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Lacrosse Ball Passing Machine

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Executive Summary

The following report outlines the design and engineering process of a lacrosse ball passing machine that is intended for use in practice settings, both for group and individual workouts. The machine was designed to throw lacrosse balls up to 60 mph, to throw said balls with 80% accuracy, and to throw 25 balls in three minutes with no human effort. Additionally, the machine should be portable, weather resistant, and safe. To accomplish the goals set for this machine's performance, the work was broken into phases. First, a conceptual design phase was completed, during which a final design was chosen from among many options. The final design consists of two horizontal wheels attached to motors that are mounted to a baseboard and backboard. This assembly, along with a housing for lacrosse balls, is fastened to a table, which allows the machine to throw lacrosse balls from a realistic height as well as reducing vibration from the motors. Next, the design was modeled in Solidworks and details were added. Then, the initial prototype was manufactured. After the construction and testing of the first prototype, another design iteration was completed, in which the focus was precision of manufacturing. The final prototype meets the speed and time goals, but fails to meet the accuracy goal.

MEMS 411: MECHANICAL ENGINEERING DESIGN PROJECT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The design goal for this project is to create an automated lacrosse ball passing machine that satisfies the user needs outlined in an interview with Coach Jaeckle and takes into account all pertinent patents and standards. The machine's passing speed, passing accuracy, and resilience were identified as some of the main user needs based on Coach Jaeckle's comments. These needs can be quantified during design testing to ensure that the desired specifications are met. The passing machine should be able to deliver an accurate pass to a player with a realistic speed, angle, and height at regular timed intervals. There are several patents related to similar technologies currently available that have similar functions to this project and can provide insight into how similar design challenges were addressed. These patents include a basketball rebounding machine, a rotating pitching machine, and a ball launcher. Additionally, ASTM standards on the components of this project will aid the design process and provide guidelines to part specifications.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

Existing Designs

Existing Design #1: “The Gun”

The “Gun” is a launching machine used in basketball practices that uses a large net to collect balls as they are shot, feeding them one at a time onto a launching arm that throws the ball with backspin to a prescribed location along the three-point arc. The timing of the launch and the position to which the balls are launched is variable allowing individuals to move from one position to another, or to allow a group of shooters to practice from any position along the arc as the “Gun” rotates with a range of up to 180° [1]

Figure 1: "The Gun"

Existing Design #2: Pitching Machine

The JUG pitching machine uses 3 rotating flywheels to launch baseballs with speeds ranging from 40-90 mph. The multiple flywheels can simulate fastballs, curveballs, sliders, and changeups from left or right-handed pitchers. The machine is approximately 6 feet tall and stands on 3 leg supports. Balls are fed manually to the machine one at a time, requiring two individuals to practice: a pitcher and a batter. The JUG pitching machine does not have adjustable height or angular rotation capabilities because the strike zone is a fixed target area. The power source for the pitching machine is a cable plug-in. [4]

Figure 2: JUG Pitching Machine

Existing Design #3: JUG Lacrosse Passing Machine

The JUG lacrosse ball passing machine uses a single flywheel to launch lacrosse balls to players. The Lacrosse Passing Machine has three heights, 43”, 54”, and 63”, so all ages can practice with the machine. The machine has a 360° swivel as well as adjustable firing angles, so any range within 60 yards can be targeted with accuracy, although range finding requires manual adjustments. The passing machine fires at 60 mph, allowing it to be used to pass to shooters or to fire shots at goalies. A separate ball loading device can be attached, using gravity to feed up to 24 balls into the machine, with a stepping machine to time the automatic release of the balls. [4]

Figure 3: JUG Lacrosse Passing Machine

Related Patents

Patent No. 9,782,658 B2

This patent describes a ball pitching device is something that includes an upper and lower frame as seen in the image below. On the upper frame is a rotation shaft and a pitching unit. The pitching unit uses 2 pitching wheels. There is also a pitching angle adjusting unit to change the vertical angle. There is a second rotation shaft that connects the upper and lower frames to allow horizontal rotation [8].

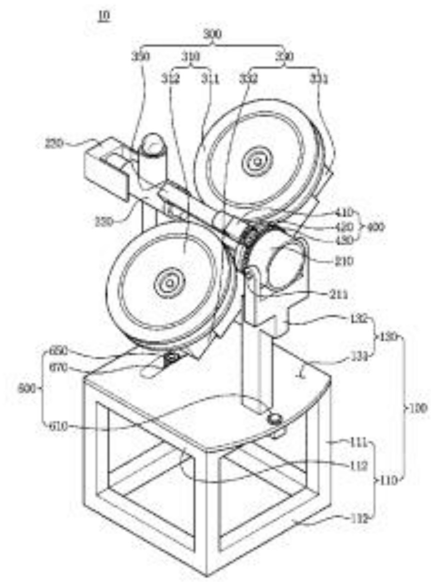


Figure 4: Pitching Machine Diagram

Patent No. 5,776,018

This patent describes a basketball passing machine that include a supply that provides basketballs for some sort of throwing device. This throwing device passes basketballs one at a time in a controlled manner to the waiting player. This machine is used in conjunction with a net assembly that recovers the ball and provides it to the basketball supply. The machine can also vary the pass rate, pass height, and pass speed by preprogrammed commands. [7]

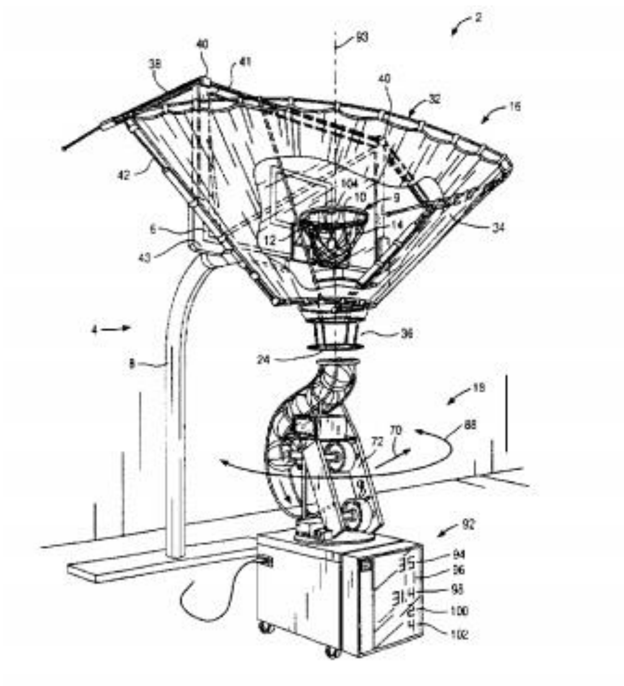


Figure 5: Basketball Launching Mechanism

<u>Standards</u>
Standard 1:
ASTM D430 - 06(2018)

This standard describes various tests to evaluate the deterioration and fatigue properties of rubber under dynamic loads. It describes two distinct tests, one that produces separation through bending and another that produces cracking at the surface through bending or extension. This standard is important for our design as a rubber flywheel is highly likely to be a part of our design and would go through many repeated stresses through compression and rotation. Ensuring minimal wear is paramount.

Standard 2:
ASTM G182 - 13(2018)

This standard describes a test for evaluating if bearings are rolling freely. It specifically deals with breakaway friction, a parameter important for bearings involved in pivoting machines or operations. As we will be attempting to have a product that can launch a ball at almost any angle, the bearing's ability to move freely is important. The standard also notes that manufacturers usually don't supply breakaway friction for their products.

2.2 USER NEEDS

Product: Lacrosse Ball Passing Machine (PM)
Customer: Wayne Jaeckle, Wash U Lacrosse Coach
Interview Date: Sep. 7, 2018

Table 1: Customer Needs Interview

Question	**Customer Statement**	**Interpreted Need**	**Importance Level**
Minimum and maximum speeds	Passes are thrown 60-70 mph for advanced players. About 30 mph for beginning players.	The PM can throw balls between 30-70 mph.	5

What window of accuracy should the PM have?	Ideal: 18"x18" centered above the shooting shoulder. Allowable: 36"x36"	The PM is accurate to an 18" square target zone approx. 6' above ground.	4
What is the preferred method of activation?	Shoot balls at a regular interval would be best for practice. Good workout.	The PM shoots balls at regular time intervals	3
What time would be appropriate between successive passes from the PM?	10 sec. for individual 3 sec. for group	The PM has adjustable time between passes, ranging from 3-10 sec	3
How much ball capacity should the PM have?	The Wash U team has approx. 30 balls. More advanced teams have excess of 100 balls.	The PM should hold at least 25 balls	3
Do you have preferences for powering the PM?	Battery powered is preferred. Players might trip on extension cables, provided that a long enough cable can be found to power the PM.	The PM should be battery powered.	3
How portable should the PM be?	It should be easily moved from one spot to another.	The PM should be portable	3
How long would you spend on setting the machine up each practice?	Most coaches would keep the machine set up at a designated net, so setup is not important.	The PM should have short setup time.	1
Would you have a preferred launching mechanism?	Whatever is the simplest design	The PM should incorporate a simple launching mechanism	4
What conditions are lacrosse played in?	Lacrosse is played in rain and snow	The PM should be weather proof	5
What range do players shoot at?	Far shots are approx. 15 yards	The PM should have a minimum range of 15 yards	5
Would an indicator be useful before the machine fires?	Yup.	The PM should alert the user before the ball is shot	4

Table 2: Interpreted Customer Needs

Number	Need	Importance
1	The PM can throw balls between 30-70 mph.	5
2	The PM is accurate to an 18" square target zone approx. 6' above ground.	4
3	The PM shoots balls at regular time intervals	**3**
4	The PM has adjustable time between passes, ranging from 3-10 sec	3
5	The PM should hold at least 25 balls	3
6	The PM should be battery powered.	3
7	The PM should be portable	3
8	The PM should have short setup time.	1
9	The PM should incorporate a simple launching mechanism	4
10	The PM should be weatherproofed	5
11	The PM should throw balls between 30-70 mph 6' above the ground at a minimum range of 15 yards	5
12	The PM should alert the user before the ball is shot	4

2.3 DESIGN METRICS

Table 3 provides target specifications for 6 measures of the passing machine's performance.

Table 3: Target Specifications Table

Metric Number	Associated Need	Metric	Units	Ideal	Acceptable
1	4	Time between passes	sec	3-10	3-10
2	5	Ball capacity	#	100	30
3	1	Max. launch speed	mph	70	60
4	2	Size of target zone	inch	18x18	36x36
5	11	Length of passes	Yards	15	15
6	2	Height of passes	Feet	6	4-8

2.4 PROJECT MANAGEMENT

Figure 6 shown below depicts our overall Gantt chart for the project.

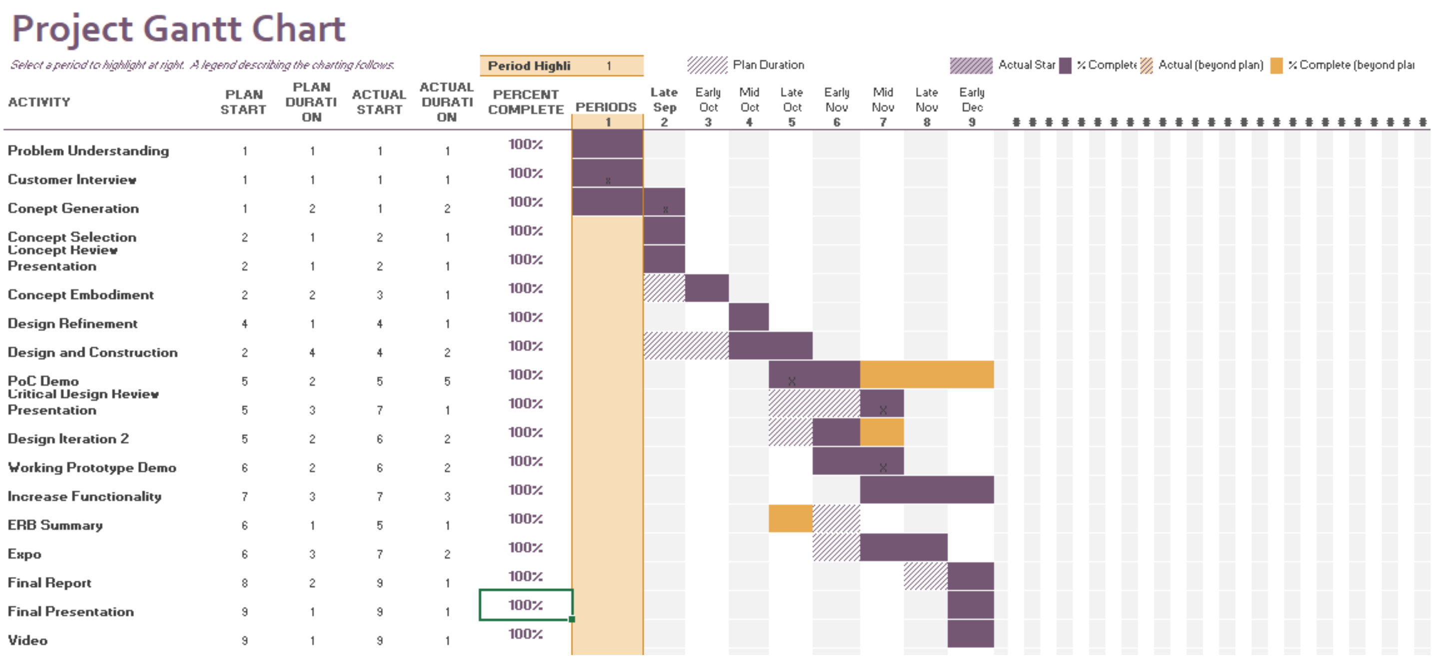


Figure 6 Project Gantt Chart

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

The mockup was helpful in allowing us to get a better sense of how the passing machine should be staged spatially. In particular, we have thought through how the balls should be loaded to the flywheel. Our mockup made us realize we needed some sort of funneling mechanism at the bottom of the ball storage for the balls to all head to the same place. We also came up with the idea of having a stepper motor transport the balls to the launcher. Our mockup used a conveyor belt with horseshoe lifts to move the balls up one at a time to the flywheel. This was one of the mechanism concepts taken into account for our designs. Additionally, the mockup influenced how we thought about balancing the machine. This lead to us considering a variety of supports that could best balance the machine.

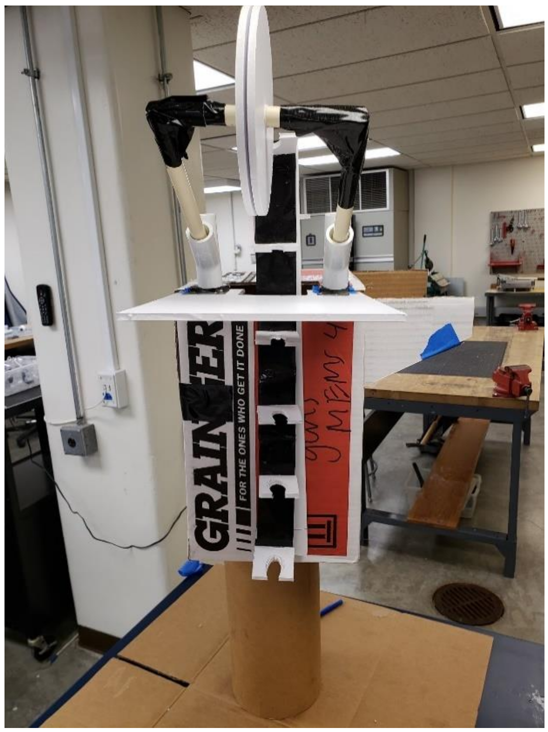


Figure 7: Mockup Front View

Figure 8: Mockup Left View

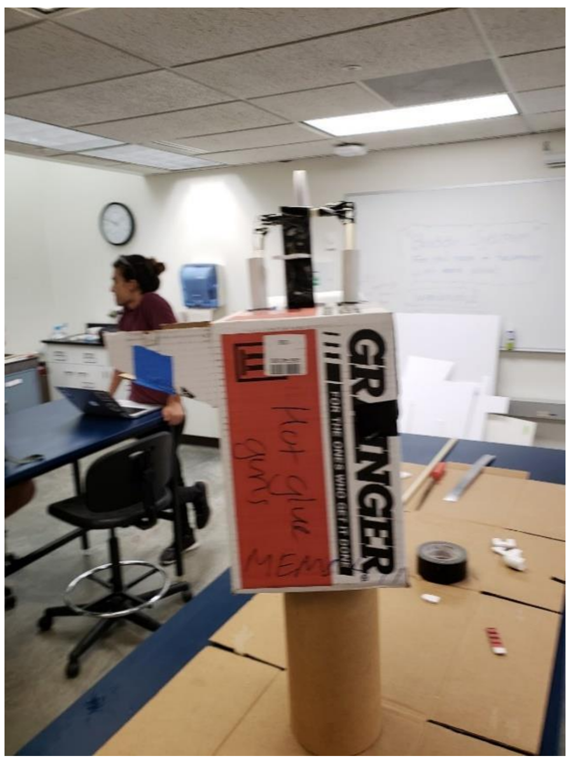


Figure 9: Mockup Back View

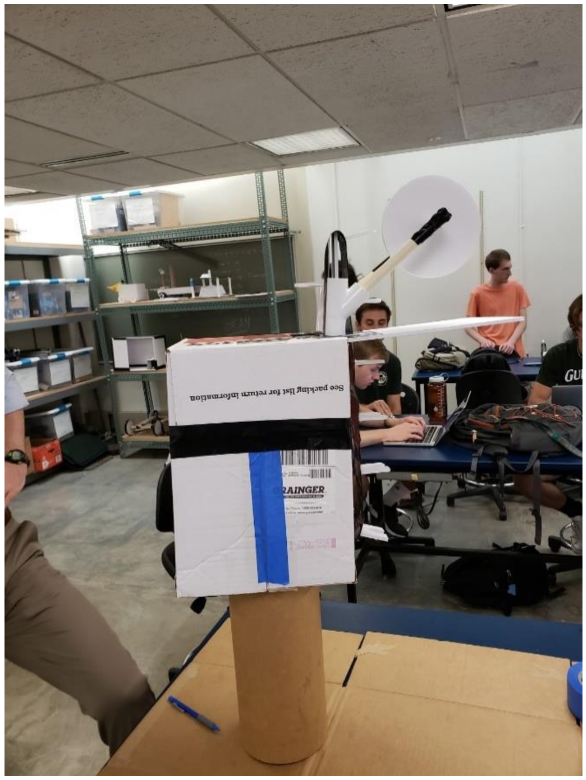


Figure 10: Mockup Right View

3.2 FUNCTIONAL DECOMPOSITION

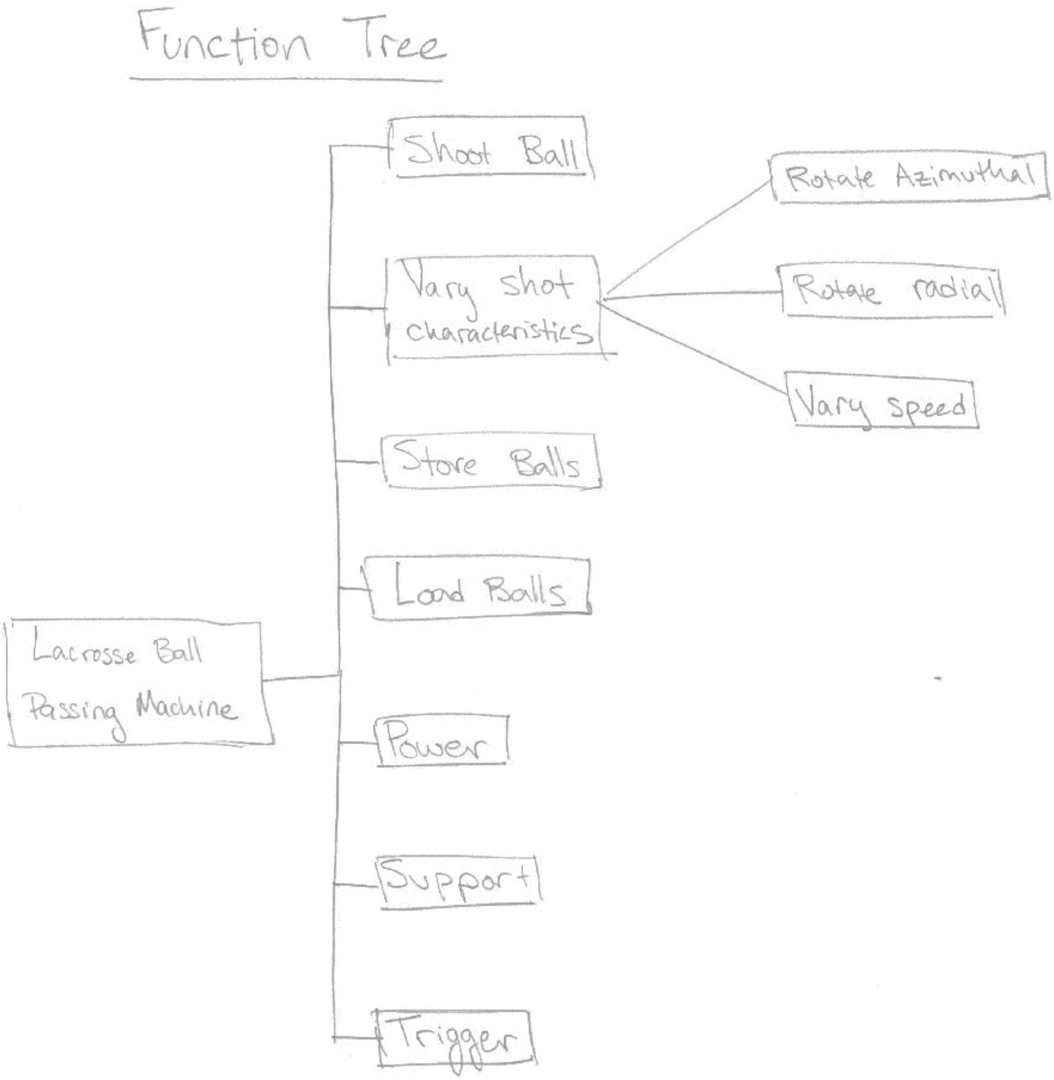


Figure 11: Function Tree

Figure 12: Morphological Chart

3.3 ALTERNATIVE DESIGN CONCEPTS

<u>Catapult Design</u>

The pitching machine uses a catapult-like throwing arm to launch the lacrosse ball instead of a flywheel like our other two designs. The balls are in a large container that is sloped to feed the balls into the catapult's head. There is a mechanized gate that allows 1 ball through at a time, utilizing gravity to load the ball into the catapult. The catapult arm is winched down with a motor and held underneath the gate. Once the ball is in position, the catapult is released, and the torsional spring powering it flings the ball in the desired direction. There is a bar that stops the arm at the appropriate angle. This can be adjusted to alter the angle that the ball is being shot at.

Implements:

- Shooting the ball: Flywheel
- Rotate Azimuthal: Stopper bar
- Rotate radial: Motor
- Ball Storage: Bucket
- Loading Mechanism: Gravity
- Power: Cord
- Support: Box
- Trigger: By hand

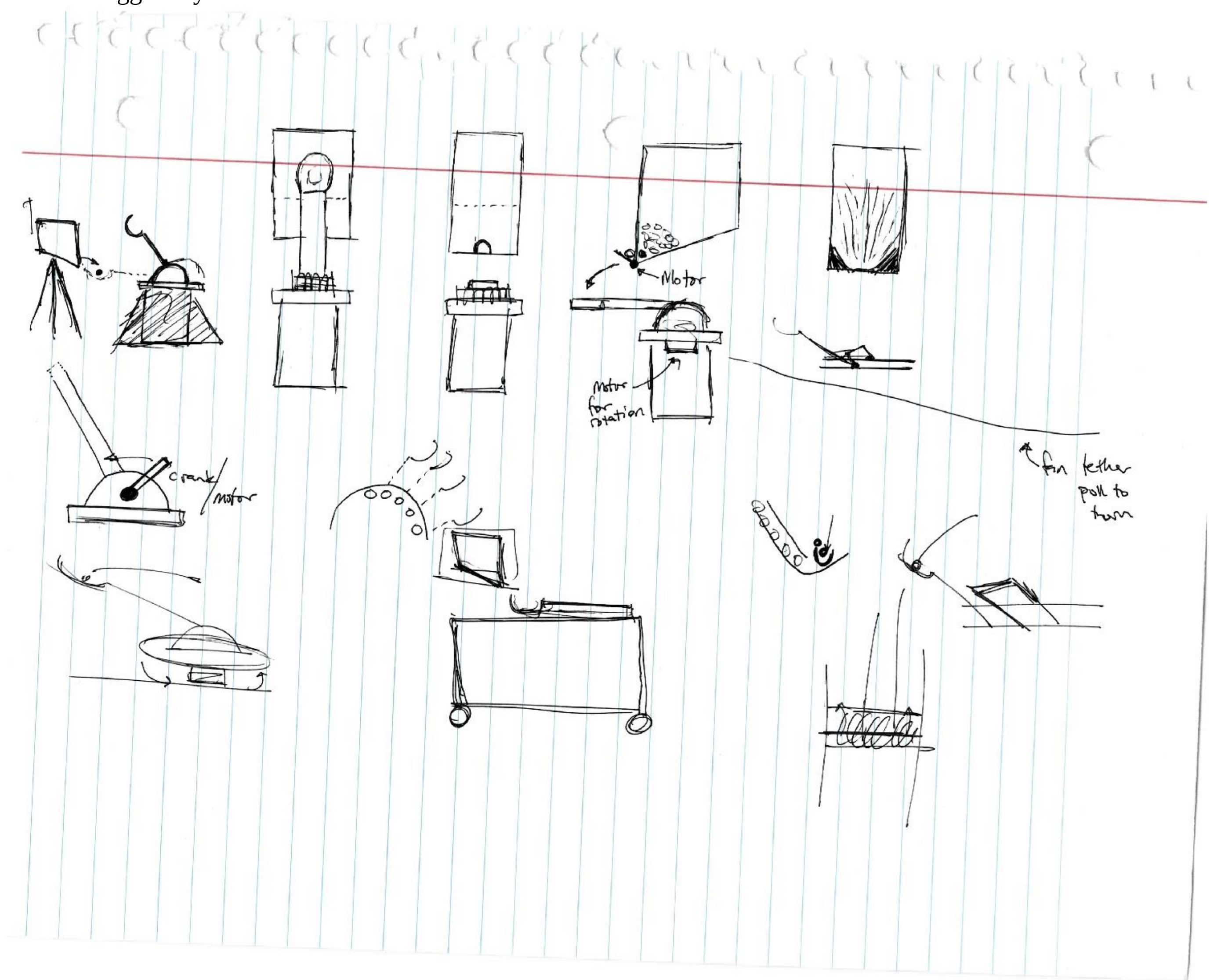


Figure 13: Preliminary sketches for the catapult passing machine

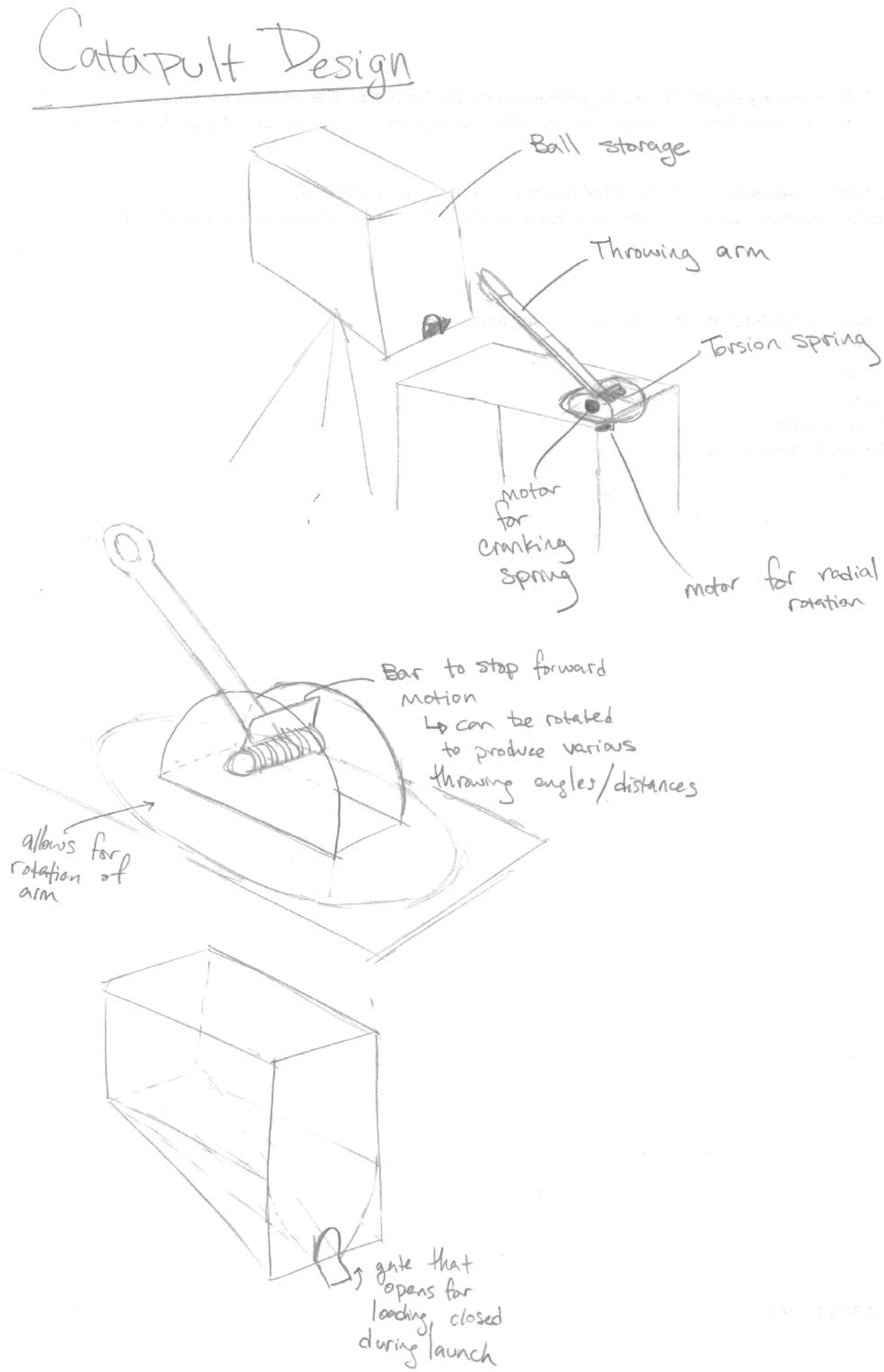


Figure 14: Final sketch for catapult passing machine

Carousel/Ramp Pitching Machine

This battery powered pitching mechanism rests on a double-layered cart. A set of two flywheels rest on a board that allows for azimuthal angle adjustments. A box-shaped container with a sloped floor rests on the second level of the cart, housing a carousel that selects one lacrosse ball at a time. The carousel is powered by a stepper motor, moving the selected lacrosse ball towards a ramp that feeds the flywheels.

Implements:

- Shooting the ball: Catapult
- Rotate Azimuthal: Set steps
- Rotate radial: By hand
- Ball Storage: Bucket
- Loading Mechanism: Carousel
- Power: Battery
- Support: Cart
- Trigger: By hand

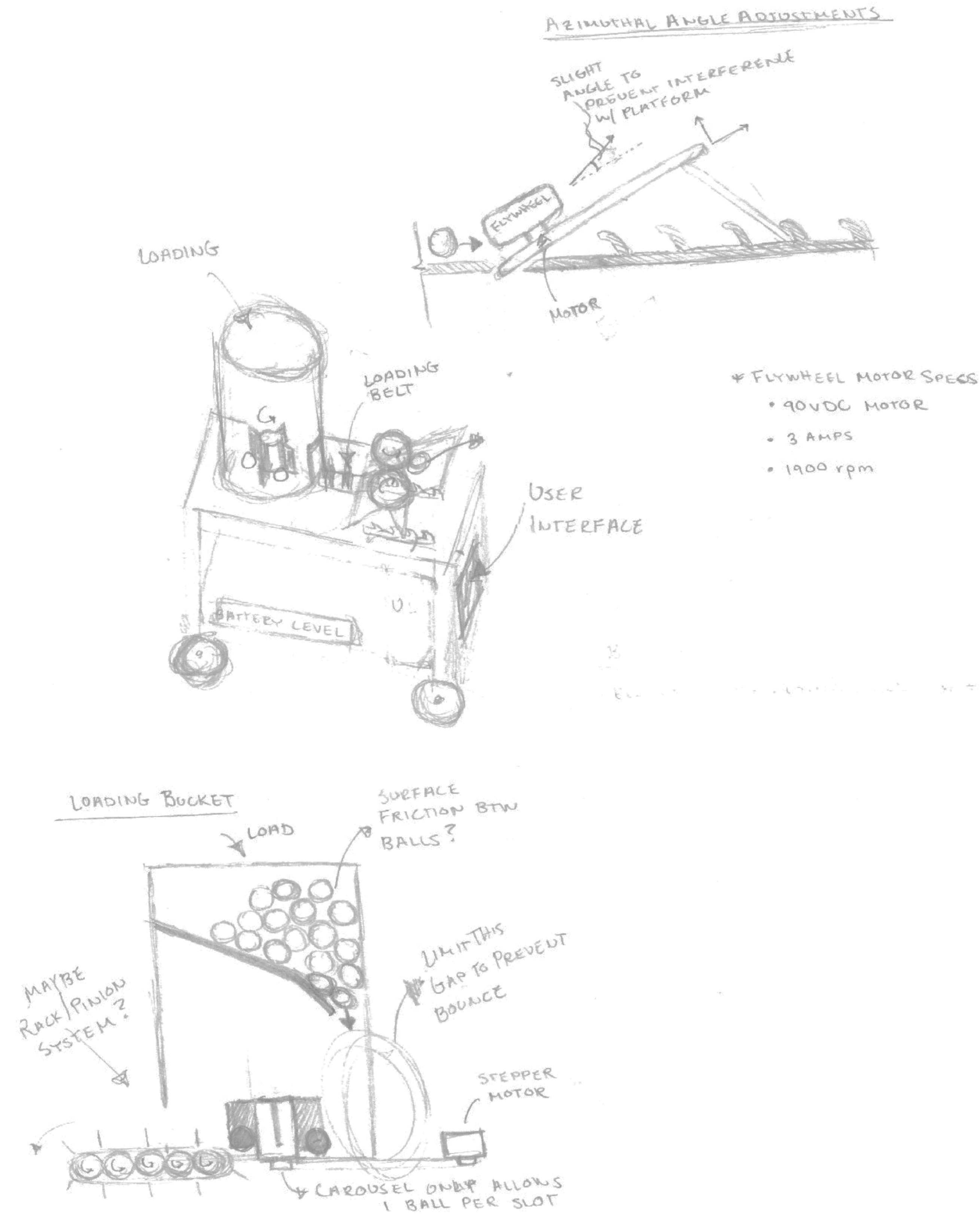


Figure 15: Preliminary sketches for carousel/ramp pitching machine

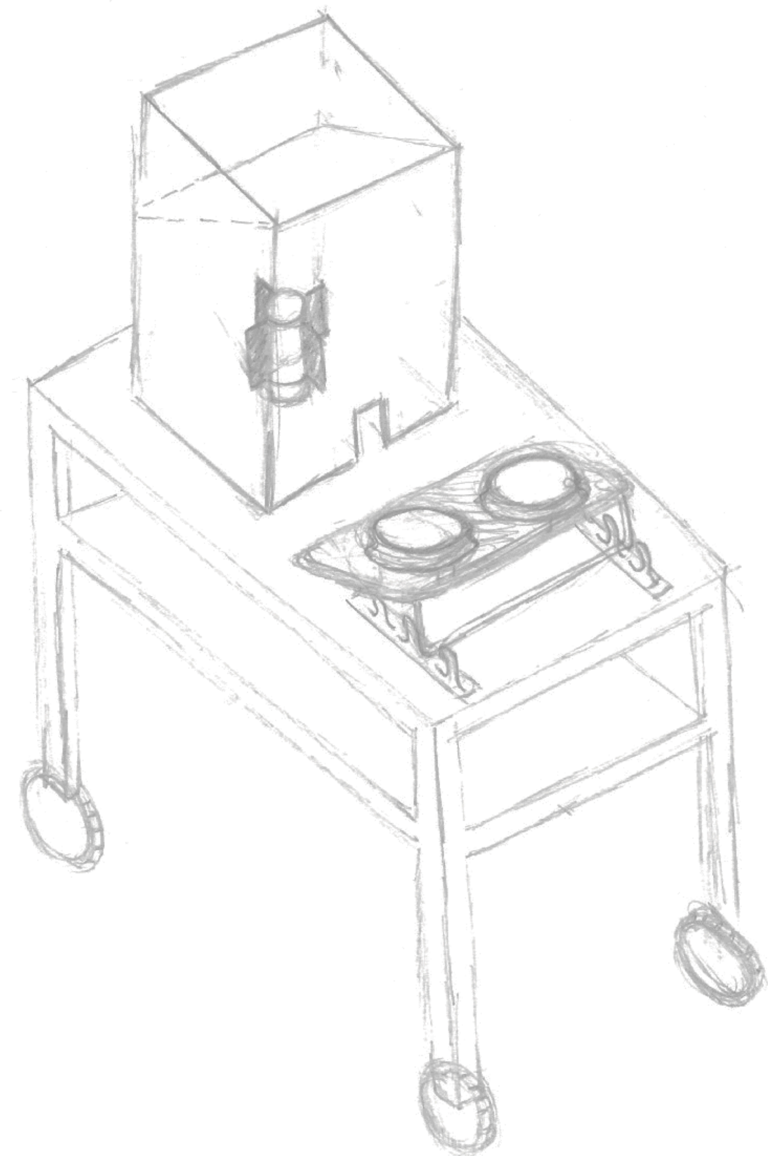


Figure 16: Additional preliminary sketch for carousel/ramp pitching machine

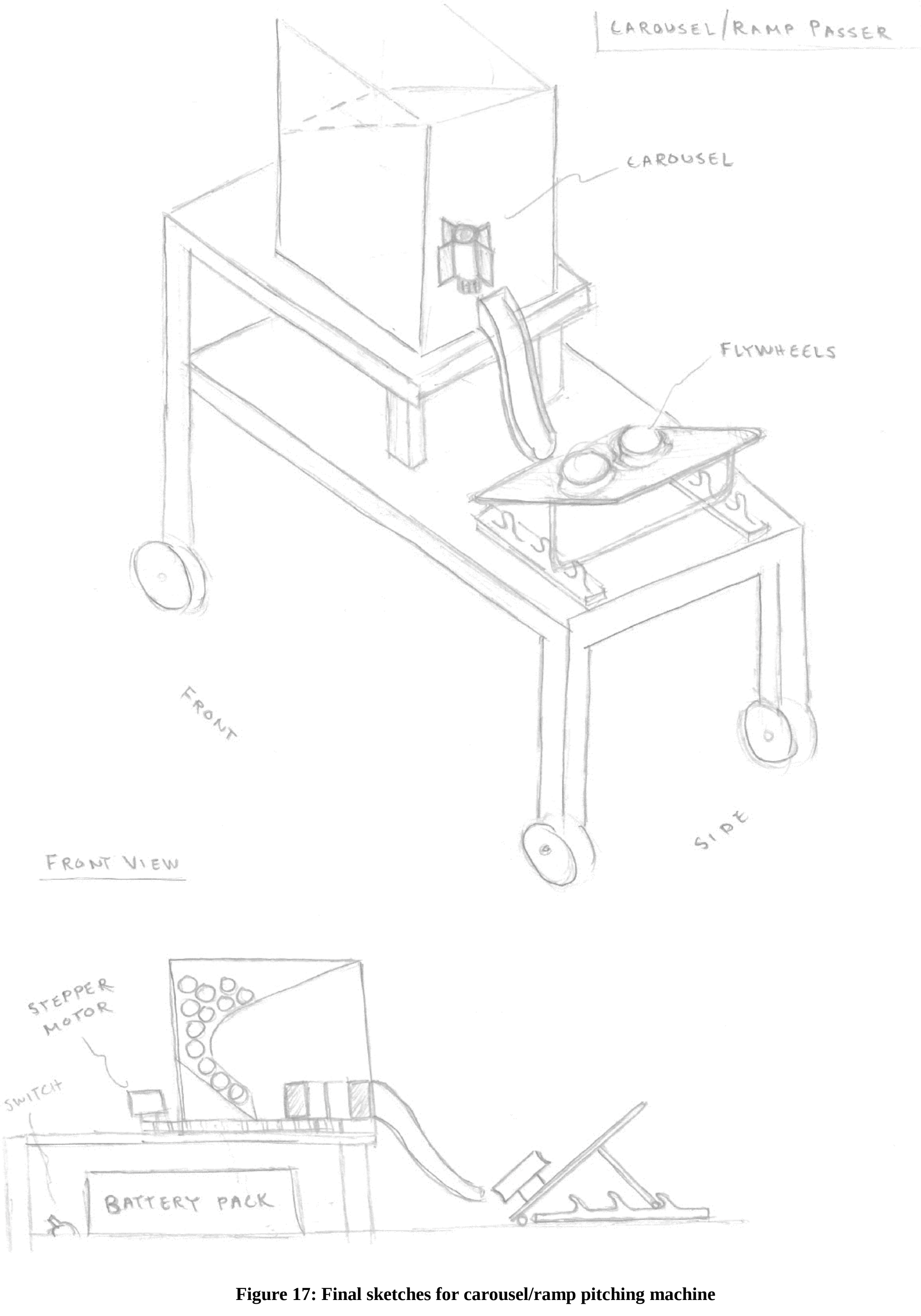


Figure 17: Final sketches for carousel/ramp pitching machine

Tripod Flywheel Pitching Machine

The pitching machine operates by plugging into an outlet using an extension cable. The balls are placed into a vessel that sits atop a motor on the tripod. A stepper operated conveyor belt with horseshoe lifts move a ball up one at a time. The ball is then dropped onto a ramp that goes to the flywheel. The angling lip is above the flywheel and used to angle the ball. There is a counter weight on the back of the machine to balance the machine.

Implements:

- Shooting the ball: Flywheel
- Rotate Azimuthal: Angling Lip
- Rotate radial: Motor
- Ball Storage: Bucket
- Loading Mechanism: Conveyor Belt
- Power: Cord
- Support: Tripod
- Trigger: By hand

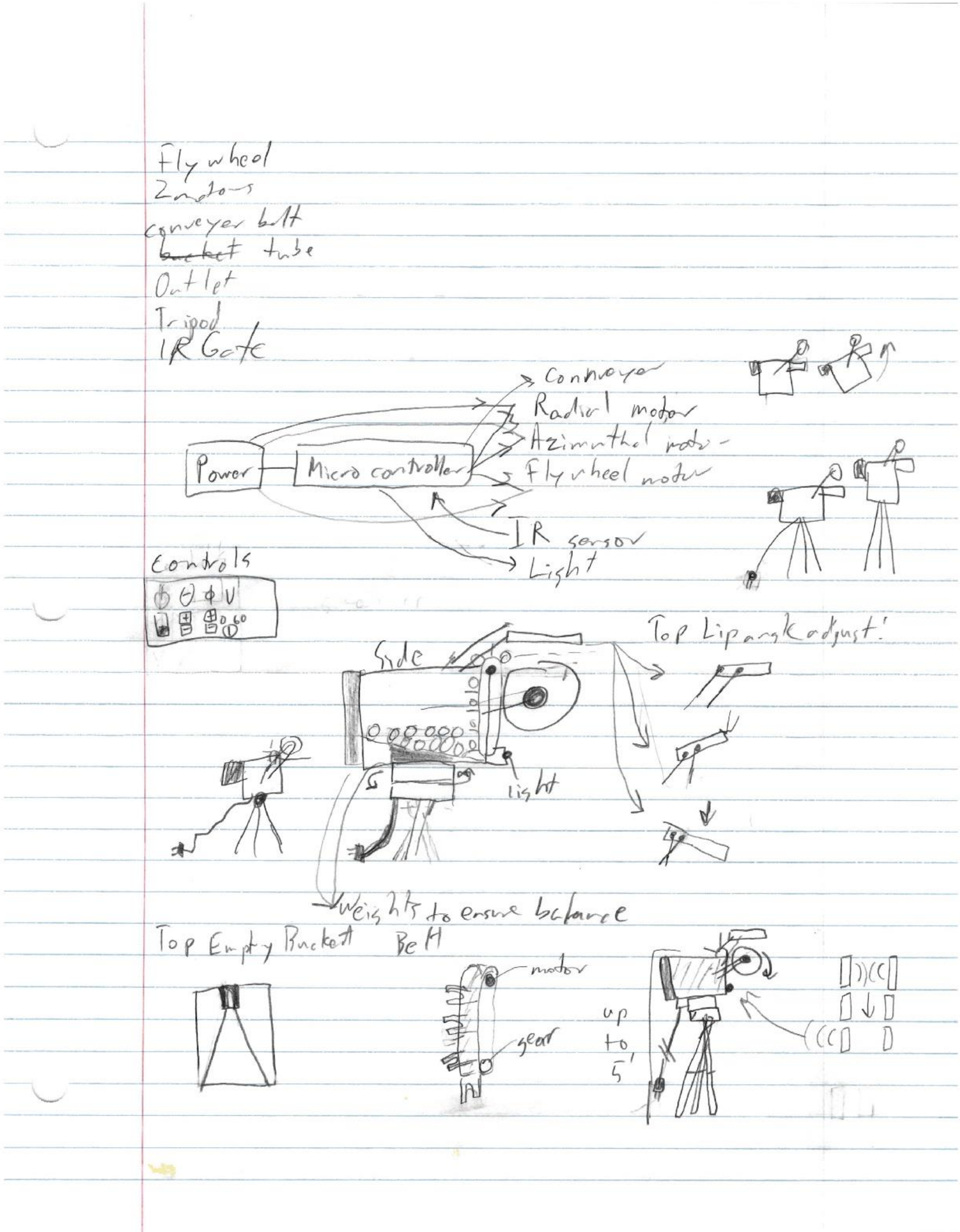


Figure 18: Preliminary sketches for tripod/flywheel pitching machine

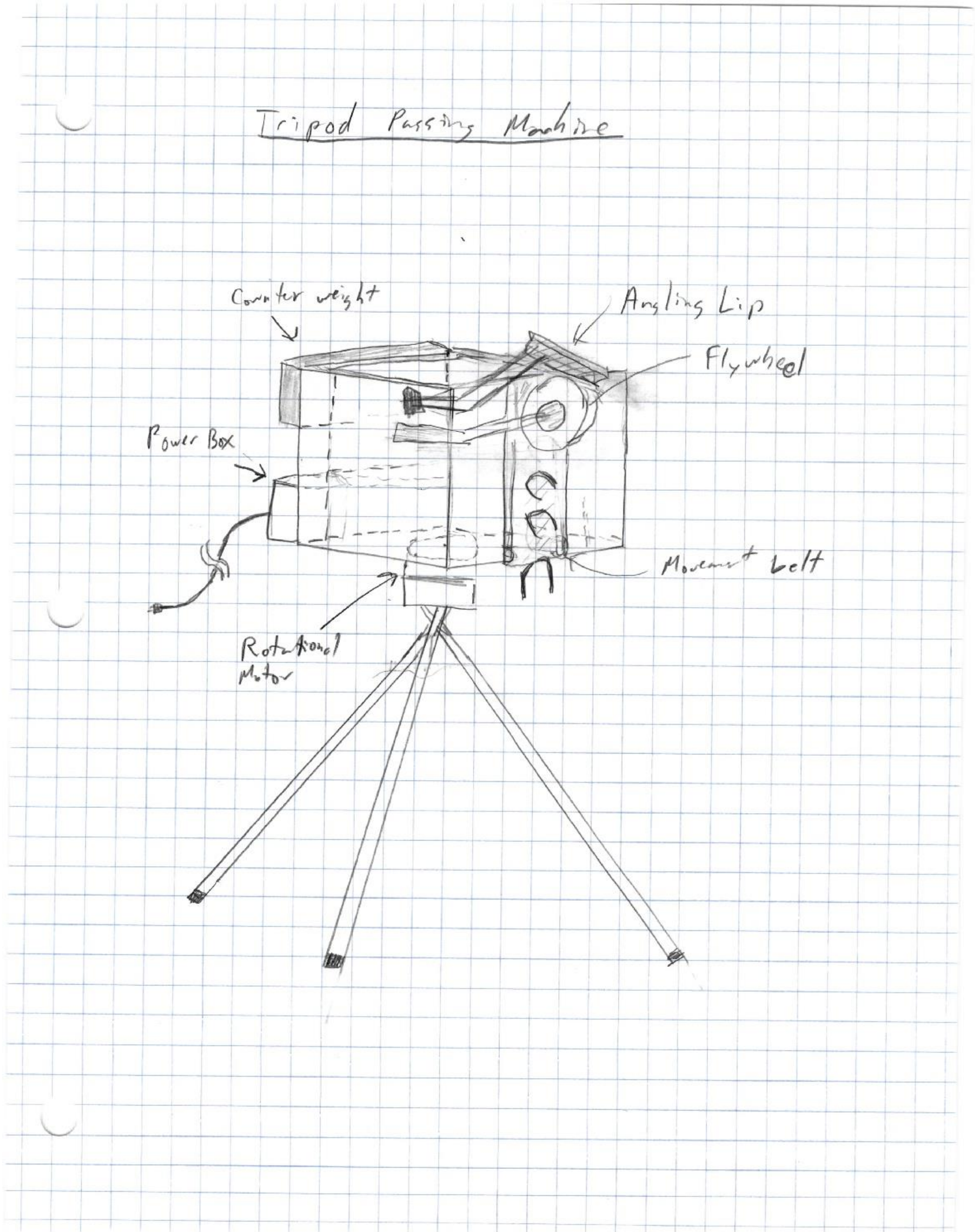


Figure 19: Final sketch for tripod/flywheel pitching machine

4 CONCEPT SELECTION

4.1 SELECTION CRITERIA

Table 4 shows the process, called the analytical hierarchy process, of assigning weights to each design metric.

Table 4: Analytical Hierarchy Process

	Varies the speed of the ball 30-70 mph	Accurate within 18" square target at 15 yards	Regular timed intervals between 3-10 seconds	Safe to the user	Capacity of 25+ balls	Portable	**Row Total**	**Weight Value**	**Weight (%)**
Varies the speed of the ball 30-70 mph	**1.00**	0.33	3.00	0.25	6.00	5.00	15.58	0.21	20.96%
Accurate within 18" square target at 15 yards	3.00	**1.00**	5.00	0.67	4.00	7.00	20.67	0.28	27.79%
Regular timed intervals between 3-10 seconds	0.33	0.20	**1.00**	0.20	3.00	2.00	6.73	0.09	9.05%
Safe to the user	4.00	1.50	5.00	**1.00**	7.00	7.00	25.50	0.34	34.29%
Capacity of 25+ balls	0.17	0.25	0.33	0.14	**1.00**	1.00	2.89	0.04	3.89%
Portable	0.20	0.14	0.50	0.14	1.00	**1.00**	2.99	0.04	4.02%
						Column Total:	**74.36**	**1.00**	**100%**

4.2 CONCEPT EVALUATION

Table 5 shows a weighted scoring metric that uses the weights from Table 4 to evaluate the effectiveness of each of the three design concepts.

Table 5: Weighted Scoring Matrix

		Catapult Design		**Tripod Design**		**Carousel Design**	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**

Varies the speed of the ball 30-70 mph	20.96%	2	0.42	5	1.05	5	1.05
Accurate within 18" square target at 15 yards	27.79%	2	0.56	4	1.11	3	0.83
Regular timed intervals between 3-10 seconds	9.05%	3	0.27	4.5	0.41	5	0.45
Safe to the user	34.29%	1	0.34	3	1.03	2	0.69
Capacity of 25+ balls	3.89%	5	0.19	5	0.19	5	0.19
Portable	4.02%	1	0.04	4	0.16	3	0.12
	Total score	**1.824**		**3.951**		**3.335**	
	Rank	**3**		**1**		**2**	

4.3 EVALUATION RESULTS

The Tripod design received the highest possible score (5) for its ability to vary the speed of the ball from 30-70mph. As flywheels are used in commercial throwing machines that can throw slower and faster than these speeds, the Tripod design can easily throw the ball anywhere in that range. It should also require little guess and check in terms of what RPM settings output the desired speeds. The Tripod received the highest score out of the designs proposed as it utilizes motors to set its azimuthal and horizontal angles. Similar to the prior score, it would also require little calculation to automate a system compared to the other 2 designs. The Tripod received the second highest score of the designs in terms of the ability to fire balls at a regular time interval. The ball selection system used in the Tripod design has potential problems compared to the carousel idea proposed in the Carousel design. This is mostly due to the fact the Tripod lifts balls from the ball storage whereas the Carousel uses gravity and a funnel to order the balls. The safety of this design was also rated highest as its moving parts are the most covered between any of the proposed designs. The capacity of each of the proposed designs could hold the desired 25 balls, and thus each received the highest score. The Tripod also scored highest on the portability as it should be taking up the least space in storage. Although the carousel design should be the easiest to move around a field (it is on a cart), the carousel design would be difficult to transport by car due to its large overall size.

4.4 ENGINEERING MODELS/RELATIONSHIPS

Azimuthal Torque Requirement

This model will be useful in choosing a motor that can raise and lower the angle of the launching mechanism. This project is at risk of running over budget, so a well-designed motor is necessary, given that motors will contribute most of the cost to the project. The motor torque and power are solved for, given assumptions of point loads and idealized geometries. Figure 20 shows a side view of the apparatus with appropriate loads and distances labeled.

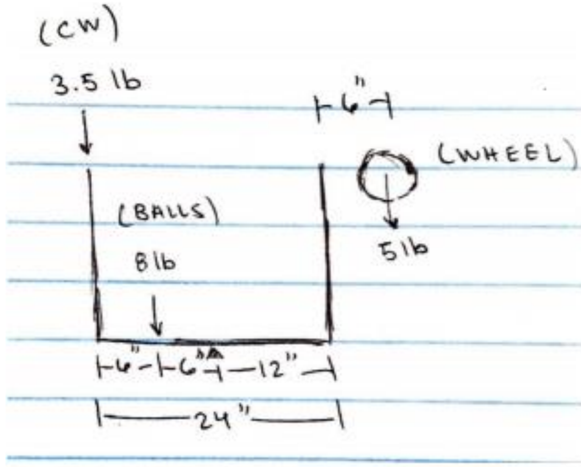


Figure 20: Simplified Loading Scenario of Tripod Design

The torque required a motor to adjust the azimuthal angle of the Lacrosse machine is given by the following equation

$$\tau = I\alpha$$

Before finding an appropriate design value, an assumption must be made to determine the desired value of α. The assumption will be that the machine should rotate through 15° within 1 second. An average value of ω is calculated as:

$$\omega_{avg} = \frac{15°}{1sec}\left(\frac{2\pi}{360°}\right) = 0.262\frac{rad}{s}$$

A constant angular acceleration will be assumed, yielding a plot of ω vs. time that is linear from $0\frac{rad}{s}$ at 0 seconds to $0.52\frac{rad}{s}$ at 1 second.

The slope of $\omega(t)$ is calculated as the angular acceleration, α, and is found to be $0.52\frac{rad}{s^2}$.

Next, moments of inertia must be calculated, by simplifying loads and geometries. The contributions are taken from the selected design, and include the loading box, the flywheel and and the lacrosse balls in the machine .

The hollow, loading box is approximated as a hoop, whose moment of inertia is found as:

$$I_{box} = I_{hoop} = \frac{1}{2}MR^2 = \frac{1}{2}(14kg)(.093m)^2 = 0.651kg\,m^2$$

The wheel, counterweight, and the lacrosse balls are all modeled as point loads, giving the following moments of inertia.

$$I_{wheel} = MR^2 = (2.3kg)(0.21m^2) = 0.483kg\,m^2$$

$$I_{cw} = MR^2 = (1.6kg)(0.093m^2) = 0.149kg\,m^2$$

$$I_{balls} = MR^2 = (3.6kg)(0.023m^2) = 0.0828kg\,m^2$$

$$I_{total} = 1.37kg\,m^2$$

From earlier, the required torque by the azimuthal motor is

$$\tau = I_{total}\alpha = (1.37kg\ m^2)\left(\frac{0.52rad}{s}\right) = 0.71\ Nm = 0.5\ ft\ lb$$

To be conservative, a motor with 1 $ft\ lb$ of torque should be purchased.

Flywheel Motor Speed Specifications

This model will help our team determine that required specifications that a motor must have. This is important, because the flywheel motors will probably be the most expensive component in our machine and knowing the specifications of the motor will allow us to purchase the right motor for our needs. The load and torque are some of the main measurable quantities we need to determine our motor.

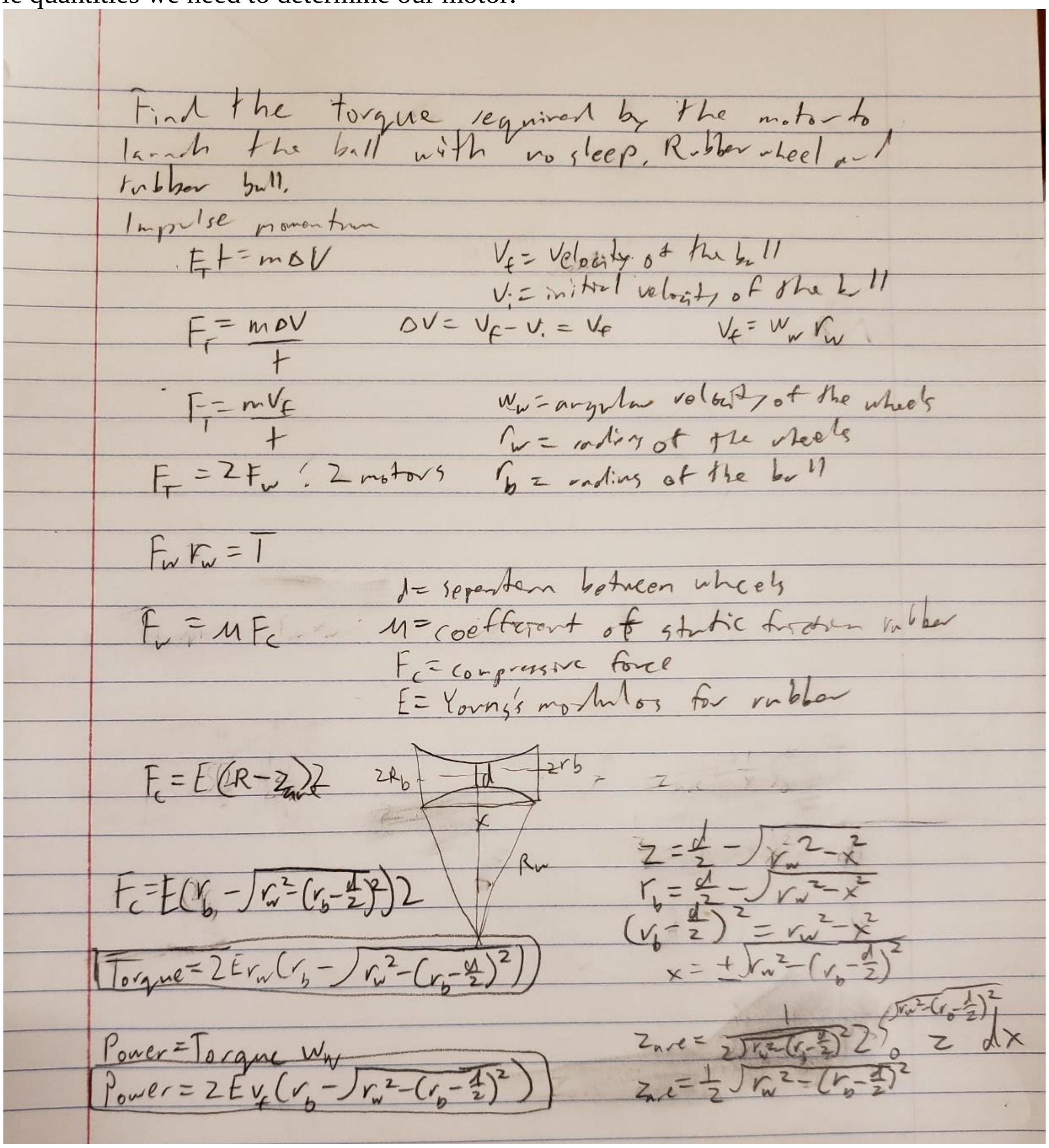
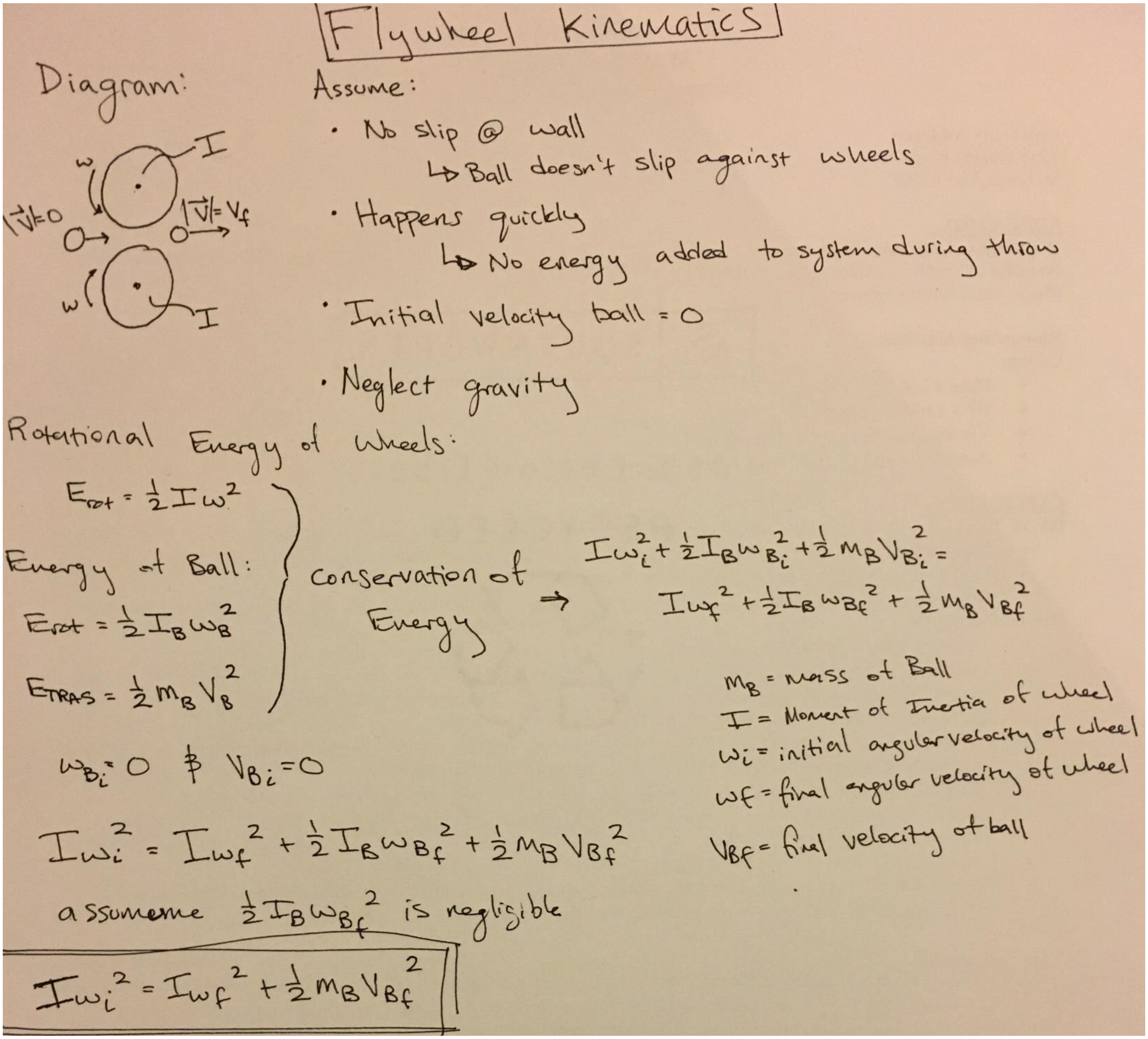


Figure 21: Calculations showing required torque and power for flywheel motors

Flywheel Kinematic Model

This model will allow our team to gain an accurate way of calculating the RPMs needed to throw the lacrosse ball at the desired speeds. The model uses the conservation of energy to account for fact that in a non-ideal system the flywheels would slow once they fired the ball. This fact is important to accurately calculate the velocity of the ball shot as well as the state of the system after the shot, which would be important in determining the cycling ability of a certain design.



Flywheel Kinematics

Diagram:

Assume:

- No slip @ wall
  - ↳ Ball doesn't slip against wheels
- Happens quickly
  - ↳ No energy added to system during throw
- Initial velocity ball = 0
- Neglect gravity

Rotational Energy of Wheels:

$E_{rot} = \frac{1}{2} I \omega^2$

Energy of Ball:

$E_{rot} = \frac{1}{2} I_B \omega_B^2$

$E_{TRAS} = \frac{1}{2} m_B V_B^2$

Conservation of Energy →

$$I\omega_i^2 + \frac{1}{2} I_B \omega_{B_i}^2 + \frac{1}{2} m_B V_{B_i}^2 = I\omega_f^2 + \frac{1}{2} I_B \omega_{B_f}^2 + \frac{1}{2} m_B V_{B_f}^2$$

m_B = mass of Ball
I = Moment of Inertia of wheel
ω_i = initial angular velocity of wheel
ω_f = final angular velocity of wheel
V_{Bf} = final velocity of ball

$\omega_{B_i} = 0$ & $V_{B_i} = 0$

$$I\omega_i^2 = I\omega_f^2 + \frac{1}{2} I_B \omega_{B_f}^2 + \frac{1}{2} m_B V_{B_f}^2$$

assumeme $\frac{1}{2} I_B \omega_{B_f}^2$ is negligible

$$I\omega_i^2 = I\omega_f^2 + \frac{1}{2} m_B V_{B_f}^2$$

Figure 22: Calculations for the exit velocity of the ball after energy is imparted by the flywheels

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

A full assembly of the Solidworks model is shown in Fig. 23 with bubble callouts for each component.

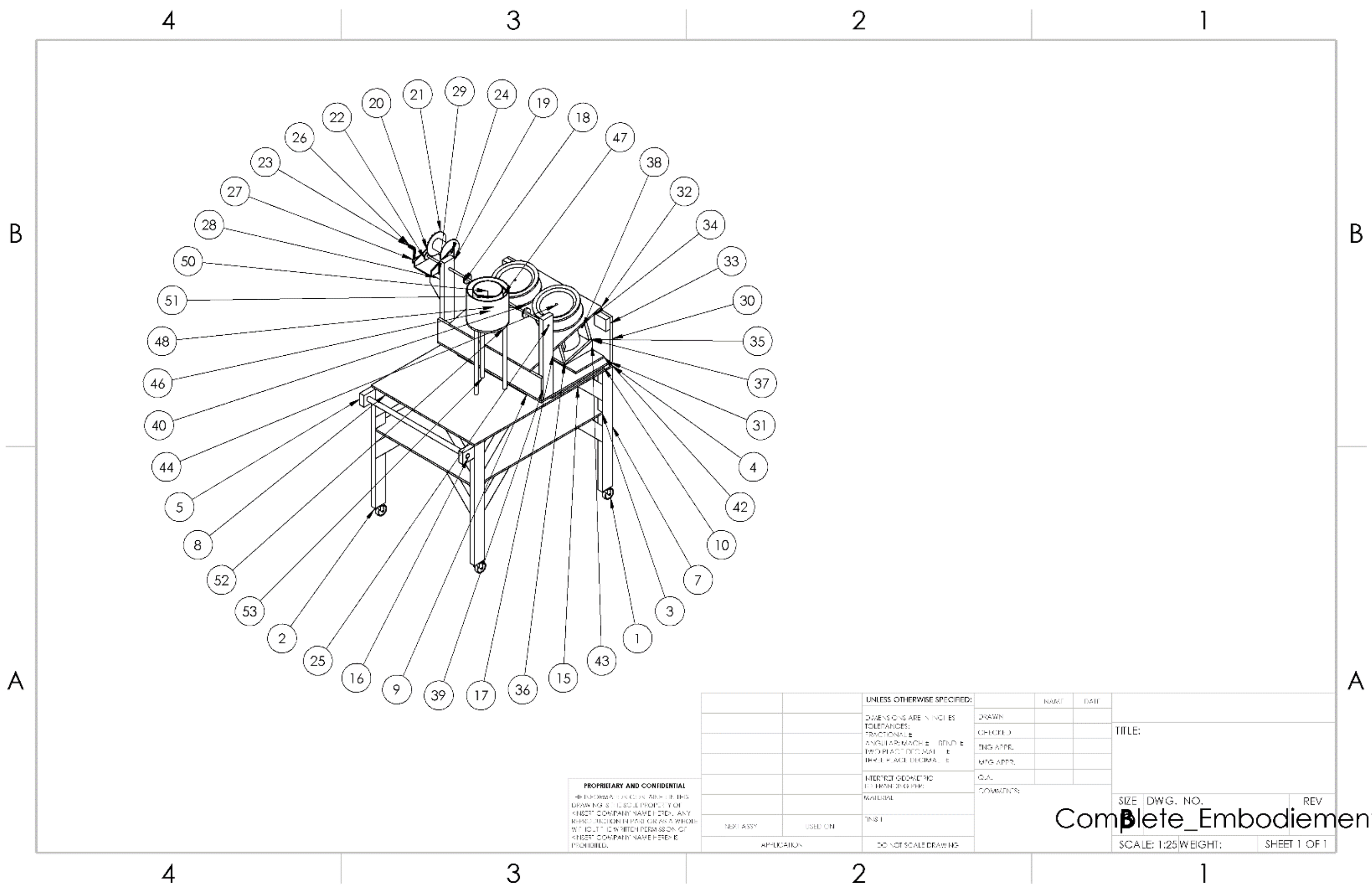


Figure 23: Full Lacrosse Ball Passer Assembly

Table 6: Lacrosse Ball Passer Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	22785T63		2
2	22785T68		2
3	Cart MidShelf		1
4	Cart Top		1
5	Handle_Mount		2
6	Lazy_Susan_Bearing		1
7	Leg		4
8	Brace		16
9	PTFESquare		1
10	Susan Top		1
11	Plunger		1
12	Plunger Hold		1
13	Power_Supply		1
14	Arduino		1
15	Motor_Controllers		1
16	Handle_Cart		1
17	Pulley_Leg		2
18	3434T118		2
19	Base		1
20	Spool		1
21	Large Gear		1
22	Small Gear		1
23	Knob		1
24	Pin 1		1
25	Pin 2		1
26	Knob cover		1
27	Handle_Winch		1
28	Winch Support		2
29	Winch Base		1
30	Mount Support		1
31	Ramp Footprint		1
32	Ramp Surface		1
33	2x4 Rod End		2
34	Rod		1
35	Cupholder Back		2
36	Cupholder		2
37	Cupholder Bottom		2
38	Motor		2

39	Short Mount Support		1
40	Flywheel		2
41	9429T36		2
42	Motor Block Base		1
43	Motor Bumper		4
44	Motor Shaft		2
45	Ball Stop		1
46	Inner Shell		1
47	Loop Tracks		1
48	Outer Shell		1
49	Mini Ramp		1
50	Carousel		1
51	Divider		1
52	Solid Bottom		1
53	PVC Legs		3

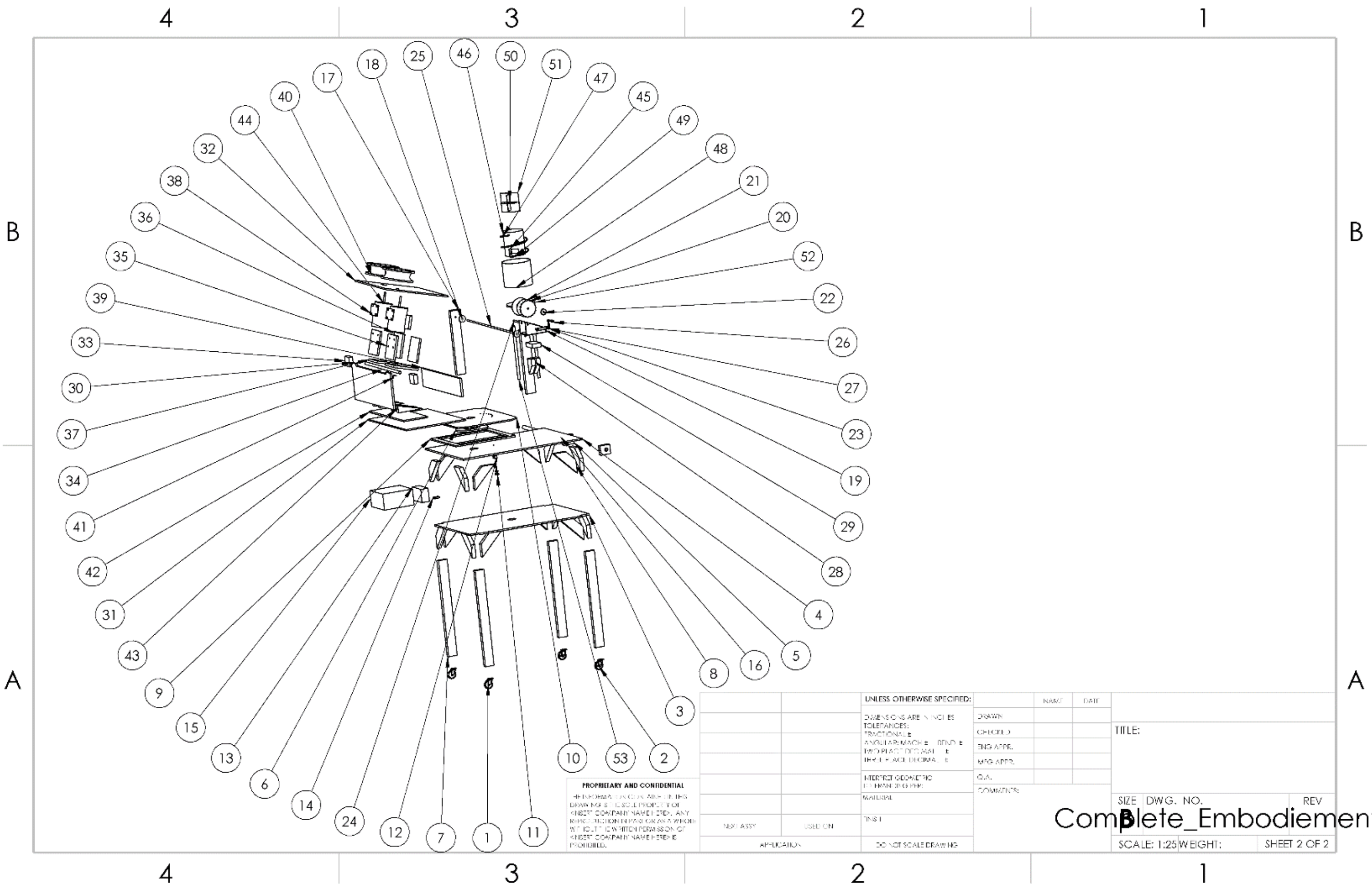


Figure 24: Exploded view assembly with bubbles

Table 7: Parts List with Prices

Item	Quantity	Color, TPI, other part IDs	Supplier Part Number	Unit Cost	Cost	Adjusted Cost
12" Flywheel	2	White Pneumatic	G0819	$101.99	$203.98	$200.00
Flywheel Motor	2	115 V, 1/3 HP, 1750 RPM	E233961	$195.00	$390.00	$0.00
2x4 8'	6	Pine	832150	$3.39	$20.34	$0.00
1/2" Plywood 4'x8' sheet	2	Sanded	454532	$35.95	$71.90	$0.00
Pulley Cord 2'	2	Nylon	4336811248	$0.50	$1.00	$0.00
Pulley	2		3434t118	8.53	$17.06	$17.06
Locking Cart Wheels	2		22785t860	$6.91	$13.82	$13.82
Cart Wheels	2		22785t830	$5.82	$11.64	$11.64
Threaded inserts PLA	1		93365a110	$9.67	$9.67	$0.00
Right angle braces	12	Steel	17715a66	$4.85	$58.20	$0.00
Washers (100)	1		92141a029	$3.37	$3.37	$0.00
Bolts (100)	1		92949a441	$6.09	$6.09	$0.00
Nuts (100)	1		95462a029	$4.40	$4.40	$0.00
Woodscrews (150)	1	Weatherproof	90031a372	$4.85	$4.85	$0.00
Set Screws	1		91375a072	$7.51	$7.51	$7.51
Winch	1			$17.99	$17.99	$17.99
1/2" Tubing	12		702361	$4.93	$59.16	$0.00
Carousel	1	Heavy Fill		$0.00	$0.00	$0.00
Stepper Motor	1		23HS22-2804S	$26.00	$26.00	$26.00
1" Steel Pipe 3'	1		T51	$2.00	$2.00	$0.00
1" PVC Pipe 3'	1		H0400100PW1000	$5.99	$5.99	$0.00
Lazy Susan Bearing	1	12"	9549	$10.20	$10.20	$0.00
Stepper Motor Controller	1		accessory-148	$8.99	$8.99	$8.99
Arduino	1	Arduino Uno	782-A000066	$22.00	$22.00	$0.00
Wires	1		BP-BB-JW350	$13.25	$13.25	$0.00
Surge protector	1		85-382	$3.40	$3.40	$0.00
Extension Cable 50'	1		74050	$34.99	$34.99	$34.99
Total Cost					$1,027.80	$338.00

5.2 PROOF-OF-CONCEPT

5.2.1 Prototype Performance Goals

Our group has three prototype performance goals, which are listed below:

1. LBP can shoot 25 balls in less than 3 minutes
2. LBP can shoot balls at least 60 mph
3. 20 out of 25 shots will be within a 1 sq. yard window, centered 6 feet off the ground 15 yards from the machine.

5.2.2 Design Rationale

When proceeding from the conceptual phase of design to design embodiment, engineering models are crucial to determining selection of components. Under-designed components will not satisfy performance goals while over-designed components will be costly and bulky. Engineering models for motor selection, shaft sizing and tipping prevention are analyzed in this section.

First, a model is created for the selection of a flywheel motor. A differential equation can be derived for the angular velocity vs time of a rotating wheel [5]:

$$J\dot{\omega} = T_s(1 - \frac{\omega}{\omega_f})$$

where ω_f is the no-load speed of the wheel, T_s is the motor stall-torque, and J is the moment of inertia of the wheel. The differential equation is solved for ω:

$$\omega = \omega_f(1 - e^{\frac{-T_s}{J\omega_f}t})$$

With the assumption that 1 second will elapse from the release of a lacrosse ball to the time at which the flywheels have accelerated to $0.99\omega_f$, a motor stall-torque can be calculated, as is shown in Fig. 25. A theoretical torque-speed curve can be drawn as a line between the two points. Potential flywheel motor specifications can be compared against the theoretical torque-speed curve to determine their feasibility. If the motor's rated torque-speed values lie outside of the theoretical curve, the motor will satisfy the project's requirements.

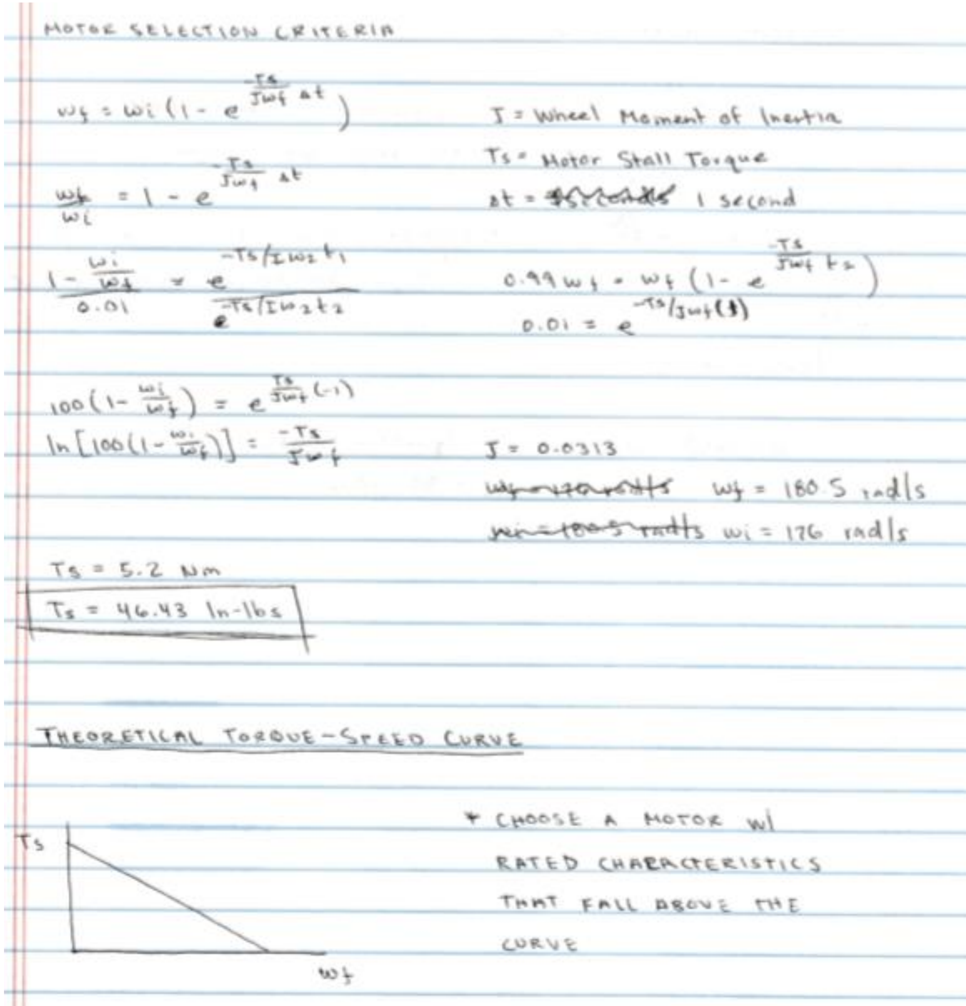


Figure 25: Calculations for determining the required stall torque of the flywheel motors

A second model solves for the forces on a pulley assembly which is located above the flywheel ramp. The forces are used to determine the pulley assembly's ability to withstand tipping, as well as to select angle brackets to fasten the assembly to the main cart. Calculations for the tipping force are given in Fig. 26, showing that tipping forces are minimal when the pulley assembly is located directly above the back edge of the ramp. A tipping force is solved for, from which a moment at the base of the assembly can be calculated.

$$M_{tip} = F_{tip}H = (1.35\ lb)(20\ in) = 27\ lb - in$$

where H is the height of the pulley above the top of the cart. Angle brackets are selected to resist the tipping moment.

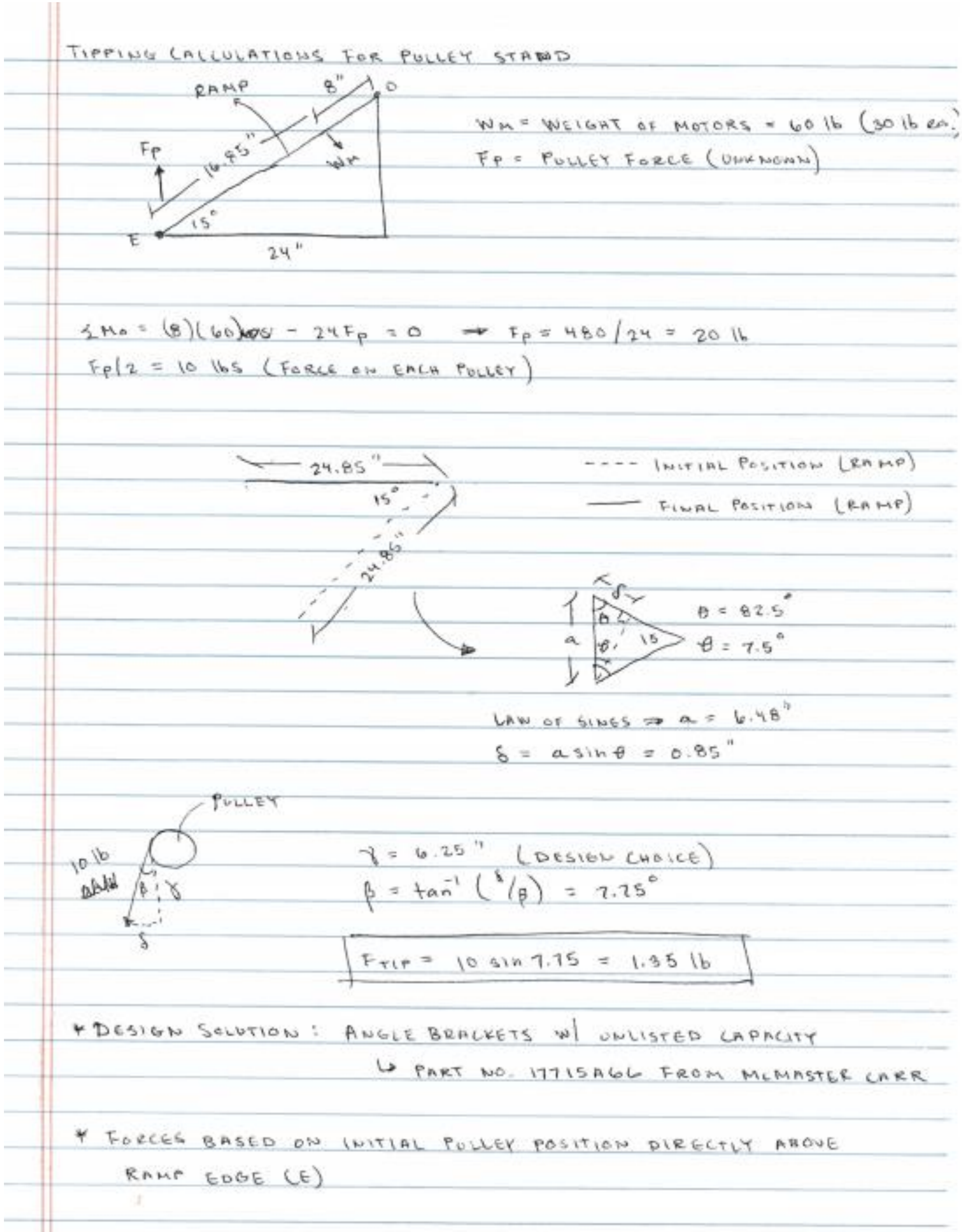


Figure 26: Design calculations for the tipping forces on the pulley stand

A third engineering model is used for the selection of a shaft upon which the ramp rotates about. Note that a tensile yield strength value of 50800 psi was found from MatWeb's online database for mild steel [6]. The calculations of Fig. 27 prove that a 1/2" hollow steel rod will withstand the shear and bending stresses induced by both motors and flywheels.

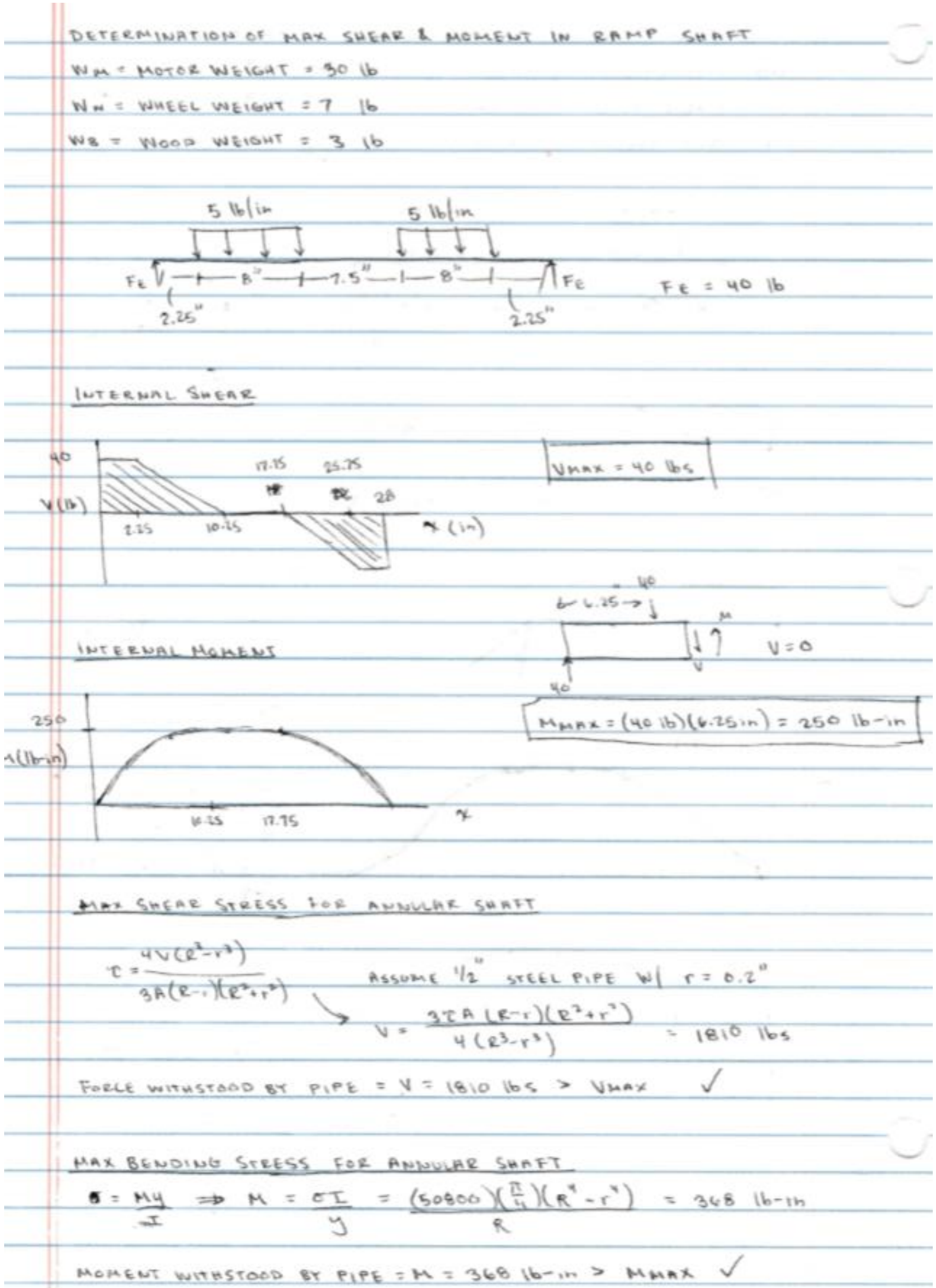


Figure 27: Design calculations for the selection of a ramp shaft to resist the maximum internal shear and moment

6 WORKING PROTOTYPE

6.1 OVERVIEW

At the proof of concept stage, our motors were mounted to a baseboard and backboard, but could only shoot by resting on the ground. To bring our design to the working prototype phase we incorporated a table into the design, upon which the wheel/motor assembly rests when shooting. The table served multiple goals, the foremost being that it allowed the lacrosse balls to be launched from four and a half feet, realistically simulating the height from which a lacrosse player would pass a ball. Additionally, the table serves as a central mounting location for not only the motor/wheel assembly, but also for the ball housing system.

For the proof of concept, our ball feeding system was rudimentary, and we did not have a housing capable of holding 25 lacrosse balls as specified in our performance goals. The proof-of-concept mechanism for filtering loaded balls was a 'carousel' approach (See Fig. 17) that used a stepper motor to push a lacrosse ball. The stepper motor we were using did not have enough torque to overcome the friction between the lacrosse ball and the wood surface upon which the ball rested. Two changes were made to remedy these difficulties. First, we changed our design to replace the stepper motor with a servo motor, the main benefit being that the servo motor had position control. Position control eliminated some issues we were having with the 'carousel' orientation getting out of line when the stepper motor stalled. However, we found that even the position-controlled motor stalled when trying to push the lacrosse ball over wood. To fix this problem, we flipped the manner in which the lacrosse ball was fed into the filtering mechanism so that the balls land on top of the filtering mechanism and roll out as the servo rotates 90. (See Fig. 29)

6.2 DEMONSTRATION DOCUMENTATION

Images of the final working prototype are shown in Figs. 28-30. Figure 28 shows the overall assembly, while Fig. 29 and Fig. 30 show individual components, the ball housing and motor assembly, respectively.

Figure 28 Complete working prototype

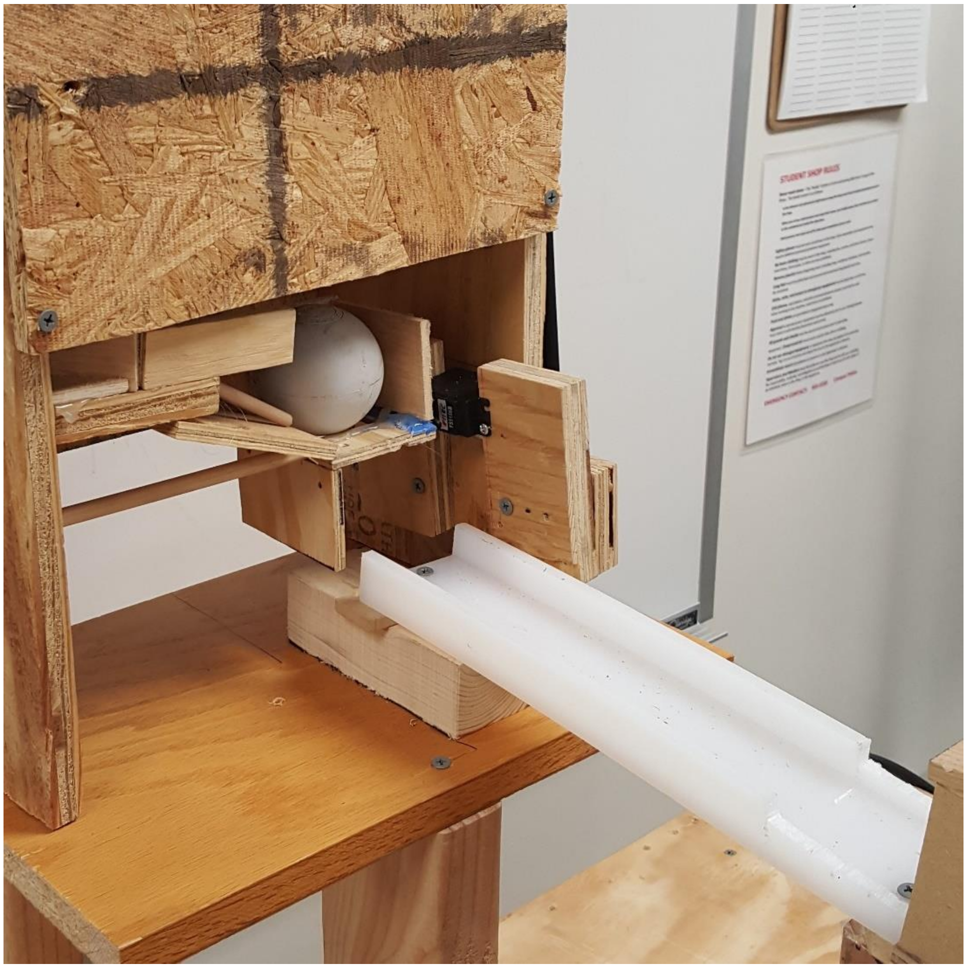


Figure 29 Final ball housing assembly

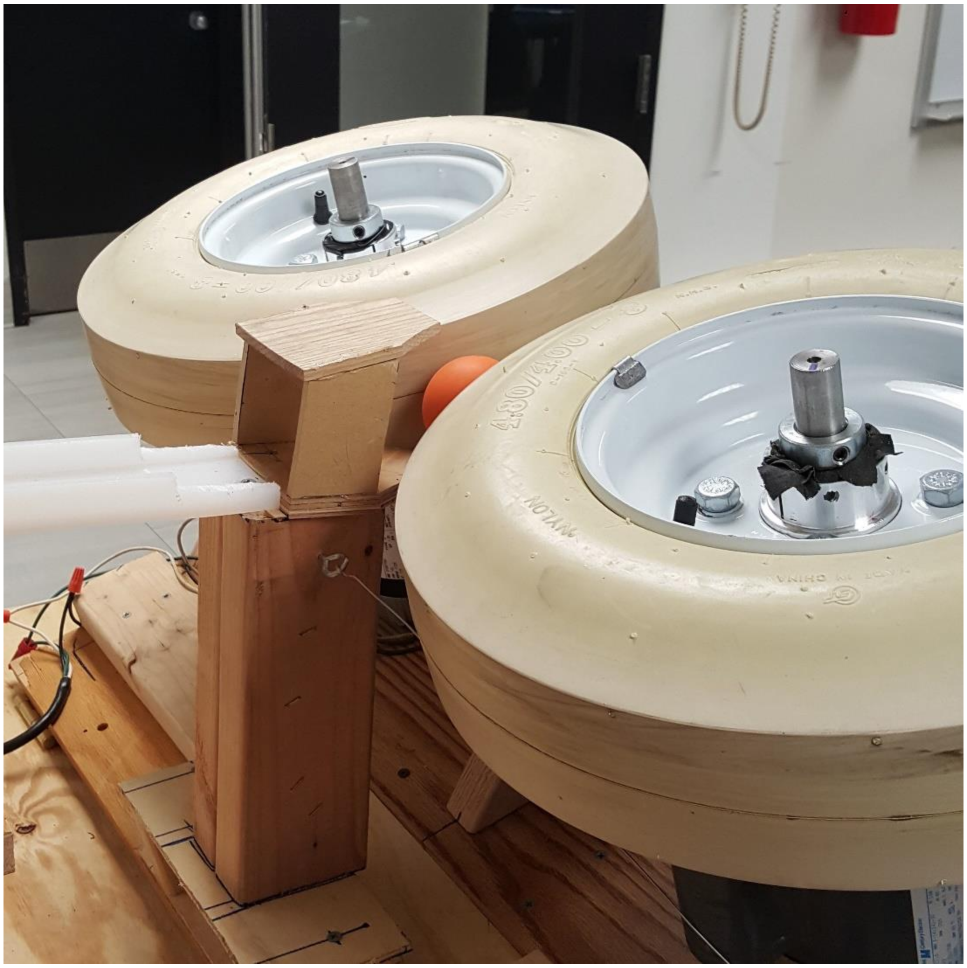


Figure 30 Final wheel/feeder assembly

6.3 EXPERIMENTAL RESULTS

Our first performance goal of shooting 25 balls in less than three minutes was achieved. With an arsenal of 8 lacrosse balls we were able to roll balls down the feeding ramp one at a time and recover balls such that balls were fed through the wheels approximately every three seconds with few intervals of disuse. To mechanize the process of loading the balls into the wheels, we used a ball housing that resembled a spiral staircase inside of which 25 balls could fit. We demonstrated the effectiveness of this device in a video where the housing stands alone but we were unable to incorporate the ball housing into the functionality of the working prototype due to the vibrations of the motors and the instability of our ball housing design, which is seen in Fig. 29.

Our second performance goal of launching a lacrosse ball at 60 mph was met, albeit not every shot. Using a frame by frame analysis for a ball with a launch angle of 15 degree we determined that when the lacrosse ball exits the rotating wheels at the designed trajectory, it travels 88.2 feet per second, or 60 mph. However, due to the sensitivity of the cantilevered feeding mechanism, shown in Fig. 30, the lacrosse ball sometimes exits the wheels at an angle with respect to horizontal that exceeds the 15-degree design angle. Compounding the sensitivity of the cantilever to the motor vibration is the curved profile of the flywheels. If the lacrosse ball enters the wheel slightly misaligned from center it will loft into the air, following the path of least resistance between the two wheels.

Our third performance goal was to strike a 1 sq. yd. target that is centered 6 feet off the ground at a distance of 15 yards from the firing mechanism 20 out of 25 shots. We did not meet this performance goal. For reasons previously discussed, the lacrosse balls do not always exit the wheel with the desired trajectory, thus reducing the accuracy of the shots.

Additionally, the 15-degree angle of inclination seems to exceed the angle that is required to hit the target. As a result, many shots fly over the target at a height of approximately 10 feet at 15 yards from the launching machine. Instead of accurately shooting 20 balls out of 25, we hit the target 10 times out of 25 shots.

7 DESIGN REFINEMENT

7.1 DESIGN FOR SAFETY

Risk Name: Free moving wheels
Description: The freely moving wheels are spinning very quickly and have no way to slow down besides air friction and the friction of the motor bearings. With no way to stop the wheels in case of disaster, this is a large liability in our design. Most likely no one will put a hand in the wheels, but it is more of a problem when something breaks nothing can stop these things and further damage will occur.
Impact: Significant. If there were to be a problem with the device where further use would result in damage, the wheel will go through several thousand revolutions before approaching a stop. This would cause further damage and cannot be reduced
Likelihood: High. Only if something were to happen/break. Which is likely due to the other safety considerations of the device. Catching clothing or body parts is also a consideration.

Risk Name: Set screw Slippage
Description: Currently the set screw connecting the shaft adapter to the motor shaft is done through the use of a ¼" set screw screwed against the flat side of the "D" profile of the motor shaft. All of the shear of the wheels is focused on this one connection, and during testing it was already loosened, causing the device to not even spin properly. It also causes slight damage to the motor shaft when free rotating about the shaft adapter (which it should not be doing).
Impact: Moderate. The long-term damage on the motor shafts is small and will likely not affect the performance of the device. However, the device cannot function without constant retightening in its current state.
Likelihood: High. It has already happened due only 5 min of running the device, so is very likely to happen again without a design change.

Risk Name: High power draw
Description: The motors draw a combined 7 A of current when in use. This could cause the tripping of circuit breakers or destruction of wall outlets. The destruction of key outlets will hamper the use of the design as well as require time and money.
Impact: Mild. This will not damage the device but will damage the surroundings.
Likelihood: Low-Medium. Standard circuit breakers can withstand 15-20 amps, so as long as the circuit behind the wall is not also attached to too many other appliances, we should be ok.

Risk Name: Support Failure
Description: This is the failure of the wood structure holding the motors in place. There are high forces on the ball when fired and thus the supports need to counter that force. Also, the fasteners connecting the motors onto supports are too small to provide maximum safety.
Impact: Catastrophic. If a motor were to become detached from the support while the wheel was spinning, it could throw itself across the room, injuring people in its path and damage both the motor and the wheel. We would have an insufficient budget to proceed with the project.
Likelihood: Low-Medium. The supports withstood the initial tests, and no further testing will be done until the fasteners and supports are of higher quality. Also, the wheels are well balanced, preventing too much rotating imbalance.

Risk Name: A shot ball
Description: The device is supposed to shoot a ball at almost 80 mph, and anyone standing in front of the device would be hit.
Impact: Insignificant. The impact on the device would be insignificant except if there was a bounce back that caused the ball to return to the machine, where the returning ball could possibly damage it. The largest impact is on the person hit, though is not exceptionally dangerous unless within 10 ft of the device. The most likely result would be a bruise but not broken bones. If the ball hits a person in the head then there could be serious damage.
Likelihood: High. People will be hit with the ball because that is where you are supposed to stand when using the machine.

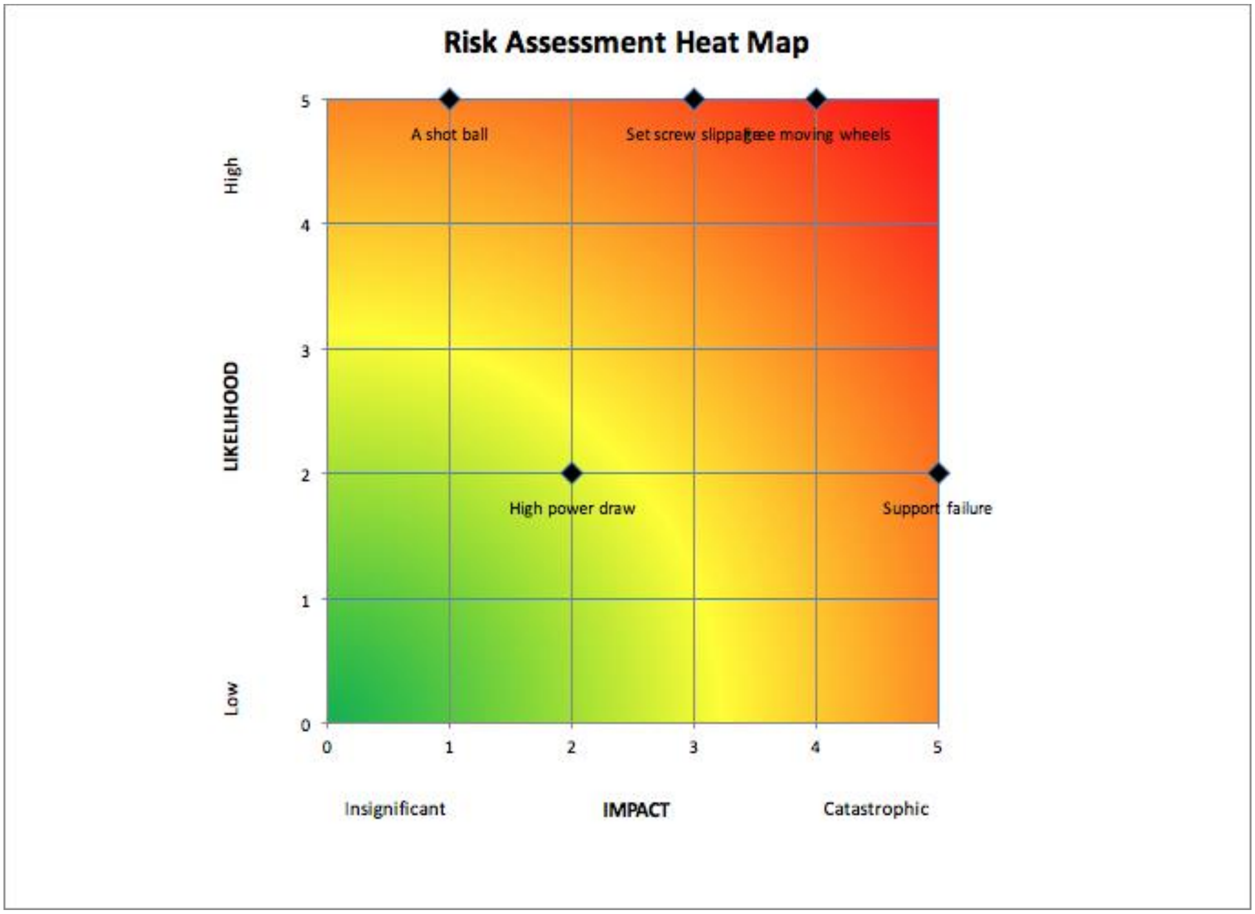


Figure 31: Risk Assessment Heat Map

The highest priority risk should be the freely moving wheels as they can cause great damage to their surroundings. Before the wheels should be tested again, a brake needs to be designed and made. The set screw slippage is the next priority, as the device can be tested but would need constant maintenance. It also will require the most work to correct and so should be tackled as early as possible. The support failure, though potentially the most dangerous, most likely will not happen (especially when the set screw is fixed) and thus reduces the priority of its fixing. That being said, the base needs to be redesigned for the final so will be made better than the mockup it is. Lastly, the power draw will only be a concern if there are multiple other high draw applications coming from the same circuit, such as 2 or more machines operating at 1+ hp. This is unlikely on wall outlets away from shops and thus should be okay.

7.2 DESIGN FOR MANUFACTURING

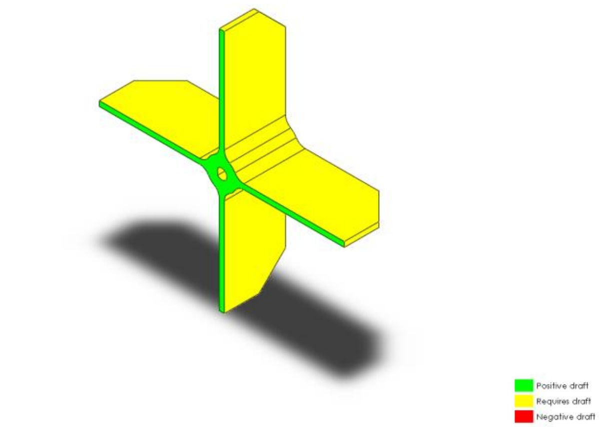


Figure 32: Sample Part Before Draft Analysis

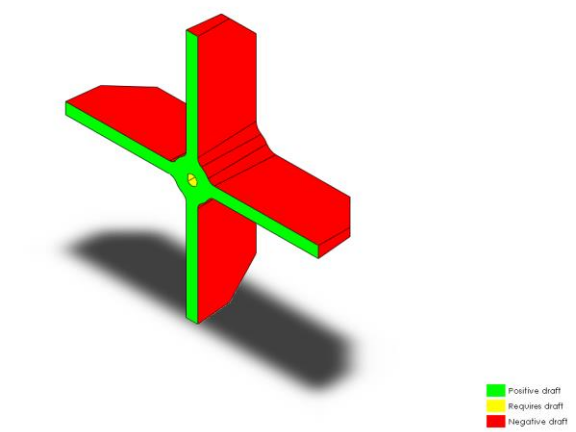


Figure 33: Sample Part after Draft Analysis

Changes made to part:

To improve the manufacturability of our part a draft angle of 3 degrees was added to all walls parallel to the pull direction. This will allow our part to more easily exit its mold by not creating a vacuum when removed. Additionally, the hole through the center remains with straight walls as the exterior draft angle should be sufficient in allow this part to be removed from its mold.

DFM Analysis Summary:

The first DFM analysis performed on the part was the injection molding analysis. Changing the maximum wall thickness of the part the design analysis was successful for both criterion. The DFM analysis performed on milling and drilling the part failed due to the existence of sharp interior corners for the D-Profile shaft. Potentially rounding these corners could make this part easier to manufacture.

.

Figure 34: The DFM analysis for injection molding for our designated part

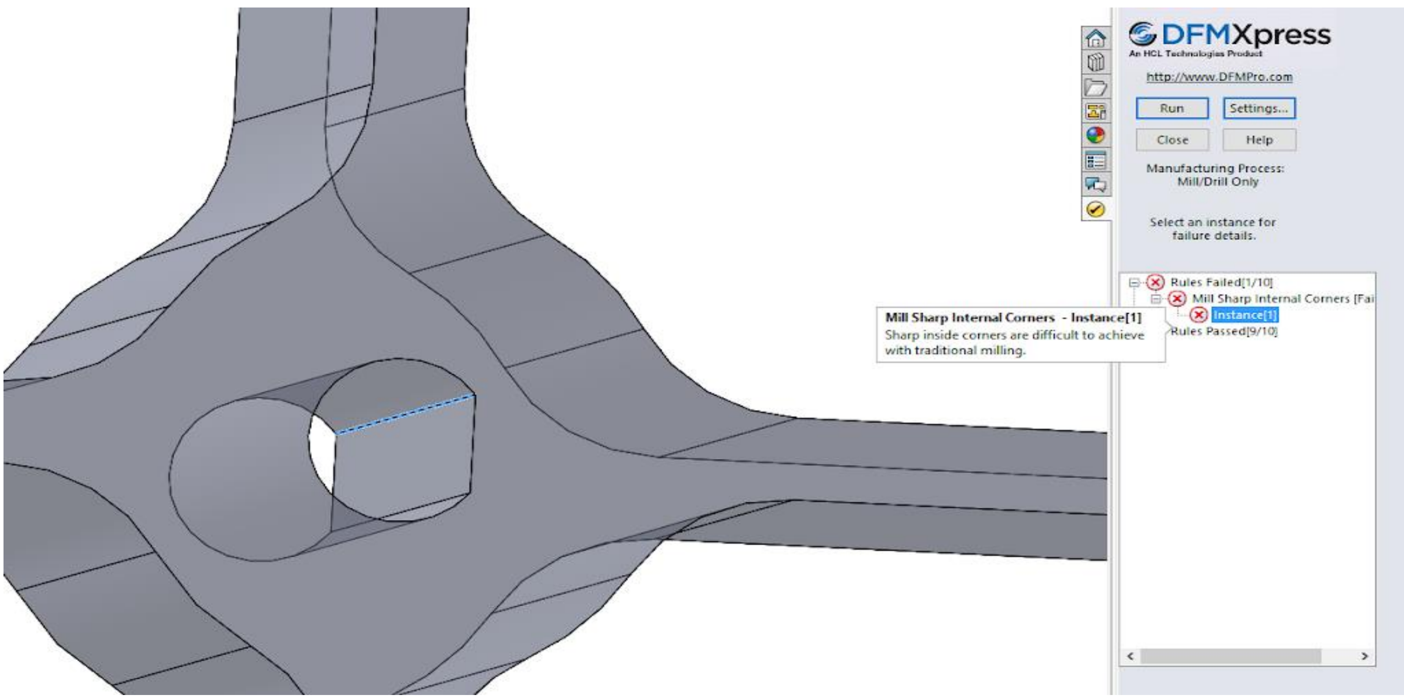


Figure 35: The DFM analysis for milling and drilling our designated part

7.3 DESIGN FOR USABILITY

Vision – Any user vision impairments will not influence the usability of the device beyond those limits that a blind or color-blind person may already have. A red-green color-blind user may want to avoid the orange lacrosse balls that are commonly used. Instead, the user may want to use white lacrosse balls. We have not yet designed a warning signal that indicates when the ball will be shot, but if the signal is visual, this could be difficult to see for a user with vision impairments.

Hearing – A deaf user may not realize when the machine is on, which is usually noted by the loud hum of the motors. In this case, the user may not be aware that balls are being propelled from the machine which could lead to the user being hit by a ball. Additionally, if the indicator for shooting a ball is audio based, a deaf user may not hear it.

Physical – Any individuals with physical impairments will probably not be using the machine; however, if a coach needs to move the machine into storage, he/she may struggle if afflicted by arthritis or muscle weakness. The passing machine's design should be light and easy to move. Our design incorporates wheels for ease of moving.

Language – A language barrier should not affect the use of the lacrosse ball passing machine. Instructions and warnings will be written in English, but the instructions will be confined to the flipping of a switch, which is obvious enough to be inferred by a non-native English speaker.

Control – The lacrosse ball passing machine should not be used by any user who is distracted or who is taking medications. Safe use of the machine requires focus, which will be impaired by distractions and medical side-effects. The design of the machine will account for control impairments with two methods. The first method will be a written warning on the machine, and the second method will be an emergency stop button located near the user just in case a distraction approaches the user.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

8.1.1 Does the final project result align with its initial project description?

The final product partially aligns with the initial project description. While each of the performance goals were satisfied in some sense, the final product is not as revolutionary as we had planned for it to be. First, the product weighs approximately 100 lbs, making it cumbersome to carry. A lacrosse team would struggle to utilize the machine in a practice setting due to this flaw. Additionally, while the automatic feeder works when 1 ball is loaded at a time, it fails when multiple balls are stacked up in the housing. Because of this, another person would be required to operate the machine, effectively eliminating the machine's efficacy for an individual workout.

8.1.2 Was the project more or less difficult than expected?

The project was much more difficult than expected. Initially, during the concept selection phase we were more concerned with the computer programming and tracking capabilities that we would incorporate into our design than we were with getting the machine to fire lacrosse balls accurately. As it turns out, we overlooked the necessity of strict manufacturing techniques. The accuracy, speed and safety of the passing machine were all adversely affected at some point during manufacturing by haste, material choice, or manufacturing inexperience.

8.1.3 On which part(s) of the design process should your group have spent more time? Which parts required less time?

Our group should have spent more time designing and testing the ball housing and filtering device. This device is the mechanism that distinguishes our project from the products that are currently on the market. Instead we spent a lot of time up front fiddling with old motors. While we learned a substantial amount from taking the motors apart and rewiring them, this endeavor did not contribute to the achievement of our performance goals.

8.1.4 Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

In order to mount the Jugs wheels/hubs we purchased to the motor shafts of the motors we salvaged we had to machine our own shaft adapters. The shaft adapters attach to the ½" diameter motor shaft and step up to the 7/8" hole in the Jugs hubs. There were multiple unexpected difficulties in machining these shaft adapters. First, the amount of time required to turn a 6" long steel shaft from 1 1/2" to 7/8" greatly exceeded our expectations. The next and by far the most critical difficulty was the precision with which the adapter had to be machined. The 7/8" shaft was machined to be less than 0.05" smaller than the hub opening. Even this tiny error rendered the shafts nearly useless. However, an ad hoc 'fix' was conceived that solved the problem, but the new solution was less effective than would be hoped for.

8.1.5 In hindsight, was there another design concept that might have been more successful than the chosen concept?

One alternative to horizontally mounted motors and wheels would have been to mount the wheels vertically, which is what is often seen in lacrosse ball passing machines that are currently on the market. For example, see Fig. 3. The vertical mounted wheels might reduce the ball's tendency to shoot at an incorrect trajectory. Additionally, a ball housing with a continuous ramp could have performed better than the staircase design we manufactured, which had intermittent pauses in the ball's motion, allowing successive balls to interact with each other and stop moving.

8.2 DESIGN RESOURCES

8.2.1 How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

When deciding which codes and standards to order, we had not fleshed out our design fully. In fact, we were still deciding between many design options. As a result, the codes and standards that we were considering did not have an impact on our design. The first standard we looked at considered the fatigue of rubber. While potentially useful for a company such as Jugs, this standard did not affect our design process because we were not manufacturing the rubber wheels ourselves. The second standard we looked at set specifications for the minimum radius that timing belts could have. When our design was completed, we did not use belts making this standard useless.

8.2.2 Was your group missing any critical information when it generated and evaluated concepts?

Instead of missing information when we were generating and evaluating design concepts, we had too much information. Our concepts had too much functionality, such as position control, player tracking techniques, and programmable routines. Trying to incorporate all these ideas into a conceptual design took focus away from the details and potential manufacturing problems. During the initial phase of searching for similar ideas, we should have searched harder. Instead, we limited our search to machines like the Jugs machine, which confirmed our pre-existing bias toward a machine with wheels.

8.2.3 Were there additional engineering analyses that could have helped guide your design?

In our design, we took the spacing of the wheels from a patent that we found online [7]. Instead of taking this spacing for granted, we might have performed an engineering analysis to determine this spacing ourselves. Some of the issues we had when shooting the ball may have arisen from a spacing that was too tight between the wheels. For instance, the lacrosse ball often took the path of least resistance between the curved profile wheels, traveling not through the middle but up, where there was greater space.

8.2.4 If you were able to redo the course, what would you have done differently the second time around?

If given the opportunity to redo this course, we would focus our efforts on precision manufacturing. Precision would require more time spent in the planning phase as well as a potential new material choice, such as aluminum. Additionally, we would incorporate more design iterations into the design and construction process so that we could fix more of the performance issues. Finally, we would purchase two new, identical motors to create a symmetric and vibration free device.

8.2.5 Given more time and money, what upgrades could be made to the working prototype?

Given more time, we would have focused our efforts on improving the ball housing and the mechanization of the ball filtering process. So much of our time was spent troubleshooting issues that originated with motor vibration because our main goal was to shoot a lacrosse ball. However, this left us no time to refine our initial design for the ball housing, which when manufactured and implemented, did not work well. The high friction of lacrosse balls currently limits the effectiveness of the ball housing.

8.3 TEAM ORGANIZATION

8.3.1 Were team members' skills complementary? Are there additional skills that would have benefitted this project?

Each team member is knowledgeable about engineering models as well as engineering analysis. However, some of the team members were more skilled in the woodshop or machine shop than others, while other teammates were more knowledgeable about computer programming and wiring of motors. These different skillsets allowed each of us to learn something from the other members. At the end of this project, each group member is a better engineer and has a more rounded knowledge base.

8.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

This design experience, while humbling, has inspired us to continue with this project through next semester. Given the rushed nature of the project, the lack of manufacturing skills that we possess, the poor tolerances that are achieved with wood and the mostly salvaged pieces we worked with, we were very pleased with the relative success of our project. It is our belief, that with an increased budget, refined design, and new material choice we can create a product that competes with similar products that are already on the market.

APPENDIX A – COST ACCOUNTING WORKSHEET

Fig. 36 shown below gives a detailed cost breakdown for this project.

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Stepper Motor	Micro Center			$14.30	1	$14.30
2	Lugs	O'Reilly Auto Parts			$2.73	8	$21.85
3	Hubs	Jugs			$48.53	2	$97.06
4	Wheels	Ebay			$99.75	2	$199.50
5	Tape	Ace Hardware			$9.89	1	$9.89
6	Lacrosse Balls	Ultimate Lacrosse			$2.17	6	$13.00
7	Shaft Collar	Ace Hardware			$5.79	2	$11.58
8	Misc. Fasteners	Menards			$17.50	1	$17.50
9	Motor	Amazon			$97.00	1	$97.00
10							$0.00
12							$0.00
13							$0.00
14							$0.00
Total:							$481.68

Figure 36 Cost accounting worksheet

APPENDIX B – FINAL DESIGN DOCUMENTATION

Solidworks drawings are shown for four of the more difficult parts to manufacture throughout this design process. Figure 37 shows a steel shaft adapter. The machining techniques to create this part were simple, but the tight tolerances required to couple a high-speed motor to a heavy wheel proved difficult to achieve.

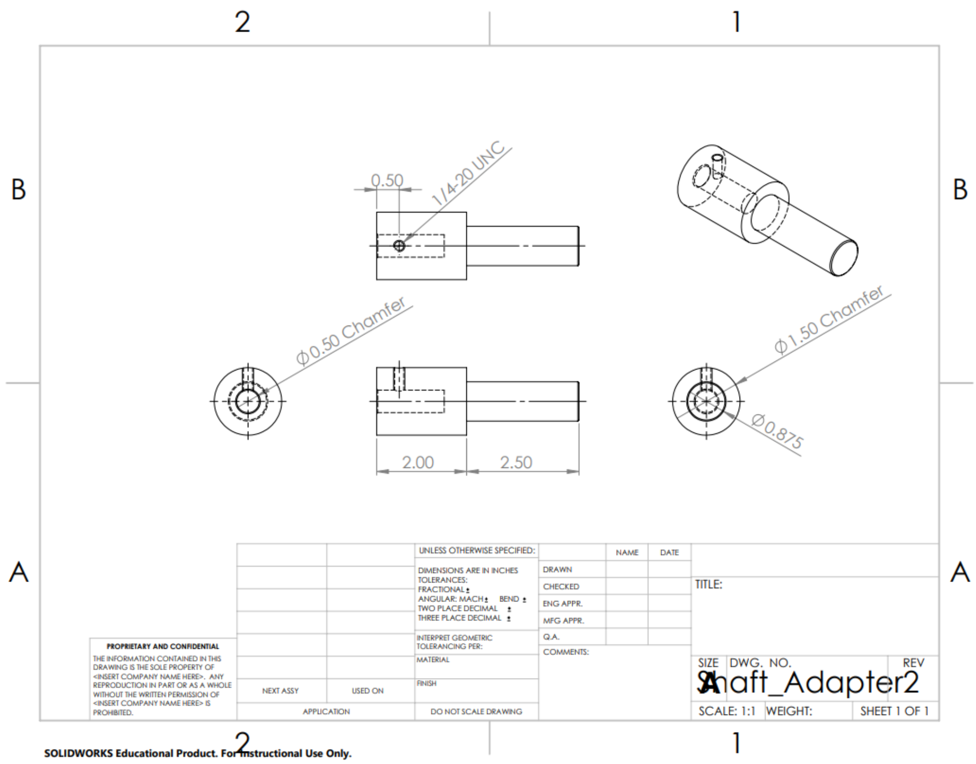


Figure 37 Steel shaft adapter

Figure 38 shows a mounting system for the motor/wheel assembly. Given that this part was constructed from salvaged wood, and provided that wood flexes when under the considerable loads that were provided by the static weight and vibration of the motors, the precision of this piece was crucial to the success of the project.

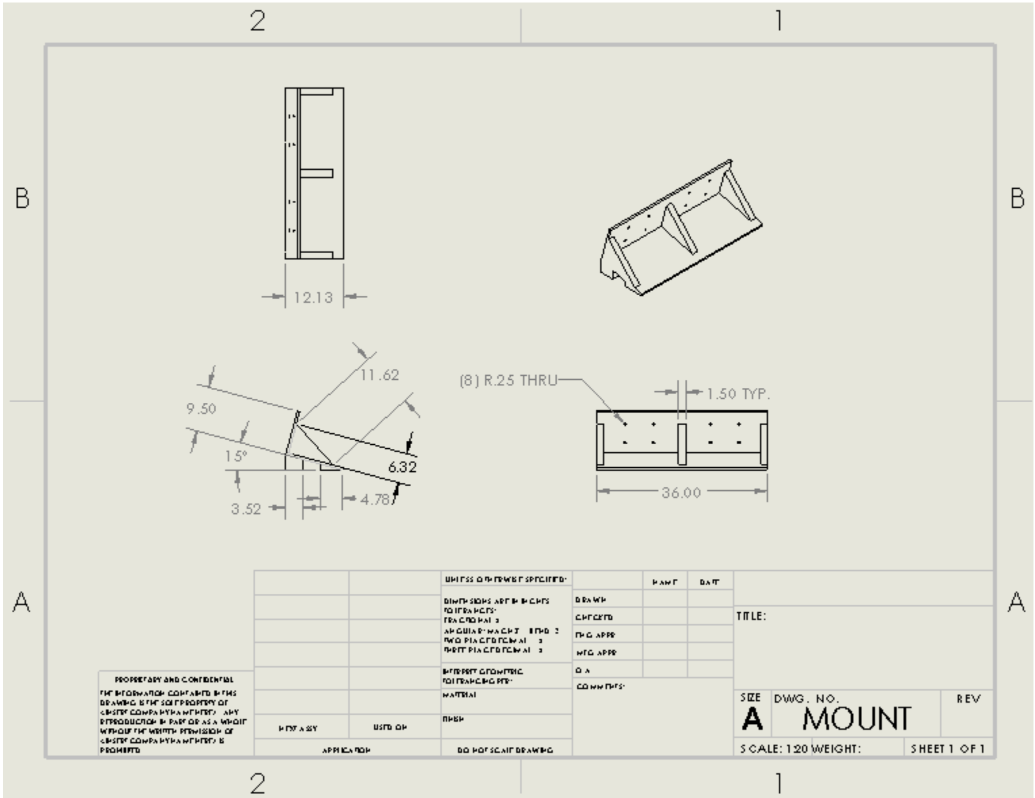


Figure 38 Wood motor mount

Figure 39 depicts the table that supported the motor/wheel assembly and the ball housing. Due to the extreme vibrations that can occur during the resonant frequencies of the motors, this table needed to be sturdy. Another factor adding to the bulk of the table was the requirement that the lacrosse balls be shot from a realistic height of at least four and a half feet.

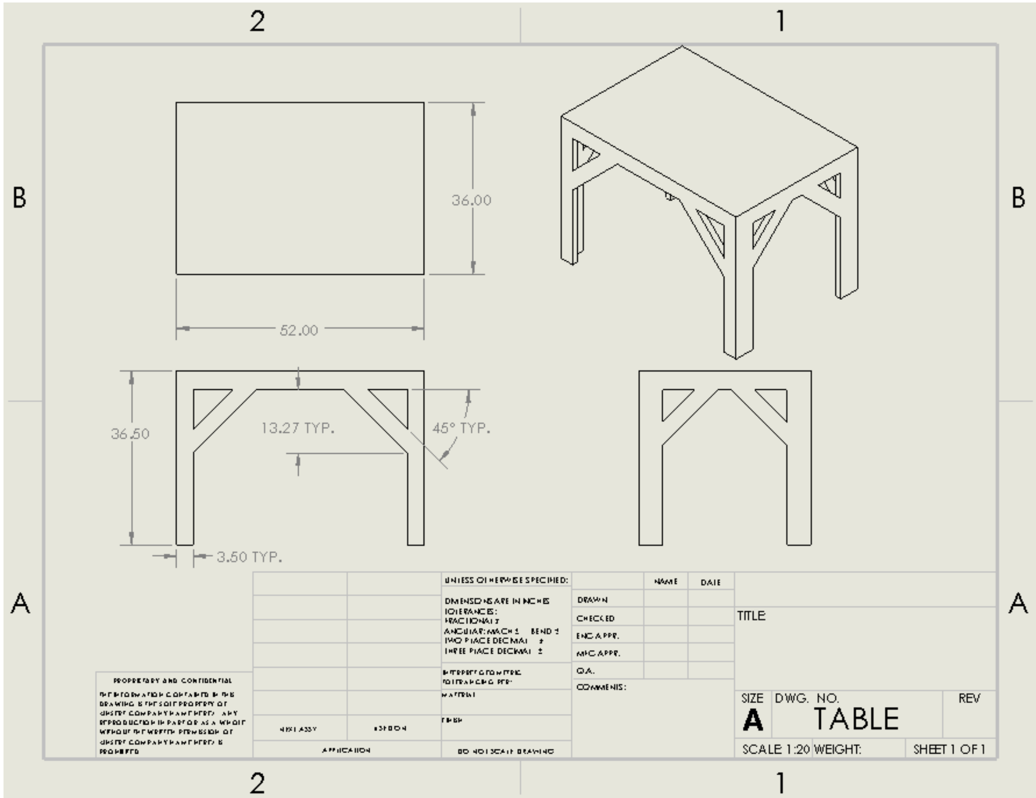


Figure 39 Wood table

Figure 40 shows the ball seat at the bottom of the ball housing. The ball seat was difficult to manufacture, mostly because the interface between the servo motor and the ball seat was flimsy. Minimal torque from the weight of the ball resting on the seat caused the seat to detach from the servo motor shaft.

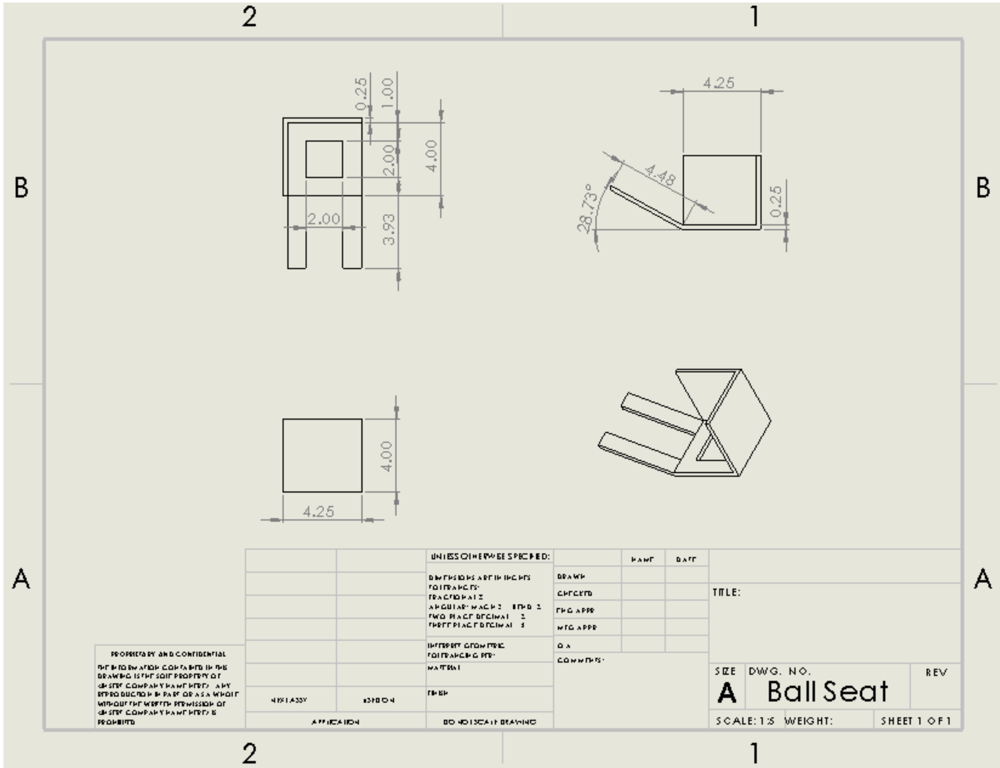


Figure 40 Ball seat

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