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Group Q- Automatic Ball Launching Entity

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Executive Summary

The goal of the project is to create a machine that can track and aim at a target and deliver a tennis ball at a safe speed. The machine can be calibrated to ensure accurate aim. The application of the product is for entertainment and sports training, with calibration being able to be used to make easy shots for fun, and difficult shot for training. The device uses a two-axis rotation, allowing it to aim up/down and left/right. The device uses a microprocessor to calculate aim based on position of target and knowledge about the strength of the firing mechanism.

MEMS 411: Senior Design Project

Automatic Ball Launching Entity (ABLE)

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1 INTRODUCTION AND BACKGROUND INFORMATION

1.1 INITIAL PROJECT DESCRIPTION

The project goal is to create a machine that can track a moving person and deliver some payload (e.g. ball) in a safe and accurate way at moderate range. This product has two main applications. The first application is as an entertainment product, allowing an individual to play with a ball alone. The second application is for sports training. Athletes could use the machine to practice catches. Additionally, the device can be configured to intentionally "miss" a target for more difficult catches. The machine will be stationary, firing from a fixed location.

1.2 EXISTING PRODUCTS

NERF Football launcher (https://www.youtube.com/watch?v=nh-nLIFMTPQ)

This project uses a large mounted air cannon that can rotate in two axes (up/down and left/right aiming) to launch a NERF football at a target. Instead of tracking a target, it seems to predict where the target will be using switches to determine the speed of the runner. This product has both auto-aiming and ball launching capabilities, but no target tracking.

Target Tracking Tripod (https://www.amazon.com/SoloShot-SOLOSHOT-Automatic-Tracking-Tripod/dp/B009NIX3ZY/ref=cm_cr_arp_d_product_top?ie=UTF8)

This product automatically launches balls placed inside. It is made so dogs can use it to play fetch by themselves. It has proximity sensors so it doesn't fire if the dog is too close. However, it has no aiming feature, it simply launches a ball whenever it is safe to do so at a fixed location. This product has ball launching capabilities, but no target tracking or auto-aiming.

Ring Security Spotlight Cam (wired) https://ring.com/spotlight-cam-wired?gclid=CjwKCAjwos7NBRAWEiwAypNCe7sn7YexL6eNxLc_yFO1pvJgaS5VFcp453V07MILvT5fk9iord35UxoCnuwQAvD_BwE&gclsrc=aw.ds

This security camera uses motion sensors to detect when someone or something has entered a pre-set security zone. It then tracks any intruders within its field of view and alerts the user in real time. The user can then hear audio, speak to any intruders, and issue an alarm to scare intruders away. This product was included due to its ability to track targets within its field of view even though it doesn't launch any projectiles.

PetSafe Automatic Ball Launcher http://store.petsafe.net/automatic-ball-launcher

The PetSafe Automatic Ball Launcher has multiple distance and angle settings which allows for tennis sized balls to be fired between eight to thirty feet, at various angles. This product can only change distance and angle settings with direct input from the user. It has built in safety settings to prevent it from shooting people or pets, via motion sensors. It can fire without user input and will shut off by itself after fifteen minutes. This product was included because of its ability to fire automatically and detect when it is safe to fire.

Skyprodigy 130 computerized telescope https://www.celestron.com/products/skyprodigy-130-computerized-telescope

The Skyprodigy 130 can automatically adjust itself automatically locate a pre-selected Celestial object if it is already in its database. This is done by changing the angle of elevation, which corresponds to altitude, and azimuthal angle, rotate clockwise or counterclockwise, without human input besides inputting which celestial body. This product was chosen as it can automatically adjust itself after being set up. Furthermore it aligns itself after using its internal camera to observe the night's sky and determine where the telescope is from its database.

iFetch Interactive Ball Launcher https://www.amazon.com/iFetch-Interactive-Ball-Launcher-Dogs/dp/B00PG3LWDK

The iFetch Interactive Ball Launcher is a device primarily oriented on playing with a dog. The angle and launch direction are preset and cannot be adjusted. This device is built for safely playing in a public place.

BallReady Auto Food Dispenser and Ball Launcher https://www.indiegogo.com/projects/ballready-auto-food-dispenser-ball-launcher-dog#/

The BallReady Auto Food Dispenser and Ball Launcher is a device oriented on playing with and feeding a dog. The angle and launch direction are preset and cannot be adjusted. This device is built for safely playing in a home.

1.3 RELEVANT PATENTS

Patent No: US 6563636 B1

The patent covers an intelligent motor control system that allows for precise control of the telescope's position and angle of elevation. The overall control system includes; two intelligent motor portions for changing the angle of elevation or azimuthal angle, a processor for receiving commands calculates the amount of movement needed about each axis, and a processor for telling the motors how much to move and correcting if it overshoots or undershoots. The telescope also limits its azimuthal rotation so that it doesn't damage any power cords that are attached to it. See figures below.

Patent No: US 7661221 B2

The mounting device as described by this patent allows a camera or another device to be mounted to a weapon. The mount contains a side partition that attaches the support partition to the weapon or scope and a support partition that can support multiple mounting configurations. See figures below.

Video camera capable of automatic target tracking (US5631697A)

This patent is for a camera with built in targeting abilities that allow it to select a target to track from predefined specifications. Once the target is selected, it processes the image in such a way to ensure the target is tracked, even when other objects are in the field of view. It does this by limiting the field of view it uses for tracking, while maintain the field of view of the whole camera, as is shown in the (quite frankly, hilarious) pictures.

Auto-alignment tracking telescope mount (US6369942B1)

Device is a telescope mount that can automatically track astronomical objects using information about the data, time, and geographical position of the mount, in addition to a manual calibration. Like the ball launcher, it has two axes for movement to allow it to aim.

Remote Digital Firing System US6860206B1

This patent covers the use of a remote firing system involving the use of a portable command console and a series of circuits.

Remote Digital Firing System US20080121097A1

This patent covers an apparatus that can be placed on a platform to hold and trigger a mechanically triggered weapon with a single remote electrical pulse.

1.4 CODES & STANDARDS

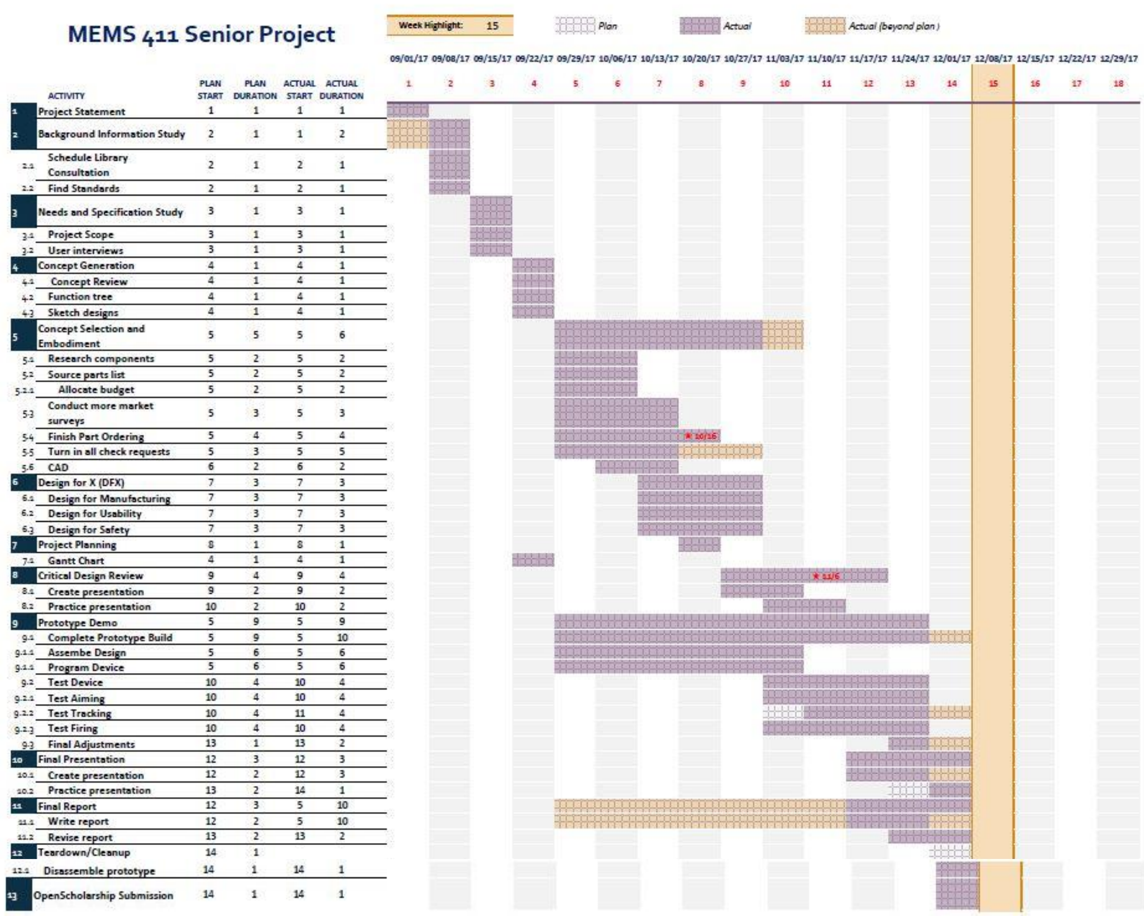
We plan to apply include mechanical and electrical toy safety standards (AS/NZS 62115:2011) and standards for kinetic energy for toys (CNS Z 8016-34).

1.5 PROJECT SCOPE

The scope of our project is limited to the following: tracking a single moving target, firing a ball at said target, and for the launcher to do all of this without any human input. What is out of the project scope would include: having various firing types, being able to override the targeting so that you could aim the launcher, or firing multiple types of projectiles.

1.6 PROJECT PLANNING

Table 1: Gantt Chart for ABLE



	ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION
1	Project Statement	1	1	1	1
2	Background Information Study	2	1	1	2
2.1	Schedule Library Consultation	2	1	2	1
2.2	Find Standards	2	1	2	1
3	Needs and Specification Study	3	1	3	1
3.1	Project Scope	3	1	3	1
3.2	User interviews	3	1	3	1
4	Concept Generation	4	1	4	1
4.1	Concept Review	4	1	4	1
4.2	Function tree	4	1	4	1
4.3	Sketch designs	4	1	4	1
5	Concept Selection and Embodiment	5	5	5	6
5.1	Research components	5	2	5	2
5.2	Source parts list	5	2	5	2
5.2.1	Allocate budget	5	2	5	2
5.3	Conduct more market surveys	5	3	5	3
5.4	Finish Part Ordering	5	4	5	4
5.5	Turn in all check requests	5	3	5	5
5.6	CAD	6	2	6	2
6	Design for X (DFX)	7	3	7	3
6.1	Design for Manufacturing	7	3	7	3
6.2	Design for Usability	7	3	7	3
6.3	Design for Safety	7	3	7	3
7	Project Planning	8	1	8	1
7.1	Gantt Chart	4	1	4	1
8	Critical Design Review	9	4	9	4
8.1	Create presentation	9	2	9	2
8.2	Practice presentation	10	2	10	2
9	Prototype Demo	5	9	5	9
9.1	Complete Prototype Build	5	9	5	10
9.1.1	Assembe Design	5	6	5	6
9.1.1	Program Device	5	6	5	6
9.2	Test Device	10	4	10	4
9.2.1	Test Aiming	10	4	10	4
9.2.2	Test Tracking	10	4	11	4
9.2.3	Test Firing	10	4	10	4
9.3	Final Adjustments	13	1	13	2
10	Final Presentation	12	3	12	3
10.1	Create presentation	12	2	12	3
10.2	Practice presentation	13	2	14	1
11	Final Report	12	3	5	10
11.1	Write report	12	2	5	10
11.2	Revise report	13	2	13	2
12	Teardown/Cleanup	14	1		
12.1	Disassemble prototype	14	1	14	1
13	OpenScholarship Submission	14	1	14	1

1.7 REALISTIC CONSTRAINTS

ABLE primarily is constrained by functional, safety, and economic constraints for the purposes of this project. In transitioning to a commercial product, quality, manufacturing, and ergonomic constraints would become more important. On the whole, the constraints of the project have led the project to adopt a more simplistic design, to minimize the amount of work required to meet the constraints.

1.7.1 Functional

ABLE has many functional constraints. ABLE has to have at least two axis of motion in order to track a target in 3D space, and requires a set amount of force in order to have good accuracy. Furthermore, it requires informational input on the targets location and computational ability to calculate the best method of aiming to launch the ball to the target. Additionally, it needs to be robust enough to withstand the forces from launching and the accelerations from aiming without breaking.

1.7.2 Safety
The primary safety concerns are centered on firing the ball. Primarily, the ball needs to be fired in a way to minimize potential injury, which constrains how the system is controlled and potential firing mechanisms. The reloading mechanism must also be safe to use. Furthermore, the device must be safe to transport and set up, not introducing undue hazards into the equations.

1.7.3 Quality
The device must comply with standards of electrical safety, and must exhibit and reasonable degree of consistency in aim and operation. Furthermore, it must be built to a standard that it does not break upon reasonable use.

1.7.4 Manufacturing
There were a few production constraints for the wooden components of ABLE due to unavailability of tools. Furthermore, there were constraints for the availability of electrical components (The solenoid in particular) that influenced design.

1.7.5 Timing
Time constraints limited the complexity of some of the parts and designs, and caused changes to the parts to make manufacturing and assembly faster. Furthermore, manufacturing and assembly was constrained by part delivery time.

1.7.6 Economic
There were initially very strict economic constraints that limited the complexity of the design and the amount of parts. However, this constraint was somewhat removed later in the project. The other primary economic constraint was the resource cost of machine time, where finding time and availability on machines and appropriate tools influenced the design process.

1.7.7 Ergonomic
The primary ergonomic constraint was centered on the reloading mechanism. The mechanism needed to be easy to use, and could not require undue amounts of force. Furthermore, the use of the system must be easy to understand for the user.

1.7.8 Ecological
There are no strong ecological constraints for this design beyond the use of sustainable materials.

1.7.9 Aesthetic
The device should look like it can launch and aim, should feel nice to use.

1.7.10 Life Cycle
The device should minimize the amount of unrecyclable parts, must be able to operate outside, and must be able to withstand basic wear and tear.

1.7.11 Legal
The device must follow all applicable regulations, and be safe to use in a public environment without excessive danger. Furthermore, the device must not infringe on existing copyrights and other intellectual properties.

1.8 REVISED PROJECT DESCRIPTION

The goal of the project is to create a machine that can track and aim at a target and deliver a tennis ball at a safe speed. The machine can be calibrated to ensure accurate aim. The application of the product is for entertainment and sports training, with calibration being able to be used to make easy shots for fun, and difficult shot for training. The device uses a two-axis rotation, allowing it to aim up/down and left/right. The device uses a microprocessor to calculate aim based on position of target and knowledge about the strength of the firing mechanism.

2 CUSTOMER NEEDS & PRODUCT SPECIFICATIONS

2.1 CUSTOMER INTERVIEWS

Table 2: Customer Interviews for ABLE

Customer Data: Customer: Zachary White
Automatic Ball Launching Entity (ABLE)
Address: 735 Westgate Apt. 3N
Date: 9/15/2017

Question	Customer Statement	Interpreted Need	Importance
Likes	I like that the product is able to track me	ABLE is able to track a target	5
	I like that the product only targets me	ABLE does fires only at user	5
Dislikes	Only able to fire in one way	ABLE has multiple firing modes	1
Needs	Able to be used on a variety of surfaces	ABLE works on any surface	3
	Needs to not hit too hard	ABLE is safe to use	5
	It needs to be able to fire accurately	ABLE fires at target accurately	5
How would you see yourself using this device	To help with hand/eye coordination		
	Use it by myself	ABLE can be operated alone	3
When/where would you use this product	Use it outside when it isn't raining	ABLE withstands outside conditions without deterioration	4
	Use in summer/fall/spring	ABLE withstands outside conditions without deterioration	4
			4

	Use mostly in afternoon, maybe evening	ABLE operates normally throughout the day	
Wants (cool additional features)	It would be cool if it could shoot various types of balls Lightweight, portable Doesn't take more than one person to set up	ABLE fires multiple types of projectiles ABLE is easy to transport ABLE can be operated alone	1 3 3

Customer Data: Customer: Brian White
Automatic Ball Launching Entity (ABLE)
Address: 21400 Van K Drive
Date: 9/16/2017

Question	Customer Statement	Interpreted Need	Importance
Likes	I like that the tracking system is self-calibrating. Like the ability to have an internal power source. Likes that it is portable.	ABLE is easy to use ABLE is easy to use ABLE is easy to transport	5 5 3
Dislikes	Dislikes it is having a fixed muzzle velocity. Dislikes the lack of user input. Dislikes that it can only use one type of ball/ projectile.	ABLE adjusts to user input ABLE adjusts to user input ABLE fires multiple types of projectiles	2 2 1
Needs	Be accurate, but not necessarily the same every time. Able to fire several types of objects. It is reliable and easy to use.	ABLE fires at target accurately ABLE fires multiple types of projectiles ABLE is easy to use	5 1 5
How would you see yourself using this device	Use it to play with a dog. Use it in the backyard to help son play catch.	ABLE is safe to use ABLE is safe to use	5 5
When/where would you use this product	Would be able to be used outside. Use on sunny or non-rainy days.	ABLE withstands outside conditions without deterioration	4

	Use it in the afternoon or morning. Able to be used on a variety of terrains ranging from grass to a tennis court.	ABLE works on any surface	3
Wants (cool additional features)	Able to paint a target using a laser. Use it just to fire projectiles without a chip. Able to fire different types of pitches or types of hits.	ABLE adjusts to user input ABLE adjusts to user input	2 2

2.2 INTERPRETED CUSTOMER NEEDS

Table 3: Interpreted Customer Needs for ABLE

Need Number	Need	Importance
1	ABLE is able to track a target	5
2	ABLE fires only at user	5
3	ABLE has multiple firing modes	1
4	ABLE works on any surface	3
5	ABLE is safe to use	5
6	ABLE fires at target accurately	5
7	ABLE can be operated alone	3
8	ABLE withstands outside conditions without deterioration	4
9	ABLE operates normally throughout the day	4
10	ABLE fires multiple types of projectiles	1
11	ABLE is easy to transport	3
12	Able is easy to use	5
13	ABLE adjusts to user input	2

2.3 TARGET SPECIFICATIONS

Table 4: Target Product Specifications for ABLE

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Degrees off of aiming at target	Degrees	<3	<1
2	2	Fires only at operator	Binary	1	1
3	3	# of firing modes	Integer	1	3
4	4,7	# of different surfaces it can work on	Integer	2	5
5	5	Device passes kinetic energy test (CNS Z 8016-34)	Binary	1	1

6	6	Range of positions around target that are hit	Meters	<3	<1
7	7,11	Mass	Kg	<60	<30
8	7,11	Volume	m^3	<2	<0.5
9	8,9	Time spent outside without breaking	Hours	>12	>24
10	10	Number of different projectiles that work with device	Integer	1	>3
11	12	Time a novice needs to spend with the device to understand use	Minutes	<60	<10
12	13	Number of parameters that can be adjusted	Integer	>3	0
13	5	Device complies with AS/NZS 62115:2011	Binary	1	1

3 CONCEPT GENERATION

3.1 FUNCTIONAL DECOMPOSITION

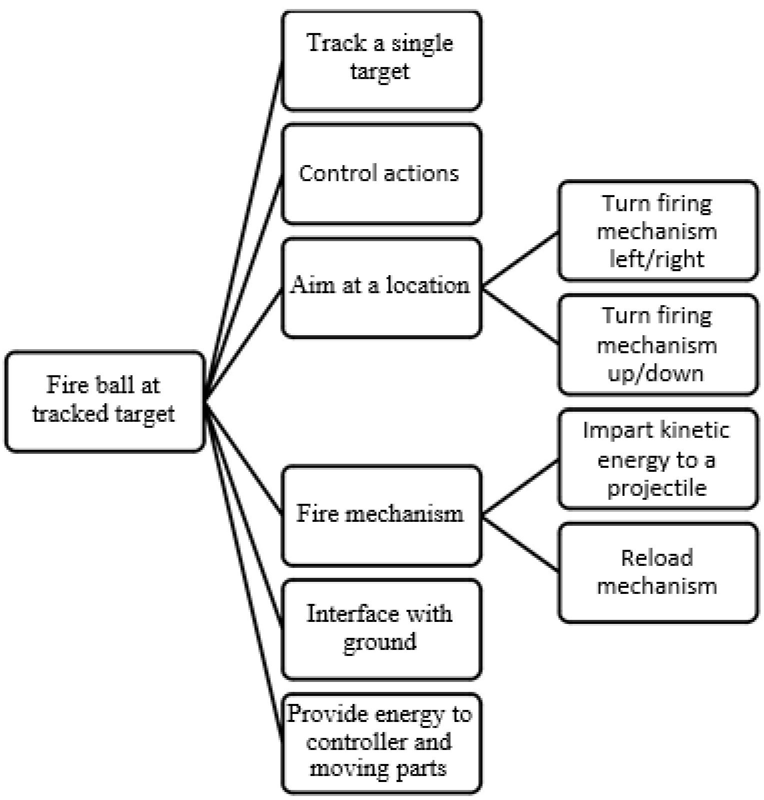
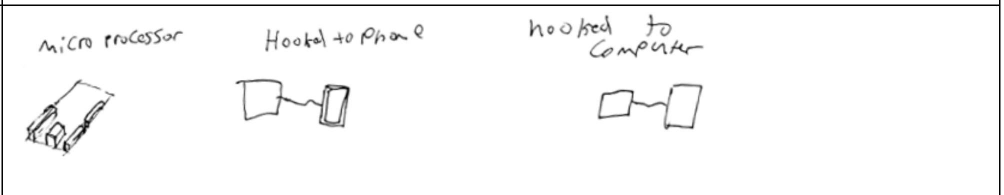
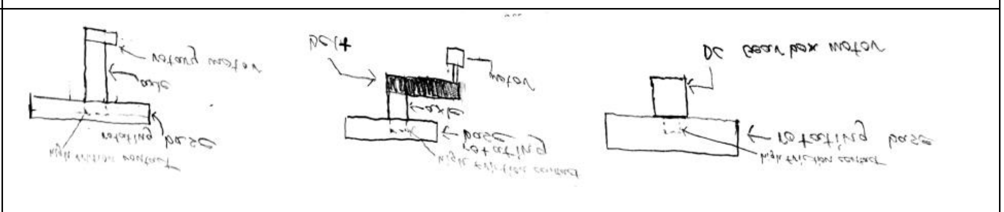
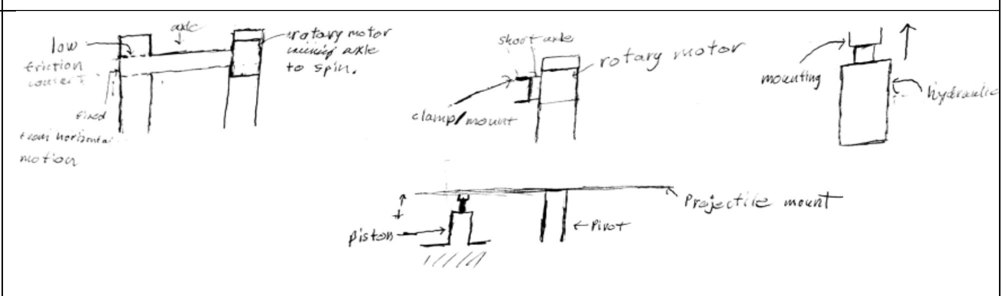
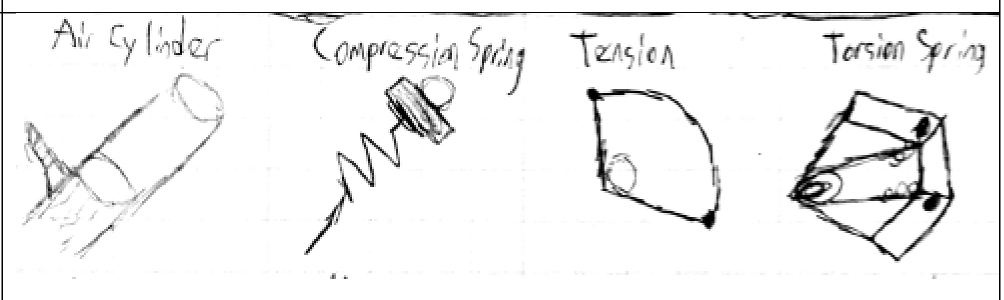
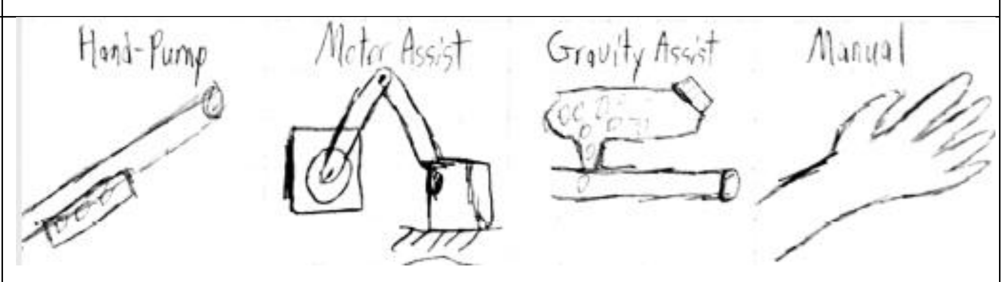
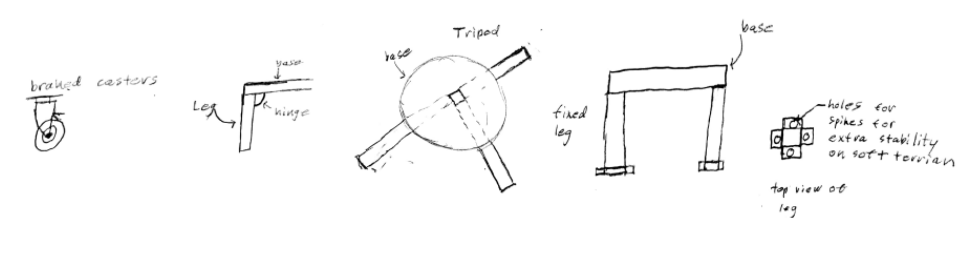
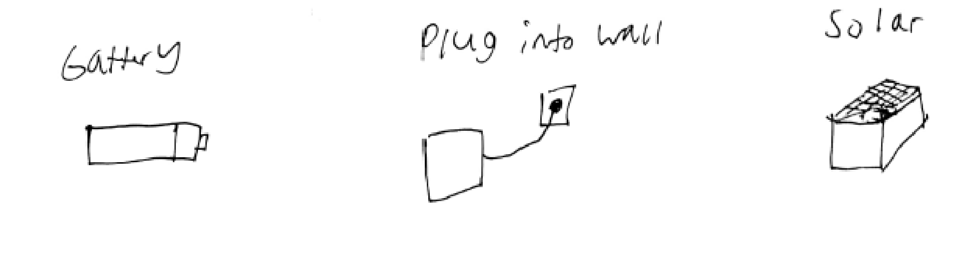


Figure 1: Function Tree for ABLE

3.2 MORPHOLOGICAL CHART

Table 5: Morphological Chart forABLE

Track position of target	
Control actions	
Turn firing mechanism left/right	
Turn firing mechanism up/down	
Impart kinetic energy to projectile	
Reload mechanism	

Interface with ground	
Provide energy to controller and moving parts	

3.3 CONCEPT #1 – "WHEELY-DEALY AIR"

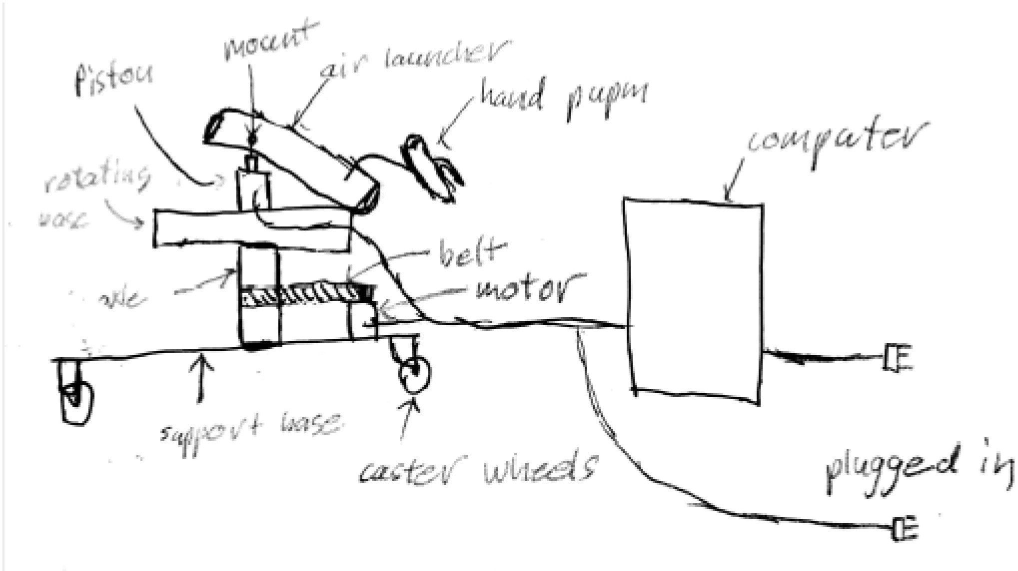


Figure 2: Design Concept 1

Air turret that fires at a tracked target via GPS and uses a computer to control motors. Uses a belt system and a piston to control vertical and horizontal adjustments. Sits on a wheeled platform. Powered by cable.

3.4 CONCEPT #2 – "TELESCOPE LAUNCHER"

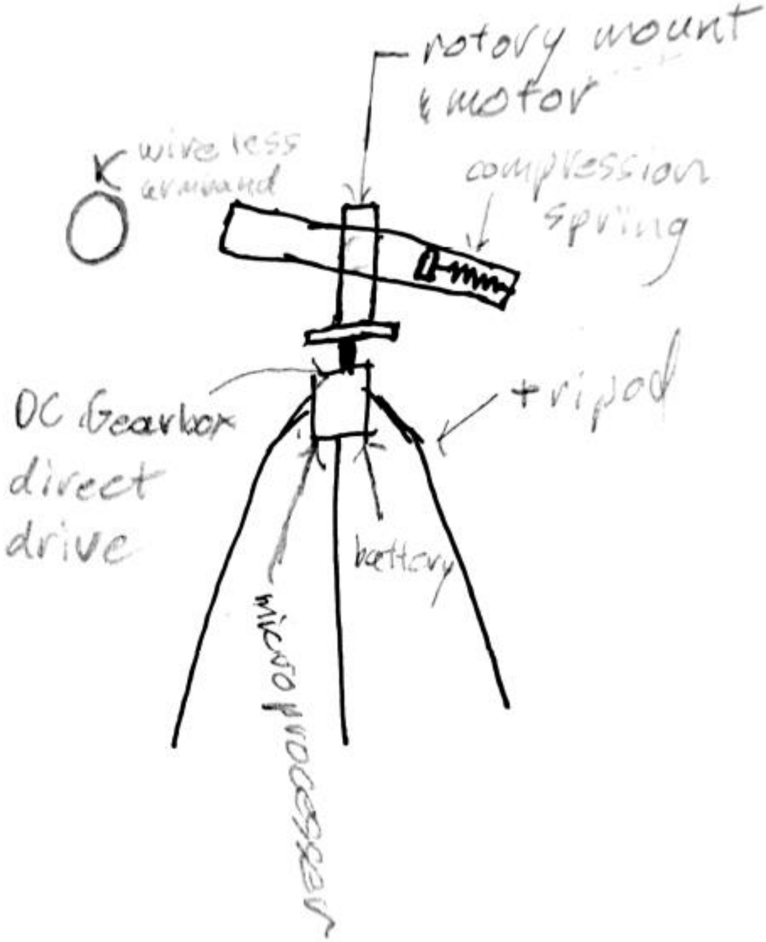


Figure 3: Design Concept 2

Auto-aiming compression spring turret that fires at a target tracked using a wireless arm band. Uses a microprocessor to control motors. Uses a gear box and rotational motors to control vertical and horizontal adjustments. Sits on a tripod. Powered by battery.

3.5 CONCEPT #3 – "TABLE BALLISTA"

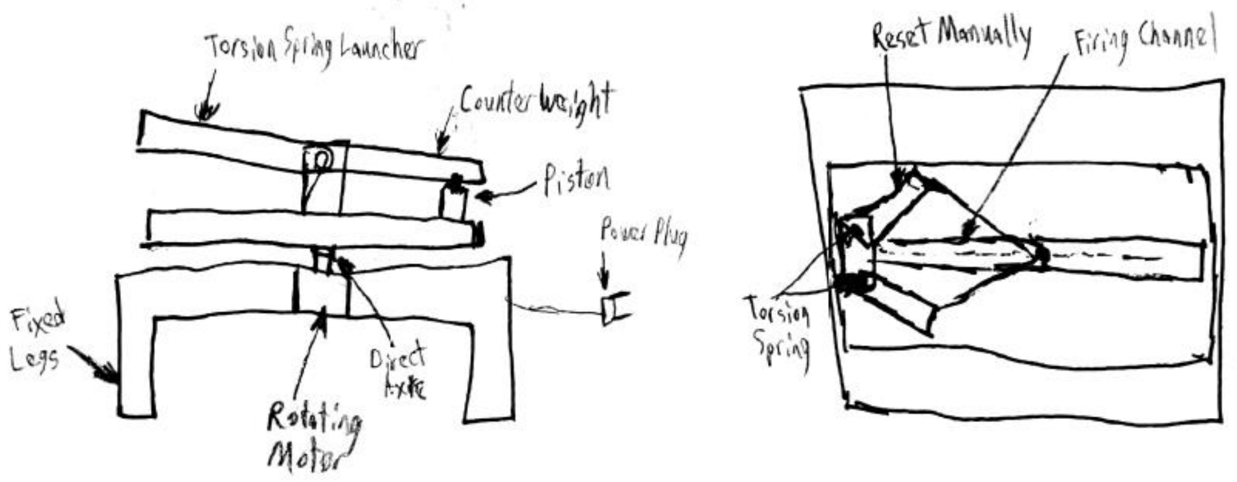


Figure 4: Design Concept 3

Torsional-spring turret that fires at a target tracked via object-tracking cameras. Uses a microprocessor to control motors. Uses a rear-mounted piston and gearbox to control vertical and horizontal adjustments. Sits on a stable table. Powered by cable.

3.6 CONCEPT #4 – "BOW-POD"

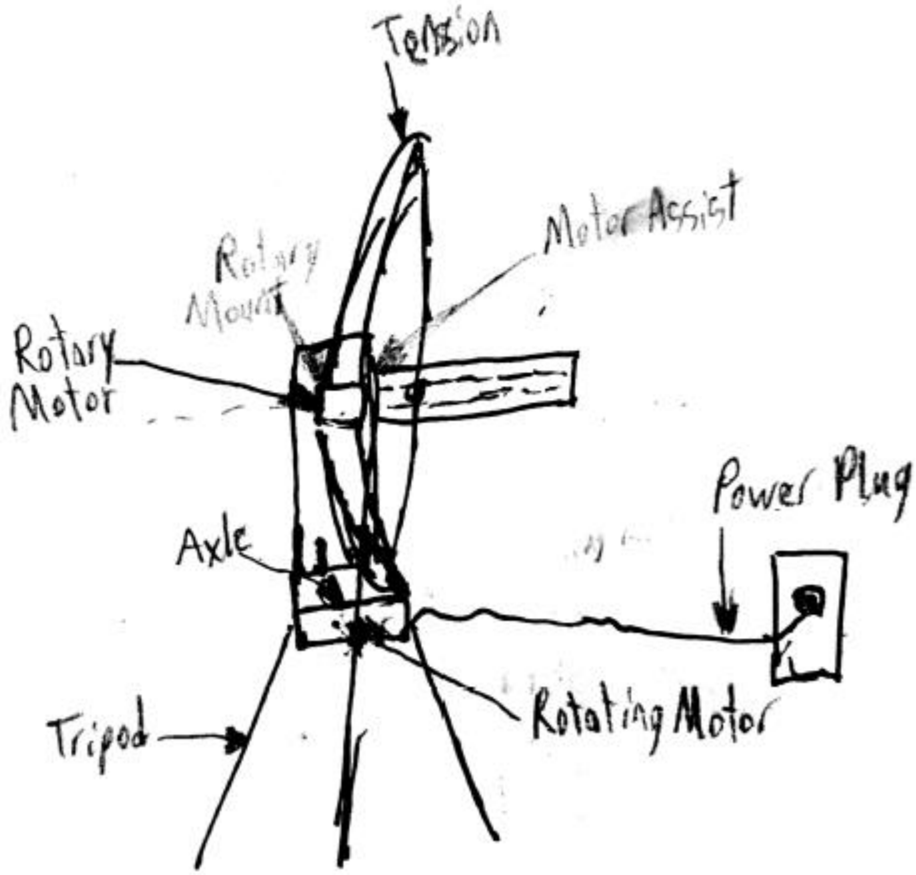


Figure 5: Design Concept 4

Tension-spring turret that fires at a tracked target via GPS. Uses a cell phone to send commands to motors. Uses two rotational motors to control vertical and horizontal adjustments. Sits on a tripod. Powered by cable.

3.7 CONCEPT #5 – "AXLE TUBE"

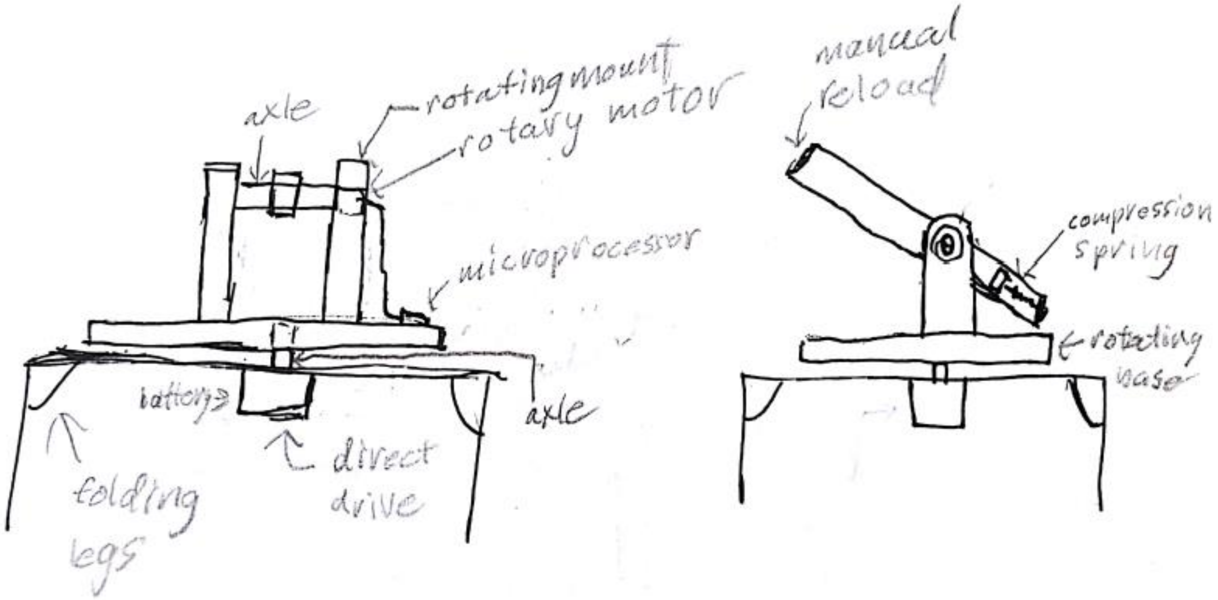


Figure 6: Design Concept 5

Compression spring turret that fires at a tracked target via Armband and uses a microprocessor to control motors. Uses an axle and gear box to control vertical and horizontal adjustments. Sits on a table with folding legs. Powered by a battery.

3.8 CONCEPT #6 – "TABLE X-BOW"

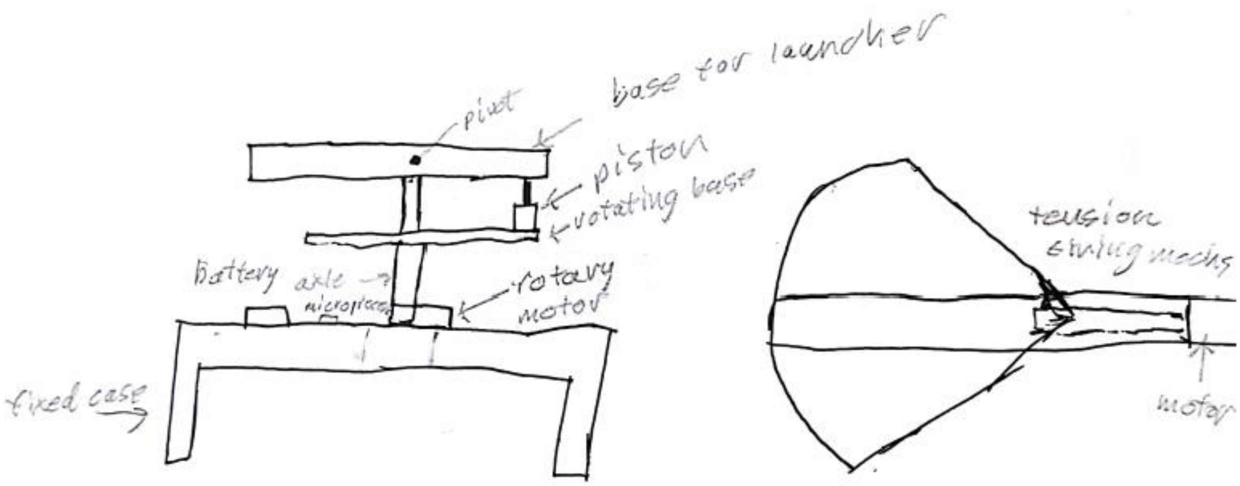


Figure 7: Design Concept 6

Tension spring turret that fires at a tracked target via Armband and uses a microprocessor to control motors. Uses a rear-mounted piston and a rotational motor to control vertical and horizontal adjustments. Sits on a stable table. Powered by battery.

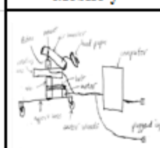
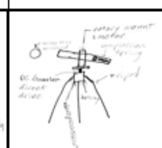
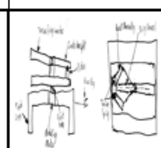
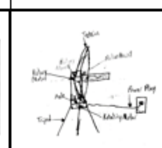
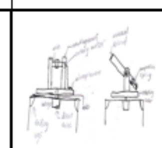
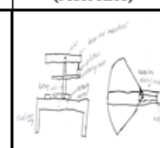
4 CONCEPT SELECTION

4.1 CONCEPT SCORING MATRIX

Table 6: Analytic Hierarchy Process

Group Q - AHP	Mechanical Safety	Cost of components	Angular Resolution-horizontal	Angular Resolution-Vertical	Weight	Tracking accuracy	Robustness	Ease of Manufacturing	Asthetic Appeal	Ease of Assembly	Distnace Resolution	Ease of reloding	Row Total	Weight Value	Weight (%)
Mechanical safety	1.00	5.00	7.00	7.00	8.00	7.00	7.00	8.00	9.00	8.00	7.00	7.00	81.00	0.25	25.26%
Cost of components	0.17	1.00	3.00	3.00	3.00	3.00	2.00	2.00	7.00	3.00	3.00	3.00	33.17	0.10	10.34%
Angular Resolution-horizontal	0.14	0.33	1.00	0.50	1.00	0.25	0.33	2.00	7.00	2.00	0.50	2.00	17.06	0.05	5.32%
Angular Resolution-vertical	0.14	0.33	2.00	1.00	1.00	0.33	0.33	2.00	7.00	2.00	5.00	2.00	23.14	0.07	7.22%
Weight	0.13	0.33	1.00	1.00	1.00	1.00	2.00	2.00	9.00	2.00	2.00	5.00	26.46	0.08	8.25%
Tracking accuracy	0.14	0.33	4.00	3.00	1.00	1.00	0.50	3.00	9.00	3.00	5.00	6.00	35.98	0.11	11.22%
Robustness	0.14	0.50	3.00	3.00	0.50	2.00	1.00	4.00	9.00	4.00	4.00	6.00	37.14	0.12	11.58%
Ease of Manufacturing	0.13	0.50	0.50	0.50	0.50	0.33	0.25	1.00	7.00	2.00	0.50	1.00	14.21	0.04	4.43%
Asthetic Appeal	0.11	0.14	0.14	0.14	0.11	0.11	0.11	0.14	1.00	0.13	0.11	0.11	2.36	0.01	0.74%
Ease of Assembly	0.13	0.33	0.50	0.50	0.50	0.33	0.25	0.50	8.00	1.00	0.50	1.00	13.54	0.04	4.22%
Distance Resolution	0.14	2.00	2.00	0.20	0.50	0.20	0.25	2.00	9.00	2.00	1.00	3.00	22.29	0.07	6.95%
Ease of reloding	0.14	0.33	0.50	0.50	0.20	0.17	0.17	1.00	9.00	1.00	0.33	1.00	14.34	0.04	4.47%
												Column Total:	320.69	1.00	100%

Table 7: Weighted Scoring Matrix for 6 design Concepts

		Alternative Deisgn Concepts											
		Wheely Dealy Air Mobile-y		Telescope Launcher		Table Ballista		Bow-Pod		Axle Tube		Table X-Bow (reference)	
Group Q - WSM													
Selection Criterion	Weight (%)	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Mechanical safety	25.26	3	0.76	4	1.01	3	0.76	2	0.51	4	1.01	3	0.76
Cost of components	10.34	2	0.21	5	0.52	4	0.41	3	0.31	4	0.41	3	0.31
Angular Resolution-horizo	5.32	3	0.16	3	0.16	3	0.16	3	0.16	3	0.16	3	0.16
Angular Resolution-vertica	7.22	2	0.14	4	0.29	3	0.22	4	0.29	5	0.36	3	0.22
Weight	8.25	3	0.25	5	0.41	3	0.25	5	0.41	4	0.33	3	0.25
Tracking accuracy	11.22	3	0.34	3	0.34	3	0.34	3	0.34	3	0.34	3	0.34
Robustness	11.58	2	0.23	2	0.23	5	0.58	1	0.12	3	0.35	5	0.58
Ease of Manufacturing	4.43	1	0.04	3	0.13	4	0.18	1	0.04	5	0.22	3	0.13
Asthetic Appeal	0.74	3	0.02	3	0.02	4	0.03	5	0.04	2	0.01	3	0.02
Ease of Assembly	4.22	1	0.04	4	0.17	4	0.17	2	0.08	5	0.21	3	0.13
Distance Resolution	6.95	1	0.07	3	0.21	3	0.21	2	0.14	3	0.21	3	0.21
Ease of reloding	4.47	2	0.09	3	0.13	3	0.13	2	0.09	3	0.13	5	0.22
	Total score	2.352		3.623		3.429		2.523		3.749		3.321	
	Rank	**6**		**2**		**3**		**5**		**1**		**4**	

4.2 EXPLANATION OF WINNING CONCEPT SCORES

Axle tube was generally an all-around better design than the others, outperforming in key categories. It is designed to be robust, yet simple, meaning the cost of components is lower, and it's easier to make and assemble the parts. Furthermore, the enclosed nature of the launcher makes it inherently safer to use. In terms of vertical angular resolution, it gives the most accuracy by supporting the axle at both ends, allowing the motor to easily control the angle of the barrel, allowing for a large degree of rotational motion at a high accuracy. This is compared to the piston/four-bar designs of the table ballista and table, which have a smaller overall range of motion that is hard to get exactly.

4.3 EXPLANATION OF SECOND-PLACE CONCEPT SCORES

Telescope launcher did almost as well as axle tube, but fell below because of a few criteria. To start, it performed the same in terms of mechanical safety, distance resolution, and ease of reloading as it used the same firing mechanism as Axle Tube. However, by the nature of the lighter design, the requirements for manufacturing and assembly were greater, and it was significantly less robust. However, because of the lightweight design, the cost and weight were both reduced. In the end, the increased robustness and ease of manufacturing outweighed the reduced cost and weight, although not by a large margin.

4.4 EXPLANATION OF THIRD-PLACE CONCEPT SCORES

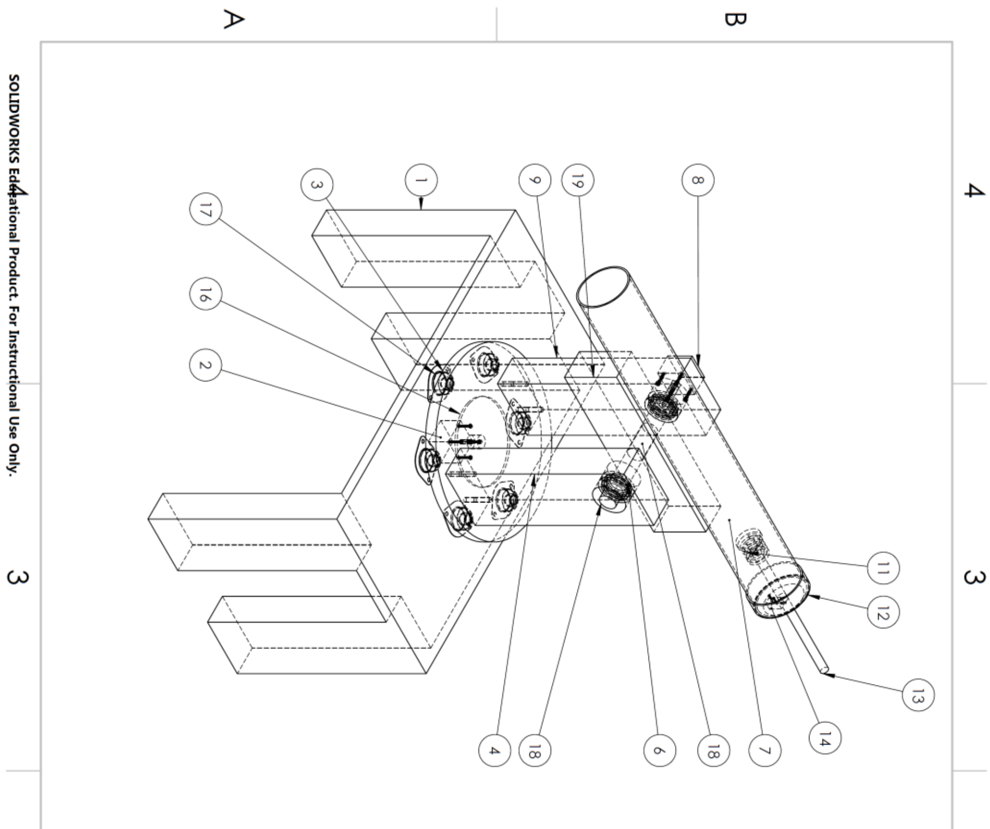
Table ballista barely eked out the table X-bow for third place. It owes this success to the removal of the reload assistance motor. While having the motor would be nice, the comparative value of ease of reloading to cost was significantly lower. Other than that difference, there was very little difference between it and the reference. It lost out to the two compression spring designs due to its lower safety and reduced vertical angular resolution. Additionally, the design was more complex than the Axle Tube, leading to harder assembly and manufacturing.

4.5 SUMMARY OF EVALUATION RESULTS

Safety was the most important feature, followed by robustness, tracking accuracy, and cost. The winning design was Axle Tube, followed by Telescope Launcher, Table Ballista, Table X-Bow, Bow-Pod, and Wheely Dealy Air Mobiley. The two last place designs did significantly worse than the other four.

5 EMBODIMENT & FABRICATION PLAN

5.1 ISOMETRIC DRAWING WITH BILL OF MATERIALS



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Table	Cut Plywood attached to four 2x4 legs with 2" wood screws	1
2	B00PNEQKCO	Stepper Motor (base)	1
3	Rotating Base	Cut Plywood	1
4	Axle Holder	2x4 cut to length with a 2 inch diameter through cut	1
5	92005A128	M3 Screws	8
6	Bearings	Non-Shielded bearings scavengened from basement	2
7	Barrel	Made out of PVC	1
8	B00PNEQ9T4	Stepper Motor (Axle)	1
9	Axle Holder (Motor side)	2x4 cut to length with a milled 2 inch diameter cut and a 1/2 inch cut	1
10	92114A138	Wood Screws 1.5"	2
11	Spring	Compression Spring	1
12	PVC Endcap	3/4 inch cut in ceneter of endcap for dowel rod and a through hole for the spring	1
13	Reloading Rod	3/4 inch dowel rod with scrap wood base	1
14	Solenoid		1
15	92095A454	M2 Screw	2
16	Shaft Expander(circular top)	3-D printed part	1
17	5674K1	Roller Mounts(similar to actual ones used)	6
18	Axle	Stell axle cut to length with a key hole and a set screw	1
19	Barrel Mount 2	Cut 2x4 reattached with two two inch screws	1
20	2-inch wood screws		24
21	12959	Solenoid Control	1
22	n/a	Pixy SMart Vision Camera	1
23	13975	Arduino	1
24	12779	Axle Motor Driver	1
25	12859	Base Motor Driver	1
26	91375A208	Set Screws	1

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Figure 8 Isometric Drawing of Axle Tube Assembly

5.2 EXPLODED VIEW

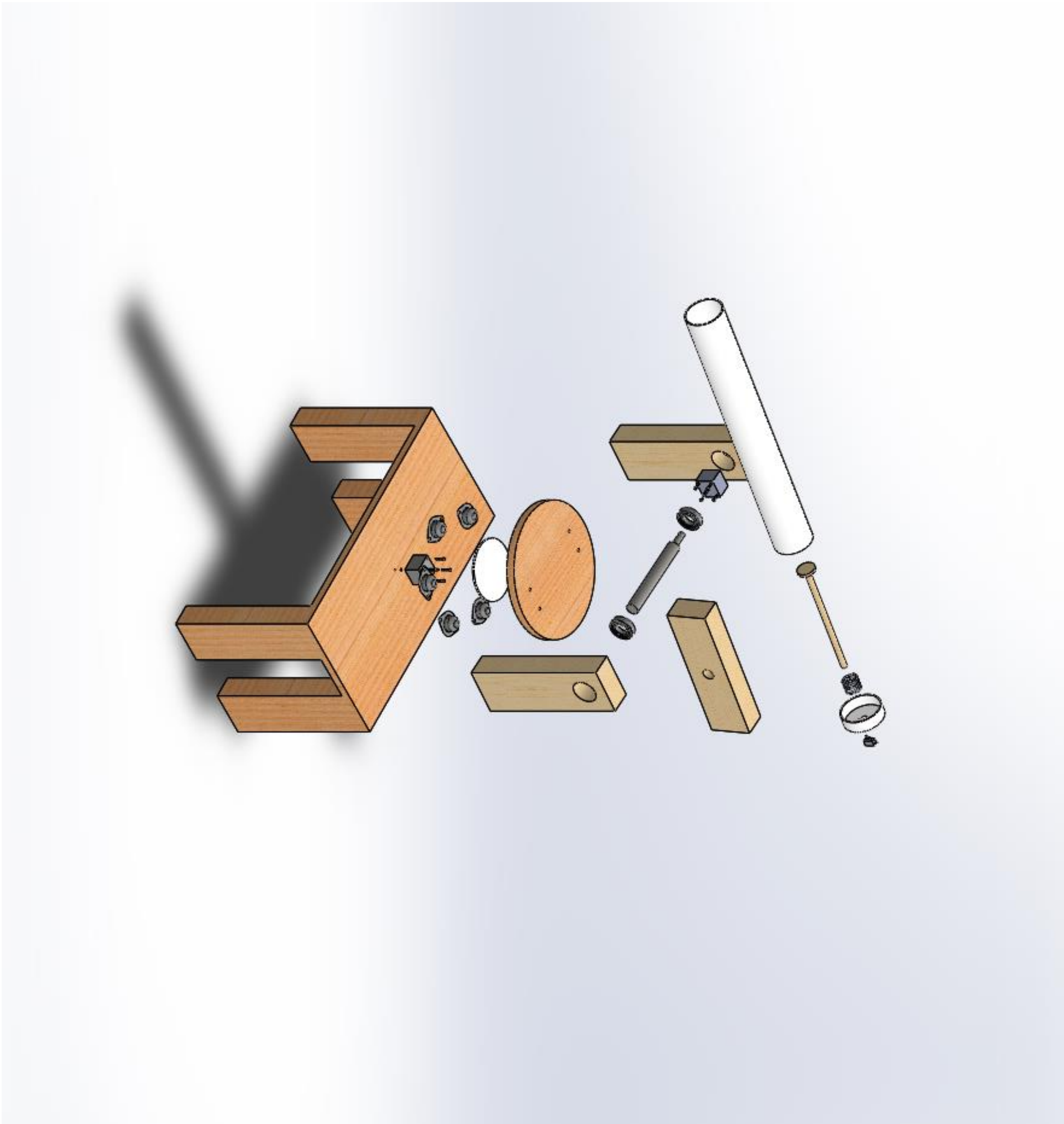


Figure 9: Exploded View of ABLE

5.3 ADDITIONAL VIEWS

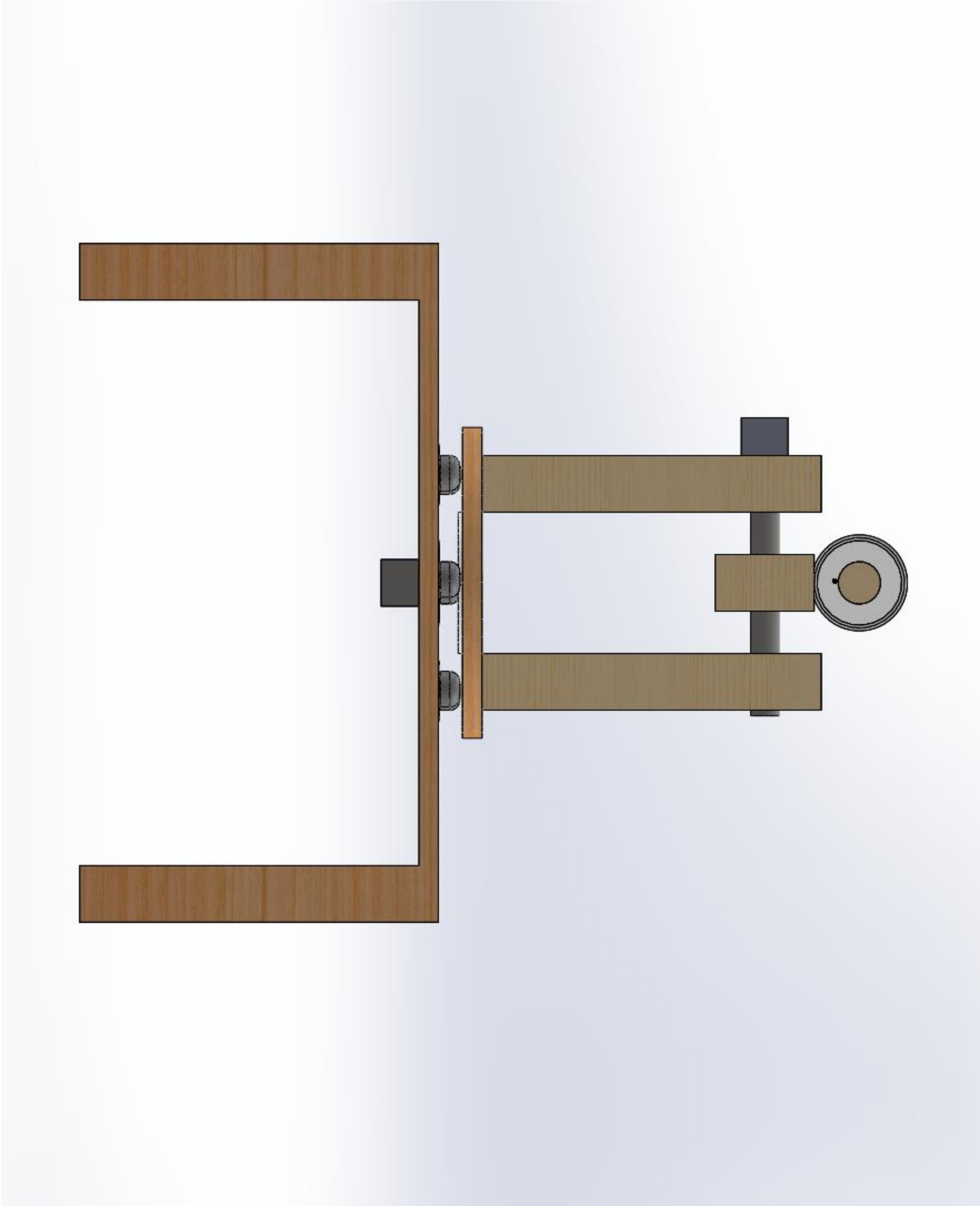


Figure 10: Front View

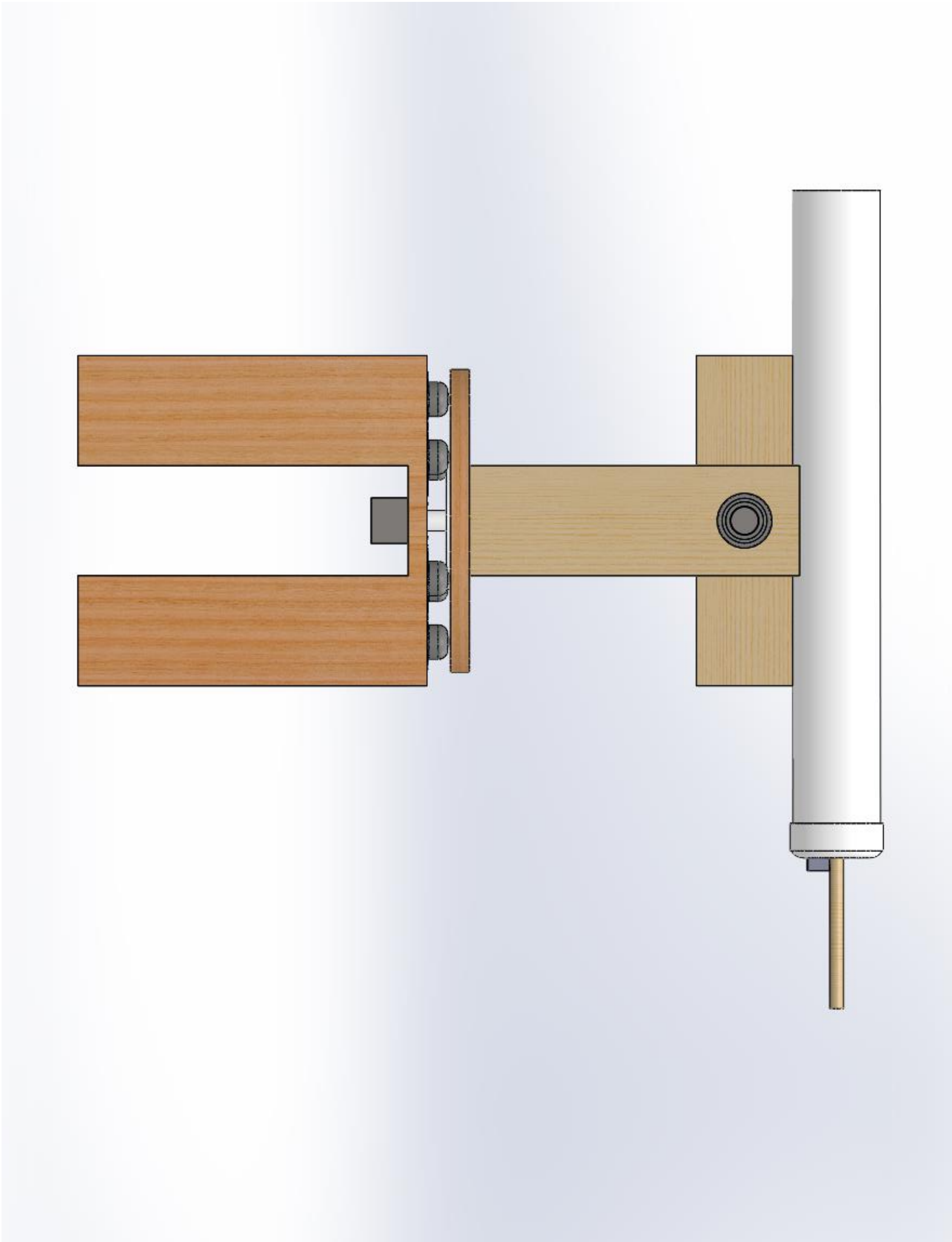


Figure 11: Side View

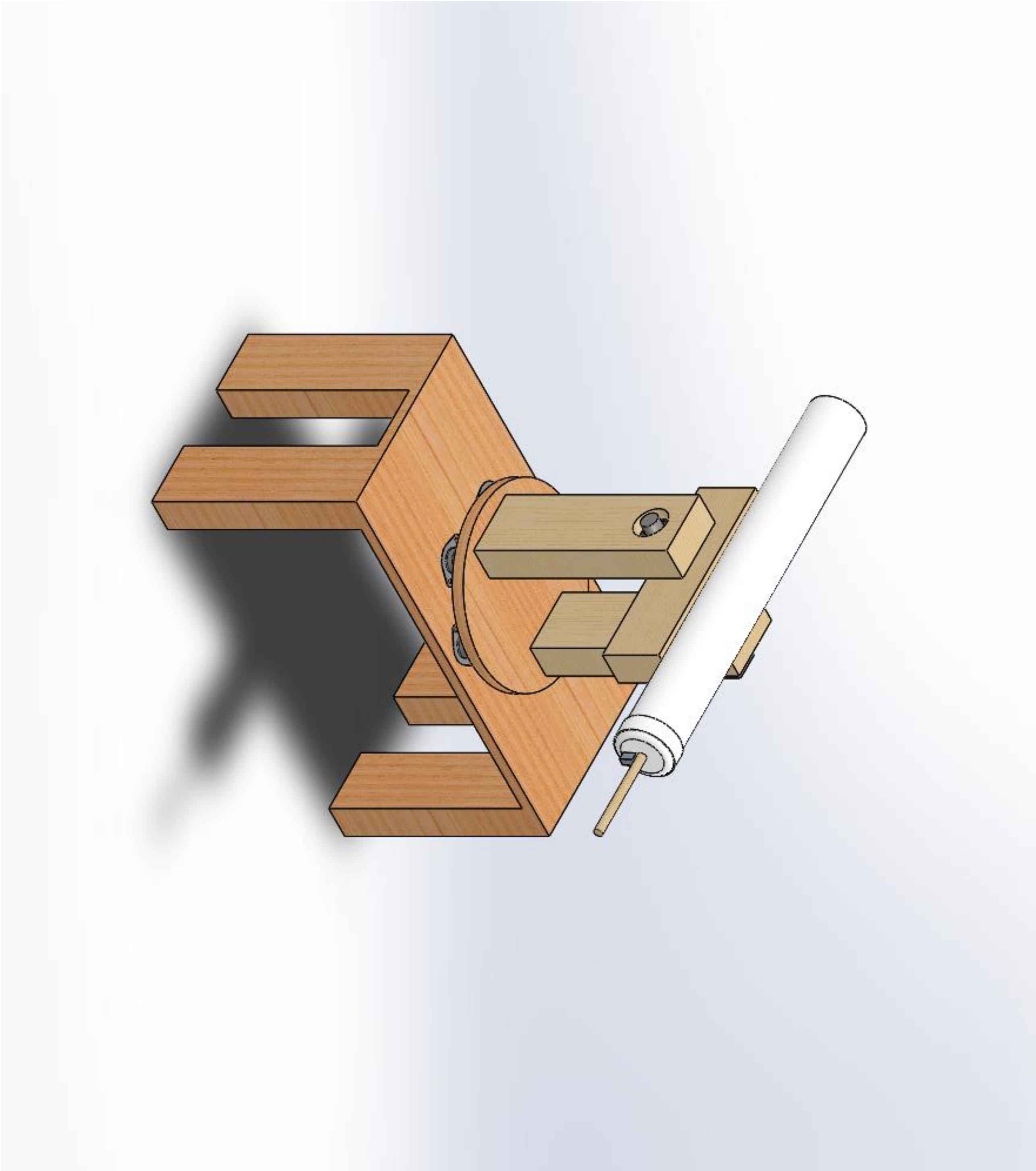


Figure 12: Back Isometric View

6 ENGINEERING ANALYSIS

6.1 ENGINEERING ANALYSIS RESULTS

6.1.1 Motivation

There are three primary forms of analysis for this project. Primarily, an analysis of the torques required to rotate the platform and the barrel will ensure that the motors can provide enough force to move our device the speeds needed to meet the performance goals. This will also influence the design to minimize the torques required to ensure smooth operation. Additionally, it will provide insight into the factors of safety of the connections, primarily the connection between the shaft expander and the rotating base. Additionally, the CAD model will be used to get a rough estimate of the weight of the device. This information will help the design meet the weight performance goal. Finally, the spring constant for the chosen compression spring needs to be measured for the tracking system to know where to aim.

6.1.2 Summary Statement of the Analysis

The torque required to accelerate an object is given by the equation

$$\tau = I\alpha$$

In order to determine the torque requirements for the motor, an acceleration profile must be determined. SolidWorks has a built-in feature for this, allowing us to determine a reasonable bound for the torque. It does this by calculating the moment of inertia of the part and the angular acceleration of the motor while maintaining the assembly mates of the part.

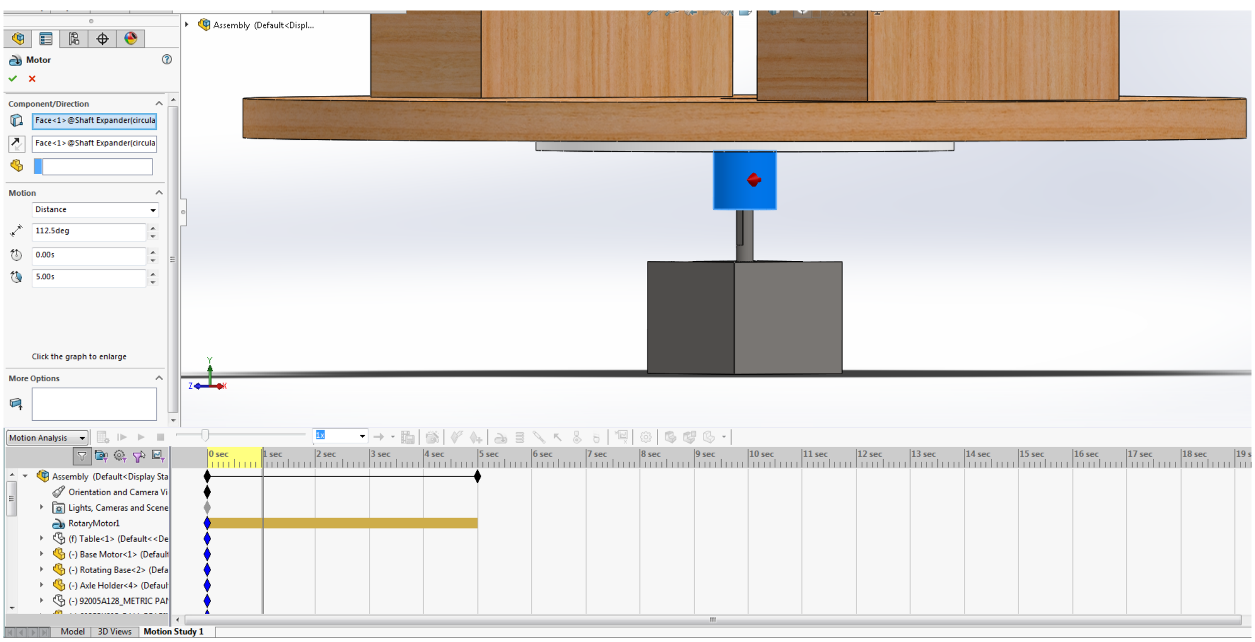


Figure 13: Graphic of the Motion Analysis Feature of SolidWorks

6.1.3 Methodology

Toque: Toque analysis is done using the CAD model and the SolidWorks motion study. The parts in SolidWorks are modeled with their material properties, meaning the program can calculate the amount of torque required to rotate parts at a certain speed. For this measurement, the performance goal of a moving target was used as a reference for the speed of rotation, including a factor of safety to make sure the device can rotate fast enough. For the measurement, we used an average rotational speed of 3.75 RPM. Furthermore, the device was tested in the worst-case scenario, with the barrel horizontal, which maximizes the moment of inertia.

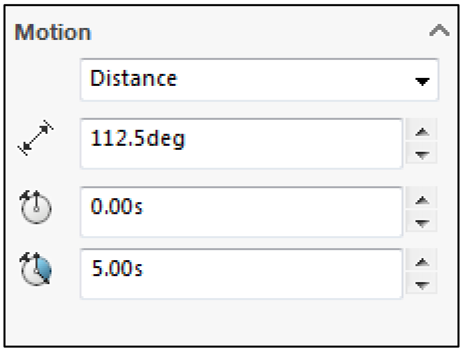


Figure 14: Settings Used for SolidWorks Motion Analysis

Mass: SolidWorks provides a built-in calculator for the overall mass.

Spring: This analysis is done by hand using a set of known masses. The force exerted by a mass on the spring was plotted against the displacement cause by the force. The slope of that line using a line of best fit is the spring constant.

6.1.4 Results

For the device rotating at an average speed of 3.75 RPM (rotating 112.5 degrees over 5 seconds), the maximum torque for the rotating base was 0.15 lbf per inch.

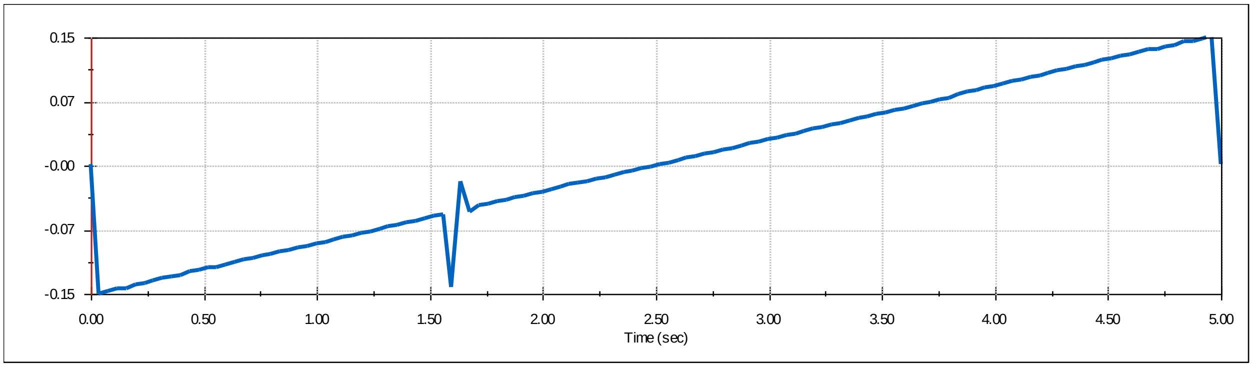


Figure 15: Graph of Motor Toque vs Time for the Rotating Base

For the vertical component of the aiming, rotating 50 degrees over 5 seconds, the maximum torque was 0.02 lbf per inch.

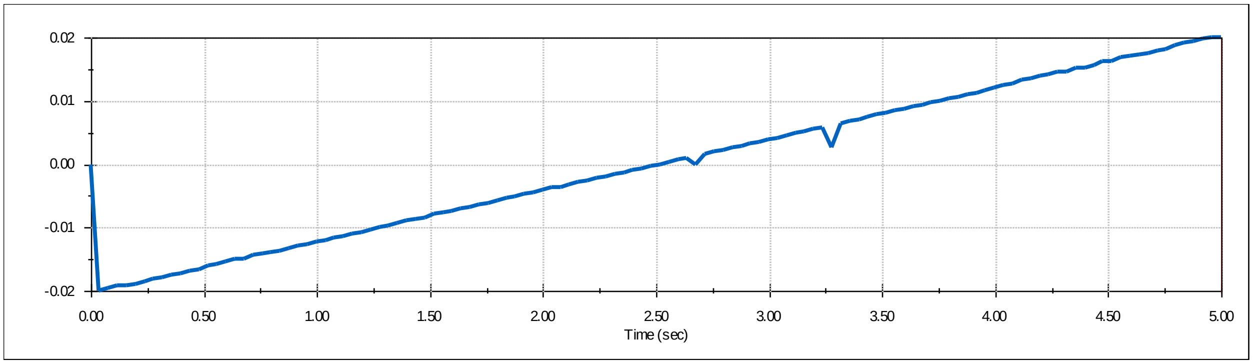


Figure 16: Graph of Motor Torque vs Time for Barrel

The mass of the whole device, excluding electronic components, is 18.70 pounds according to the SolidWorks analysis.

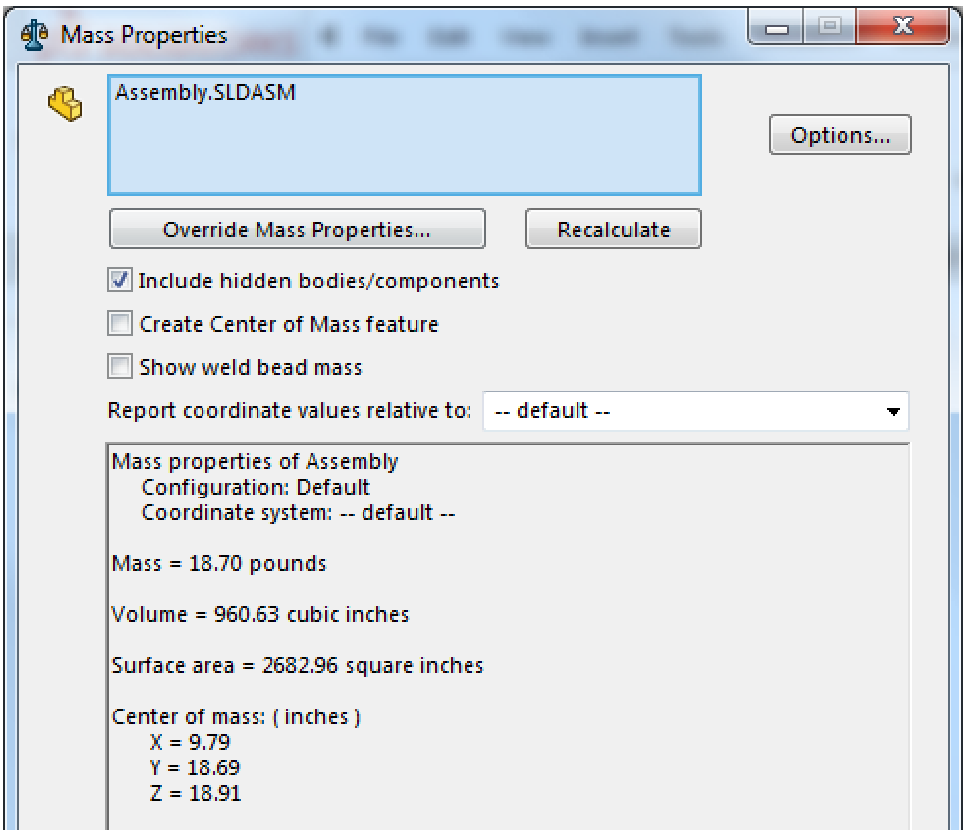


Figure 17: Mass Properties Analysis with SolidWorks

From our trendline we got that the spring constant was 119.96 Newtons per meter with a pre-load of -.1371 Newtons. We then converted this from Newtons per meter to pounds force per inch and got a spring constant of 0.685 lbf/in. This constant may not be accurate, as it was measured in tension instead of compression.

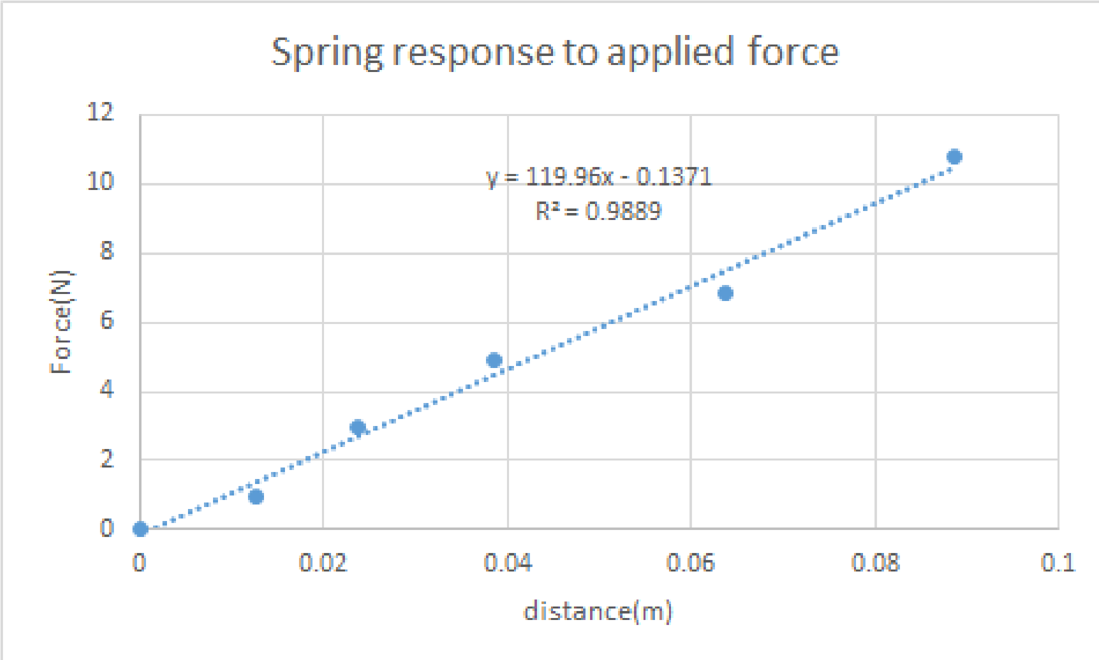
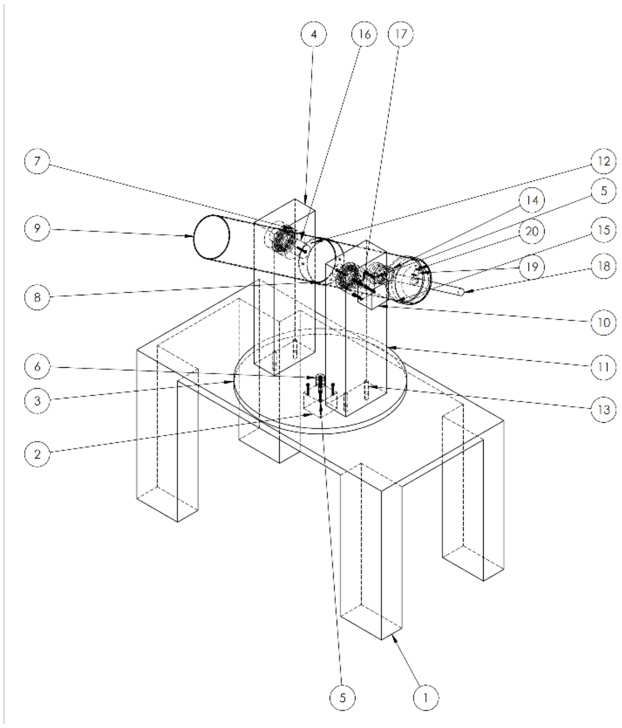


Figure 18: Spring Response to Applied Force

6.1.5 Significance

Both the torques were well beneath the torque output of their respective motors, meaning that the design can progress using the same configuration, and no special care needs to be taken to reduce the moments of inertia. This also gives us a large factor of safety for the weights that were not included in this analysis with the electronics. Furthermore, the design is well under the weight requirements. The measured value for the spring constant is lower than optimal, meaning it will be insufficient to launch our ball any significant distance. Overall, the analysis supported our design decisions, at least in terms of structure. A few changes were made from non-numerical analysis in order to increase the safety of the design against potential failure modes, including a redesign shaft expander to withstand more torque, and a redesign barrel mount to distribute the load across the barrel.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Table	Cut Plywood attached to four 2x4 legs with 1.5" wood screws	1
2	B00PNEQKC0	Stepper Motor (base)	1
3	Rotating Base	Cut Plywood	1
4	Axle Holder		1
5	92005A128	M3 Screws	10
6	Shaft Expander		1
7	60355K605	Double Shielded Bearing	2
8	Barrel Mount		1
9	Barrel	Made out of PVC	1
10	B00PNEQ9T4	Stepper Motor (Axle)	1
11	Axle Holder (Motor side)		1
12	91375A208	Set Screws	7
13	92114A138	Wood Screws 1.5"	24
14	9657K103	Compression Spring	1
15	PVC Endcap		1
16	Axle (non motor)	Machined Steel	1
17	Axle (motor)	Machined Steel	1
18	Reloading Rod		1
19	Solenoid		1
20	92095A454	M2 Screw	2

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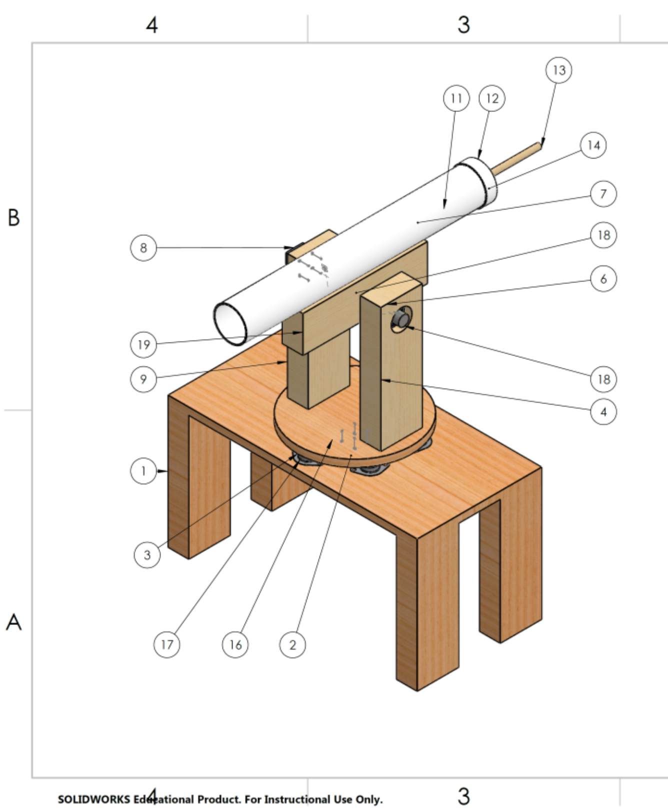
Figure 19: Design Before Analysis



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Table	Cut Plywood attached to four 2x4 legs with 2" wood screws	1
2	B00PNEQKC0	Stepper Motor (base)	1
3	Rotating Base	Cut Plywood	1
4	Axle Holder	2x4 cut to length with a 2 inch diameter through cut	1
5	92005A128	M3 Screws	8
6	Bearings	Non-Shielded bearings scavengened from basement	2
7	Barrel	Made out of PVC	1
8	B00PNEQ9T4	Stepper Motor (Axle)	1
9	Axle Holder (Motor side)	2x4 cut to length with a milled 2 inch diameter cut and a 1/2 inch cut	1
10	92114A138	Wood Screws 1.5"	2
11	Spring	Compression Spring	1
12	PVC Endcap	3/4 inch cut in ceneter of endcap for dowel rod and a through hole for the spring	1
13	Reloading Rod	3/4 inch dowel rod with scrap wood base	1
14	Solenoid		1
15	92095A454	M2 Screw	2
16	Shaft Expander(circular top)	3-D printed part	1
17	5674K1	Roller Mounts(similar to actual ones used)	6
18	Axle	Stell axle cut to length with a key hole and a set screw	1
19	Barrel Mount 2	Cut 2x4 reattached with two two inch screws	1
20	2-inch wood screws		24
21	12959	Solenoid Control	1
22	n/a	Pixy SMart Vision Camera	1
23	13975	Arduino	1
24	12779	Axle Motor Driver	1
25	12859	Base Motor Driver	1
26	91375A208	Set Screws	

SIZE B DWG. NO. Revised2 2 REV
SCALE: 1:12 WEIGHT: SHEET 1 OF 9

Figure 20: Design After Analysis

6.2 PRODUCT RISK ASSESSMENT

6.2.1 Risk Identification

6.2.1.1 Tracking

Description: A tracking error could cause the device to aim and fire at a bystander, or to miss the intended target.

Impact: 2. Although being hit by a rogue ball may cause injury, the chance of it being severe is low due to the nature of the ball.

Likelihood: 3. Due to time and knowledge constraints, the tracking system will have limitations and flaws that will cause tracking issues. However, the chances of injury occurring from any individual error is decently low.

6.2.1.2 Kinetic Energy

Description: The spring transfers an unsafe level of energy to the ball, causing it to move faster than is safe.

Impact: 3. Using the full force of the spring could cause moderate injuries if it is not controlled.

Likelihood: 1. This risk is well managed with our design, as the compression of the spring is set by the firing mechanism, meaning it can be controlled in normal circumstances. However, the user could still manually compress the spring more.

6.2.1.3 Firing Angle

Description: If the firing angle is too low or too high, it will be unsafe to catch the ball due to the speed and trajectory they are moving.

Impact: 2. Despite the unsafe firing method, the maximum energy in the ball would still be limited by the compression of the spring, meaning severity of injury would be moderately low.

Likelihood: 2. Although programming will attempt to stop this from happening, lack of sensors will limit the devices knowledge of its vertical position.

6.2.1.4 Rotation

Description: Excessive base rotation will cause the wiring the tangle and break, leading to equipment failure and potential injury to the user.

Impact: 4. This mode of failure would damage the device in such a way that it would be non-functional.

Likelihood: 2. With no good way for the device to sense its absolute position (just relative position to the target), it has no safeguards preventing it from rotating past certain points. However, the user can account for this with their positioning.

6.2.1.5 Motor Torque

Description: The torque from the motors can exert toque that can damage the user if the device is improperly handled, such as sticking an arm through the axle holding arms or in the barrel.

Impact: 5. The device does not care about obstructions to its motion, and will do its best to move despite them. If that obstruction happens to be a limb, it would try to turn until either it, or the limb, was broken.

Likelihood: 1. This risk requires gross misuse of the device to manifest.

6.2.1.6 Splinters/cuts

Description: Many parts of the device are manufactured using wood, meaning splinters are a risk when handling the device. Although the largest offenders have been sanded down, the risk remains for the user to get small splinters when setting up or operating the device.

Impact: 1. The sections with the largest risk of giving splinters have been taken care of, meaning the remaining splinters would be small nearly insignificant.

Likelihood: 2. Despite the best efforts, some splinters will remain.

6.2.1.7 Failure

Description: Failure of one or more parts, causing the device to break apart. The most likely parts to fail are the shaft expander and the PVC endcap.

Impact: 5. Either of these failure modes would cause a sudden release of energy, and would damage the device to the point of needing significant repair.

Likelihood: 2. Time constraints and material constraints limit the fortification of the design against failure. When removing the bearing from the motor holder only superficial damage occurred.

6.2.2 Risk Heat Map

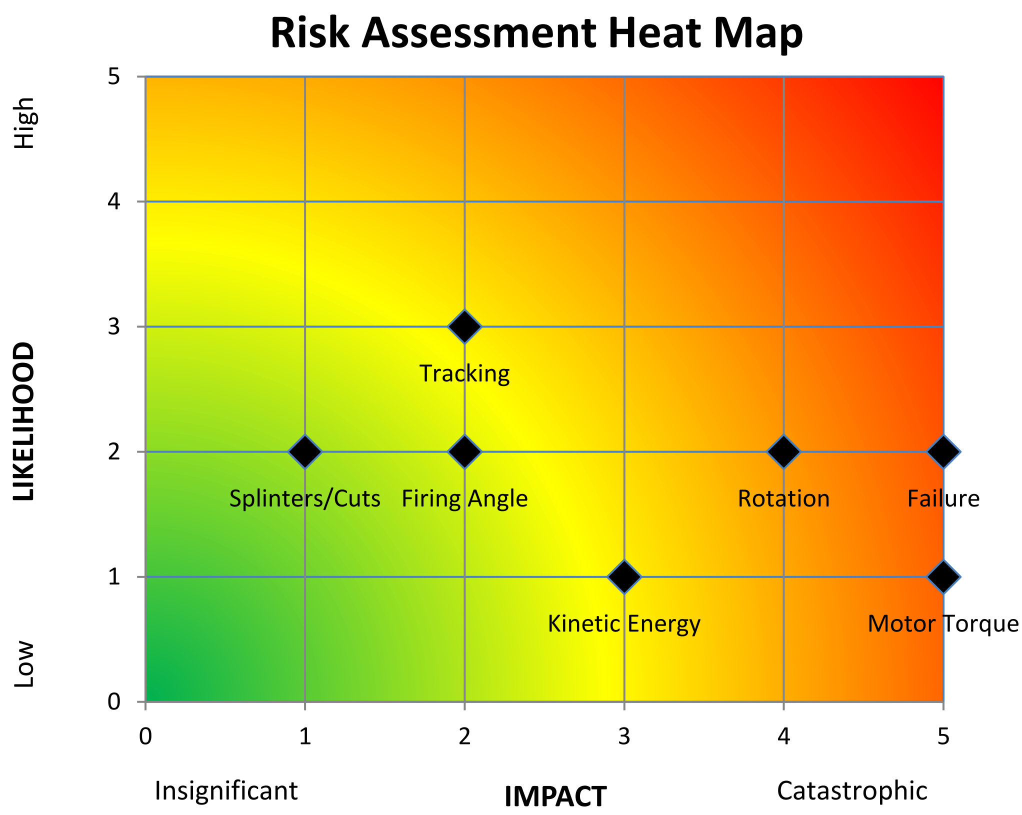


Figure 21: Risk Heat Map for ABLE

6.2.3 Risk Prioritization

The most important risks for the design process are failure and rotation. Both of these risks would cause irreversible damage to the device and potentially the user. The risks from failure were mitigated by designing parts to be thicker than needed to minimize the chance that the stresses cause them to fail. Future prototypes could use stronger materials to increase this factor of safety. For the rotation and firing angle issues, sensors that give an absolute position would ensure that the device could be programmed to never pass certain thresholds. For the current iteration, these risks are mitigated through close monitoring and calibration. Although the motor torque issues is high impact, there is very little that can be done without additional components that can detect when the device is blocked, meaning the primary design for the current iteration to mitigate the issue is in ensuring the user has proper knowledge of how to operate the device. Instruction would also minimize the kinetic energy risk. A future prototype would also benefit from an improved tracking scheme to minimize the risk of wrongful aiming and misfires. The least important risk by far is the risk of splinters. This could be fixed by using a safe covering material over the wood, or by wearing gloves during setup and transport.

7 DESIGN DOCUMENTATION

7.1 PERFORMANCE GOALS

1. ABLE must fire ball at least 20 yards.

2. ABLE must fire on average within a 1-yard circle around target running at 4 mph at 15 yards away over 5 shots.

3. ABLE must be able to be reloaded within 20 seconds, from having a ball in hand to ball launch.

4. ABLE must land ball +/- 1 yard on average of 5 shots when a static target is 15 yards away.

5. ABLE (including table) must weigh less than 30 lbs.

7.2 WORKING PROTOTYPE DEMONSTRATION

7.2.1 Performance Evaluation

Our device was able to fully reach two goals, and partially reach all of the others. The device was able to meet the weight and reload speed requirements fully with no issue. However, it was unable to fire a full 20 yards, instead having a range of around 6 yards. This could be improved with a redesign of the launching mechanism, replacing the PVC barrel with a mechanism more suited for holding the surgical tubing. Additionally, the device was able to fire consistently at its maximum range within a much tighter range than 1 yard. While tracking was successfully implemented, the device was not able to fire and track safely at the same time, meaning it was not able to meet the second performance evaluation very well at all.

7.2.2 Working Prototype – Video Link

https://youtu.be/NLtWWr0Za5U

7.2.3 Working Prototype – Additional Photos

Figure 22: First Additional View of Finished Device

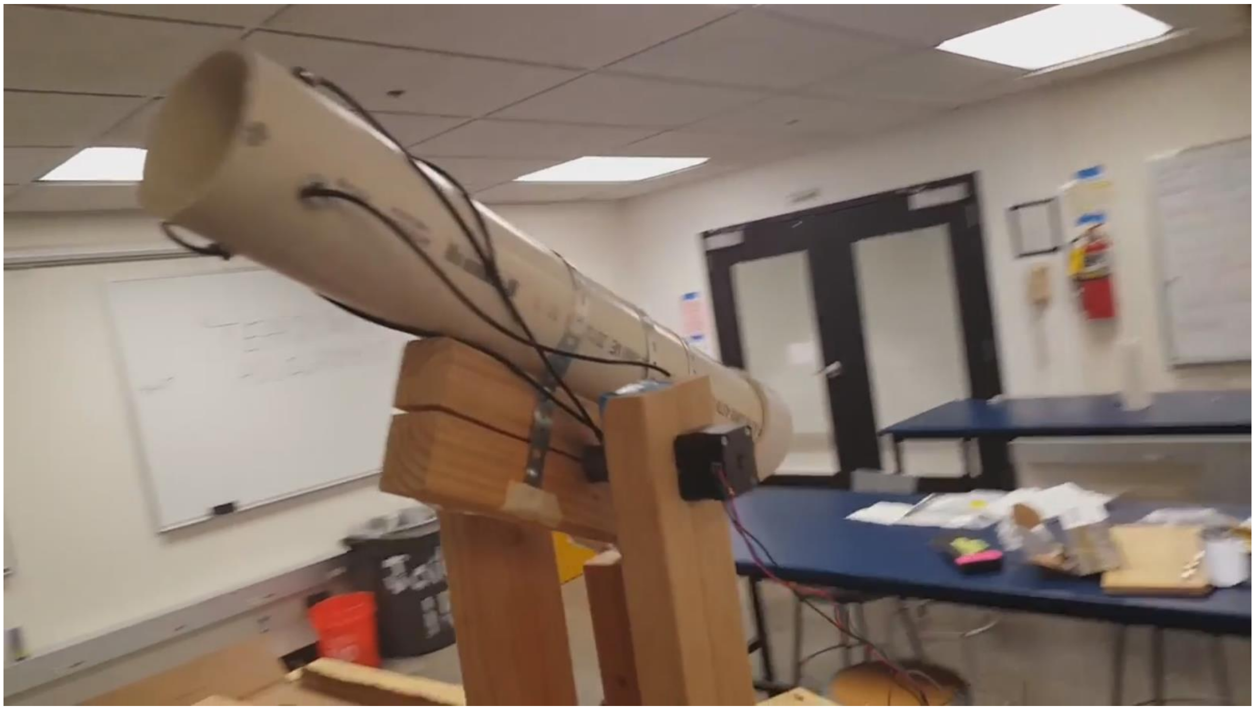


Figure 23: Second Additional View of Finished Device

8 DISCUSSION

8.1 DESIGN FOR MANUFACTURING – PART REDESIGN FOR INJECTION MOLDING

8.1.1 Draft Analysis Results

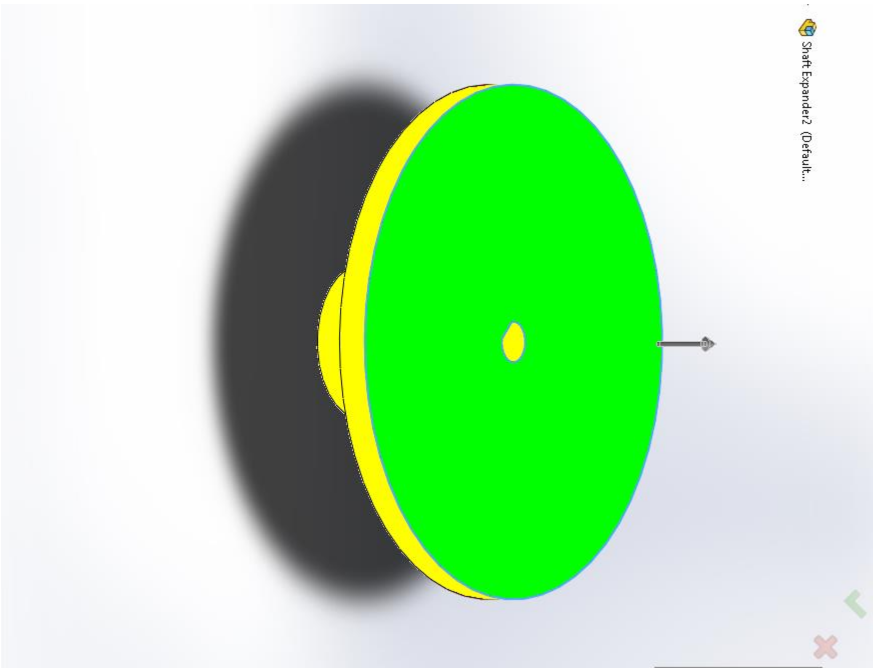


Figure 24: Shaft Expander Before Draft

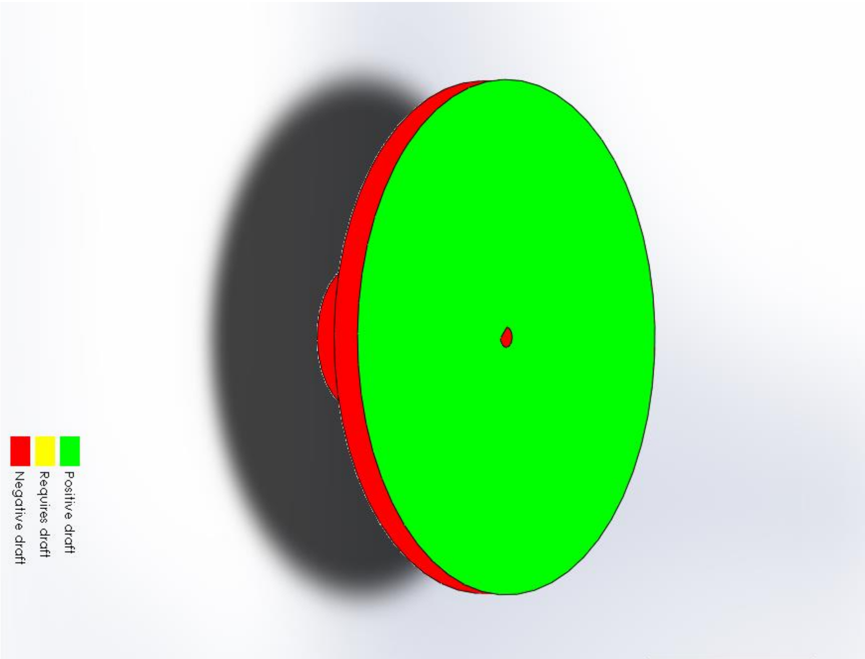


Figure 25: Shaft Expander After Draft

8.1.2 Explanation of Design Changes

Adding draft to the outside portions of the design represented a minimal change, as neither of those sides interfaced with other parts. However, the draft of the internal hole was more difficult. The primary issue was that the dimensions of the hole are dependent on the shaft of the stepper motor. Thus, the shaft was added making sure that the dimensions of the hole are the same at the bottom of the part (where it interfaces with the shaft of the motor). This has a positive benefit, however, of allowing the shaft expander to attach via a force fit rather than needed a set screw.

8.2 DESIGN FOR USABILITY – EFFECT OF IMPAIRMENTS ON USABILITY

8.2.1 Vision

The device would be almost entirely unusable for a blind individual, due to the person needing to see the ball in order to catch it. For a color blind individual, there is no issue using the device, as color is not an important factor in the design, and each shape is highly distinguishable. Furthermore, there is only a single projectile being launched, which should be easily seen by color blind individuals.

8.2.2 Hearing

Use of the device is entirely unaffected by a hearing impairment, as it does not rely on sound cues, and catching the projectile does not require sound.

8.2.3 Physical

Physical impairments will limit the ability of an individual to reload the device. This can be minimized by reducing the amount of force required to pull back the reloading rod, either by using as light as possible of a rod or by automating the reload mechanism with a motor. Furthermore, physical impairments may affect how an individual catches a ball, meaning the ball may need to be launched shorter distances so it does not move as fast or impart as much force.

8.2.4 Language

A language impairment will make it harder to understand how to use the device and how to set it up. This can be dealt with by including instructions in different languages, or by including pictorial instructions to the user.

8.2 OVERALL EXPERIENCE

8.2.1 Does your final project result align with the initial project description?

The final prototype aligns moderately well with the initial project description. It is able to track a target and fire a ball a modest distance, but still requires human input to fire, and can't achieve the desired ranges. Additionally, it lacks vertical aiming needed for properly calibrated distance firing. Nevertheless, it remains a good proof-of-concept towards fully meeting the project description.

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

The project ended up being more difficult than expected particularly in terms of time spent on the project. This ended up being mainly due to unforeseen issues when it came to assembly and manufacture of the project, centered around a lack of engineering knowledge of attachments between moving parts..

8.2.3 In what ways do you wish your final prototype would have performed better?

Having more effective means of transferring the energy of the motors to the rotation of parts would have improved the project significantly, making the tracking system work better and would have reduced concerns with wiring.

8.2.4 Was your group missing any critical information when you evaluated concepts?

The main issue with the evaluation of concepts was an overestimate of the ability of a simple spring to provide enough energy to the ball to launch it forward without causing structural issues elsewhere in the design. With that issue in mind, a different design would have likely won.

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

For the most part, additional engineering analysis would not have influenced our design all too much. The primary area where it could have accelerated our design process was looking more in depth as to the forces required to launch the ball using different mechanisms, and working to maximize a person's ability to supply that force.

8.2.6 How did you identify your most relevant codes and standards and how they influence revision of the design?

The primary concern with our device was safety. Thus, we looked up standards regarding safety for electrical toys and kinetic energy toys. Fundamentally, we were unable to reasonably include these standards in their normal form in our project, because the kinetic energy considerations from the standard would be insufficient to meaningfully launch a ball. Furthermore, the standards for electrical safety were not the focus of the project, as for the initial prototype, getting the device to function was the priority.

8.2.7 What ethical considerations (from the Engineering Ethics and Design for Environment seminar) are relevant to your device? How could these considerations be addressed?

The primary ethical concern for our device is in the waste caused by manufacturing and disposal. These issues are addressed by ensuring that it minimizes the use of non-sustainable materials, and contains many recyclable components.

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

Once the issues surrounding getting the vertical rotation set up started to surface, it should have been deemphasized and given less time. This way, more time could have been given to the programming and firing mechanism, both of which needed significantly more time than they were given.

8.2.9 Was there a task on your Gantt chart that was much harder than expected? Were there any that were much easier?

Manufacturing of parts was much harder than expected as we had conflicts with some of the machine shop times. Furthermore, due to some scheduling issues and difficulty getting two people in for manufacturing/assembly made much of the early construction of the design more time consuming than expected and when it came to anything involving the heavier tools delayed it unless another group was present.

8.2.10 Was there a component of your prototype that was significantly easier or harder to make/assemble than you expected?

Getting the firing mechanism to fully function was much significantly harder than we thought due to a variety of reasons. The biggest reason is that we had to go through multiple iterations with the launching mechanism, as our plan to use a spring didn't end up working due to issues with it strength and stability. Furthermore, there were several issues attaching the firing mechanism to the axis, and it took several iterations to get a method that worked well.

8.2.11 If your budget were increased to 10x its original amount, would your approach have changed? If so, in what specific ways?

The main change that would be made with a larger budget would be a more accurate tracking method that provided a good sense of distance and position. Furthermore, more power motors and proper wiring supplies would improve the ability of the device to act on the new position information. Finally, inclusion of some form of mechanical assistance on the reloading mechanism would allow the device to launch further by storing more energy without placing an undue burden on the user.

8.2.12 If you were able to take the course again with the same project and group, what would you have done differently the second time around?

One thing that we would have done differently is to use the earlier time more effectively and work on manufacturing during other assignments, as well as making sure everyone was on the same page in terms of expectations for the project. Additionally, we would put more work into ideas for the firing mechanism, as that was one of the most frustrating aspects of the project. Finally, we would scale back the expectations of the project to be more reasonable for the limited amount of time we had.

8.2.13 Were your team member's skills complementary?

For the most part, team members were able to work well together and specialized at different things. However, there was an amount of codependence that negatively influenced the group, with some members unable to fully contribute without the help of others.

8.2.14 Was any needed skill missing from the group?

The main issue of the project was a lack of time and materials as opposed to a lack of skill. For example, a team member possessed the skill to improve tracking programming and wiring, but lacked the time to do so as they helped with the construction aspects.

8.2.15 Has the project enhanced your design skills?

The project has improved the design skills of the team, primarily in their ability to work around roadblocks in the design process, as well as teaching them more about how to feasibly connect different members together and transfer motion.

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

Yes.

8.2.17 Are there projects you would attempt now that you would not have attempted before?

While the project did improve the skills of the team members, it did not change their drive to attempt difficult assignments.

9 APPENDIX A - PARTS LIST

Table 8: Parts List for ABLE

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Tax ($0.00 if tax exemption applied)	Shipping	Quantity	Total price	Aquired From:
1	Set Screws	McMaster	91375A208	Black	$0.00			1	$0.00	Basement
2	Springs	McMaster	9657K103		$0.00			1	$0.00	Basement
3	Bearings	McMaster	60355K605	double shielded	$0.00			2	$0.00	Basement
4	Wood for legs	Homedepot		cedar	$5.17	$0.31	$0.00	1	$5.48	
5	Wood for axle mounts	Homedepot		cedar	$0.00	$0.00	$0.00	1	$0.00	Basement
6	Wood for base	Homedepot		plywood	$0.00	$0.00	$0.00	1	$0.00	Basement
7	Barrel	Homedepot		PVC pipe	$0.00	$0.00	$0.00	1	$0.00	Basement
8	Endcap	Homedepot		PVC Endcap	$0.00	$0.00	$0.00	1	$0.00	Basement
9	Motor Screws	McMaster	92005a128	20mm M3	$3.16			1	$3.16	
10	Solenoid Screws	McMaster	92095a454	8mm M2	$6.38			1	$6.38	
11	Wood Screws	McMaster	92114A138	1.5"	$7.79			1	$7.79	
12	Axle/Rod	McMaster	6628K53	steel, 1 ft	$22.77		$0.00	1	$22.77	
13	Base Stepper Motor	Amazon	B00PNEQKC0	84 oz.in	$13.99	$0.84	$0.00	1	$14.83	
14	Axle Stepper Motor	Amazon	B00PNEQ9T4	36.8 oz.in	$11.99	$0.72	$0.00	1	$12.71	
15	Power Supply	Amazon	B073GH3TLG	12V/2A	$7.99	$0.48	$0.00	2	$16.46	
16	Base Motor Driver	Sparkfun	12859	Big EasyDriver	$19.95	$1.20	$0.00	1	$21.15	
17	Axle Motor Driver	Sparkfun	12779	EasyDriver	$14.95	$0.90	$0.00	1	$15.85	
18	Arduino	Sparkfun	13975	RedBoard	$19.95	$1.20	$0.00	1	$21.15	
19	Solenoid	Amazon	DS-0420S	5V	$7.99	$0.48	$0.00	1	$8.47	
20	Wood Screws	Amazon		.5 in	$5.99	$0.36	$0.00	1	$6.35	
21	Rollers	Amazon	2634038		$10.00	$0.60	$0.00	1	$10.60	
22	Dowel Rods	Amazon		.75 and 1 inch	$9.99	$0.60	$0.00	1	$10.59	
23	Pixy Smart Vision Camera	Amazon			$69.00	$4.14	$0.00	1	$73.14	
24	pvc endcap	Amazon			$1.92	$0.11		1	$2.03	
25	forney compression spring	Amazon	72653		$5.59	$0.55	$3.99	1	$10.13	
26	Surgical Tubing	Amazon			$12.84	$0.77		1	$13.61	
27	Plumber Tape	Amazon			$10.99	$0.66		1	$11.65	
26	Solenoid Control	Sparkfun	12959	MOSFET	$3.95	$0.24	$20.00	1	$24.19	
Total:									$318.47	

10 APPENDIX B - CAD MODELS

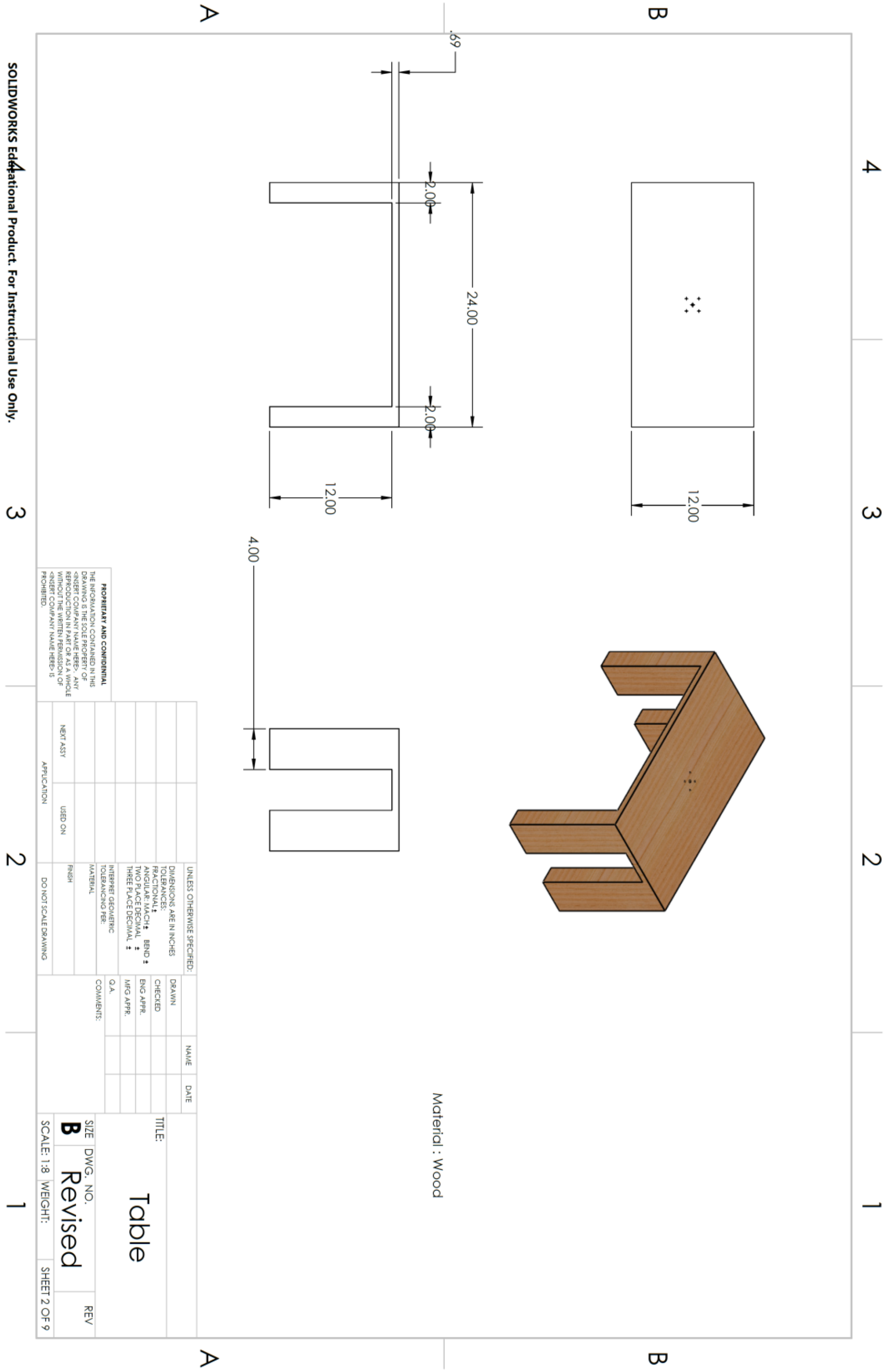


Figure 26: CAD Model for Table

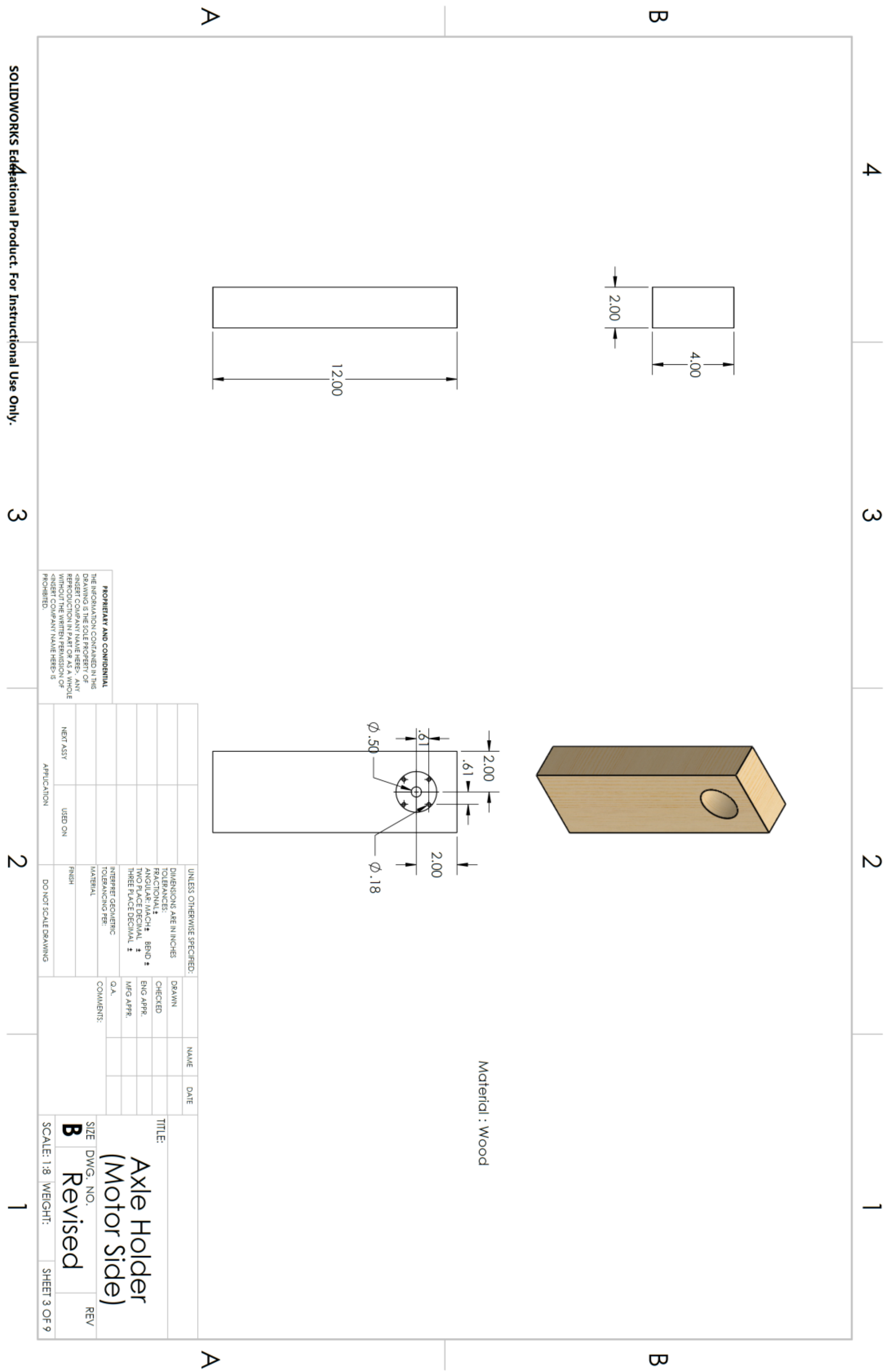


Figure 27: CAD Model for Axle Holder (Motor Side)

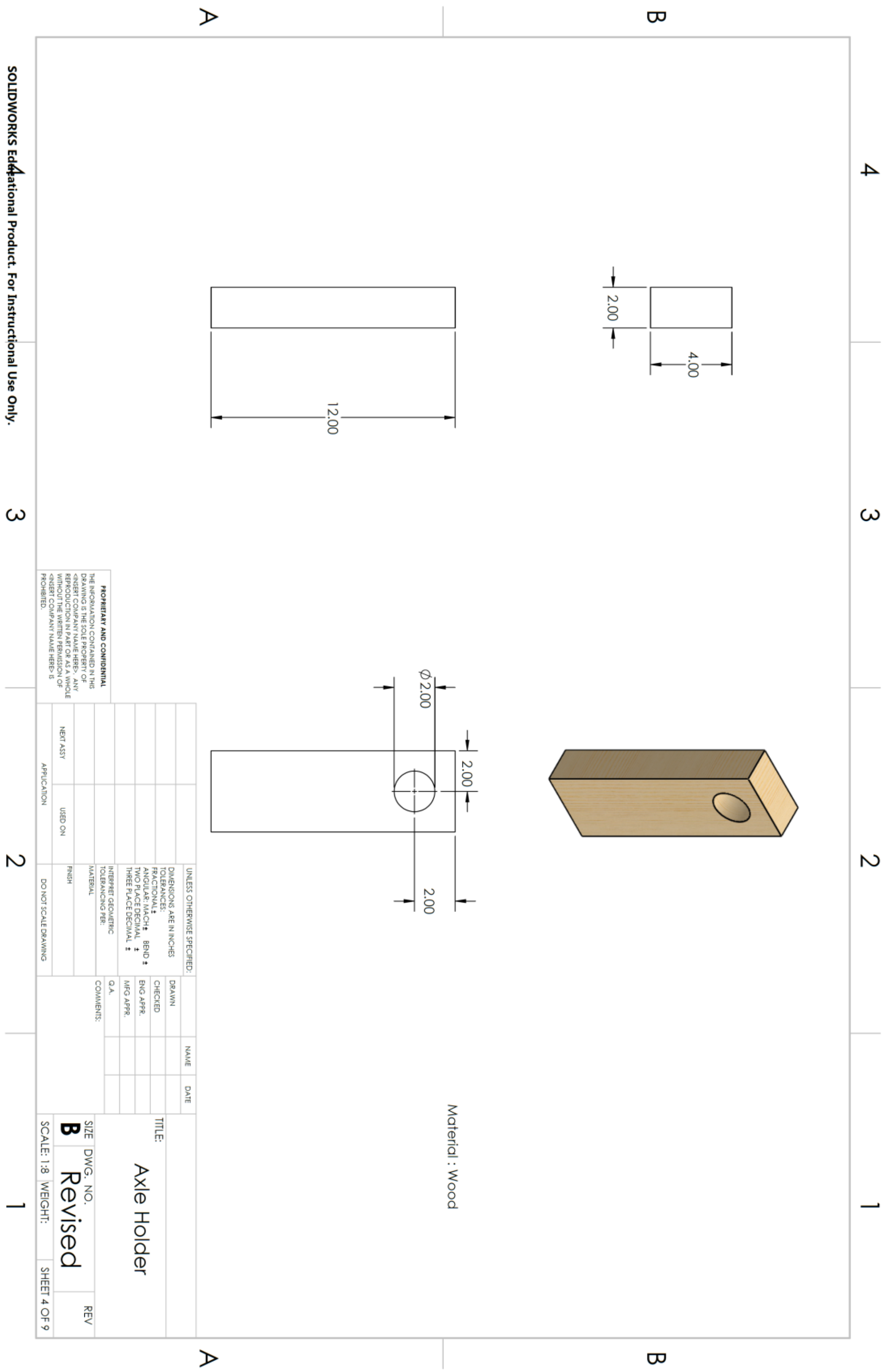


Figure 28: CAD Model for Axle Holder

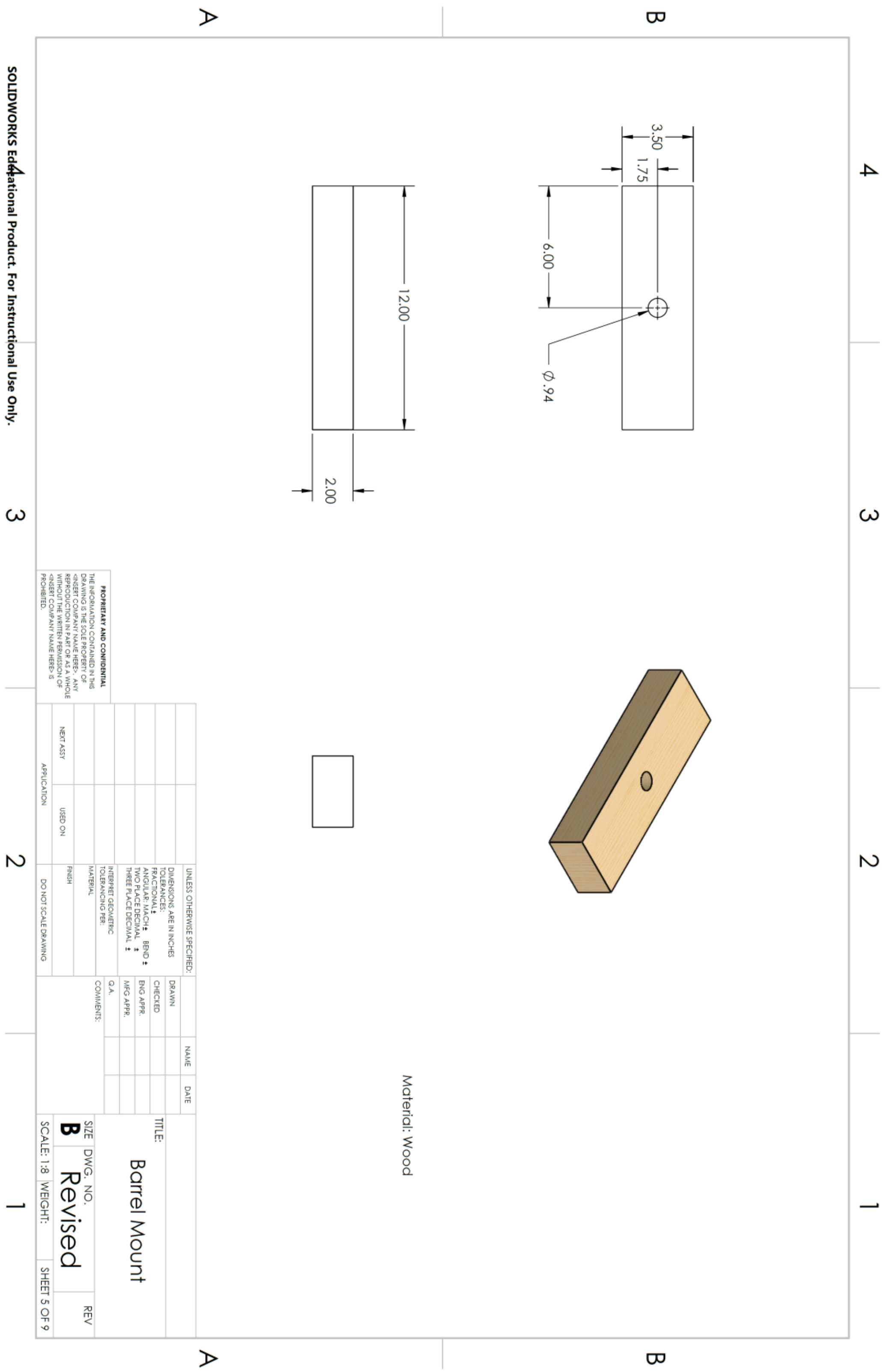


Figure 29: CAD Model for Barrel Mount

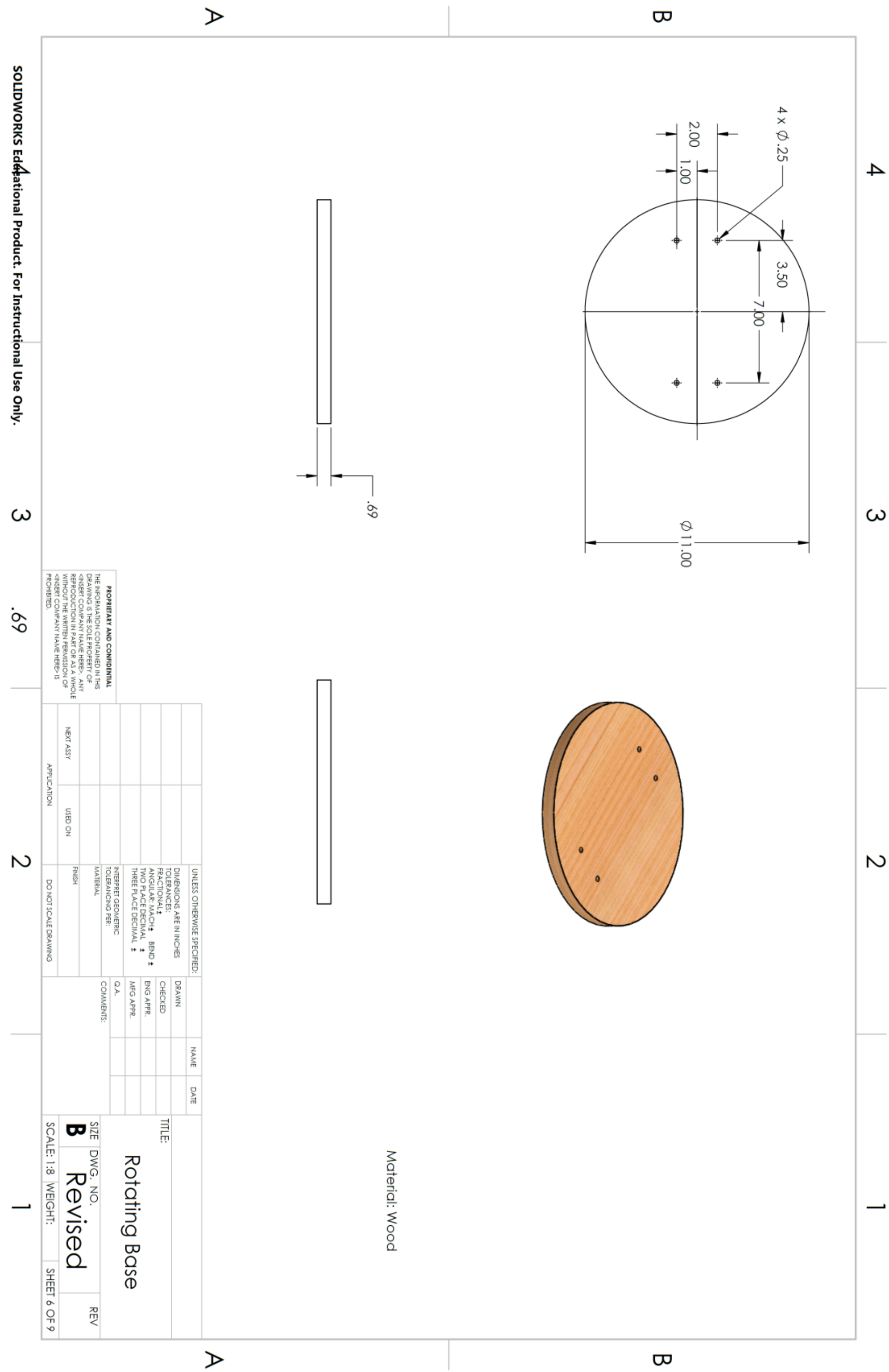


Figure 30: CAD Model for Rotating Base

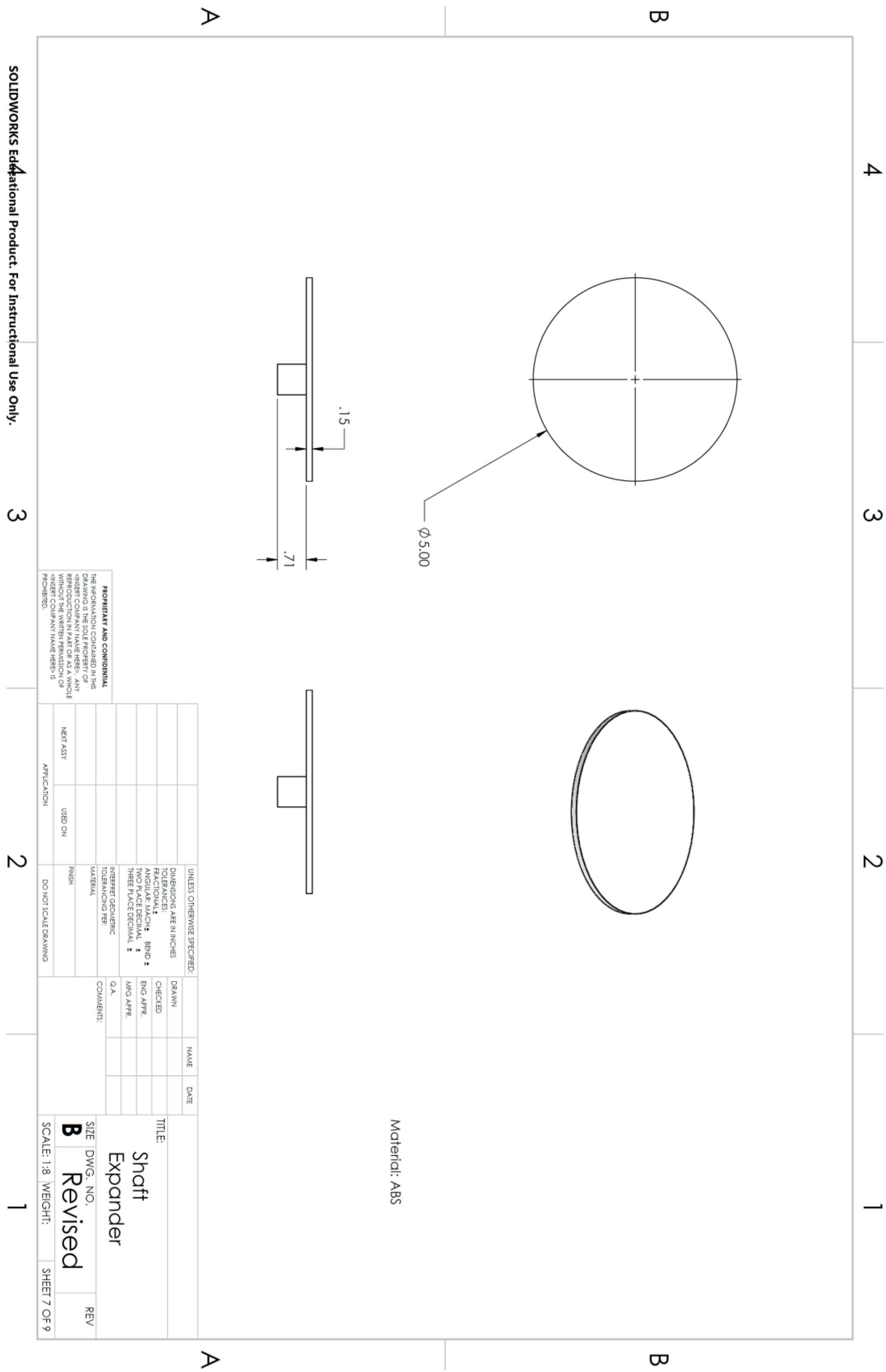


Figure 31: CAD Model for Shaft Expander

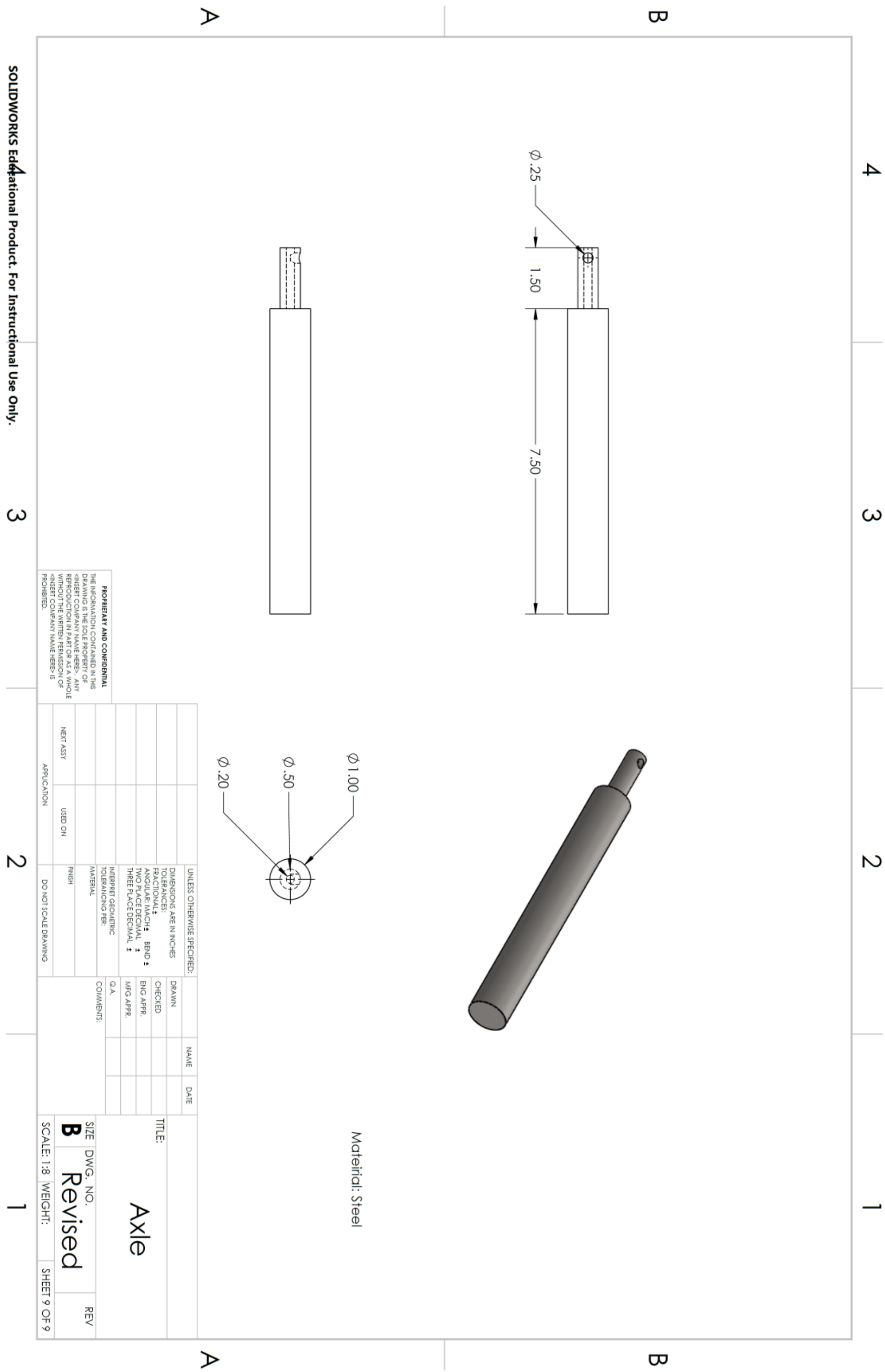


Figure 32: CAD Model for Axle

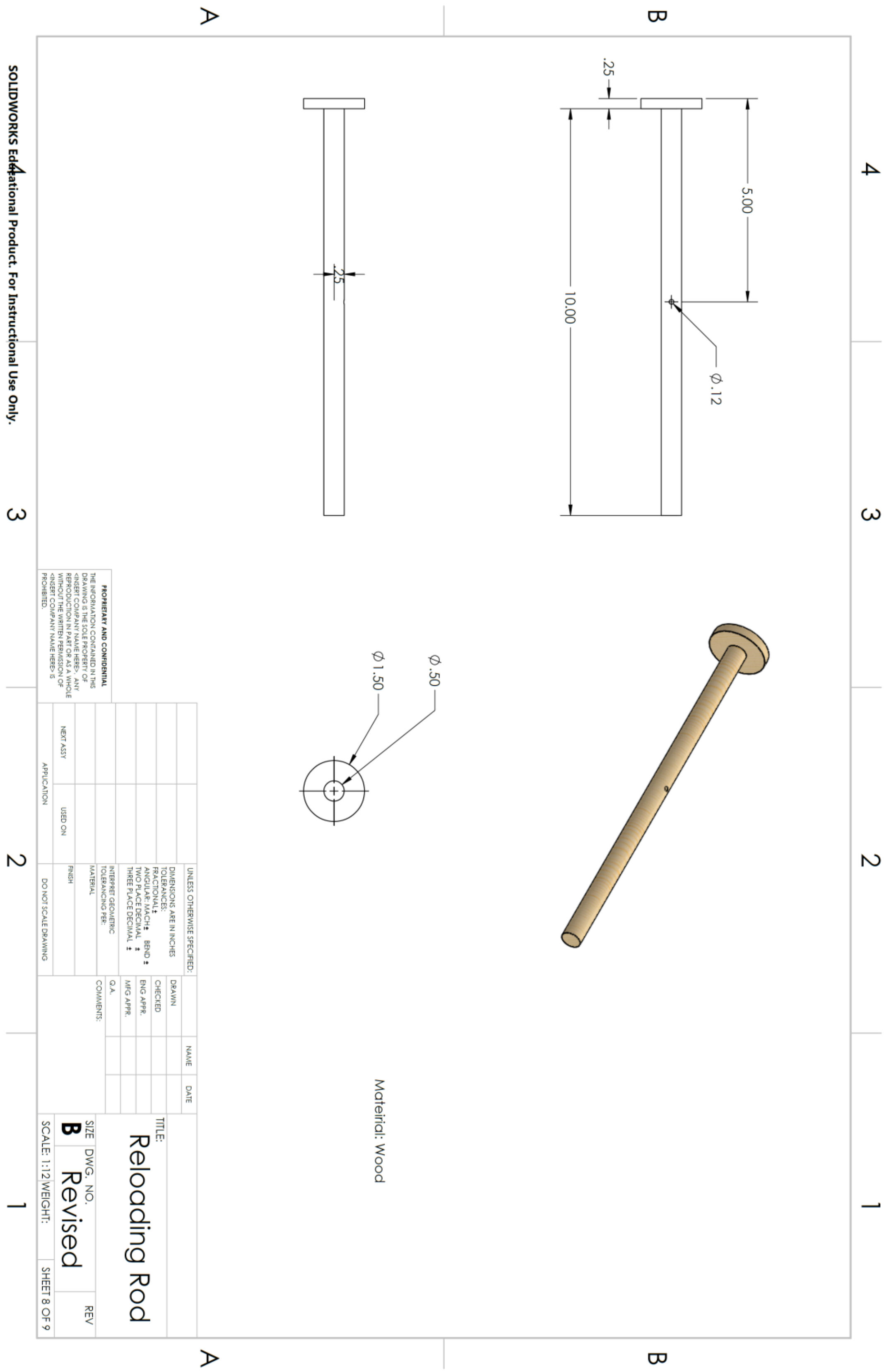


Figure 33: CAD Model for Reloading Rod

11 ANNOTATED BIBLIOGRAPHY