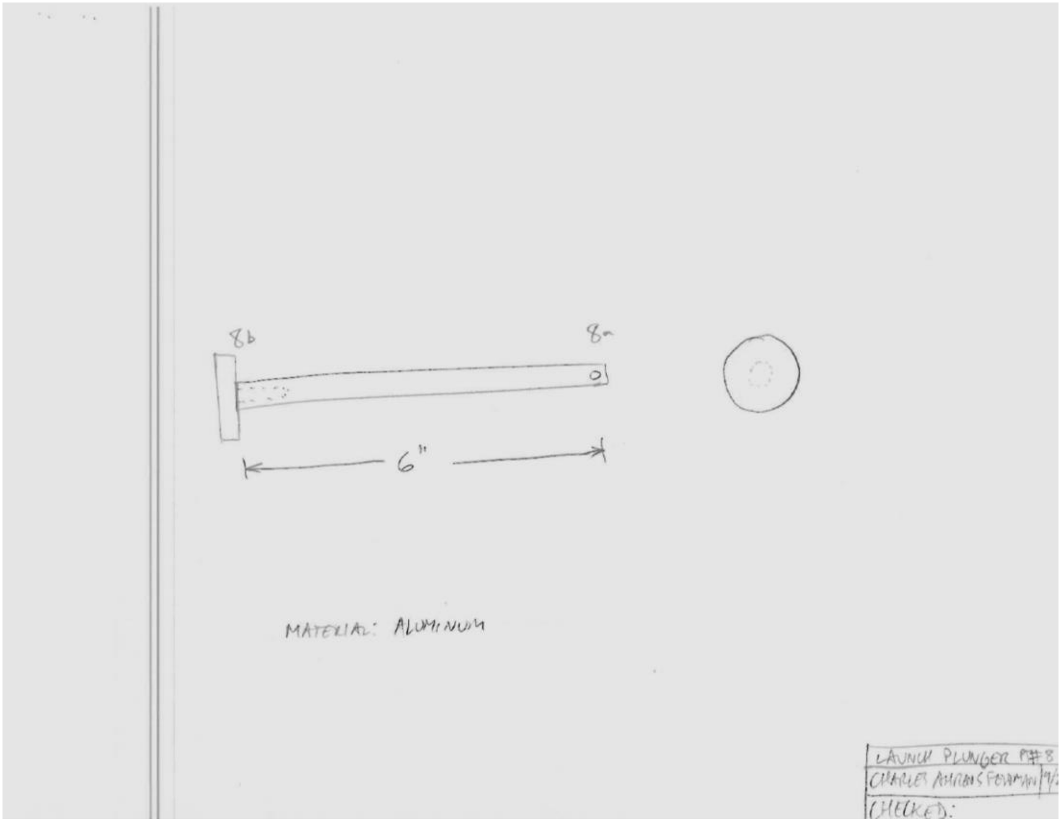


Figure 12: Launch Plunger Drawing

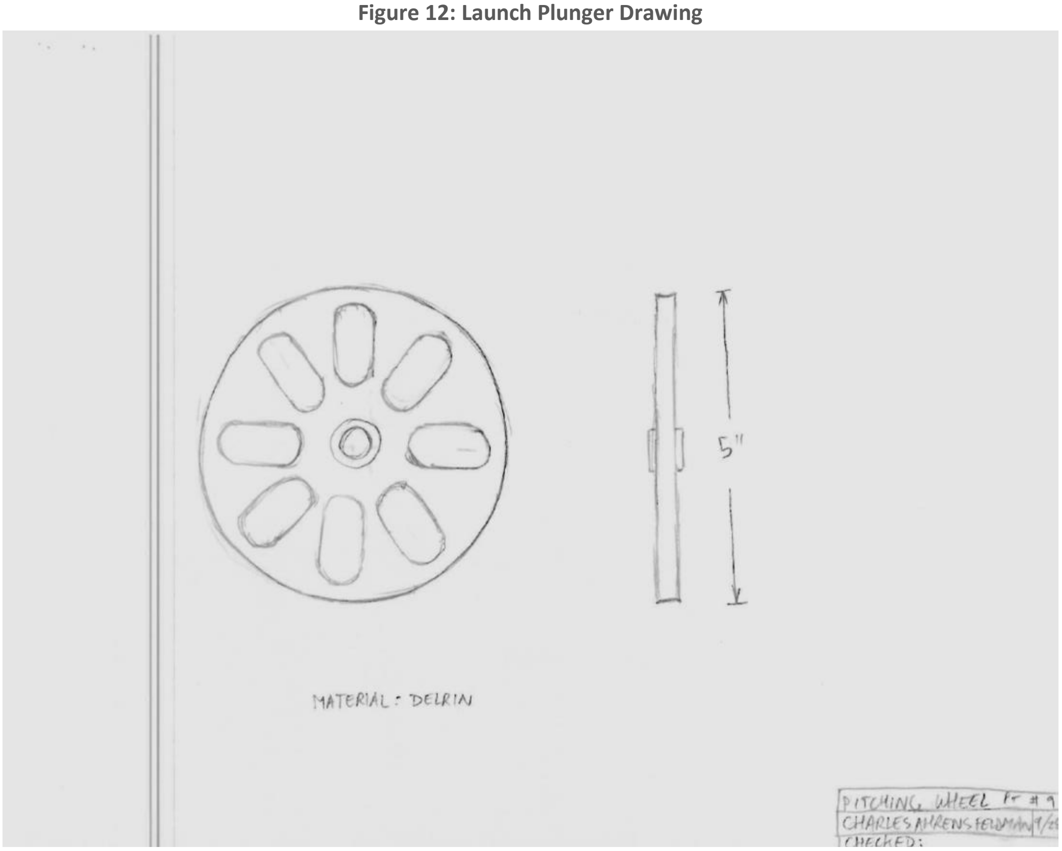


Figure 13: Pitching Wheel Drawing

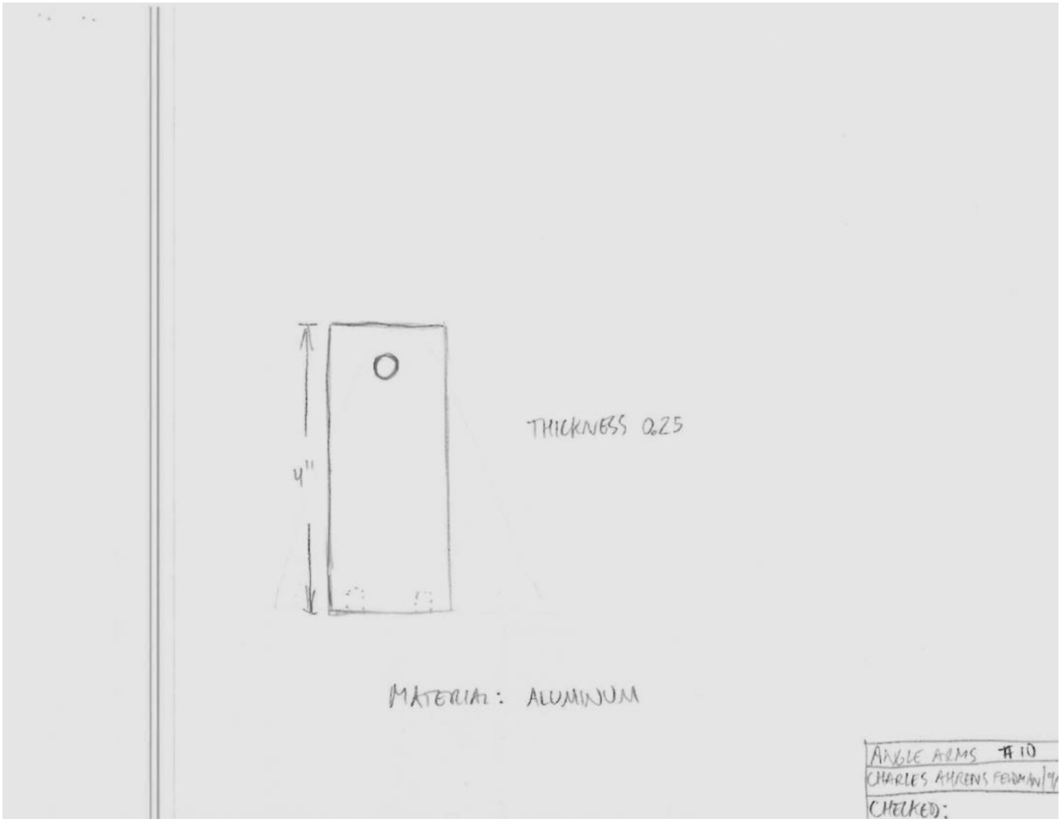


Figure 14: Angle Arms Drawing

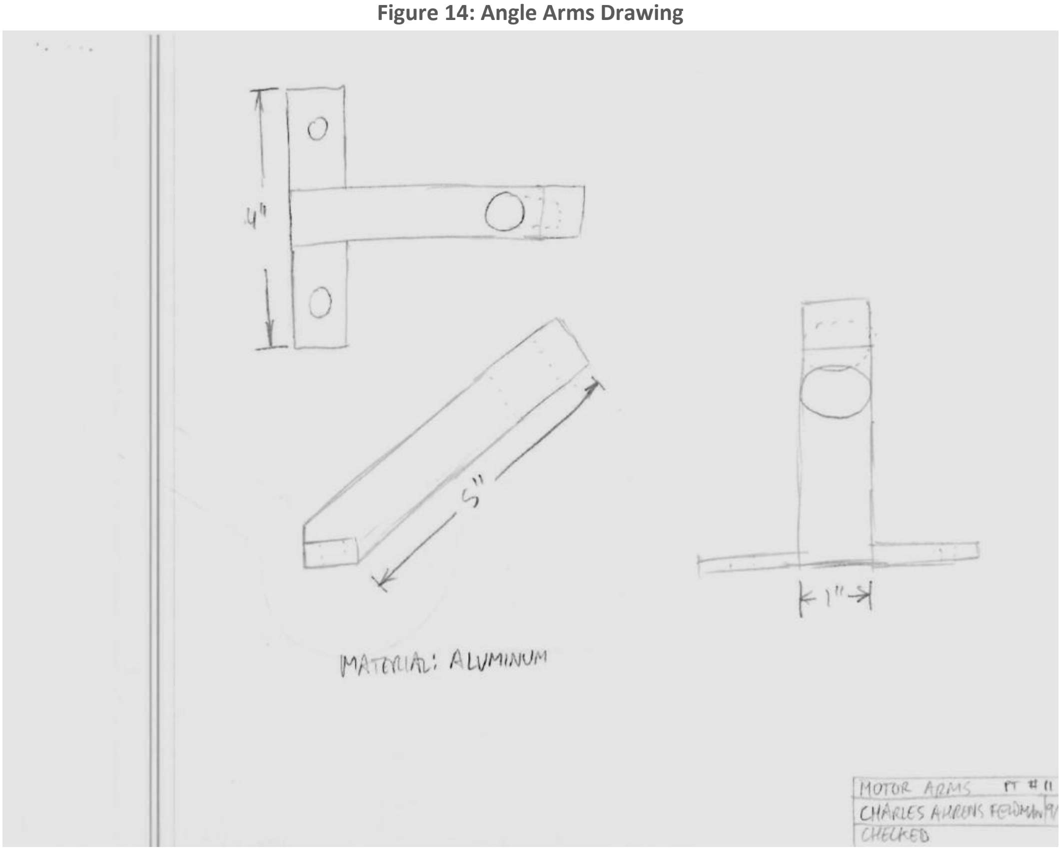


Figure 15: Motor Arms Drawing

4.4 Design Rationale for the Choice/Size/Shape of Each Part

Table 5: Design Rationale

Part Name	Design Rationale
Printer Rollers	Recycled from an HP OfficeJet 4500 series in order to feed the flat sheet of paper into the machine.
Crumpler Barrel	Tube is made of steel in order to withstand the stresses of crumpling the sheet of paper.
Crumpler Guide	The guide is aluminum since it does not need to be as strong as the crumpling barrel. The diameter is wider than that of the crumpling barrel to allow the ball to drop into the launch barrel.
Crumpler Holder	The holder is aluminum to save weight. It attaches the barrel to the frame.
Crumpler Plunger	The crumpling plunger is aluminum and small in order to not be too heavy. The sides are hemispheres and come together to crush the paper into a ball.
Launching Barrel	The launching barrel is aluminum tube stock of 2" inner diameter. It has slots machined in the sides to allow for the pitching wheels to extend inside the barrel. It also has a cutout to allow the paper ball to be dropped in from above.
Crank	The crank assembly is comprised of a wheel, 7A, and the crank arm, 7B. This assembly is connected to a motor which turns and moves the crank arm. The crank arm transfers rotary motion into linear motion that is used to crumple the paper.
Launching Arm (8A)	The launching arm will be moved by the servo and attach to the launching plate. The launching plate will be machined down to fit inside the launching barrel. It forms a base to push the paper forward.
Launching Plate (8B)	
Pitching Wheels	The pitching wheels are made of Delrin in order to have a lightweight wheel with good grip on the paper ball when launching. When machining them, as much weight as possible will be removed in order to make the wheels lighter.
Angle Arms	The angle arm is made of aluminum to save weight, and holds the launch barrel. It is 1/4" x 1", which should be sufficiently robust to support the system while not adding weight.
Motor Arms	The motor arms will support the motors for the two pitching wheels. The arms will be machined from 6061 Aluminum Rod, 3/8" Diameter.
Servo - Generic High Torque (Standard Size)	The servo motor will be connected to the Arduino and used to move the launching mechanism to push the ball forward into the pitching wheels. It is small, simple, and affordable.

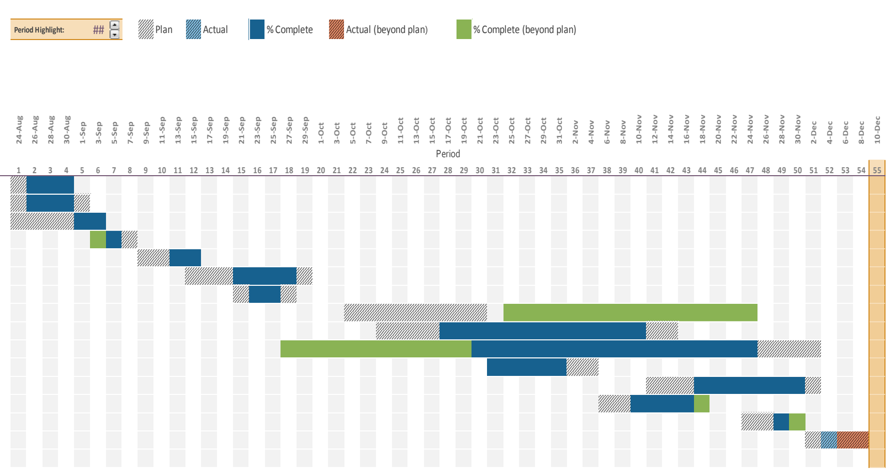
Arduino Uno - R3	The Arduino Uno provides an affordable system for controlling the timing and movement of the motors, rollers, pitching wheels, crumpling wheels, and launching plunger.
Battery	Lithium ion batteries provide compact power sources. The current that is supplied by the battery is sufficent to run the motors selected and can be used to power the Arduino Uno. They are reasonably priced and are rechargeable so are ideal for this protype's power supply.
Motors for Pitching Wheels	This is a high RPM motor that can run off a 12 V battery. These are ideal because this is the main power of our machine and can easy launch this paper ball.
Motors for Crank Shaft	This is a high torque 12 volt motor that will supply over 10 lbs of force toward "crumpling" the paper into a ball when attached to the crank. The compression needed to crush the ball was measured to be about 10 lbs.
Frame	The frame is made of Aluminum 8020 slotted T-channel extrusions for robustness, ease of assembly, and strength.

4.5 Gantt Chart

Table 6: Gantt Chart

ASME Design Gantt

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Elevator Pitch	1	4	2	3	100%
Background Information	1	5	2	3	100%
Project Selection	1	6	5	2	100%
Teams Formed	7	2	6	2	100%
Concept Design and Specification	9	4	11	2	100%
Embodiment and Fabrication Plan	12	8	15	4	100%
Engineering Analysis Proposal	15	4	16	2	100%
Parts Ordering	22	9	32	16	100%
Engineering Analysis Result	24	19	28	13	100%
Design Documentation	30	22	18	30	100%
Initial Prototype	31	7	31	5	100%
Gantt Chart	41	11	44	7	100%
Final Prototype	38	6	40	5	100%
Final Presentation	47	3	49	2	100%
Teardown	51	2	52	3	0%



5 Engineering Analysis

5.1 Engineering Analysis Proposal

The following engineering analysis tasks will be performed:

Battery

- **Load**
  - How many amps can the battery supply at once and for how long?
- **Drain/Charge Length**
  - Will the battery supply enough power to run the device for the required time?
- **Temperature**
  - Will the battery be too hot under the load?
  - We will include ventilation if necessary to cool the battery.

Motors

- **Max Torque**
  - We cannot exceed the torque limit on the motors, so we should do a calculation to determine the maximum torque that the motors will experience.
- **Stalling**
  - We need to design the system such that none of the motors will stall and cause the system to stop moving. Most motors have the stall conditions listed, so we will need to design around these.
- **Max Speed**
  - We need to launch the ball with the motors spinning at approximately 5000 rpm so the motors must be able to handle that speed with the required torque and without stalling.

Crank Wheel

- **Speed**
  - The crank wheels must operate with enough speed to crush the paper as fast as possible, but without tearing the barrel or putting too much torsion or vibration in the system.
- **Torque**
  - The wheels must have enough torque to crush the paper effectively (approximately 10 lbs), but not too much to over-torque either the wheels or the motors.
- **Alignment**
  - If the wheels are off-center or misaligned, the crank will not be effective or have too much vibration, so the tolerances will need to be more precise than other systems in the design.

- **Timing**
  - The cranks have to push at the same time in order to correctly crumple the ball, so the mounting on the motors as well as the length of each arm and the design of each crank wheel must be precise to prevent jams or other problems.
- **Material/Weight**
  - If the cranks are too heavy, they will cause friction and make the entire system top-heavy and therefore unstable. If they are too light or too weak, they will be ineffective for the crumpling mechanism.

Crank Plungers

- **Friction/Jams**
  - The plungers must be made of a material so that they will not get stuck in the barrel or have too much friction against the sides in order to prevent lost energy and jams.
- **Torsion**
  - The plungers must be machined and fit to the barrel in such a way as to prevent excessive torsion during the compression process.
- **Clearances**
  - If the clearances are large, the plungers will slide easily without friction or jams, but the torsion will be much more likely and the paper will not be crumpled as effectively. If the clearances are very small, the paper will be crumpled much better, but jams and friction are much more likely. We will need to determine the optimum design to balance these characteristics.
- **Weight**
  - The plungers must have enough weight that the paper cannot resist being crumpled, but not be too heavy as to put an excessive amount of torque on the motor and crank.
- **Hemispherical Depth**
  - If the hemispherical depth of the plungers is too deep, the paper ball will become stuck in one of the plungers when they retract, preventing the proper launch of the projectile. If the hemispheres are too shallow, the paper might not crumple into a ball. The profile of the hemisphere must be machined with this consideration in mind.

Pitching Wheels

- **Grip**
  - The pitching wheels have to be able to catch the ball without ripping it to shreds or compressing it and jamming, so the edges of the wheels must have a certain roughness, either through a coating or a machining process, to have the desired grip.
- **Safe Speed**
  - Since the motors need to spin at a rate of approximately 5000 rpm, we will need to determine the maximum speed at which the motors can be operated with the wheels attached while remaining within the safe operating conditions.

- **Vibrations**
  - The wheels will be spinning quickly, so the vibration in the launch system must be eliminated as much as possible to prevent the wheels from hitting any part of the launch barrel and tearing themselves apart.
- **Stalling**
  - The wheels must be light enough to spin quickly, but not too light that they will stop against the paper ball when it launches and stall the motors.
- **Angle**
  - The pitching wheels must hold the paper ball in such a way as to ensure the consistent flight path of the ball when exiting the barrel. If the wheels are parallel to each other and perpendicular to the launch barrel, the ball is in danger of veering over the wheels and launching straight up with less velocity than desired.
- **Torque**
  - The wheels must operate at a high speed to make the ball travel as far as possible, but they must also have a decent amount of torque so that the ball does not jam in the wheels when it is pushed in by the plunger.

Motor Arms

- **Material**
  - The motor arms need to be rigid for the best flight path, but light enough so that they do not weigh down the barrel, but sturdy enough to hold up the half pound (or more) motors, so the material used is very important.
- **Load**
  - The arms must be able to withstand the motion of the two motors with the pitching wheels attached without bending or flexing too much.
- **Moment**
  - The arms will be extended from the launch barrel with most of the weight at the end of the arms, so the bending moment through the arm must be accounted for.

Frame

- **Rigidity**
  - The frame must not vibrate. A vibrations analysis should be done to reduce the vibration of moving parts.
- **Weight**
  - The machine should be travel friendly. It should be lightweight and easy to lift.
- **Volume**
  - For competition scoring, the volume of the frame must be minimized to maximize score. The smaller the outer dimensions, the better the overall score.

- **Ease of Assembly**
    - For competition scoring, the machine must be assembled and the 3 paper balls fired within 5 minutes. Reducing the number of fasteners and making everything modular will reduce the time it takes to assemble.
- **Overall Structural Stability**
    - The frame must be able to support the launching mechanism with minimum recoil. No human interaction outside of feeding the paper is allowed. If the machine falls over due to recoil, we are helpless to fix it.

Fasteners

- **Max Load**
    - Each fastener must be strong enough to withstand the maximum load at that point so that the launch of a paper ball or the crumpling of the paper does not shear the nuts and bolts off of the system.
- **Stress Analysis**
    - Fasteners must be able to withstand stresses from the high torque motors and weight of the structure.

Force Analysis

- **Drag**
    - We must calculate the drag force that acts on a paper ball in flight and use the value to improve the simulation of the paper ball in flight.
- **Launch**
    - Calculations need to be performed to determine the proper wheel speed in order to achieve the desired launch velocity at the end of the barrel.

Barrels

- **Fitting and Tolerances**
    - The crumpling barrel must fit well with the crankshaft assembly to eliminate friction and jams.
    - The launching barrel must fit well with the pitching wheel assembly to prevent vibrations and have a consistent launch.
    - The paper ball cannot snag on any internal mechanisms.
- **Rigidity**
    - The crumpling barrel must be able to withstand the stress of the crankshaft motion coupled with the torsion and friction of the crumpler plungers
    - The launching barrel must be sturdy to provide reliant launch characteristics and not bend under the weight of the motor arms and pitching wheels.

The work will be divided among the group members in the following way:

Ashley

- Force Analysis: Launch
- Motors
- Pitching wheels
- Crank

Chase

- Crank Plungers
- Motor Arms

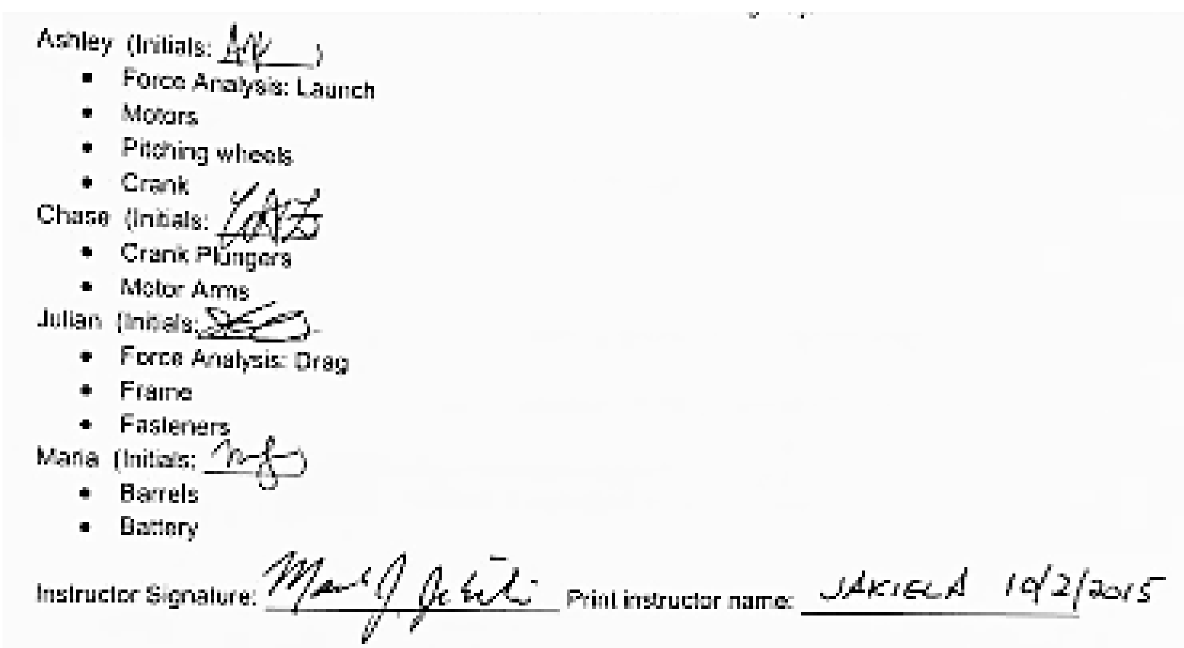
Julian

- Force Analysis: Drag
- Frame
- Fasteners

Maria

- Barrels
- Battery

5.1.1 Signed Form of Instructor Approval


Ashley (Initials: AW)
- Force Analysis: Launch
- Motors
- Pitching wheels
- Crank

Chase (Initials:)
- Crank Plungers
- Motor Arms

Julian (Initials:)
- Force Analysis: Drag
- Frame
- Fasteners

Maria (Initials:)
- Barrels
- Battery

Instructor Signature: Print instructor name: JAKIELA 10/2/2015

5.2 Engineering Analysis Results

5.2.1 Motivation

Battery

When selecting batteries to power the motors, several factors must be considered. The voltage of the battery must agree with the max voltage of the motors, and the batteries must be able to power the system.

Pitching Wheel Motors

In order to launch our ball the farthest possible distance, we knew that our pitching wheel design needed to be fast but robust enough to launch our paper ball.

Type of Projectile

Three different types of projectiles were tested to determine which would travel the farthest and be the most reliable in a common launch scenario by hand and with the aid of a sling shot.

Launching Mechanisms

Preliminary analysis was done on the device to determine the potential launching mechanisms that could be used. Some minor analysis was done on two different mechanisms that were not chosen for our final design. These two designs were not chosen for use once the analysis was performed on all the launching mechanisms. The goal was to determine the most effective method from the mechanisms we could use. Besides the pitching wheels, both a catapult and spring cannon design were considered.

High Torque Motors

Strong, high torque motors will be needed to form our projectile. To ensure that our motors will not fail, they will needed to be analyzed.

5.2.2 Summary of Analysis Done

Battery

The battery capacity and constant discharge determine whether the batteries will be able to power the system. The battery life in minutes when powering given motor(s) is given by the expression

$$\left[\frac{1000\ N_m I}{Ca/_{60}}\right]^{-1}$$

where N_m is the number of motors, I is the current draw of the motor in amps, and Ca is the capacity of the battery in mAh.

The continuous discharge, C, determines the maximum number of amps that can be drawn by the motor. To ensure we bought a battery with a high enough C to accommodate our motors' current draw, we ensured that the battery specifications satisfied the equation

$$\frac{Ca \cdot C}{1000} < I$$

where Ca is the capacity of the battery in mAh, C is the battery's continuous discharge, and I is the current draw of the motor in amps. (Salt)

Pitching Wheel Motors

Projectile motion analysis for a hard sphere with drag was used to determine the launch speed the projectile would require to reach a reasonable distance (Projectile). This speed was then used to calculate the necessary energy, momentum transfer, and speed of the pitching wheels to achieve the desired result. This was an optimistic model of the system, but with realistic conditions, a reasonable performance can still be expected.

Type of Projectile

A paper airplane, a paper football, and paper ball were made by hand in a similar method to how the device would make them. They were then thrown by hand and with a slingshot to determine which projectile flew the farthest most reliably.

Launching Mechanisms

A simple moment analysis or Hooke's law was used to determine the forces that would need to act on the system to launch the paper ball at the desired speed. These results were then compared to realistic constraints to determine the best launching mechanism.

High Torque Motors

An analysis on the max torque that these motors will have to face will be completed to ensure they will not fail.

5.2.3 Methodology

Battery

For our system, we searched for high discharge Li-Po batteries available on Amazon Prime and calculated the battery life for the batteries in our price range, using the specifications of the motors we had decided upon.

Pitching Wheel Motors

The first analysis that was done was to determine the velocity needed to reach the farthest distance with the smallest required velocity. To determine the RPM needed by the motors the following equation was used: (Jewett)

$$RPM = \frac{v}{d\pi}$$

where *d* is the diameter of the pitching wheels, *v* is our desired speed, and *RPM* is the design requirement our motors will need.

To then determine the power needed to launch the ball under the assumption that the pitching wheels were massless, the following equation was used: (Jewett)

$$P = \frac{J}{s}$$

where *P* is the power needed to launch the ball in Watts, *J* is the kinetic energy in joules needed to launch the paper ball while *s* is the time is sec that paper ball is in contact with the wheels. To calculate the contact time that the ball will have with wheels the following equation was used: (Jewett)

$$s = \frac{d}{v}$$

where *d* is the diameter of the paper ball in meters and *v* is the desired speed of the ball in m/s. The kinetic energy of the ball is calculated by the following: (Jewett)

$$J = \frac{mv^2}{2}$$

where *m* is the mass of the paper ball, and *v* is the speed in m/s. This was found not to be negligible so a power analysis involving the wheels themselves must be analyzed.

To analyze the momentum transfer between the wheels and the ball was calculated the same power expression but the kinetic energy of the pitching was found using: (Jewett)

$$L = I\omega^2$$

where *L* is the angular momentum of the wheels and I_{wheel} is the moment of inertia for the wheels, and *w* is the speed of the wheels in rad/s. (Jewett) I_{wheel} is calculated using the following expression for the moment of inertia for a cylinder: (Jewett)

$$I_{wheel} = \frac{mr^2}{2}$$

where *m* is the mass of the wheels, *r* is the radius of the wheel. The speed was converted to rads/s using common unit conversions.

The moment of inertia of the ball I_{ball} is given by the equation:

$$I_{ball} = \frac{2m_{paper}{r_{paper}}^2}{3}$$

The combined moment of inertia of the both the ball and the wheels, I_{total}, is given by the following equation:

$$I_{total} = I_{wheel} + (I_{ball} + m_{ball}(r_{wheel} + r_{ball})^2)$$

where m_{ball} is the mass of the paper ball, r_{wheel} radius of the wheel, r_{ball} is the radius of the ball, and the *I*s are as previously defined.

Using I_{total} in the *L* expression, the change in momentum that the system will experience when launching the ball can be solved for and then evaluated.

With 100% efficient motors and batteries, the best energy transfer we can have using

$$P = IV$$

where *V* is voltage and *I* is current, is 35 m/s.

Type of Projectile

A test rig was assembled as shown in Figure 16 was used as a generic way of consistently launching our test projectiles:

Figure 16: Early Projectile and Launch Testing

Some modification such as a shuttle was made for the paper airplane to assist in launching. The projectiles were also thrown by hand. The distance of each projectile was measured and then averaged.

Launching Mechanisms

An analysis was done using Hooke's law and the sum of the moments as shown: (Jewett)

$$F = kx$$

$$0 = \sum M = \sum F * d$$

The schematics of these launching mechanism are shown in Figure 17 and Figure 18.

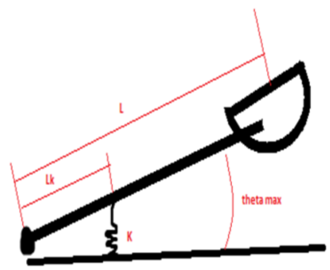


Figure 17: Catapult Launch Mechanism

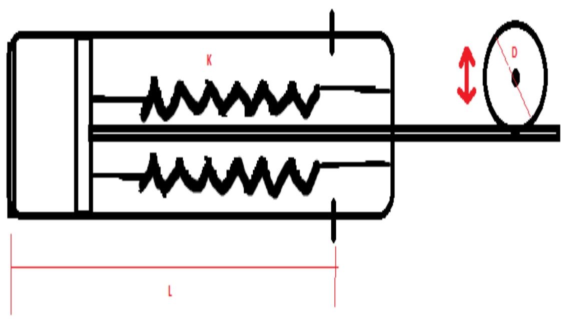


Figure 18: Spring Launch Mechanism

The force needed to launch the ball was determined using kinetic energy of a spring and the resulting momentum.

$$KE = \frac{1}{2}kx^2$$

$$KE = momentum = mv^2$$

Where *x* is the displacement of the spring, *m* is mass and *v* is velocity. By solving for *k* and assuming a deflection of 1/3 the length of the spring, the catapult and spring style were analyzed and compared.

High Torque motors

By using the following expression for torque: (Jewett)

$$T = \vec{r} \times \vec{F} = |r||F|\sin(\theta)$$

where *T* is torque, *r* is the radius, *F* is the force applied at that radius, and θ is the angle between them. The max torque experienced by the yoke mechanism and thus the motors was:

$$T_{max} = |r||F|$$

The force needed to crush a paper tube was found using a mechanical kitchen scale.

5.2.4 Results

Battery

In our case, the pitching wheel motors could handle a maximum of 11.1 V and the crushing motors could handle a maximum of 12 V. Thus, an 11.1 V battery would be a perfect fit for our system.

We found an 11.1 V Li-Po battery with a minimum capacity of 5200 mAh and continuous discharge (C) of 50. Plugging these specifications into our equations, we found that the battery more than met the needs of the crushing motors, providing a battery life of over 17 hours. The primary concern was whether it could power the pitching wheel motors. The battery life would be 2.36 minutes running at the maximum I of 66 A, or 3.47 minutes running at the continuous current value of 45 A. The value of the maximum current that could be drawn from the 50 C battery was 260 A, which was well above the 66 maximum current of each pitching wheel motor. These calculations were performed in Excel as shown in Appendix E: Analysis.

Since we were not planning to run the motors at full speed or continuously, we concluded that the chosen battery with approximately 3.5 minutes of battery life at full operation would satisfy our needs.

Pitching Wheel Motors

By determining the point at which the velocity vs. distance graph starts to plateau, an ideal velocity was determined to be 50 m/s. The motor speed was determined to be ~25000 RPM assuming a ball with 1.5 inch diameter.

Solving for the power needed to launch the ball from rest, 5625 W will be needed. This is not negligible, so a power analysis involving the momentum of the wheels themselves must be performed.

The energy needed to provide enough momentum to the wheels was 586 Joules using a 3 inch diameter, 1 inch thick wheel made of Delrin. Allowing these pitching wheels 30 seconds to ramp up to speed and using this ramp as the time value in the power expression, it will only take 19.5 W of power to get the wheels spinning.

Using this in the *L* expression, the momentum of the ball and wheel can be found to be 664 Joules. When using this *J* value in the power expression along with the time in which the ball will be in contact with the wheels, the resulting power is 664 kW, which is by no means reasonable for our device.

Type of Projectile

After testing the projectiles we saw that a paper ball was the most reliable, easily replicated projectile. The plane tended to turn if not folded perfectly and was difficult to launch and fold. The paper football was easy to launch but difficult to fold.

Launching Mechanisms

To get the velocity we desired for our paper ball, assuming a 1/3 deflection, the stiffness needed for the springs was found to be too high to use motors to return the springs to the starting position. The recoil from the springs also posed a problem. The catapult had a risk of possibly tipping during launch due to recoil from the amount of force needed to launch the ball.

High Torque motors

The analysis resulted in a needed torque of about 17 kg*cm for the 8 lbs of force necessary to crumple the sheet of paper. The necessary force was determined by crumpling a piece of paper into a mechanical kitchen scale.

5.2.5 Significance

Battery

The results of our analysis indicated that our one battery should suffice to power the system, although if we wished to run the system longer without needing to charge the battery, we could connect two batteries in parallel.

Pitching Wheel Motors

As long as the motors can relay 25 Watts of power, which our battery and the motors can, the motors can apply sufficient force.

Type of Projectile

The reliability and ease of producing the paper ball led us to choose this over the other projectiles.

Launching Mechanisms

Due to the fact that it was not reasonable to have springs of the necessary thickness compress to the degree needed to launch the ball, the springs were rejected. Since the catapult posed issues of tipping when launching the ball, it was also rejected. The recoil in both systems was also undesirable whereas the lack of recoil from the pitching wheels appeared ideal.

High Torque Motors

If these motors fail, one of the main subassemblies of our device will also fail, leading to the entire device failing to meet the requirements needed to run.

5.2.6 Relevant Codes and Standards

Code §3583. Portable Abrasive Wheels (f).

Though our device did not feature abrasive wheels, the mounting requirements addressed in this code were followed due to the potential hazard associated with running the wheels at high speeds. Care was taken to ensure that the wheels did not come in contact with anything besides the paper at any given time to prevent possible injury. This modified the design to allow for firmly mounted wheels with clearance allotted for the wheels near the launching barrel so the wheels would only ever come in contact with the paper ball. (3583)

ASTM Standard for Toys: F963-86, "Consumer Safety Specification on Toy Safety" 4.20.

This standard discusses the restraints for safely launching projectiles in toys. Thankfully our device will only launch light projectiles with a thickness of 1.5 inch if left unmodified. The motors are not strong enough to launch heavy projectiles like rocks due to the torque required and the wheels are not close enough in the final prototype to launch smaller harder projectiles like pencils or bolts effectively. Additionally, the assembly is hard to take apart due to lock washers, which prevent the choking hazard also discussed in these standards. (ASTM)

Battery Safety and IATA Policy

There are important safety instructions and warnings related to Lithium Polymer batteries, since they are volatile and can catch fire if used improperly (incorrect charger, overcharging, impact, etc). E-flite provides thorough instructions for proper battery use, none of which interfered with our plans for the battery. (E-flite)

Per the International Air Transport Association’s policy on lithium batteries, we would not transport our battery on a commercial airplane en route to the ASME competition. (IATA)

Additional Standards

Due to the unique nature of our design, most codes and standards did not relate perfectly to our device, so personal codes and standards were adopted to ensure personal safety while running the device. One such precaution was to avoid over-powering the motors. The working parameters of the motor were stated with the specifics of the motor requirement and caution was taken to ensure that these parameters were considering in designing the device. Precautions were also taken to properly insulate all wires used in the system to prevent accidental shorts and shocking hazards.

5.3 Risk Assessment

5.3.1 Risk Identification

We approached risk identification by knowing that risks are heavily tied to the project constraints. Naturally, we made decisions with causation mentality, with an “if-then” logic flow. It was determined early in project development that the driving constraints were budget allowances, schedule deadlines, safety, manufacturability, and functional needs. Failure to comply with these constraints would result in consequences affecting the quality of the overall project and satisfaction of the customer. Even before the design stage of the project, these risks were taken into consideration. Initial risks were identified by looking at a constraint and predicting what would happen if it were exceeded. Some consequences were direr than others. For example, if we exhausted the budget before we bought all of the necessary parts, the device would not be complete and the whole project would fail. If we created a dangerous machine, someone could get hurt, which could result in legal disputes. The extent of damage done by failing to meet the requirements is an indicator of priority. The risks were identified often in the order of severity. Some risks were initial and steady, like our budget constraints. Other risks were continuously changing, like our project schedule deadlines. Some risks that were identified in the course of the project are listed below, and are categorized by the type of risk.

1. Money
    - Failure to stay under budget
    - Designing a machine with many parts
    - Relying on third parties to deliver parts or services
    - Shipping costs across providers
2. Time
    - Failure to meet a project deadline
    - Designing a machine that was difficult to manufacture
    - Waiting on feedback from testing or interviews
    - Shipping times across providers
3. Personal
    - Designing a dangerous machine
    - Designing an adaptable machine
    - Failure to meet functional needs demanded by the customer
    - Aesthetic appeal
4. Unexpected
    - Part failure and defects
    - Sickness or injury
    - Worker morale and happiness

5.3.2 Risk Impact

The difficulty in analyzing the consequences of each risk stems from the interdependency of one risk with many other risks. One risk may be affected by three or more others, and may be inversely proportional. There is also a probability aspect of assessment. Each risk can be ranked by the likelihood of it happening, from low to high probability. Each risk was analyzed by both its short term and long term impact on the quality of the project, the customer, and the project group. Each risk can also be ranked by the impact to the project, from critical to low impact. The machine was designed to minimize as many risks as possible.

Probability

1. Money

   The project was designed so that the probability of any money related risks was minimized. The probability that we would exceed the budget was low, because we designed the project around the budget, and chose parts accordingly. The probability of exceeding the budget increased when parts failed, resulting in the team having to spend more money to replace the part.

2. Time

   The project was scheduled to be completed within the time allotted. There was a medium probability that intermediate deadlines would not be met. This was due to the team's other commitments with school and work. The project was designed to use as few parts as possible, which minimized the manufacturing time. The probability of failing to meet manufacturing time was medium. The probability of waiting for a third party before we could continue with our project was high. There were many points in the project when we had to consult with an outside source. The large number of consulting meetings increased the chance that we would fail to meet the deadline, due to waiting on an outside party. The probability that parts we ordered would have a long shipping time was medium. The team ordered parts during the holiday season, which increased the chance that shipping times would be delayed.

3. Personal

   The project was designed with adaptability and safety in mind. The probability that the machine we created would be dangerous was high because of the high speed nature of our pitching wheels. There was an increased risk of parts breaking and flying off, injuring someone. We reduced this risk by gluing the shafts, adding collars, and machining a higher tolerance to reduce wiggle in the system. The probability was low that we would design a machine that did not meet the needs of the customer, because fulfilling the design challenge requirements was the main reason for making the machine. The probability that it would fail to have an aesthetic appeal was high, because of the strict time restraint and machining capability of the team.

4. Unexpected

   The probability that a part would break is undetermined. It is, however, related to the quality of the parts. The crumpling system motors were cheap, low-quality motors that had a higher probability of failing than our pitching wheel motors, which were of high quality. The probability that team members would get sick was undetermined, but likely low. The probability that team morale would become low was high, because the project was stressful with many late nights spent manufacturing.

Impact

1. Money

   The impact of exceeding the budget was critical. If we exceeded the budget, there was a chance that the device would be unfinished. If we had an incomplete machine, we would fail to meet the customer needs, and that was unacceptable. Choosing a shipping provider that was expensive or making a machine with many parts would have the same impact.

2. Time

   The impact of not meeting a project deadline was critical. If we failed to meet a deadline, the project would become delayed as we tried to catch up, and increase the chance of delivering an incomplete machine. Failing to meet manufacturing deadlines and waiting on consulting meetings would have the same impact.

3. Personal

   The impact of designing a dangerous machine was high. If we designed a machine that ended up hurting someone, legal issues and liabilities would result. If we designed a machine that did not meet the customer needs, the project would be a complete failure, and thus meeting the customer needs had a critical impact. The impact of not making an aesthetically appealing device was very low. As long as it functions to the customer needs, first generation devices do not need to look nice.

4. Unexpected

   The impact of a part breaking was variable, depending on which part broke. If a screw sheared, it would be relatively easy to replace. If a motor broke, it would affect the performance of the machine, and its ability to meet the customer needs. Critical parts have a high impact when breaking, and other parts have a low impact when breaking. The impact of sickness or injury to the project is medium. It would increase the time needed from the remaining members. This would also affect the team morale. Team morale had a medium impact because well-rested workers make better parts and are less likely to stab each other.

5.3.3 Risk Prioritization

Risks were prioritized based on their probability and impact to the project. It was determined that delivering an incomplete project to the customer was unacceptable. This resulted in ranking money-related and time-related risks high in priority. Also high in priority was addressing the needs of the customer. Even if we produced a device within the allotted time and budget, it would not mean anything if the device did not perform to the customer's specifications. Team and customer safety was also prioritized high. Risks are listed below in order from most important to least important.

1. Failure to meet the needs demanded by the customer
2. Exceeding the budget

3. Exceeding the allotted time
4. Designing a dangerous machine (safety)
5. Designing a machine that was difficult to manufacture (time and safety)
6. Waiting on feedback from testing or interviews
7. Relying on third parties to deliver parts or services
8. Part failure and defects
9. Worker morale and happiness
10. Designing an adaptable machine
11. Aesthetic appeal

6 Working Prototype

6.1 Preliminary Demonstration of the Working Prototype

This section intentionally left blank.

6.2 Final Demonstration of the Working Prototype

This section intentionally left blank.

6.3 Final Prototype Images

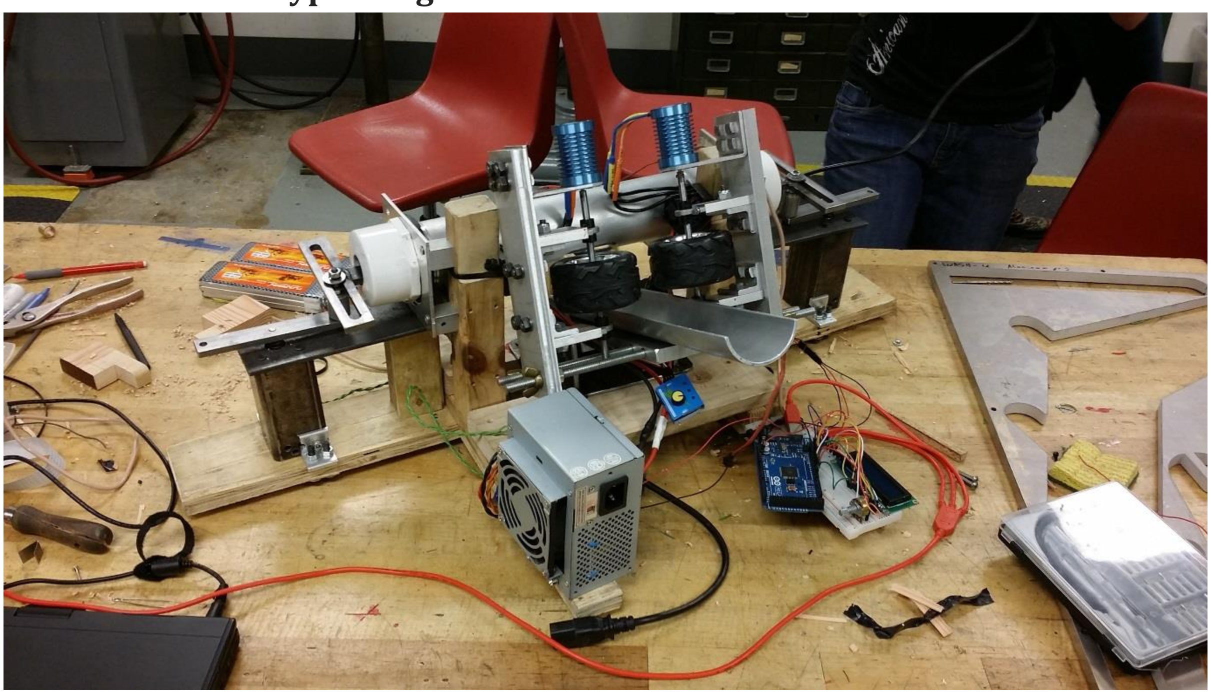


Figure 19: Front of Completed Final Prototype

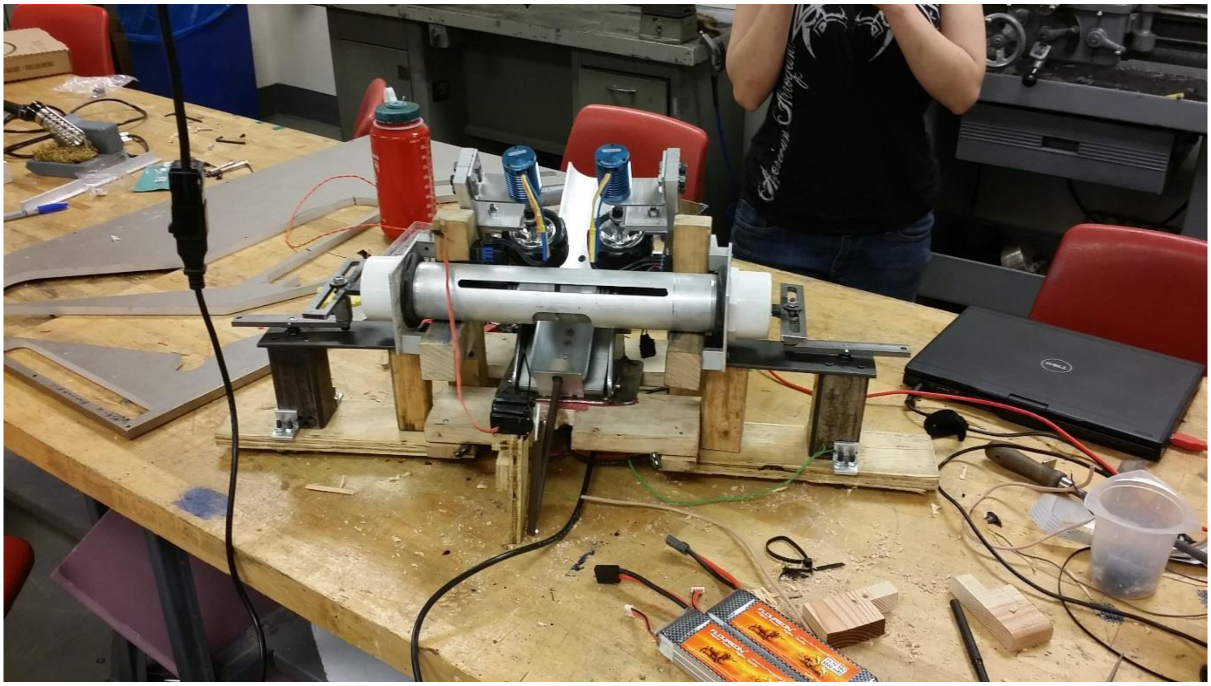


Figure 20: Back of Completed Final Prototype

6.4 Video of Final Prototype

A video showing a complete run through of the final prototype, from crumpling to launch, is shown in the following video. For this prototype, the crumpling motors had arrived broken, so the mechanism would not automatically crumple. The extent of the human interaction in the system is to feed the paper (which is allowed in the competition), push the crumpler plungers, and dislodge the paper into the launch barrel. In the final system for competition, these crumpler mechanisms would have high-torque motors that would take care of the crumpling of the paper ball without human interaction. The rest of the system, from the spinning of the pitching wheels, the timing of the paper ball launch, and the push from the servo to launch the paper ball all occur automatically.

https://youtu.be/VHHBqd1d2FQ

6.5 Additional Images

The following image shows the Arduino and the circuit that controls the machine. The LCD screen displays messages that show the current state that the machine is in to allow for better debugging of the system. The Arduino code for the system is shown in Appendix D - Arduino Code. The Arduino controls the Electronic Speed Controllers for each of the brushless motors that spin the pitching wheels, as well as the motors to crumple the paper, and the servo that pushes the paper ball into the pitching wheels.

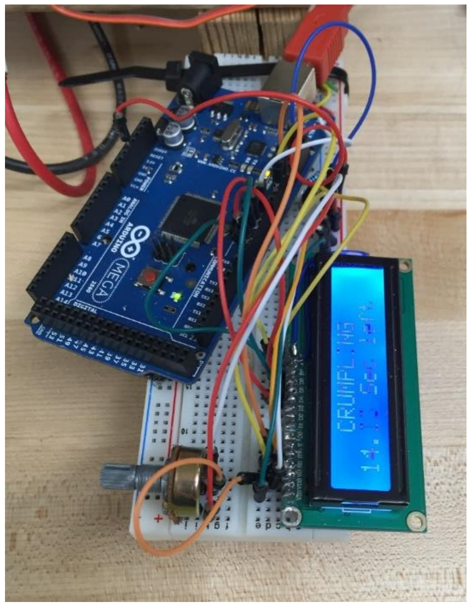


Figure 21: Arduino Control Circuit

The following image is the front of the device, showing the pitching wheels connected to the brushless motors above them, as well as the servo pushing arm, the white circle in the center of the barrel.

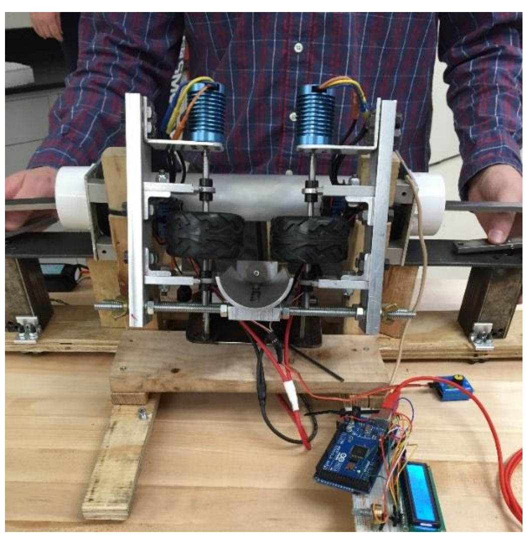


Figure 22: Pitching Wheel and Launch Barrel View

The following image shows the launch barrel without the crumpling barrel attached above it during the middle of the construction phase. The launch barrel is attached to the launch angle bracket (the steel angled piece beneath it) which allows the barrel angle to be adjusted in order to change the distance of the projectile.

Figure 23: Launch Barrel and Angle Bracket

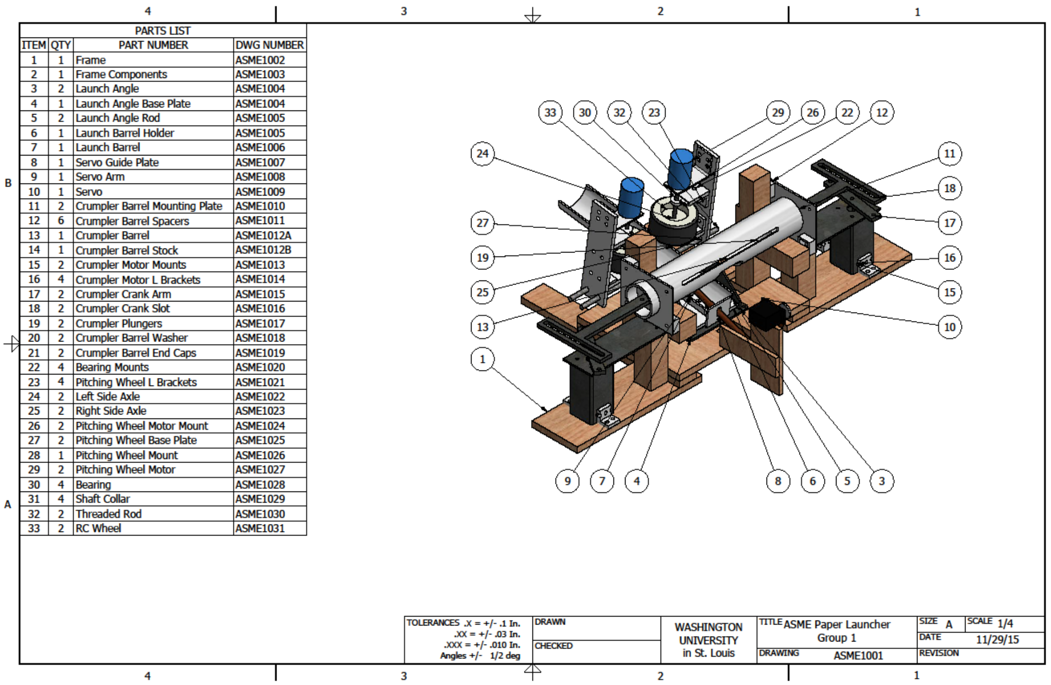
The last image shows the crumpler plunger inside of the crumpler barrel, with the hemispherical cut into the plunger that allows the paper to be crumpled into a spherical shape. On the lower left side of the picture, the feeding slit can be seen where the paper enters the tube. This image was taken before the cut was made to allow the paper ball to exit the barrel.

Figure 24: Crumpler Plungers Inside Crumpler Barrel

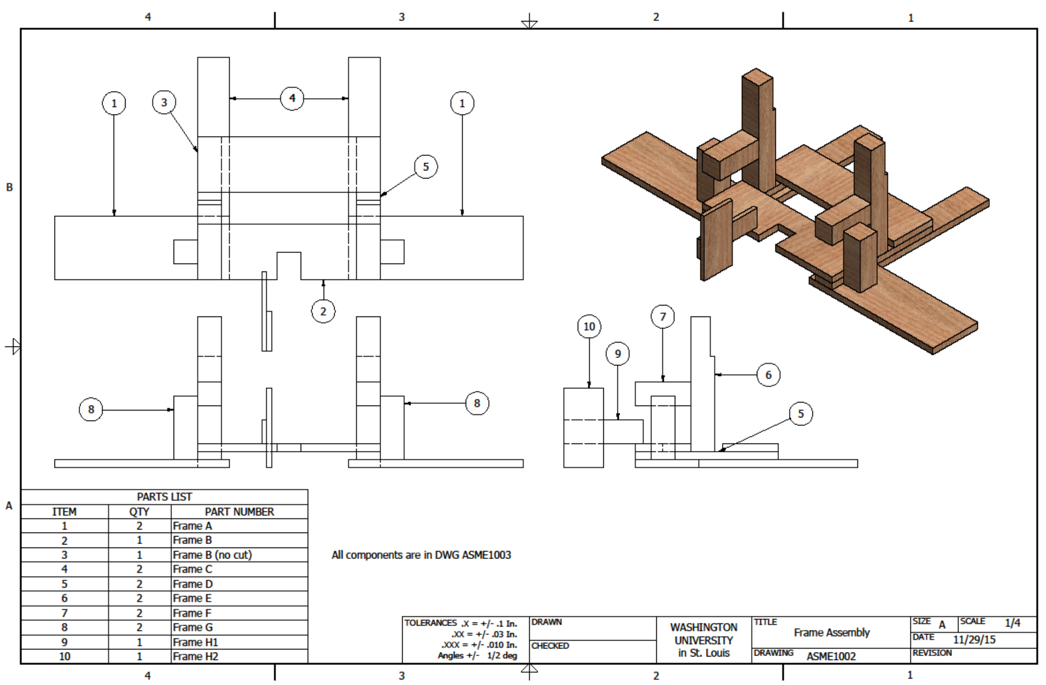
7 Design Documentation

7.1 Final Drawings and Documentation

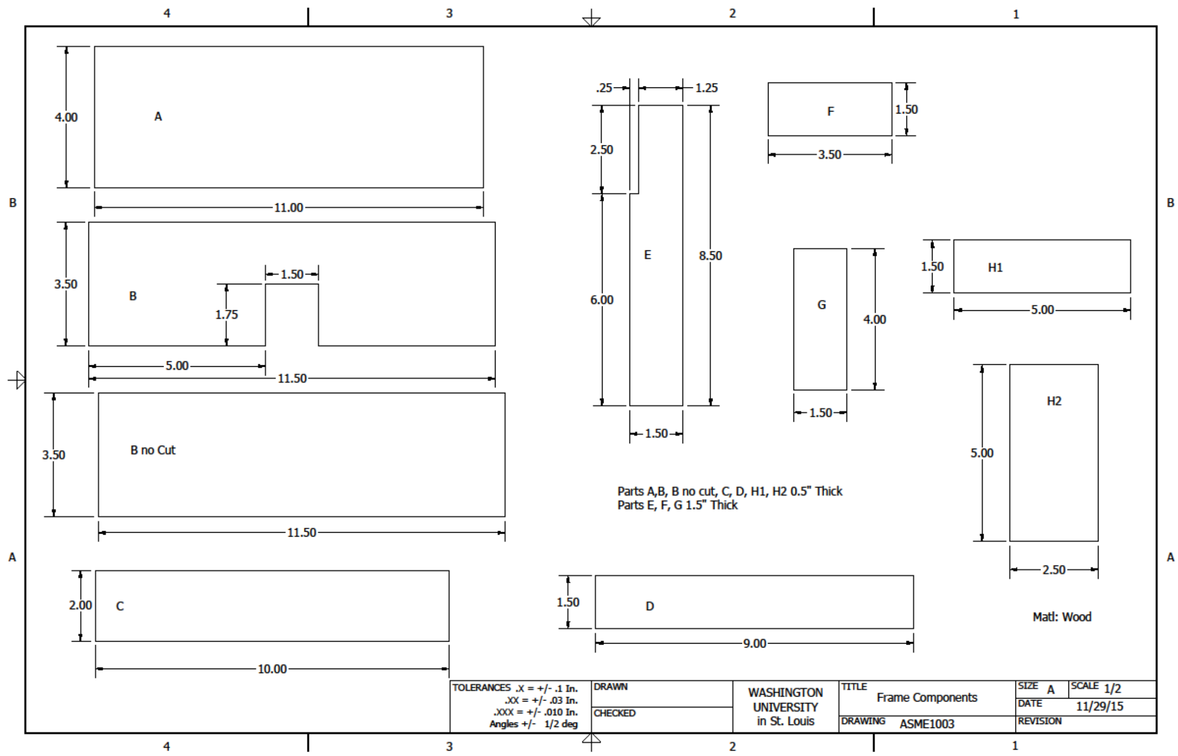
7.1.1 Engineering Drawings



PARTS LIST			
ITEM	QTY	PART NUMBER	DWG NUMBER
1	1	Frame	ASME1002
2	1	Frame Components	ASME1003
3	2	Launch Angle	ASME1004
4	1	Launch Angle Base Plate	ASME1004
5	2	Launch Angle Rod	ASME1005
6	1	Launch Barrel Holder	ASME1005
7	1	Launch Barrel	ASME1006
8	1	Servo Guide Plate	ASME1007
9	1	Servo Arm	ASME1008
10	1	Servo	ASME1009
11	2	Crumpler Barrel Mounting Plate	ASME1010
12	6	Crumpler Barrel Spacers	ASME1011
13	1	Crumpler Barrel	ASME1012A
14	1	Crumpler Barrel Stock	ASME1012B
15	2	Crumpler Motor Mounts	ASME1013
16	4	Crumpler Motor L Brackets	ASME1014
17	2	Crumpler Crank Arm	ASME1015
18	2	Crumpler Crank Slot	ASME1016
19	2	Crumpler Plungers	ASME1017
20	2	Crumpler Barrel Washer	ASME1018
21	2	Crumpler Barrel End Caps	ASME1019
22	4	Bearing Mounts	ASME1020
23	4	Pitching Wheel L Brackets	ASME1021
24	2	Left Side Axle	ASME1022
25	2	Right Side Axle	ASME1023
26	2	Pitching Wheel Motor Mount	ASME1024
27	2	Pitching Wheel Base Plate	ASME1025
28	1	Pitching Wheel Mount	ASME1026
29	2	Pitching Wheel Motor	ASME1027
30	4	Bearing	ASME1028
31	4	Shaft Collar	ASME1029
32	2	Threaded Rod	ASME1030
33	2	RC Wheel	ASME1031



PARTS LIST		
ITEM	QTY	PART NUMBER
1	2	Frame A
2	1	Frame B
3	1	Frame B (no cut)
4	2	Frame C
5	2	Frame D
6	2	Frame E
7	2	Frame F
8	2	Frame G
9	1	Frame H1
10	1	Frame H2


A
4.00
11.00
B
3.50
1.50
1.75
5.00
11.50
B no Cut
3.50
11.50
C
2.00
10.00
.25
1.25
2.50
E
6.00
8.50
1.50
F
1.50
3.50
G
4.00
1.50
H1
1.50
5.00
H2
5.00
2.50
D
1.50
9.00
Parts A,B, B no cut, C, D, H1, H2 0.5" Thick
Parts E, F, G 1.5" Thick
Matl: Wood
TOLERANCES .X = +/- .1 In. .XX = +/- .03 In. .XXX = +/- .010 In. Angles +/- 1/2 deg
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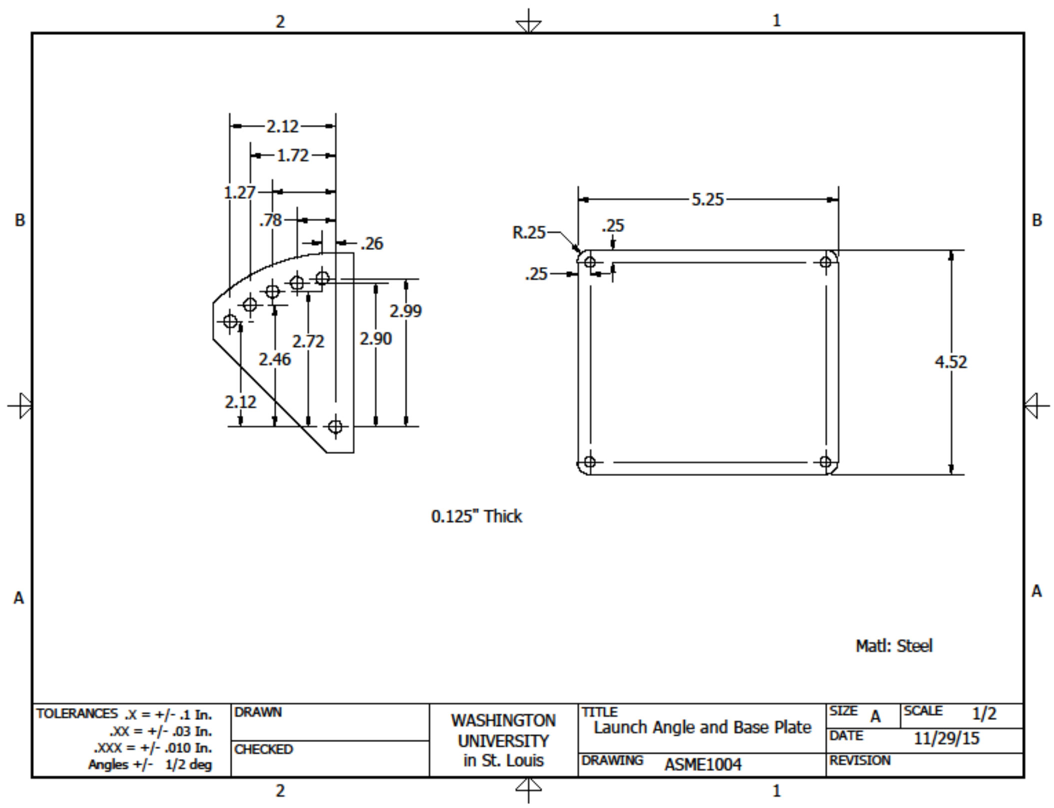
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Frame Components
DRAWING ASME1003
SIZE A
SCALE 1/2
DATE 11/29/15
REVISION


2.12
1.72
1.27
.78
.26
2.99
2.72
2.90
2.46
2.12
5.25
R.25
.25
.25
4.52
0.125" Thick
Matl: Steel
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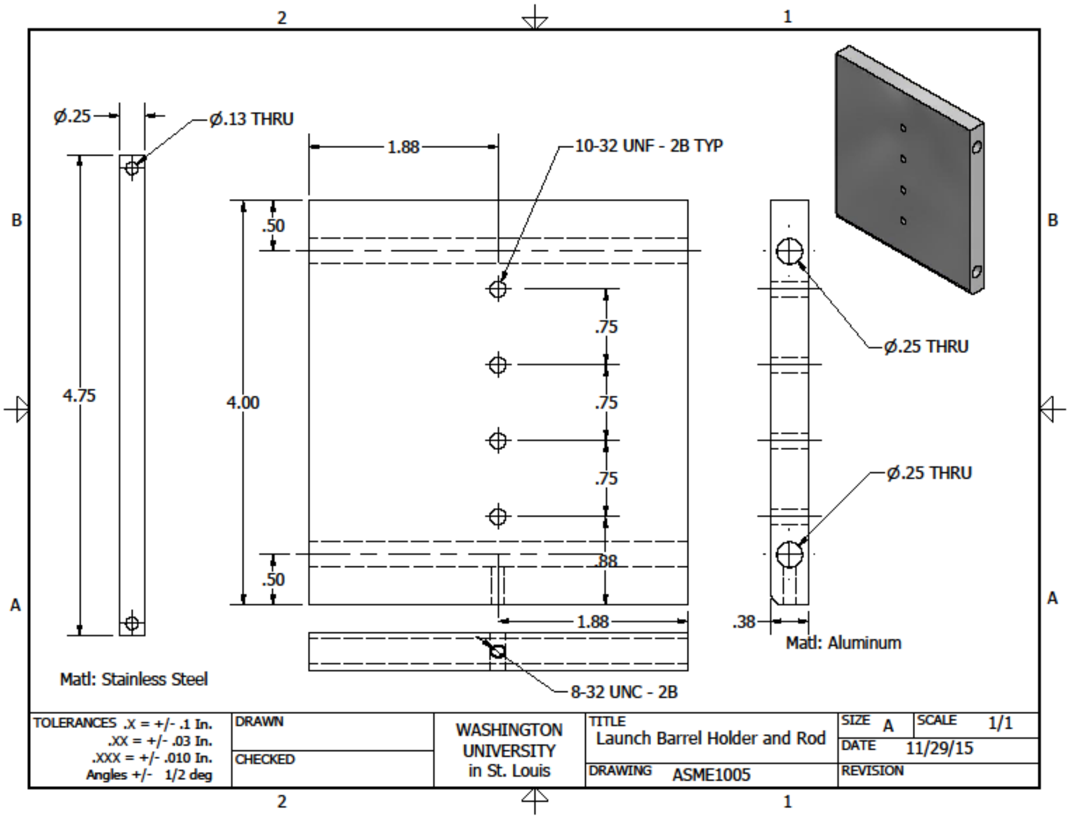
SIZE A
SCALE 1/2
DATE 11/29/15
REVISION


Ø.25
Ø.13 THRU
1.88
10-32 UNF - 2B TYP
.50
.75
.75
.75
.88
.50
4.75
4.00
1.88
.38
Ø.25 THRU
Ø.25 THRU
Matl: Aluminum
Matl: Stainless Steel
8-32 UNC - 2B
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
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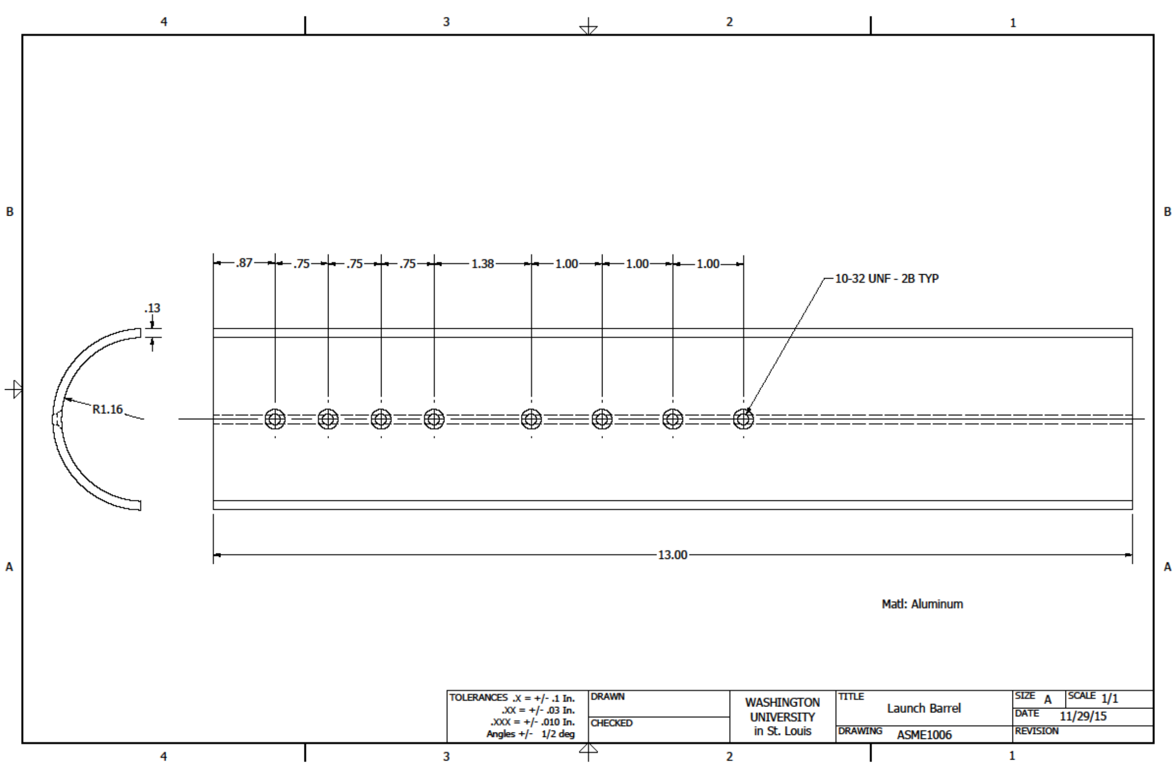
TITLE Launch Barrel Holder and Rod
DRAWING ASME1005
SIZE A
SCALE 1/1
DATE 11/29/15
REVISION


.87
.75
.75
.75
1.38
1.00
1.00
1.00
10-32 UNF - 2B TYP
.13
R1.16
13.00
Matl: Aluminum
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
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WASHINGTON UNIVERSITY in St. Louis
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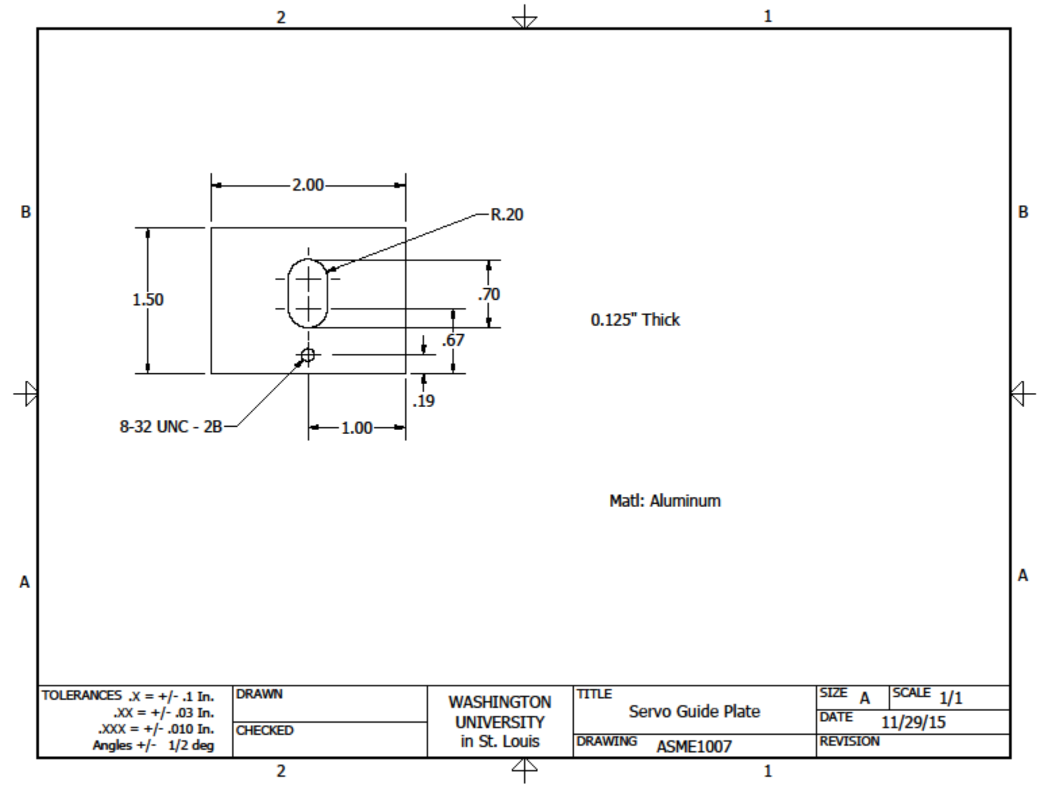
DRAWING ASME1006
SIZE A
SCALE 1/1
DATE 11/29/15
REVISION


2.00
R.20
1.50
.70
0.125" Thick
.67
.19
8-32 UNC - 2B
1.00
Matl: Aluminum
TOLERANCES .X = +/- .1 In. .XX = +/- .03 In. .XXX = +/- .010 In. Angles +/- 1/2 deg
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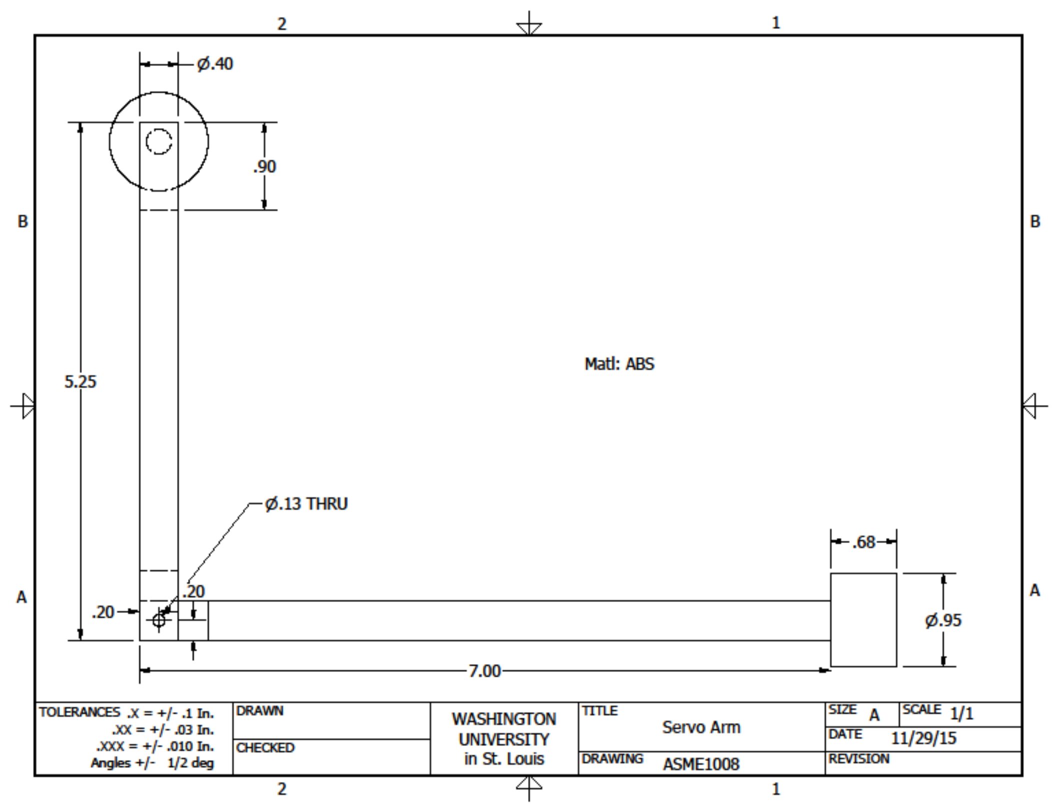
WASHINGTON UNIVERSITY in St. Louis
TITLE Servo Guide Plate
SIZE A
SCALE 1/1
DATE 11/29/15
DRAWING ASME1007
REVISION

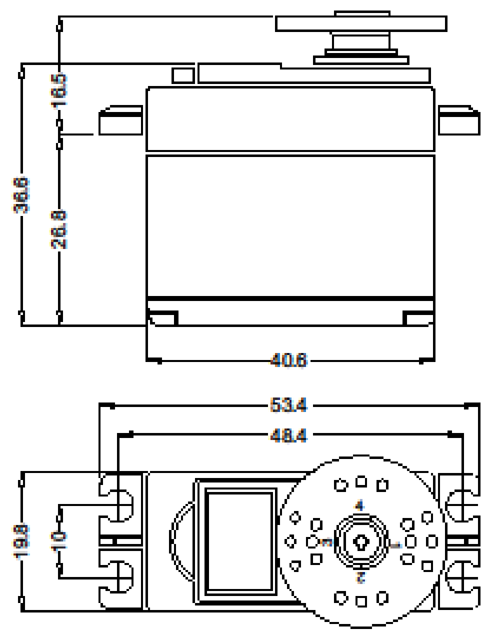

Ø.40
.90
5.25
Matl: ABS
Ø.13 THRU
.68
.20
.20
Ø.95
7.00
TOLERANCES .X = +/- .1 In. .XX = +/- .03 In. .XXX = +/- .010 In. Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Servo Arm
SIZE A
SCALE 1/1
DATE 11/29/15
DRAWING ASME1008
REVISION

•

ANNOUNCED SPECIFICATION OF HS–425BB STANDARD DELUXE BALL BEARING SERVO

1.TECHNICAL VALUES

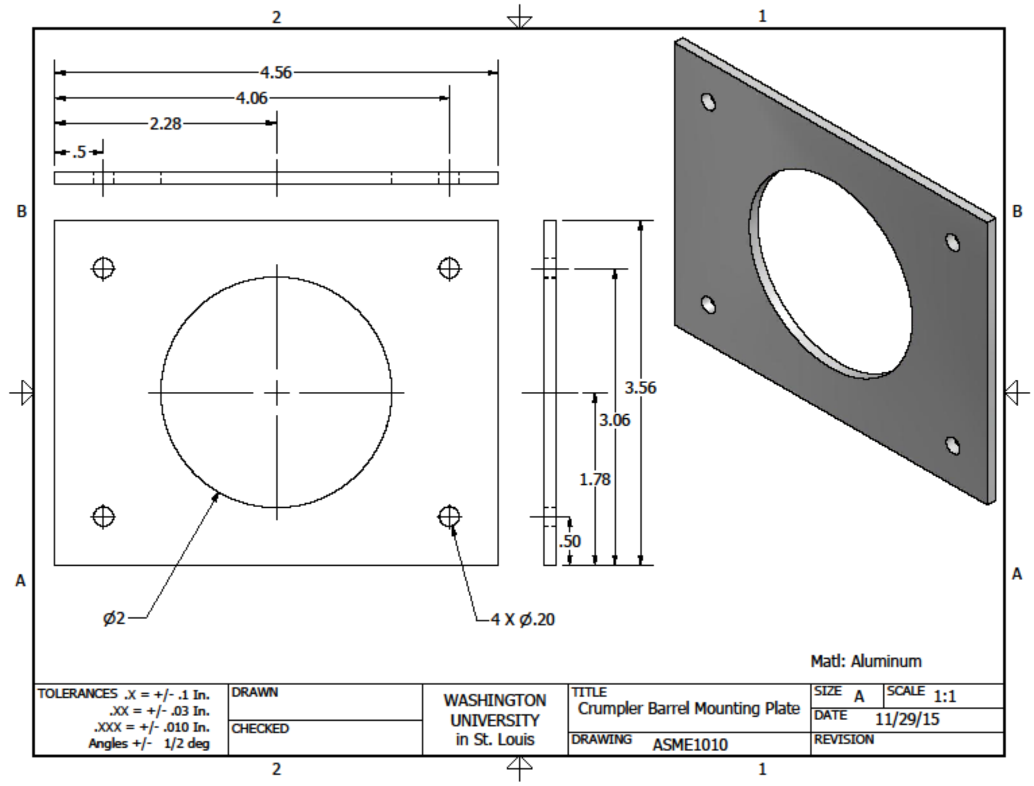
CONTROL SYSTEM	: +PULSE WIDTH CONTROL 1500usec NEUTRAL	
OPERATING VOLTAGE RANGE	: 4.8V TO 6.0V	
OPERATING TEMPERATURE RANGE	: -20 TO +60°C	
TEST VOLTAGE	: AT 4.8V	AT 6.0V
OPERATING SPEED	: 0.21sec/60° AT NO LOAD	0.16sec/60° AT NO LOAD
STALL TORQUE	: 3.3kg.cm(45.82oz.in)	4.1kg.cm(56.93oz.in)
OPERATING ANGLE	: 45°/ONE SIDE PULSE TRAVELING 400usec	
DIRECTION	: CLOCK WISE/PULSE TRAVELING 1500 TO 1900usec	
CURRENT DRAIN	: 8mA/IDLE AND 150mA/NO LOAD RUNNING	
DEAD BAND WIDTH	: 8usec	
CONNECTOR WIRE LENGTH	: 300mm(11.81in)	
DIMENSIONS	: 40.6x19.8x36.6mm(1.59x0.77x1.44in)	
WEIGHT	: 45.5g(1.6oz)	



2.FEATURES
3-POLE FERRITE MOTOR
LONG LIFE POTENTIOMETER
DUAL BALL BEARING
INDIRECT POTENTIOMETER DRIVE

3.APPLICATIONS
AIRCRAFT 20-60 SIZE
30 SIZE HELICOPTERS
STEERING AND THROTTLE SERVO FOR CARS
TRUCK AND BOATS

ASME1009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4.06
2.28
.5
3.56
3.06
1.78
.50
Ø2
4 X Ø.20
Matl: Aluminum
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.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
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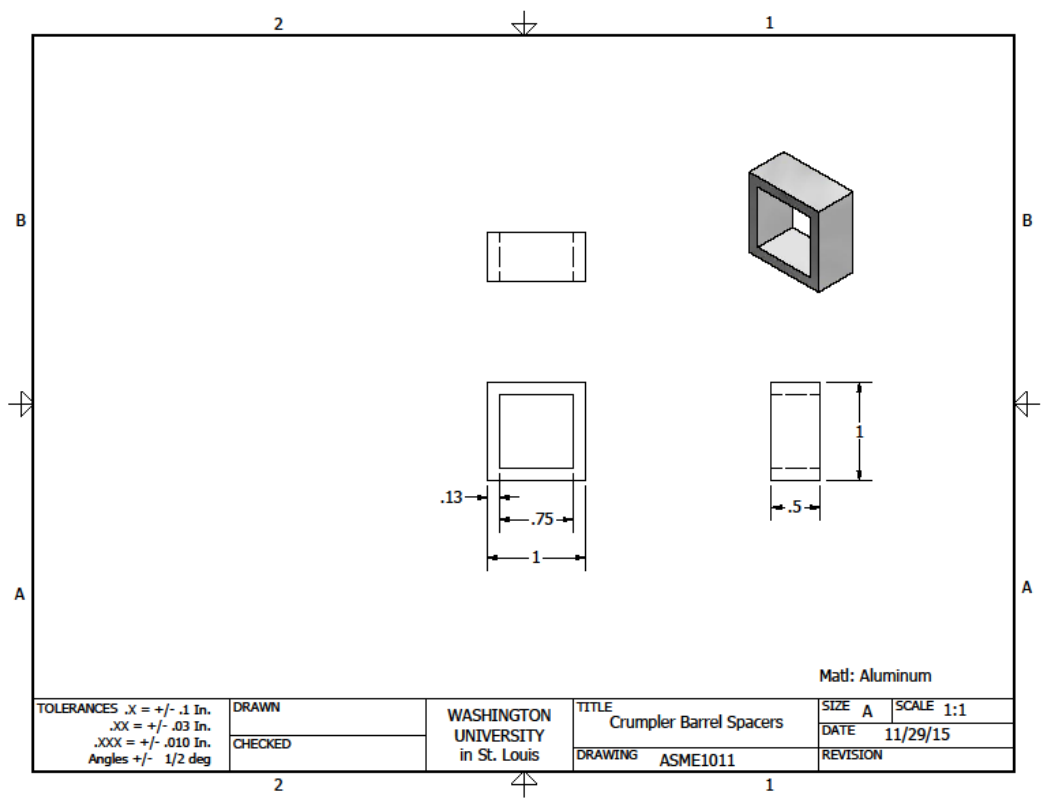
SIZE A
SCALE 1:1
DATE 11/29/15
DRAWING ASME1010
REVISION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.75
1
1
.5
Matl: Aluminum
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.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Crumpler Barrel Spacers
SIZE A
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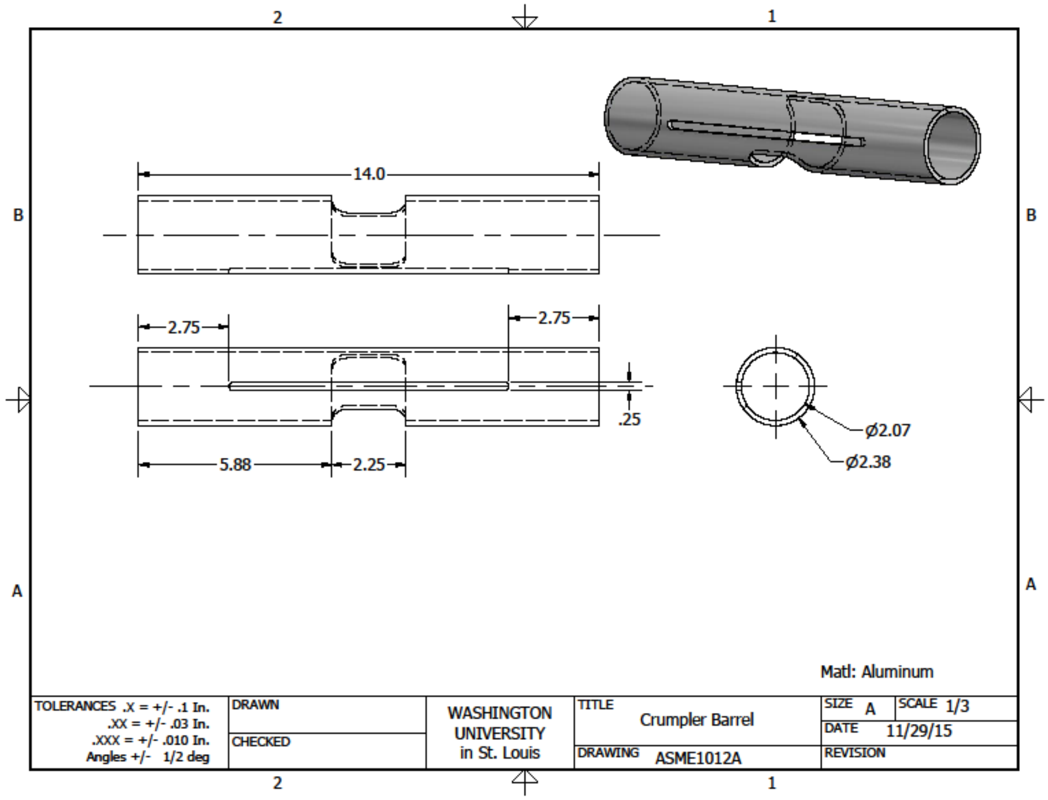
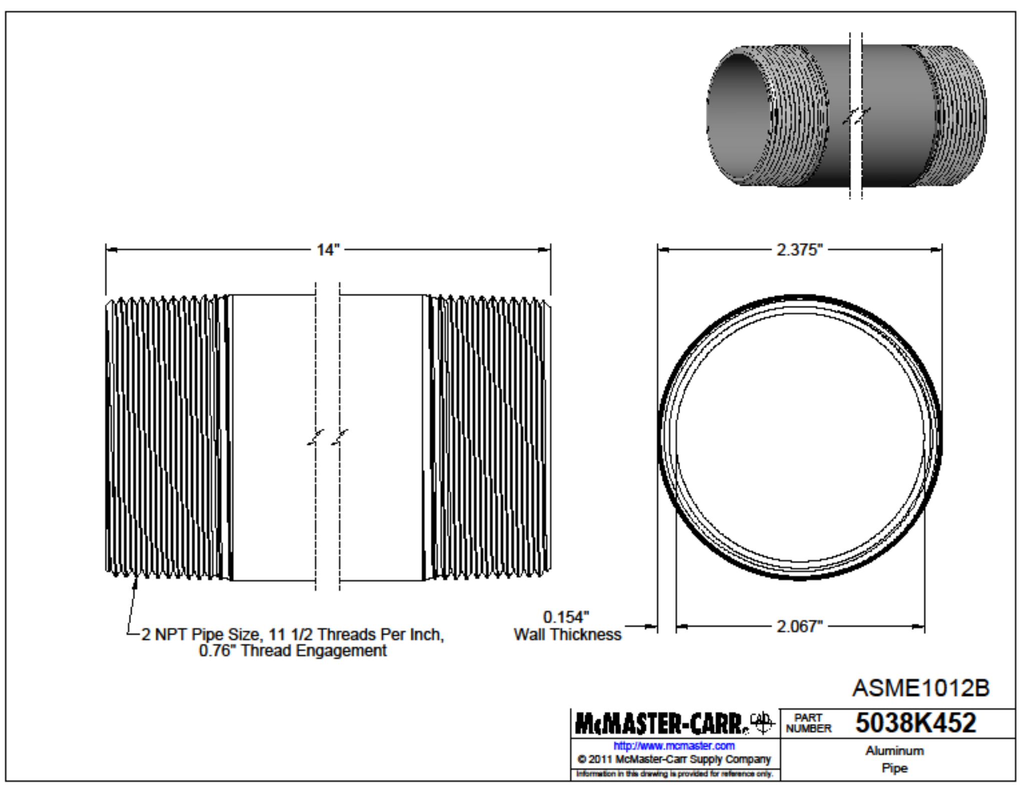
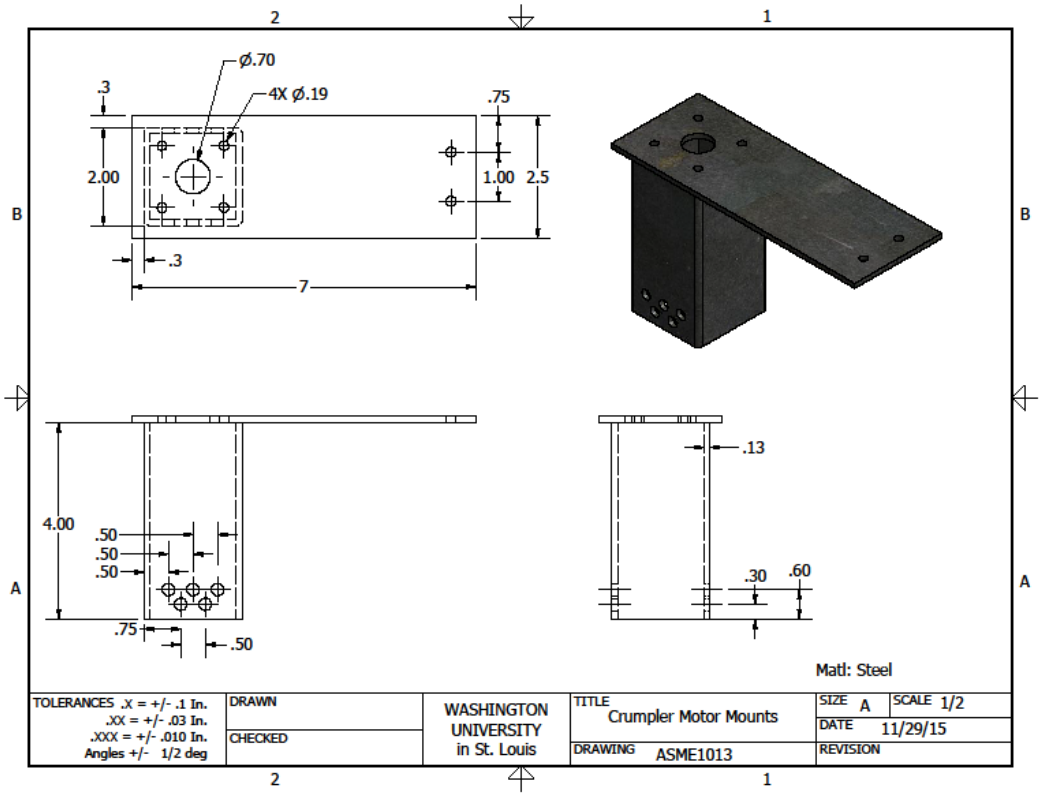
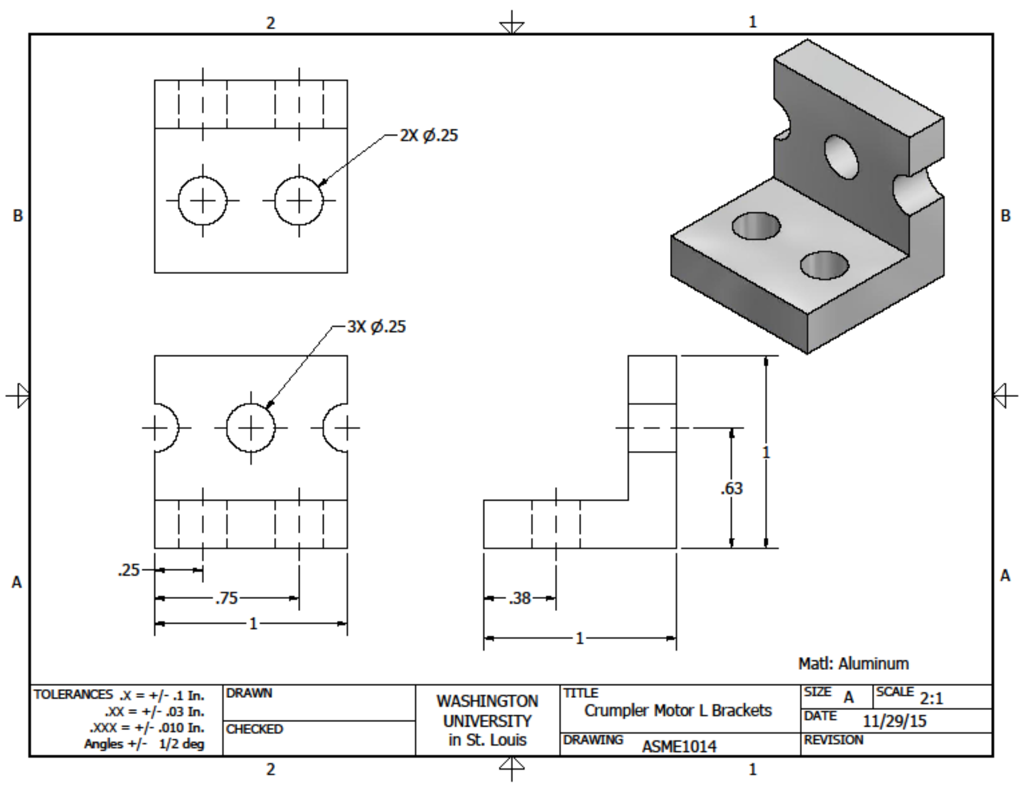
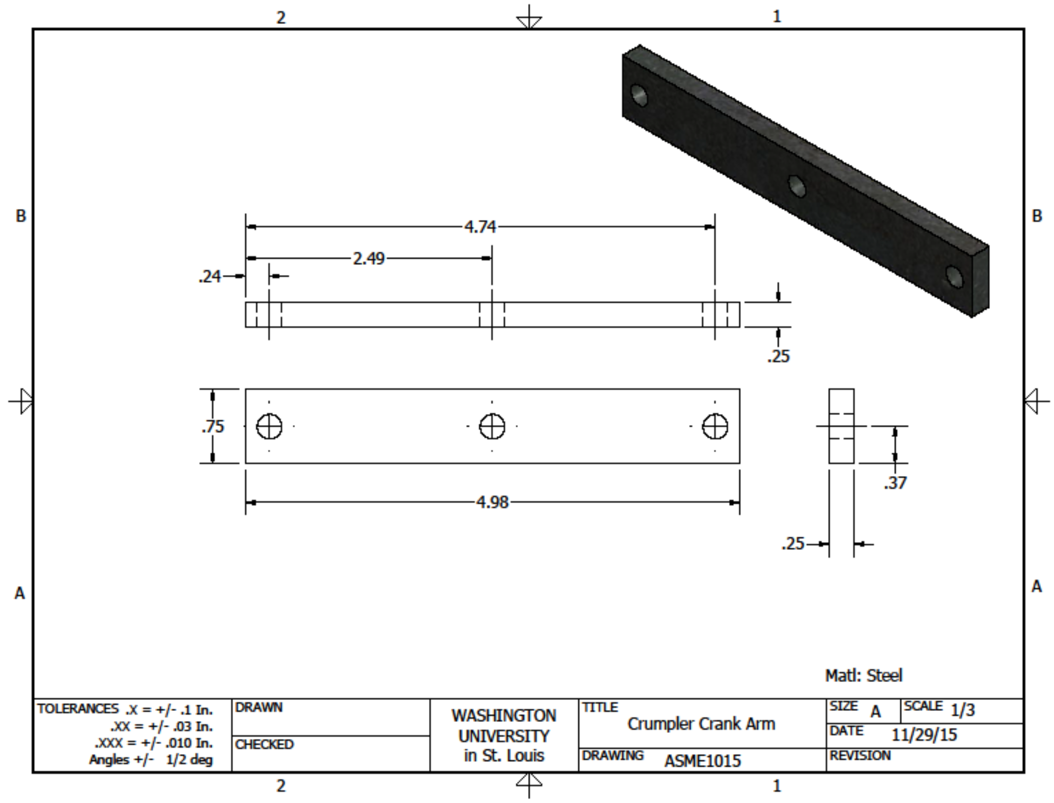
DATE 11/29/15
DRAWING ASME1011
REVISION

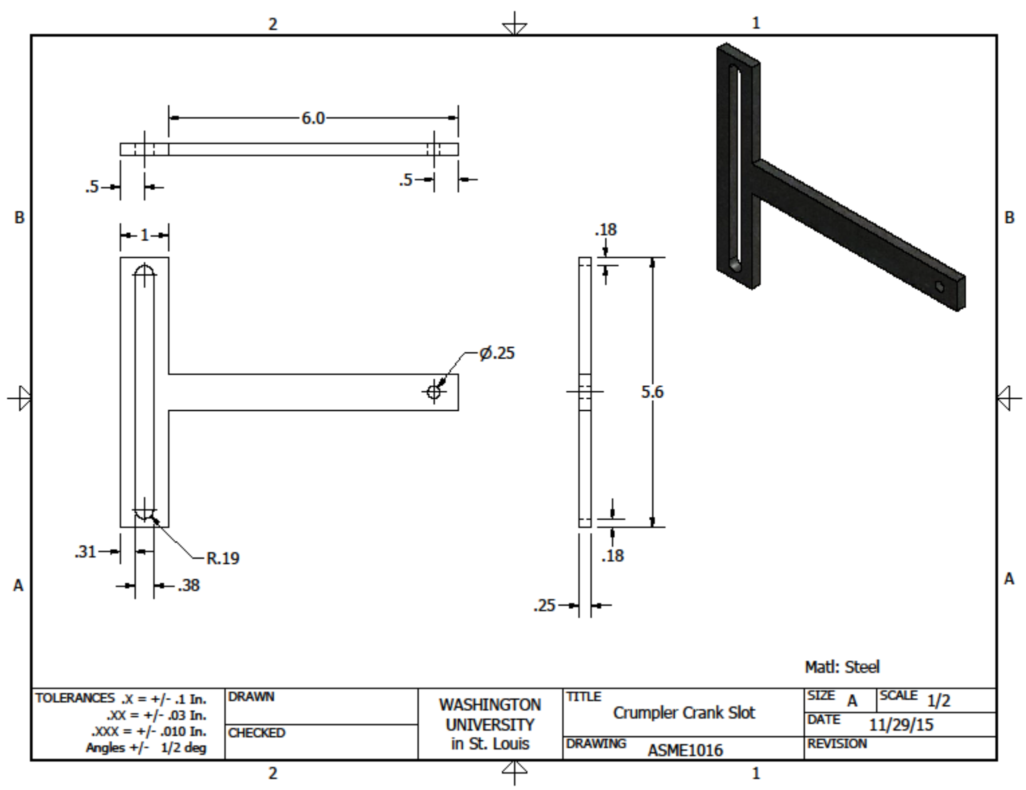

14.0
2.75
2.75
.25
5.88
2.25
Ø2.07
Ø2.38
Matl: Aluminum
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Crumpler Barrel
DRAWING ASME1012A
SIZE A
SCALE 1/3
DATE 11/29/15
REVISION

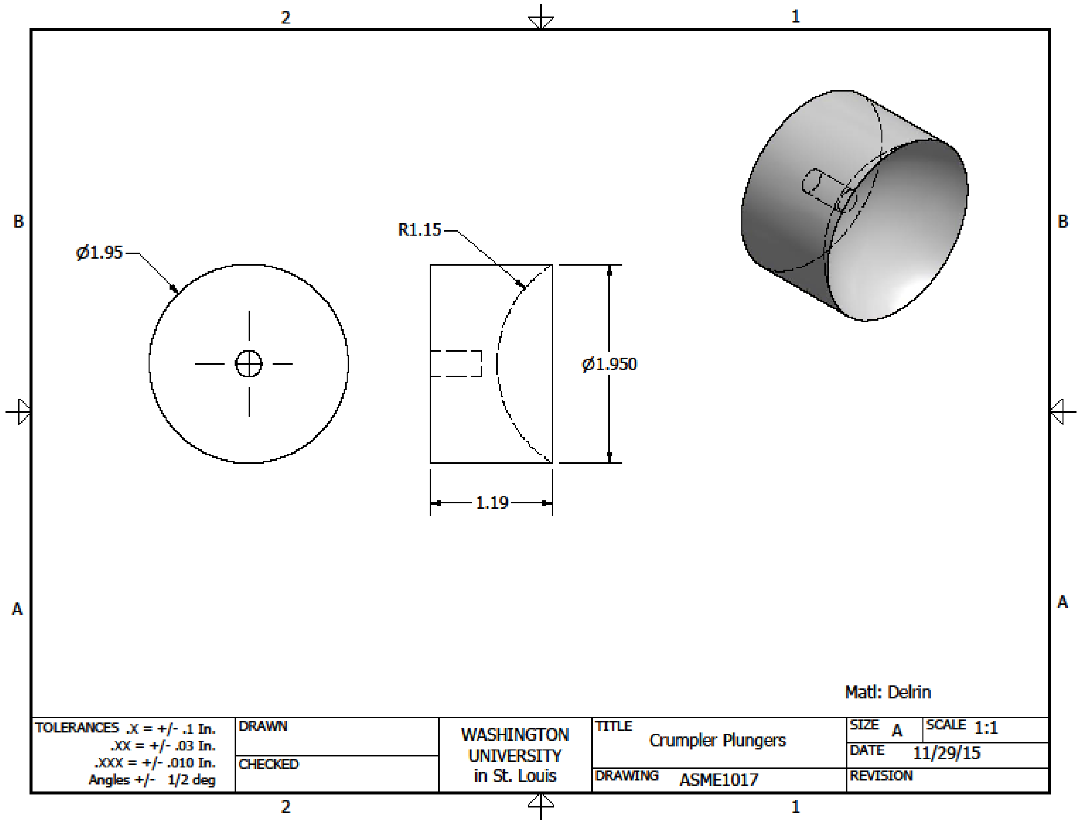

14"
2.375"
2 NPT Pipe Size, 11 1/2 Threads Per Inch, 0.76" Thread Engagement
0.154" Wall Thickness
2.067"
ASME1012B
McMASTER-CARR
PART NUMBER 5038K452
http://www.mcmaster.com
© 2011 McMaster-Carr Supply Company
Aluminum Pipe


Ø.70
4X Ø.19
.3
2.00
.3
7
.75
1.00
2.5
4.00
.50
.50
.50
.75
.50
.13
.30
.60
Matl: Steel
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Crumpler Motor Mounts
DRAWING ASME1013
SIZE A
SCALE 1/2
DATE 11/29/15
REVISION

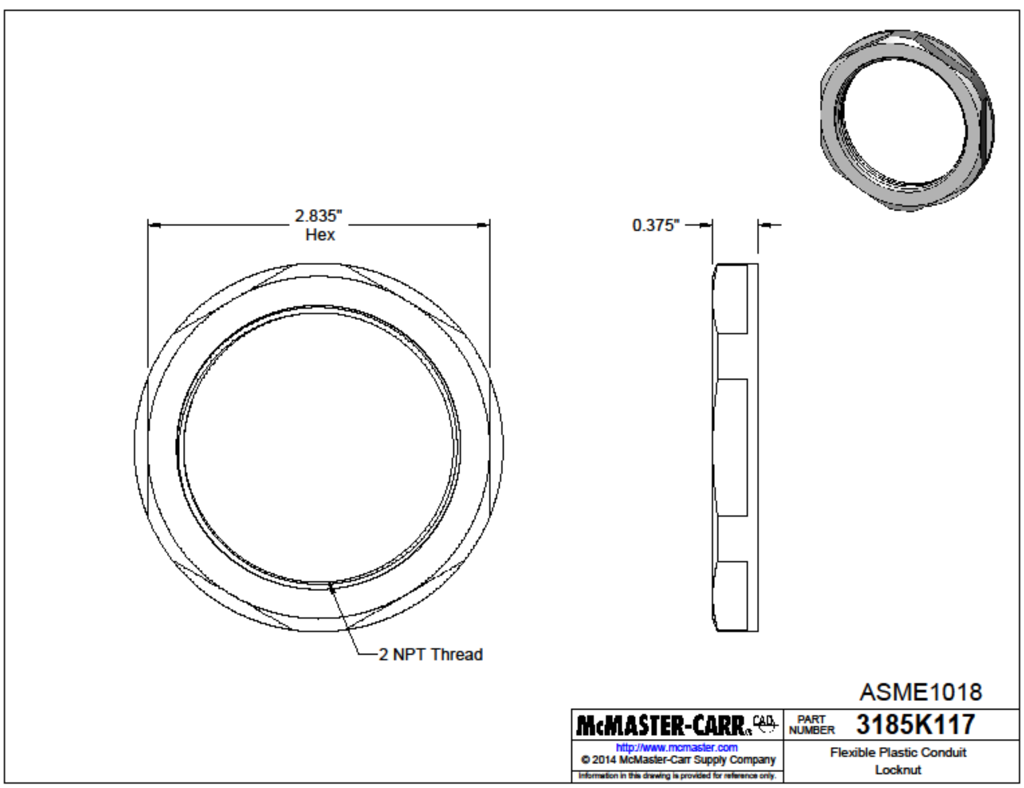

2X Ø.25
3X Ø.25
.25
.75
1
.38
1
.63
1
Matl: Aluminum
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Crumpler Motor L Brackets
DRAWING ASME1014
SIZE A
SCALE 2:1
DATE 11/29/15
REVISION


4.74
2.49
.24
.25
.75
4.98
.37
.25
Matl: Steel
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Crumpler Crank Arm
SIZE A
SCALE 1/3
DATE 11/29/15
DRAWING ASME1015
REVISION

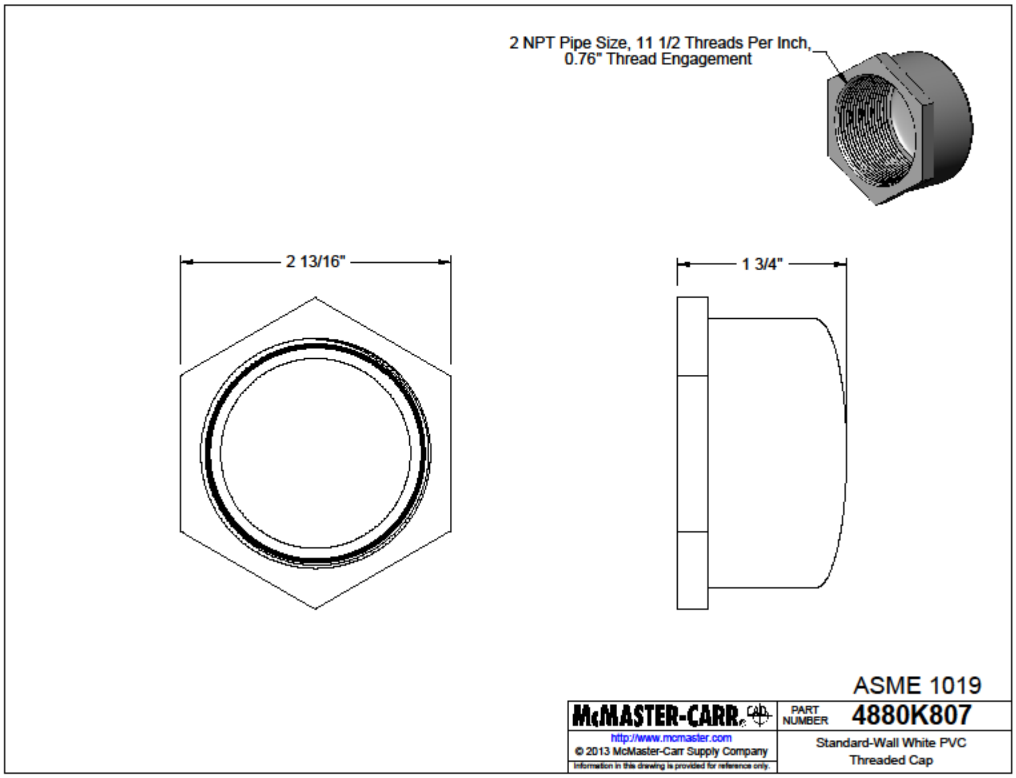

6.0
.5
.5
1
.18
Ø.25
5.6
.18
.31
R.19
.38
.25
Matl: Steel
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Crumpler Crank Slot
SIZE A
SCALE 1/2
DATE 11/29/15
DRAWING ASME1016
REVISION



2
1
B
A
Ø1.95
R1.15
Ø1.950
1.19
Matl: Delrin
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Crumpler Plungers
DRAWING
ASME1017
SIZE A
SCALE 1:1
DATE 11/29/15
REVISION



2.835"
Hex
0.375"
2 NPT Thread
ASME1018
McMASTER-CARR
PART NUMBER
3185K117
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Flexible Plastic Conduit
Locknut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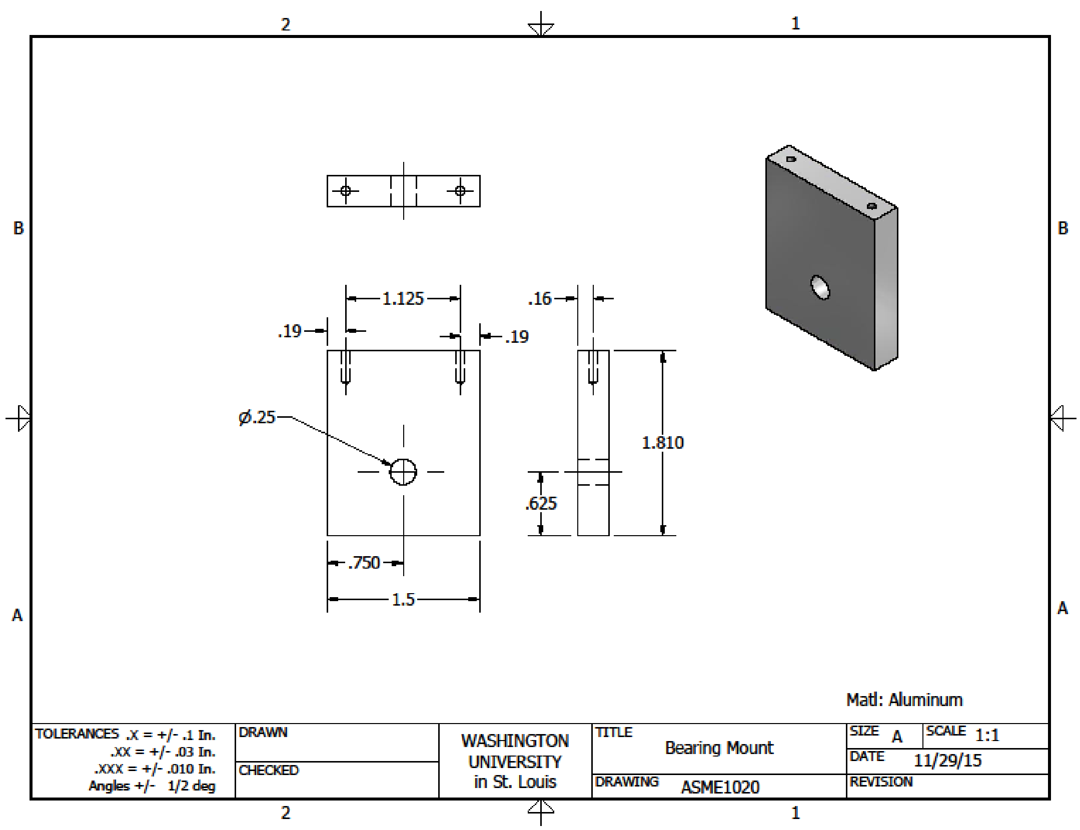
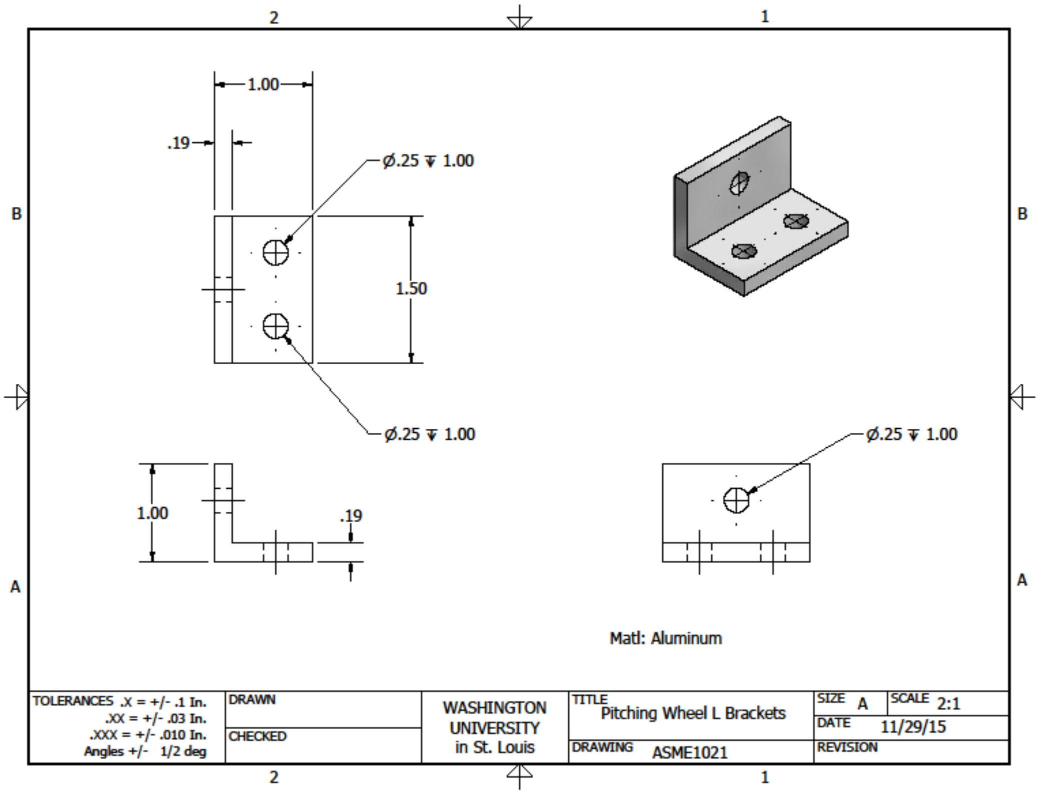
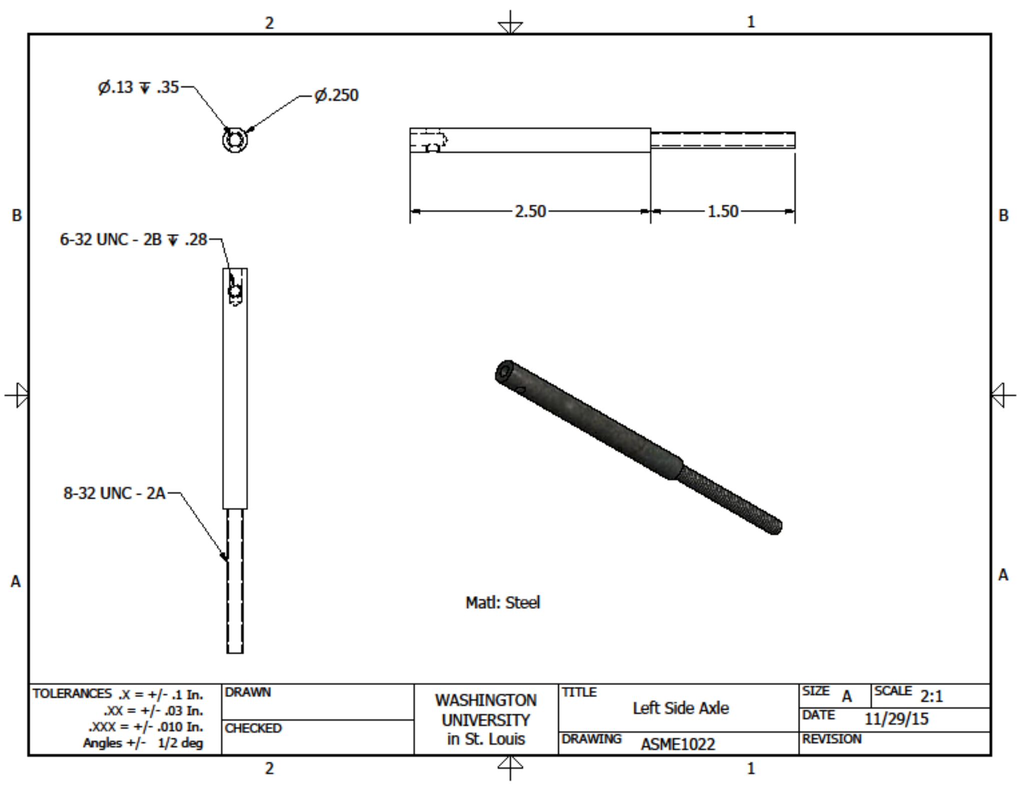
0.76" Thread Engagement
2 13/16"
1 3/4"
ASME 1019
McMASTER-CARR
PART NUMBER
4880K807
http://www.mcmaster.com
© 2013 McMaster-Carr Supply Company
Standard-Wall White PVC
Threaded Cap


1.125
.16
.19
.19
ø.25
1.810
.625
.750
1.5
Matl: Aluminum
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Bearing Mount
DRAWING
ASME1020
SIZE A
SCALE 1:1
DATE 11/29/15
REVISION


1.00
.19
Ø.25 ↧ 1.00
1.50
Ø.25 ↧ 1.00
Ø.25 ↧ 1.00
1.00
.19
Matl: Aluminum
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Pitching Wheel L Brackets
DRAWING ASME1021
SIZE A
SCALE 2:1
DATE 11/29/15
REVISION


Ø.13 ↧ .35
Ø.250
2.50
1.50
6-32 UNC - 2B ↧ .28
8-32 UNC - 2A
Matl: Steel
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
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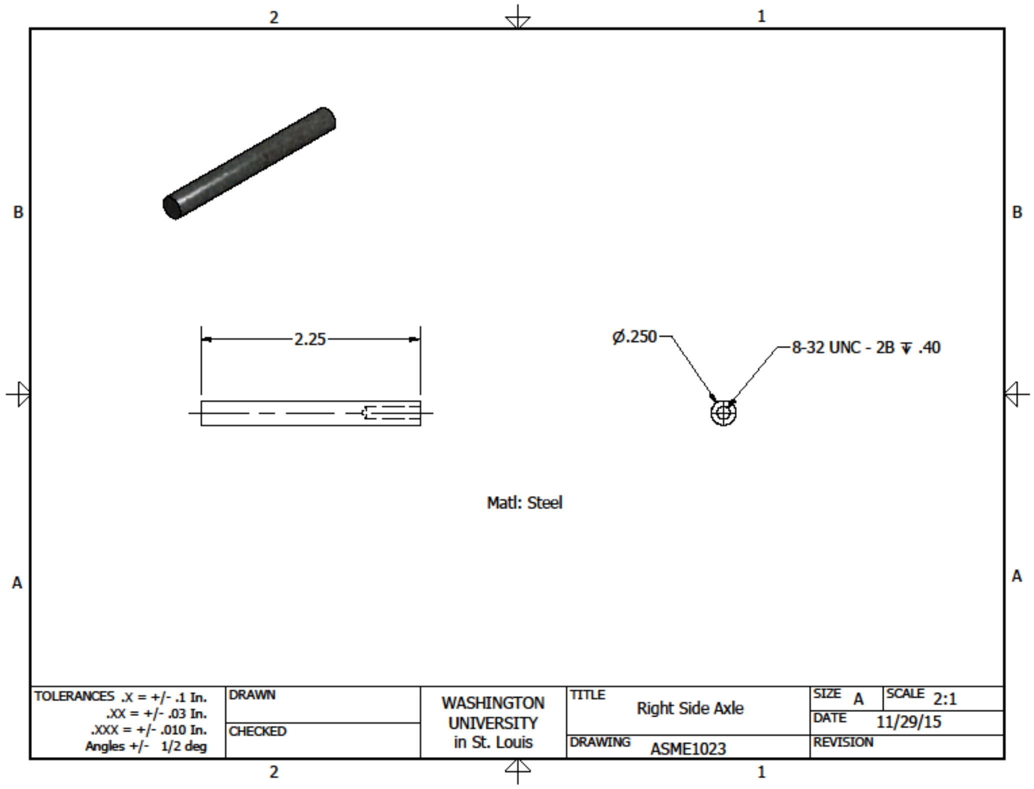
SIZE A
SCALE 2:1
DATE 11/29/15
REVISION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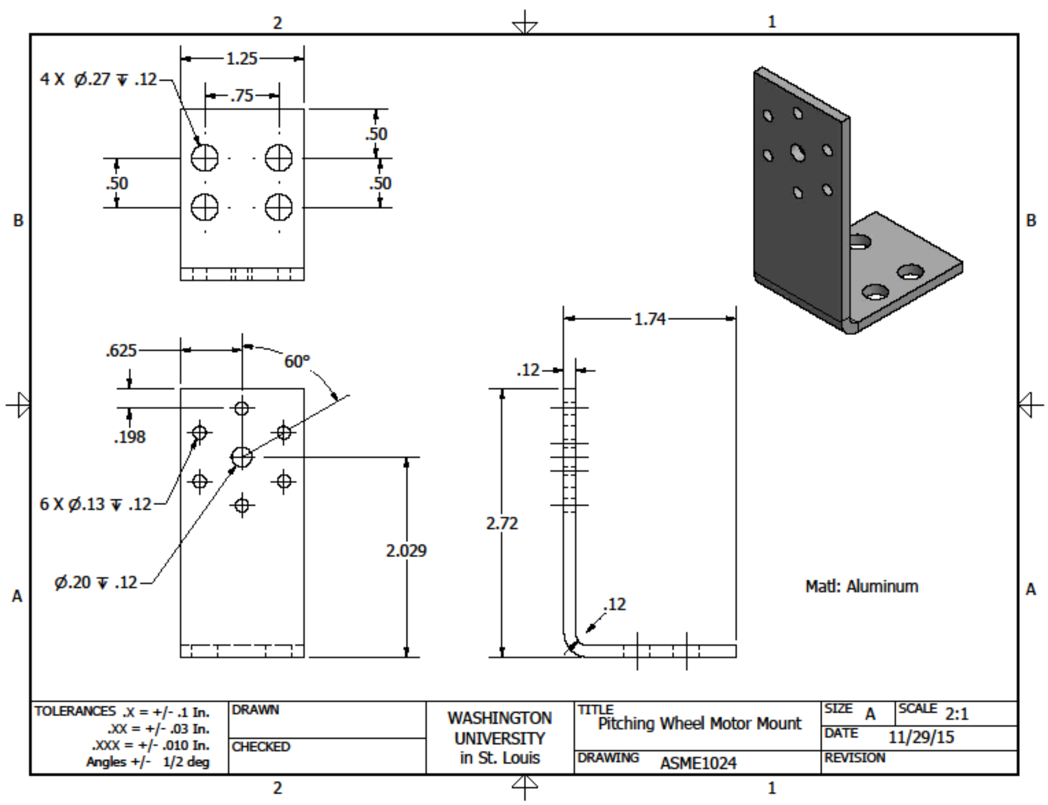
DATE 11/29/15
REVISION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.12
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.12
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SIZE A
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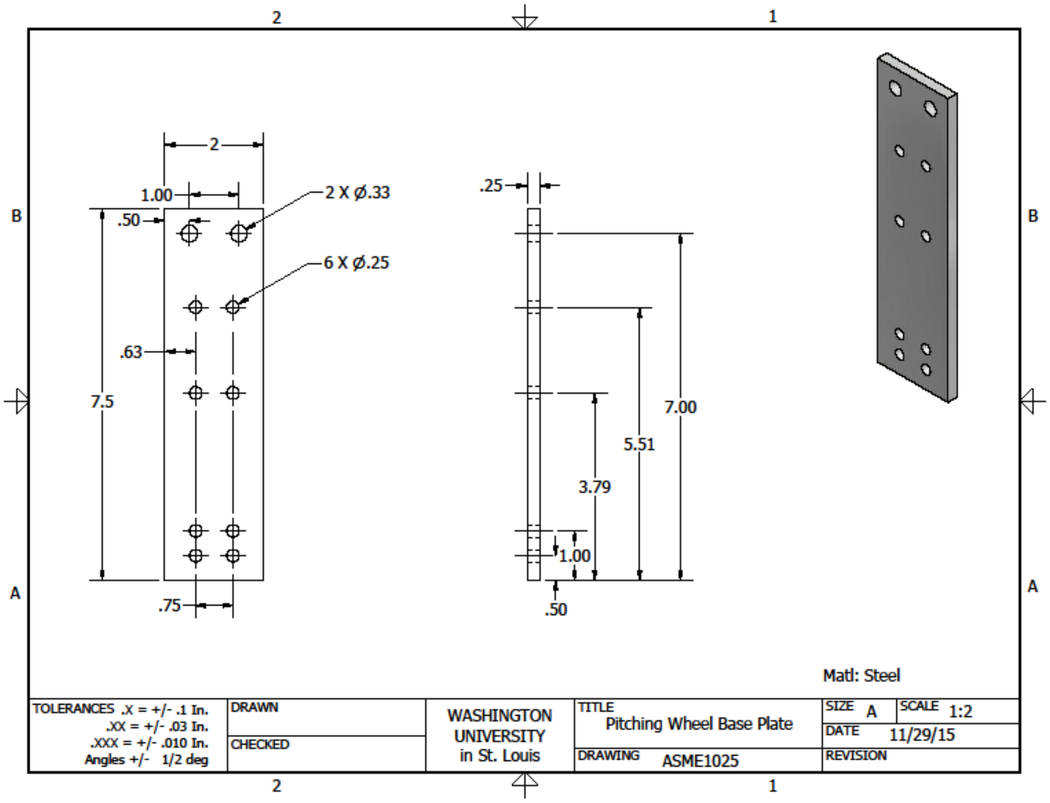
DATE 11/29/15
REVISION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6 X Ø.25
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.75
.25
7.00
5.51
3.79
1.00
.50
Matl: Steel
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Angles +/- 1/2 deg
DRAWN
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WASHINGTON UNIVERSITY in St. Louis
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SIZE A
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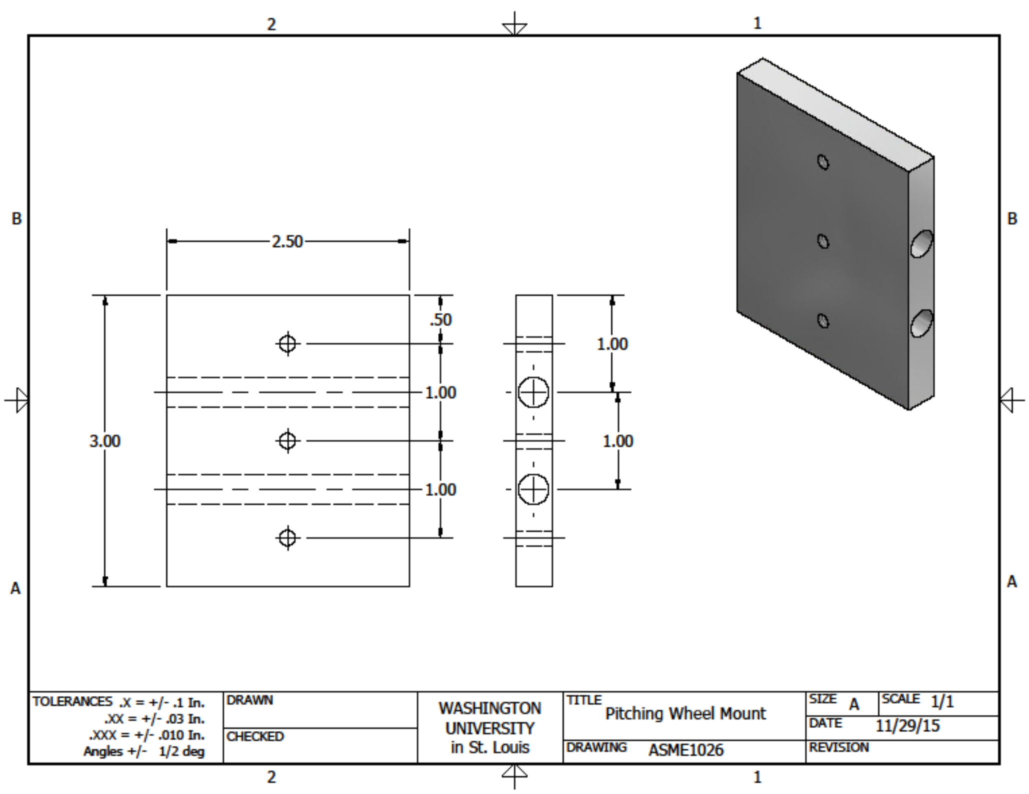
DATE 11/29/15
REVISION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Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE Pitching Wheel Mount
DRAWING ASME1026
SIZE A
SCALE 1/1
DATE 11/29/15
REVISION

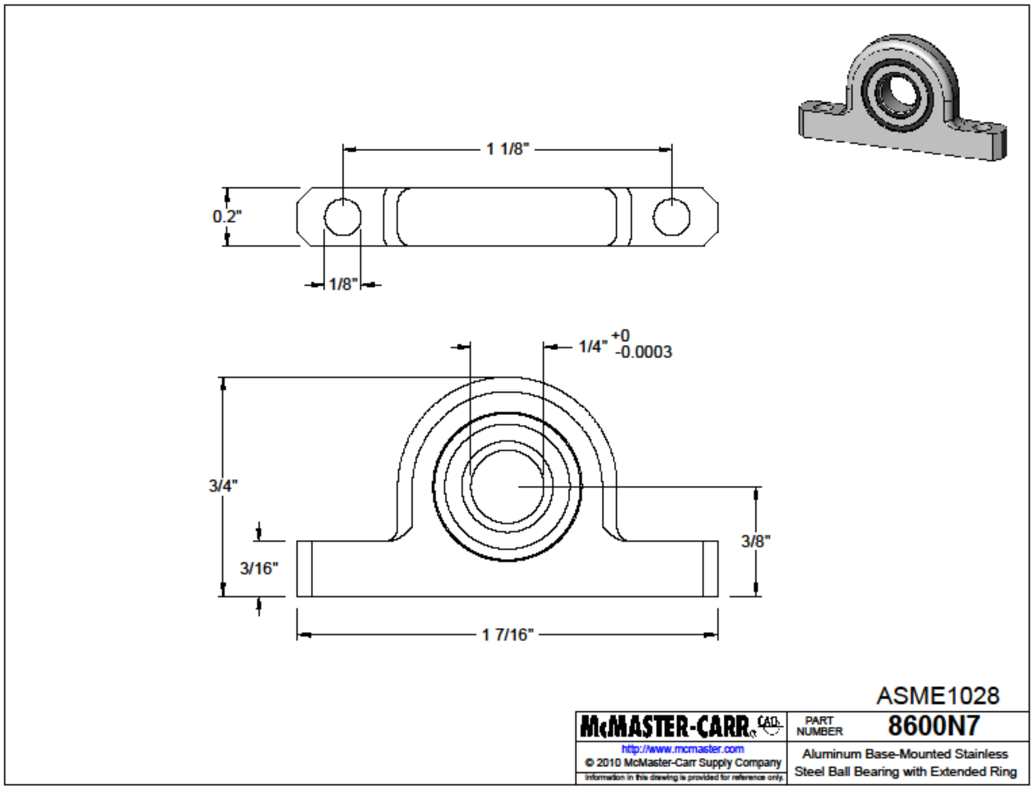
Motor
Features:
4 poles Hi-torque motor design.
CNC machined 6061 T6 billet aluminum heatsink can.
High purity copper windings maximizes efficiency.
High RPM ABEC5 oversized bearings.
Universal fit all 1/10 brushless cars-multi-mounting system for M3 screws.
Precision balanced rotor, smoothness for best reliability and maximum RPM.
Stator - Super Thin (0.35mm) laminations.
Removable/replaceable.
Precision engineered for maximum energy conversion.
ROAR legal.

Specification:
RPM: 4370KV
Max Current: 66A
Max Watts: 820W
Can Size: 3650
Sensored: No
Can Diameter: 36mm
Can Length: 50mm
Shaft Diameter: 3.175mm
Shaft Length: 15mm
Bullet Connector: 4mm
Weight: 146g/5.2oz
Max voltage: 7.4V(2S)-11.1V(3S)

Electric Speed Controller
Features:
Compatible with sensorless brushless motors.
High anti-interference capability.
Using advanced software interface to set up or update the software.
Super smooth and accurate throttle linearity.
Fast response to throttle input.
Mutiple protection features: low voltage cut-off protection, over-heat protection and throttle signal loss protection.

Specifications:
Cont. Current: 45A
Burst Current: 260A/10sec
Battery: 2-3 Cell Lipo / 4-9 Cell NiMh
SBEC: Yes
SBEC Output: 5.8V/3A
Power Supply Plugs: T Male
Motor Plugs: Female 4mm Bullet Connector
Size: 45*35*35mm(with out fan)
Weight: 76g /2.7oz

ASME1027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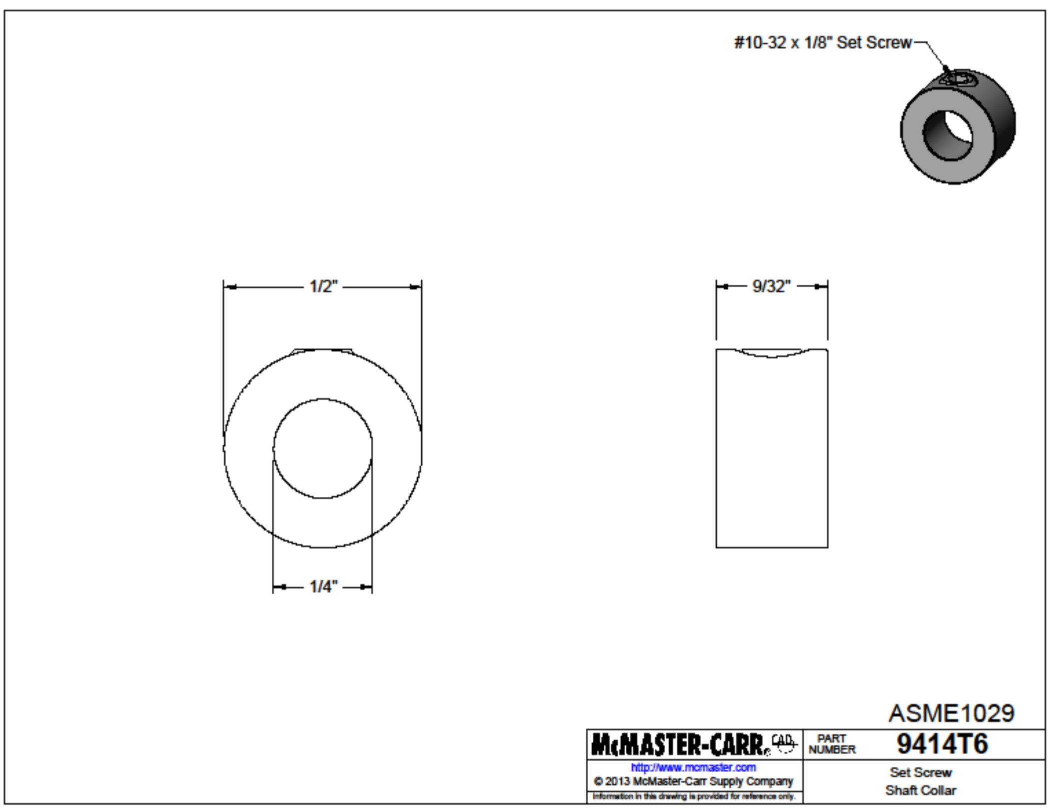
0.2"
1/8"
1/4" +0 -0.0003
3/4"
3/16"
3/8"
1 7/16"
ASME1028
McMASTER-CARR CAD
PART NUMBER
8600N7
http://www.mcmaster.com
© 2010 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Aluminum Base-Mounted Stainless Steel Ball Bearing with Extended Ring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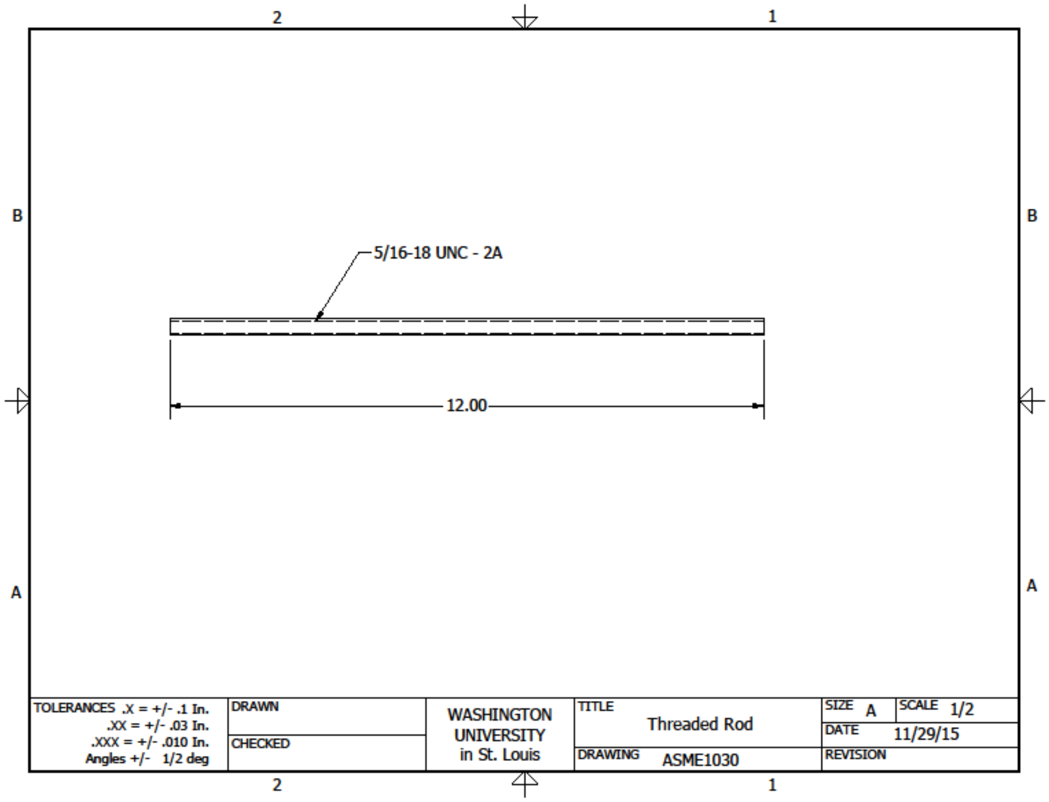
1/2"
9/32"
1/4"
ASME1029
McMASTER-CARR CAD
PART NUMBER
9414T6
http://www.mcmaster.com
© 2013 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Set Screw Shaft Collar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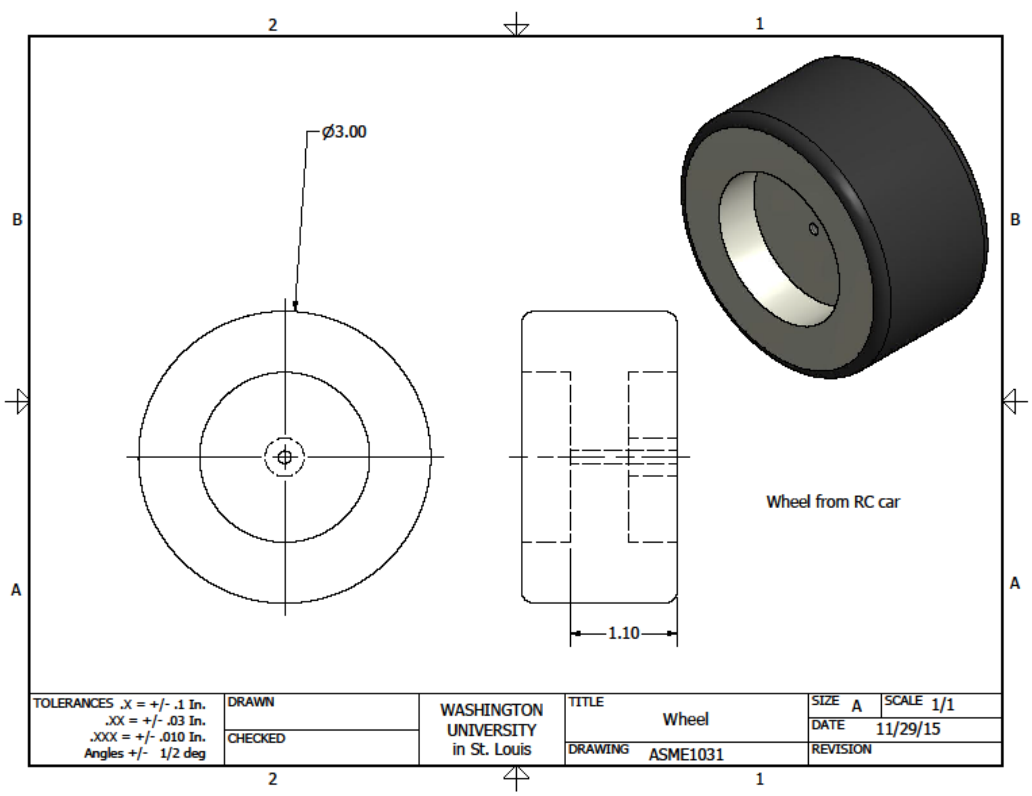
12.00
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Threaded Rod
DRAWING ASME1030
SIZE A
SCALE 1/2
DATE 11/29/15
REVISION


Ø3.00
1.10
Wheel from RC car
TOLERANCES .X = +/- .1 In.
.XX = +/- .03 In.
.XXX = +/- .010 In.
Angles +/- 1/2 deg
DRAWN
CHECKED
WASHINGTON UNIVERSITY in St. Louis
TITLE
Wheel
DRAWING ASME1031
SIZE A
SCALE 1/1
DATE 11/29/15
REVISION

7.1.2 Sourcing Instructions

Table 7: Final Part Uses

# PARTS NEEDED	PART NAME	SOURCE	CATALOG NUMBER	PART USE
10	Frame	Scrounged	----	Support
2	Launch Angle	Scrounged	----	Adjusts the angle of the barrel, welded to base plate
1	Launch Angle Base Plate	Scrounged	----	Supports launch angle pieces
2	Launch Angle Rod	Scrounged	----	Holds launch barrel holder in place
1	Launch Barrel Holder	Scrounged	----	Holds launch barrel at desired angle
1	Launch Barrel	Scrounged	----	Crumpled ball falls into barrel and is pushed along barrel into pitching wheels
1	Servo Guide Plate	Scrounged	----	At base of launch barrel, supports servo arm
2	Servo Arm	Scrounged	----	Connected to servo motor, pushes crumpled ball into pitching wheels
1	Servo	Scrounged	----	Rotates servo arm
2	Crumpler Barrel Mounting Plate	Scrounged	----	Supports crumpler barrel and screws into wooden frame
6	Crumpling Barrel Spacer	Scrounged	----	Supports screws used to attach barrel to frame
1	Crumpler Barrel	McMaster	5038K452	Facilitates rolling paper into cylinder; crumpler plungers slide inside
2	Crumpling Motors	Amazon	a12032000ux0221	Drives crumpler crank arm
2	Crumpler Motor Mounts	Scrounged	----	Houses and holds crumpling motors
4	Crumpling Motor L Brackets	Scrounged	----	Attaches mount to frame
2	Crumpler Crank Arm	Scrounged	----	Attaches to motor to drive plungers
2	Crumpler Crank Slot	Scrounged	----	Pushes plungers into barrel
2	Crumpler Plungers	Scrounged	----	Slide in barrel to crush paper into ball
2	Crumpler Barrel Washer	McMaster	3185K117	Supports way of mounting barrel to frame
2	Crumpler Barrel End Caps	McMaster	4880K807	Prevents plungers from coming out of barrel
4	Bearing Mounts	Scrounged	----	Lifts bearing to be level with motor axle
4	Pitching Wheel L Brackets	Scrounged	----	Attaches the bearing mounts to the base plate for the pitching wheel assemblies
2	Left Side Axle	Scrounged	----	Threads into pitching wheel and connects to motor

2	Right Side Axle	Scrounged	----	Screws onto left side axle and supports wheel in bearing
2	Pitching Wheel Motor Mounts	Scrounged	----	Hold the pitching wheel motors to the base plate
2	Pitching Wheel Base Plate	Scrounged	----	Connects the pitching wheel motors, bearing mounts, and L brackets
2	Pitching Wheel Mount	Scrounged	----	Hold the pitching wheel assembly to the launch barrel with threaded rods
2	Pitching Wheel Motors with ESC	Amazon	B00Z9QF8UC	These motors and speed controllers spin the pitching wheels to launch the paper ball
4	Bearing	McMaster	8600N7	The bearings allow the axles to spin freely while attached to frame
8	Shaft Collar	McMaster	9414T6	Hold the axles in place so they do not slip out of the bearings
2	Threaded Rod	Scrounged	----	Connect the pitching wheel assemblies to the pitching wheel mount and adjust distance between wheels
2	RC Wheel	Scrounged	----	Pitching wheels to launch the crumpled ball
1	Arduino	Scrounged	----	Controls the crumpling motors, pitching wheels, and servo
15	Small components in circuit	Scrounged	----	Complete circuit with arduino
1	Battery	Mark Twain Hobby Center	CSR3S5200-50T	Powers the pitching wheel motors
20	1/4 " Screws	Scrounged	91465A101	Connect the pieces of the machine together
20	Lock Washers	Scrounged	92147A029	Hold the nuts on each bolt
20	Nut	Scrounged	94895A029	Hold the bolts to the piece
8	Rubber Washers	Scrounged	90133A053	Reduce vibration in the mechanism
20	wood screws	Scrounged	-----	Attachment to frame
20	Misc. nuts and bolts	Scrounged	-----	Attachment to frame

Table 8: Part Sourcing Instruction

PART NAME	SOURCE	CAT. #	PRICE EACH	TOTAL PRICE	SOURCING INSTRUCTIONS
FRAME	Scrounged	----	1.00	10.00	Look for wood in discarded pallets or old 2 x 4s. Any size will do, as long as it is free of rot.
LAUNCH ANGLE	Scrounged	----	3.00	6.00	Steel or a similarly strong metal must be used. The pieces here could have been cut from any 1/8 inch thick steel.
LAUNCH ANGLE BASE PLATE	Scrounged	----	4.00	4.00	The base plate must be sturdy enough to hold the angle pieces together without flexing under the weight of the launch barrel and pitching wheel assemblies.

LAUNCH ANGLE ROD	Scrounged	----	3.00	6.00	These can be any rod or bolt that fits through the holes in the launch barrel holder and can support the weight.
LAUNCH BARREL HOLDER	Scrounged	----	5.00	5.00	This must be made of something sturdy enough to hold the weight of the launch barrel and pitching wheel assemblies.
LAUNCH BARREL	Scrounged	----	5.00	5.00	This piece just has to be round, smooth, and hold the weight of the pitching wheel assemblies. PVC would have probably worked fine, but aluminum was light and sturdy.
SERVO GUIDE PLATE	Scrounged	----	1.00	1.00	Any scrap piece of metal of any thickness should work here; just needs to be big enough to block the ball from falling past base of the launch barrel. Aluminum recommended (easy to machine).
SERVO ARM	Scrounged	----	0.50	1.00	Look for easily machined material in shop, size is key here, not support or strength
SERVO	Scrounged	----	10.00	10.00	Look for a machine that can rotate the servo arm assembly. It does not have to be really strong, it just has to rotate about 45 degrees.
CRUMPLER BARREL MOUNTING PLATE	Scrounged	----	3.00	6.00	This is just a simple plate found in the shop. It needs to be thin so that it can be held between cap and washer but strong to be able to securely attach the aluminum barrel. Strong Plastic or metal would be good.
CRUMPLING BARREL SPACER	Scrounged	----	1.00	6.00	The material this is made of is not important. These just allowed us screw the crumpling barrel mount into the wood frame easily at the distance we needed without having exposed screw threads.
CRUMPLER BARREL	McMaster	5038K 452	33.73	33.73	Most important part is inner diameter and length greater than the width of the paper. Should be easy to machine (aluminum). Threads are necessary only if using the mounting system with end caps and washers.
CRUMPLING MOTORS	Amazon	a1203 2000ux 0221	20.00	40.00	http://www.amazon.com/150mA-20-9Kg-cm-Torque-Permanent-Magnetic/dp/B00858SRHC/ref=sr_1_1?ie=UTF8&qid=1448763165&sr=8-1&keywords=dc+12v+150ma+10rpm+20.9kg-cm+high+torque+permanent+magnetic+gear+motor
CRUMPLER MOTOR MOUNTS	Scrounged	----	5.00	10.00	Square pipe worked for this design; motor should fit closely inside the pipe. Steel was used and welded, but the material is unimportant.
CRUMPLING MOTOR L BRACKETS	Scrounged	----	1.00	4.00	Aluminum L-Stock makes for easy machining of holes.
CRUMPLER CRANK ARM	Scrounged	----	4.00	8.00	Metal must be used; steel was used for strength and weldability. Should be thick

					enough (~1/4 in) to push plungers without bending
CRUMPLER CRANK SLOT	Scrounged	----	4.00	8.00	Metal must be used; steel was used for strength and weldability. Should be thick enough (~1/4 in) to push plungers without bending
CRUMPLER PLUNGERS	Scrounged	----	3.00	6.00	Delrin is recommended as it is easy to machine into the desired shape. Stock should be of greater diameter than the inner diameter of the crumpler barrel so it can be machined to a precise tolerance in a lathe.
CRUMPLER BARREL WASHER	McMaster	3185K 117	6.04	12.08	Must match threads and diameter of Crumpler Barrel
CRUMPLER BARREL END CAPS	McMaster	4880K 807	2.21	4.42	Must match threads and diameter of Crumpler Barrel
BEARING MOUNTS	Scrounged	----	2.00	8.00	The thickness is unimportant as long as it is strong enough to withstand bending; thickness and width should be determined based on bearing dimensions
PITCHING WHEEL L BRACKETS	Scrounged	----	1.00	4.00	These must be sturdy, so metal is preferred. All the mounting blocks must be the exact same height and would be best to be the same material to prevent unnecessary vibrations
LEFT SIDE AXLE	Scrounged	----	1.00	2.00	Steel is needed for the axle because it needs to be strong to support the wheel at fast RPM. Just find a small steel rod and machine.
RIGHT SIDE AXLE	Scrounged	----	1.00	2.00	Steel is needed for the axle because it needs to be strong to support the wheel at fast RPM. Just find a small steel rod and machine.
PITCHING WHEEL MOTOR MOUNTS	Scrounged	----	2.00	4.00	This has to be thin, strong metal. Steel or aluminum plates could be used for this of no more than 1/8 of an inch thick so that the motor axle has plenty of clearance.
PITCHING WHEEL BASE PLATE	Scrounged	----	5.00	10.00	Metal must be used for this. It needs to be strong to handle the vibrations from the
PITCHING WHEEL MOUNT	Scrounged	----	5.00	10.00	A regular flat plate of aluminum, though any metal above a 1/4 " thickness will do
PITCHING WHEEL MOTORS WITH ESC	Amazon	B00Z9 QF8U C	40.25	80.50	http://www.amazon.com/GoolRC-Sensorless-Brushless-Electric-Controller/dp/B00Z9QF8UC/ref=sr_1_4?s=toys-and-games&ie=UTF8&qid=1448760685&sr=1-4&keywords=brushless+motor
BEARING	McMaster	8600N 7	17.02	68.08	http://www.mcmaster.com/#standard-mounted-bearings/=100hlt5
SHAFT COLLAR	McMaster	9414T 6	0.98	7.84	http://www.mcmaster.com/#shaft-collars/=100hhog

THREADED ROD	Scrounged	----	5.00	10.00	Can be found in different mechanisms and at most hardware stores, but does not need to be adjustable for this design. Any attachable rod will do.
RC WHEEL	Scrounged	----	5.00	10.00	These can be scavenged from broken RC cars, small vehicles, or made. Any size will do as long as it can attach to an axle that works with the motor.
ARDUINO	Scrounged	----	25.00	25.00	Arduinos can be found at many stores, such as sparkfun, ebay, or amazon. Local electronics stores might have them as well, but it is hit or miss. Any microcontroller would work for this part, however.
SMALL COMPONENTS IN CIRCUIT	Scrounged	----	1.00	15.00	Scrap wire can be found in almost any electronic device, and transistors and resistors can too.
BATTERY	Mark Twain Hobby Center	CSR3 S5200-50T	66.67	66.67	http://www.hobby1.com/Lectron-Pro-5200mAh-50C-11.1v-LiPo-Soft-Pack.html
1/4 " SCREWS	Scrounged	91465 A101	0.10	2.00	Any bolt would work, as long as it can hold tightly on the piece. (http://www.mcmaster.com/#91465a101)
LOCK WASHERS	Scrounged	92147 A029	0.05	1.00	Any matching lock washer would be fine so that the bolt and nut do not vibrate apart. (http://www.mcmaster.com/#92147a029)
NUT	Scrounged	94895 A029	0.15	3.00	Any nut that fits the bolt would be good. (http://www.mcmaster.com/#94895a029)
RUBBER WASHERS	Scrounged	90133 A053	0.23	1.85	Can be found from McMaster-Carr or most hardware stores(http://www.mcmaster.com/#90133a053)
WOOD SCREWS	Scrounged	-----	0.10	2.00	Just find screws that will work with wood that are the right length.
MISC. NUTS AND BOLTS	Scrounged	-----	0.10	2.00	Just find nuts and bolts that will attach various pieces into the frame.

7.2 Final Presentation

7.2.1 Live Presentation

This section intentionally left blank.

7.2.2 Presentation Link

The video recording of the live presentation is viewable on YouTube, at the following link.

https://youtu.be/5decbI8-VGA

7.3 Teardown

The machine was set to be disassembled in the following ways:

- The pitching wheel assembly will be removed from the rest of the device and given to Ashley.
- All large metal pieces, such as the motor mounts, cranks, etc., will be returned to the scrap metal cabinets in the machine shop.
- The wood screws will be removed from the frame and the wooden frame will be disassembled. The wood pieces will be returned to the scrap wood pile in the basement.
- Large nuts and bolts will be returned to their respective boxes and given to the machine shop.
- The plastic PVC and washers will be thrown away (since they have been drilled and modified).
- The rubber washers and spacers and the lock washers will be returned to the shop if they are still in good shape, or thrown away if they are not reusable.
- The electronics that belong to Chase will be returned to him.
- The battery will be given to Chase.
- We will clean up at least one section of the machine shop as requested by Pat Harkins.

This Tear Down was approved by Professor Mark Jakiela on 12/1/15 at 2:35 p.m.

8 Discussion

8.1 Quantified Needs Equations for Final Prototype

Using the quantified needs equations from Section 3.1.3, the Final Prototype was scored at 0.801.This value is slightly lower than the scoring for Concept 1, the selected concept that became the final prototype. This difference between the two scores is due mostly to the size of the final device. The concept design envisioned a 1 foot by 1 foot by 1 foot cubic shape, but the feeding and crumpling mechanism used in the final version was much less compact than the design in order to facilitate the movement of the crumpling arms.

8.2 Part Sourcing Issues

We had a difficult time finding batteries and motors that would work for our system, as the motors needed to have a high enough torque to crumple the paper and the batteries needed to last long enough to power the system. Buying quality parts that would meet our needs would have cost more than our budget allowed, so we looked for cheaper parts on Amazon that nominally met our needs.

One of the two motors arrived defective and the other failed during testing. We saw that the gears were plastic and the teeth easily stripped, indicating that our parts had not come from a reliable source.

Similarly, the batteries arrived defective, with one of the three cells dead.

We had planned to use 8020 Aluminum for the frame, but it was far too expensive, so we settled on a wooden frame.

8.3 Overall Experience:

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

We knew from the outset that our project was ambitious, but doable. At the individual parts level, we ran into more difficulties than we had anticipated. Most of the tolerances for our machined parts had to be very precise; for example, the crumpling wheels had too much play and put too much strain on the crumpling motors. Machining the parts was time-consuming in itself, so having to re-machine parts because they broke, were defective, or did not have a high enough tolerance proved an ongoing struggle for our group.

The initial analysis was not quite sufficient to assist in buying the proper motors – we should have bought better motors and known to budget for a higher price. As it was, the crumpling motors were expected to run at 95% the strain they were rated for. It was somewhat difficult to perform analysis for and purchase motors and batteries when we were not very familiar with them.

Due to the uniqueness of the design itself, it was difficult to find specific codes and standards that related to our device directly. To ensure the safety aspects of the device, codes and standards regarding similar products that could be related to subassembly of our device should be considered. For example, specific codes related to pitching machines, laptop batteries, quadcopters, and other such devices that touch upon some relevant aspect to our design should be reviewed and potentially integrated into our device before our design can be used in the competition.

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

Our final project aligns with the project description, in that it fits what we set out to do. It did not, however, function autonomously or within the time limit. We would have met the requirements of the ASME competition if we had not encountered problems with our equipment.

8.3.3 Did your team function well as a group?

We managed. We were able to work past a lot of hardships and difficulties and power through a high-stress process. There were no terrible fights or absent members. Toward the end of the semester in particular, all four members of the group gave their all to the project and worked together to complete the final prototype on time.

8.3.4 Were your team members' skills complementary?

Yes. We all have very diverse skills. Julian is very good with machining and welding, Chase is good with electronics, Ashley is good at sourcing and physics, and Maria is good at writing/formatting.

Everyone was good at machining and contributed to many brainstorming and troubleshooting sessions throughout the semester.

8.3.5 Did your team share the workload equally?

Yes, for the most part. Ashley did a lot of the early analysis work, and Chase did a lot of the early drawings. But as the project progressed, the workload evened out and everyone worked their fair share.

8.3.6 Was any needed skill missing from the group?

When we began the process, we did not know much about motors or batteries, so we were entering the project without much background knowledge of our key system parts. We researched and performed analysis calculations for both and learned what we needed to know to complete the project. Many gaps in our knowledge were filled by our Very Helpful TA, Ethan Glassman.

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

We worked to the original, since the requirements were very clear. They could not change because it was a competition rule book.

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

No. The rules and regulations were set for the competition and did not change.

8.3.9 Has the project enhanced your design skills?

Definitely. Every single member has increased their proficiency in machining, CAD, background research and part ordering, and working with limited free time to complete large projects by a hard deadline. Going through the design and build process helped us recognize areas for improvement in our schedule, process flow, and specific design decisions.

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

Yes, although in the future we would hope to work on a design project with a bigger budget of both money and time.

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

Most machining projects would have given us pause before, but now we are able to tackle them with ease.

9 Appendix A - Parts List

Table 9: Final Parts List

Number of Parts Needed	Part Name	Part Use
10	Frame	Support
2	Launch Angle	Adjusts the angle of the barrel, welded to base plate
1	Launch Angle Base Plate	Supports launch angle pieces
2	Launch Angle Rod	Holds launch barrel holder in place
1	Launch Barrel Holder	Holds launch barrel at desired angle
1	Launch Barrel	Crumpled ball falls into barrel and is pushed along barrel into pitching wheels
1	Servo Guide Plate	At base of launch barrel, supports servo arm
2	Servo Arm	Connected to servo motor, pushes crumpled ball into pitching wheels
1	Servo	Rotates servo arm
2	Crumpler Barrel Mounting Plate	Supports crumpler barrel and screws into wooden frame
6	Crumpling Barrel Spacer	Supports screws used to attach barrel to frame
1	Crumpler Barrel	Facilitates rolling paper into cylinder; crumpler plungers slide inside
2	Crumpling Motors	Drives crumpler crank arm
2	Crumpler Motor Mounts	Houses and holds crumpling motors
4	Crumpling Motor L Brackets	Attaches mount to frame
2	Crumpler Crank Arm	Attaches to motor to drive plungers
2	Crumpler Crank Slot	Pushes plungers into barrel
2	Crumpler Plungers	Slide in barrel to crush paper into ball
2	Crumpler Barrel Washer	Supports way of mounting barrel to frame
2	Crumpler Barrel End Caps	Prevents plungers from coming out of barrel
4	Bearing Mounts	Lifts bearing to be level with motor axle
4	Pitching Wheel L Brackets	Attaches the bearing mounts to the base plate for the pitching wheel assemblies

2	Left Side Axle	Threads into pitching wheel and connects to motor
2	Right Side Axle	Screws onto left side axle and supports wheel in bearing
2	Pitching Wheel Motor Mounts	Hold the pitching wheel motors to the base plate
2	Pitching Wheel Base Plate	Connects the pitching wheel motors, bearing mounts, and L brackets
2	Pitching Wheel Mount	Hold the pitching wheel assembly to the launch barrel with threaded rods
2	Pitching Wheel Motors with ESC	These motors and speed controllers spin the pitching wheels to launch the paper ball
4	Bearing	The bearings allow the axles to spin freely while attached to frame
8	Shaft Collar	Hold the axles in place so they do not slip out of the bearings
2	Threaded Rod	Connect the pitching wheel assemblies to the pitching wheel mount and adjust distance between wheels
2	RC Wheel	Pitching wheels to launch the crumpled ball
1	Arduino	Controls the crumpling motors, pitching wheels, and servo
15	Small components in circuit	Complete circuit with Arduino
1	Battery	Powers the pitching wheel motors
20	1/4 " Screws	Connect the pieces of the machine together
20	Lock Washers	Hold the nuts on each bolt
20	Nut	Hold the bolts to the piece
8	Rubber Washers	Reduce vibration in the mechanism
20	wood screws	Attachment to frame
20	Misc. nuts and bolts	Attachment to frame

10 Appendix B - Bill of Materials

Table 10: Bill of Materials

Number of Parts Needed	Part Name	Price per Each	Total Price
10	Frame Components	1	10
2	Launch Angle	3	6
1	Launch Angle Base Plate	4	4
2	Launch Angle Rod	3	6
1	Launch Barrel Holder	5	5
1	Launch Barrel	5	5
1	Servo Guide Plate	1	1
2	Servo Arm	0.5	1
1	Servo	10	10
2	Crumpler Barrel Mounting Plate	3	6
6	Crumpling Barrel Spacer	1	6
1	Crumpler Barrel	33.73	33.73
2	Crumpling Motors	20	40
2	Crumpler Motor Mounts	5	10
4	Crumpling Motor L Brackets	1	4
2	Crumpler Crank Arm	4	8
2	Crumpler Crank Slot	4	8
2	Crumpler Plungers	3	6
2	Crumpler Barrel Washer	6.04	12.08
2	Crumpler Barrel End Caps	2.21	4.42
4	Bearing Mounts	2	8
4	Pitching Wheel L Brackets	1	4
2	Left Side Axle	1	2
2	Right Side Axle	1	2
2	Pitching Wheel Motor Mounts	2	4
2	Pitching Wheel Base Plate	5	10
2	Pitching Wheel Mount	5	10
2	Pitching Wheel Motors with ESC	40.25	80.5
4	Bearing	17.02	68.08
8	Shaft Collar	0.98	7.84
2	Threaded Rod	5	10
2	RC Wheel	5	10
1	Arduino	25	25
15	Small components in circuit	1	15

1	Battery	66.67	66.67
20	1/4 " Screws	0.1	2
20	Lock Washers	0.05	1
20	Nut	0.15	3
8	Rubber Washers	0.23	1.85
20	wood screws	0.1	2
20	Misc. nuts and bolts	0.1	2
		Total Cost	**$521.17**

The cost of most parts are approximations, as they were scrounged for use with this device. For the scrounging instructions, please refer to Section 7.1.2.

11 Appendix C - CAD Models

ASME.iam
Base Plate.ipt
Bearing Mounts.ipt
Bearing.ipt
Crumpler Barrel Mounting Plate.ipt
Crumpler Barrel.ipt
Crumpler Crank Arm.ipt
Crumpler Crank Slot.ipt
Crumpler Motor Mount L Bracket.ipt
Crumpler Motor Mounts.ipt
Crumpler Plungers.ipt
Crumpling Barrel Spacers.ipt
Frame A.ipt
Frame B cut.ipt
Frame B no cut.ipt
Frame C.ipt
Frame D.ipt
Frame E.ipt
Frame F.ipt
Frame G.ipt
Frame H1.ipt
Frame H2.ipt
Frame.iam
L brackets.ipt
Launch Angle Base Plate.ipt
Launch Angle.ipt
Launch Barrel Angle Rod.ipt
Launch Barrel Holder.ipt
Launch Barrel.ipt
Left Side Axle.ipt
Pitching Wheel Motor Mount.ipt
Pitching Wheel Motor.ipt
pitching wheel mount.ipt
Right Side Axle.ipt
Senior Design.ipj
Servo Arm.ipt
Servo Guide Plate.ipt
Servo.ipt
Threaded Rod.ipt
Wheel assembly senior design.ipj
Wheel.ipt

12 Appendix D - Arduino Code

```
/*  LiquidCrystal Library - display() and noDisplay() Demonstrates the use a
16x2 LCD display.  The LiquidCrystal library works with all LCD displays that
are compatible with the Hitachi HD44780 driver. There are many of them out
there, and you can usually tell them by the 16-pin interface. This sketch
prints "Hello World!" to the LCD and uses the display() and noDisplay()
functions to turn on and off the display. The circuit: * LCD RS pin to
digital pin 12 * LCD Enable pin to digital pin 11 * LCD D4 pin to digital pin
5 * LCD D5 pin to digital pin 4 * LCD D6 pin to digital pin 3 * LCD D7 pin to
digital pin 2 * LCD R/W pin to ground * 10K resistor: * ends to +5V and
ground * wiper to LCD VO pin (pin 3) Library originally added 18 Apr 2008 by
David A. Mellis library modified 5 Jul 2009 by Limor Fried
(http://www.ladyada.net) */

// include the library code:
#include <LiquidCrystal.h>
#include <Servo.h>

Servo myservo;  // create servo object to control the servo
Servo esc;      // create servo to control pitching wheels (actually electric
speed controller, not a servo)

int pos = 0;    // variable to store the servo position
int motorpin = 9;

// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(10, 11, 5, 4, 3, 2);

void start() {
  lcd.print("  ASME DESIGN   ");
  lcd.setCursor(0,1);
  lcd.print("   CHALLENGE    ");
  delay(2000);
  lcd.clear();
  delay(1000);
}

void crumple(int t){
  lcd.clear();
  lcd.print("   CRUMPLING    ");
  digitalWrite(8,LOW);
  digitalWrite(8,HIGH);
  t = t*100;
  for(int i = t; i>=0;i--){

    lcd.setCursor(0,1);
    lcd.print(i%10000/100);
    lcd.print(".");
    lcd.print(i%100);
    lcd.print(" Sec left   ");
```

```
    //delay(1);
  }
}

void servo(int angle) {
  lcd.clear();
  lcd.print("    PUSHING    ");
  lcd.setCursor(0,1);
  lcd.print("   PAPER BALL  ");
  for (pos = 0; pos <= angle; pos += 1) { // goes from 0 degrees to 90 
degrees
    // in steps of 1 degree
    myservo.write(pos);// tell servo to go to position in variable 'pos'
    Serial.println(pos);
    delay(15);                       // waits 15ms for the servo to reach the 
position
  }
  delay(500);
  for (pos = angle; pos >= 0; pos -= 1) { // goes from 90 degrees to 0 
degrees
    myservo.write(pos);              // tell servo to go to position in 
variable 'pos'
    Serial.println(pos);
    delay(15);                       // waits 15ms for the servo to reach the 
position
  }
  lcd.clear();
}

void pitching(int throt) {
   lcd.print("   PITCHING   ");
   int throttle = map(throt,0,100,0,179); // scale the throttle percentage to 
the pwm signal for the speed controllers
   for(int i = 0; i<=throttle; i+=2){ // step through the throttle values by 
2% every 100ms until the desired speed is reached
      esc.write(throttle);
      lcd.setCursor(0,1);
      lcd.print(i);
      lcd.print(" % Throttle  ");
      delay(100);
      Serial.begin(9600);
   }
}


void setup() {
  // set up the LCD's number of columns and rows:
  lcd.begin(16, 2);
  myservo.attach(6);  // attaches the servo on pin 9 to the servo object
```

```
  myservo.write(0);
  esc.attach(motorpin);
  pinMode(8, OUTPUT);
  digitalWrite(8, LOW);
  start();

}

void loop() {
  //Turn on the display:
  lcd.display();
  //Print a message to the LCD.
  crumple(30); // crumple the paper for 30 seconds

  lcd.clear();
  lcd.print(" PITCHING WHEELS");
  lcd.setCursor(0,1);
  lcd.print("    SPINNING    ");
  pitching(50); //start the pitching wheels and spin them to desired speed
  delay(2000); // wait 2 seconds
  lcd.clear();

  lcd.print("  LAUNCHING IN  ");

  for(int i = 10; i>=0; i--){  //countdown to launch to warn people to clear
front of barrel
     lcd.setCursor(0,3);
     lcd.print(i);
     lcd.print("  Seconds  ");
     delay(1000);
  }
  servo(45);
  lcd.clear();
  lcd.print("    LAUNCHED    ");
  delay(5000); //once the ball has left the barrel, wait 5 seconds and repeat
  lcd.clear();

}
```

13 Appendix E: Analysis

Battery Analysis for Motors									
Pitching Wheel Motor Specs			**Crushing Barrel Motor Specs**				**Battery Specs**		
Max Current	66	A	Rated Current	0.15	A		Voltage	11.1	V
Max Watts	820	W	Rated Voltage	12	V		Minimum Capacity	5200	mAh
Max Voltage	11.1	V					Continuous discharge, C	50	
Cont. Current	45	A							
Burst Current	260	A/10sec							
Battery Life			**Battery Life**				**Motor amps cannot exceed**		
2.36	min	at Max Current	1040.00	min			260	A	
3.47	min	at Cont. Current	17.33	hours					

Torque analysis										
In order to crush the paper is was measured to need 10 lbs for force using an mechanical spring kitchen was approx										
torque=	rxF	r*F*sin(theta)								d=
Torque M/	F*r	when theta=90								r=
Torque ma	2.033727	N*m								
	18	lb*in								
	15.62331	kg*cm								

14 Annotated Bibliography

American Society of Mechanical Engineers, comp. *Student Design Competition: Manufacturing the Future: 2016 Challenge*. Issue brief. N.p.: ASME, n.d. Print.

ASME-issued design competition brief. Lays out, in detail, the design problem and constraints. Also discusses the competition course and parameters. Effectively functioned as our primary source for major design decisions.

Salt, John. "Understanding RC LiPo Batteries." *RCHelicopterFun.com*. RC Helicopter Fun, n.d. Web. 04 Dec. 2015. <http://www.rchelicopterfun.com/rc-lipo-batteries.html>.

A guide to LiPo batteries, including the using the capacity and discharge rating to calculate the battery life and the speed at which current can be drawn from the battery safely.

"Lithium Polymer Batteries." *E-flite* (n.d.): n. pag. Web. 1 Dec. 2015. <http://www.horizonhobby.com/pdf/EFL-LiPoSafetyWarnings.pdf>.

Safety warnings for Li-Po batteries, which are volatile and can catch fire if used improperly. Includes charging, lead shorts, storage and transportation, discharging, and operating temperature.

Jewett, W., and R. A. Serway. *Physics for Scientists and Engineers*. 8th ed. Belmont: Brooks/Cole, 2010. Print.

A comprehensive textbook of general physics material, including projectile motion, torque analysis, kinetic energy analysis, and momentum energy transfer. Useful for performing pre-analysis on the pitching wheel system.

"Projectile Motion with Gravity and Air Resistance." http://www.baranidesign.com/projectile-motion/Projectile-Motion-Acceleration-with-Drag-Resistance.htm. N.p., n.d. Web.

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"Lithium Batteries – Significant Changes on the Way." International Air Transport Association (2007): n. pag. IATA. Web. 1 Dec. 2015. <http://www.iata.org/html_email/car1001654/lithium_batteries.pdf>.

The International Air Transport Association's policy on lithium batteries. Includes very specific instructions for air transport, whether shipping or flying on commercial aircraft.

"ASTM STANDARD FOR TOYS." American Society for Testing and Materials (ASTM), n.d. Web. <http://www.cs.rochester.edu/u/roche/rec.wood.misc/rec.wood.toy_safety>.

These are standards address toys made in America. Standards regarding the safety of the projectiles and what could be launched were considered in our design.

"§3583. Portable Abrasive Wheels." Subchapter 7. General Industry Safety Orders Group 3. General Plant Equipment and Special Operations Article 21. Use, Care, and Protection of Abrasive Wheels. Department of Industrial Relation, n.d. Web

This is California Codes for abrasive wheels. The mounting codes were considered in our design.