MSE 312: Mechatronics Design II

Summer 2021

Project Type Selected:

Design of a throwing arm

Brief Mechanical Design Report

Prepared by: Long March

Students Name	Student ID
Arash Pour-zargar	301123105
Chad Graham	301308419
Darwin Chang	301315054
Sepehr Rezvani	301291960

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1 Introduction

This report outlines the potential conceptual design along with the Mechanical design of a throwing arm mechanism. Each conceptual design is analyzed and verified to investigate its performance in its deflection, stiffness, stress, strain, and inertia. Firstly each member has developed a couple of conceptual designs individually and then all the concepts are shared between all team members. The pros and cons of each concept are investigated and checked by all team members to finally come up with three potential final concepts. Finally, the selected conceptual design are compared using a decision matrix to clarify the priority of each design in our team. The next step was to design the selected concept using the CAD tool which in our case the software is Solidworks. Mechanical design and detailed design in Solidworks are performed to determine detailed information about our selected design. Some of the problems in conceptual design are improved in this section. For example, we have improved the joint and connections in the Mechanical design to have only one degree of freedom since it was the requirement of the project. Another example would be decreasing the length of one of the links in order to decrease the weight of the system and have a more optimized detailed design for this project. The next step was to determine the stress, strain, and displacement of the arm using finite element analysis known as FEA in Solidworks .therefore we imported the CAD model into the simulation section in Solidworks and clarified the fixed point, forces on the arm, and a proper mesh for the arm. Then we ran the system to see the result of our mechanical design with the specifications ball in the throwing arm system. Also, a Bill Of Material known as BOM is added to the CAD model for the next steps in the design. Lastly, a MATLAB/Simulink model was created for the throwing arm system to analyze the motion of the inertia and the motion of the throwing arm system. In the following sections, we will explain all the details in a proper sequence.

2 Design Criteria

For this project, our team will be focused on the functional requirements of the end product, and non-functional aspects will have a lower priority. Our group will use a combination of Human-Centered Design and Design Thinking. At the end of this semester, professors, who are considered our clients, will test our products through random target locations on test day and it is imperative that the system meets the design requirements discussed in the project description.

3 Proposed Concepts

3.1 Design I - Tennis Ball Launcher

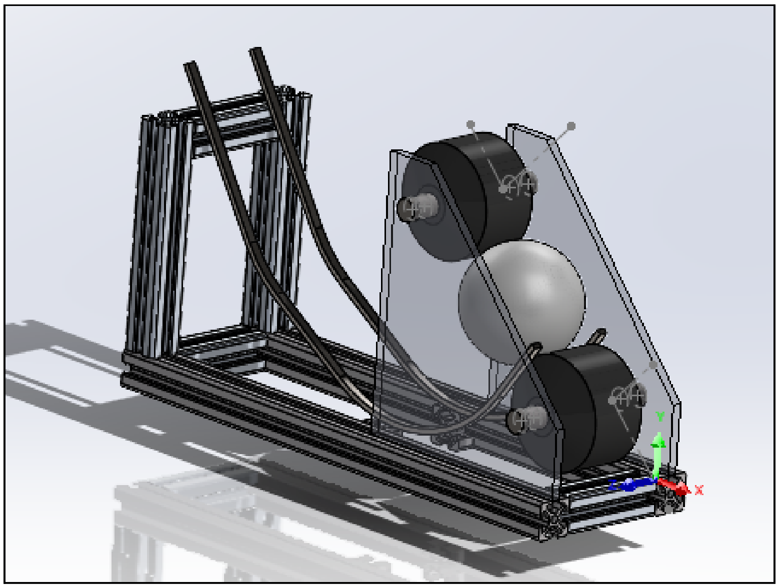


Figure 1: Tennis Ball Launcher

The first proposed design was a tennis ball or batting cage-style ball launcher. The system will have the ball rolling down an inclined slope, landing in the launch area. In this area, two wheels spinning would pull and squeeze the ball and propel it to the desired position. Due to the fixed launch angle and start position, the only input variable that would need to change is the angular velocity of the rollers. To protect the motor, and to increase torque a simple gearbox would be chosen to apply the propulsion to each roller at the same angular velocity.

3.2 Design II - Catapult Arm

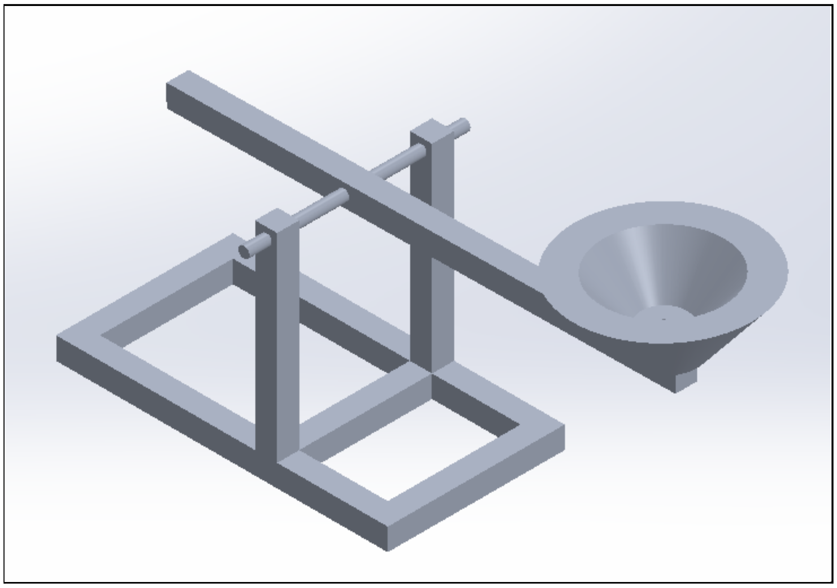


Figure 2: Catapult Launcher

The second proposed conceptual design was inspired by a catapult distance. This design will have the ball at the end of the arm in a bowl-like part. The important point about this conceptual design is that it is designed to be modular. What it means by modular is that the middle link and the bowl part are flexible and it can be reshaped and resized in order to have an optimized result. This conceptual design has 1 degree of freedom in the middle link to rotate this link in a way that it can provide proper acceleration to throw the ball. The DC motor is considered to be added at the bottom of this design and the rotary torque is transferred to the shaft using a belt. The main reason behind that is to have the COM(Centre of Mass) of the system as low as possible to have a stable system while throwing the ball. This mechanical design can be controlled using an encoder for the DC motor to provide the proper angle and acceleration for throwing the ball in order to reach the goal position. Depending on the power and ratio that is needed in this mechanical design we can use a gearbox system to have a proper input to the throwing arm.

3.3 Design III - Lacrosse Ball Launcher

The third design is partly inspired by the medieval trebuchet. A DC motor, represented by the black box, is connected to the side of the throwing arm via a rope. Once the motor starts rotating, it will pull the rope downwards, causing the arm to rotate, and launch the ball at the end of its rotation. Similarly, another rope connects the other side of the throwing arm to the screen door once the arm is in a vertical position (end of launch). That causes the screen door to open and release an additional ball for the second launch. While the arm is rotating back to its starting position after the first launch, the second ball has been released from ramp 2 and is rolling on the ground towards ramp 1. Once the throwing arm is back on the ground to the start position, the ball will backward from ramp 1 and fall at the end of the throwing arm.

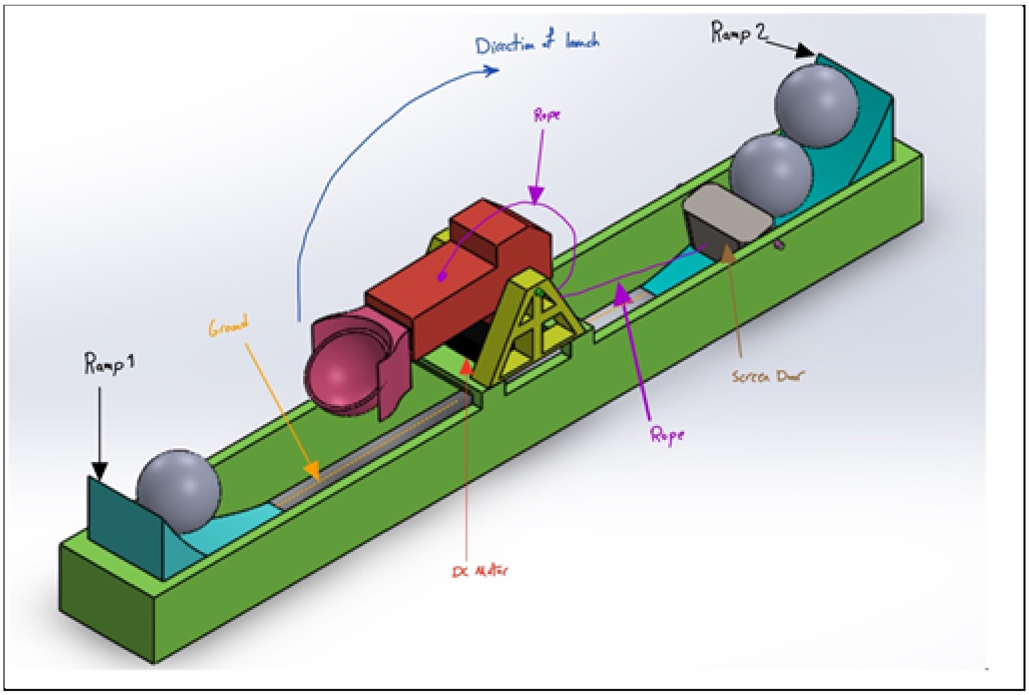


Figure 3: Lacrosse Ball Launcher

4 Analytical Calculations

4.2 Structural (Stiffness and Deflection)

4.2.1 Design I

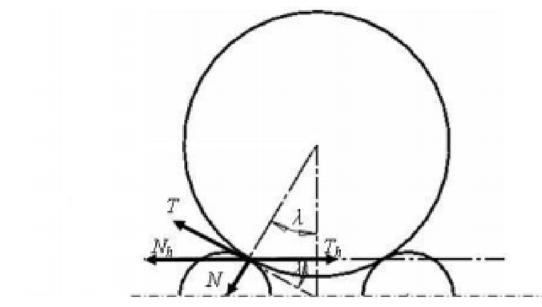


Figure 4: Forces and geometry at the contact between the ball and the rollers during pulling the ball in between the rollers. [1]

When the ball is being pulled by the rollers, two main forces appear at the contact points between the ball and the rollers. These are: the pressure force ‘N’, which is normal to the contact surface, and the tangent friction force ‘T’ [1].

The relationship between the pressure force and the friction force is proportional to the coefficient of friction between the materials. This coefficient will be taken from online resources for approximate materials.

$T = \mu \cdot N$

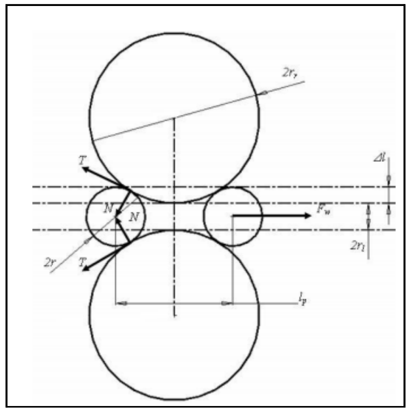


Figure 5: Forces and geometry at the contact between the ball and the rollers [1]

The condition for throwing the ball away from between the rollers states that the friction force between the ball and the rollers should be equal or greater than the inertia force of the ball. The pressure force can be obtained from the definition of Young's modulus for the ball:

$$N = \frac{E \cdot s \cdot \Delta l}{2r}$$

Where 's' is the contact area of the ball under compression. The pressure force and tangent force were determined to be 113.1N and 82.56N respectively. See Appendix A for calculations. Thus the maximum external load on the system is 113.1N distributed onto the drive shaft. This force will be used for bending moment calculations performed on the motor drive shaft to ensure it is within the specifications.

4.2.2 Design II

The first step in static analysis is to have FBD of the system therefore we have added FBD of our system in the Appendix with all forces on the throwing arm. Then we have used a second Newton's law to calculate forces in the joint.

In static equilibrium position at an arbitrary angle:

$$\sum F_x = 0 \Rightarrow R_x = 0$$
$$\sum F_y = 0 \Rightarrow R_y - W_{arm} - W_{ball} - W_{ball-holder} = 0 \Rightarrow R_y = W_{arm} + W_{ball} + W_{ball-holder}$$
$$\sum M_o = 0 \Rightarrow M_{motor,static} = W_{arm} \times d\cos\theta + \left(W_{ball} + W_{ball-holder}\right) \times L_1 \cos\theta$$

4.2.3 Design III

Two "Arm_support" parts as shown in the following figure must balance out forces and moments against the rotating arm. Static equations, free body diagrams and detailed calculations of results
are included in Appendix A.

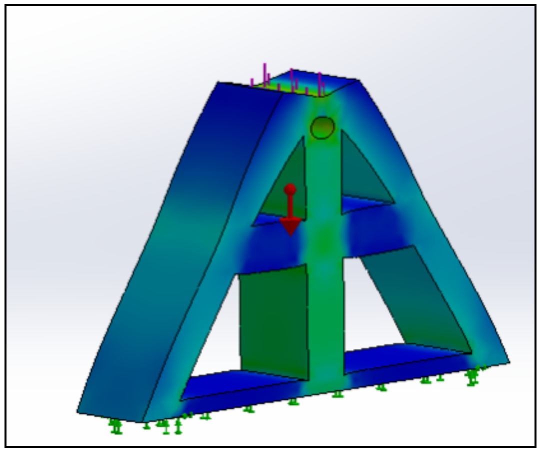


Figure 6: Static study of support system generate through Solidworks simulation

4.3 Dynamic (Inertia and Kinematics)

4.3.1 Design I

The system will consider the start position of the ball to be between the two rollers at a fixed angle of 45 degrees to optimize trajectory. The input into the plant will be the angular velocity of the rollers.

During the throw, the ball takes some energy from the rollers while going through them. This decreases the rotational speeds of the rollers. To analyze this further we must consider the kinetic energy of the rollers at the time of the ball being thrown. We came to the conclusion that the initial angular velocity must be adjusted to the following. See Appendix A for the breakdown.

$$\omega_0 = \omega + \sqrt{\frac{1}{2} I_{ball} \omega^2}$$

Now that the input has been determined, the landing position of the ball can be determined using standard projectile motion calculations.

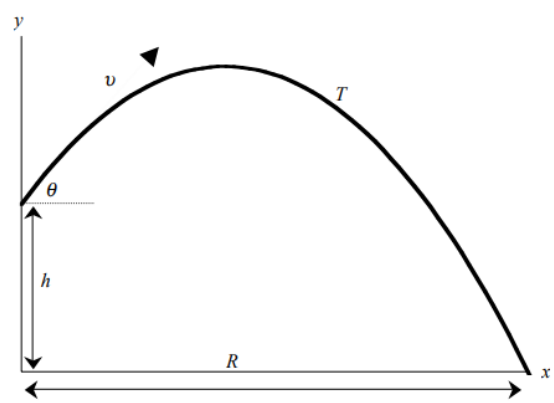


Figure 7: Projectile Motion Diagram

4.3.2 Design II

The second step is to calculate the moment of inertia for the arm using the following equation

During motion of the system as the motor applied a torque:

$$\sum M_o = I_o\ddot{\theta} \Rightarrow M_{motor} - W_{arm} \times d\cos\theta - (W_{ball} + W_{ball-holder}) \times L_1 \cos\theta = I_o\ddot{\theta}$$

where $I_o = I_{arm,G} + m_{arm}d^2 + \left(m_{ball} + m_{ball-holder}\right)L_1^2$

Then we would be able to calculate all the Mechanical design parameters which are added in a table in the appendix.

For the other part which is the base of the catapult design we only need a static analysis to make sure the base will be stable during the throwing period using the following equation. The corresponding image is added in the appendix

$$\sum F_x = 0 \Rightarrow S_{x1} + S_{x2} - R_x = 0$$
$$\sum F_y = 0 \Rightarrow S_{y1} + S_{y2} - R_y - W_{motor} = 0$$
$$\sum M_o = 0 \Rightarrow \left(S_{x1} + S_{x2}\right) \times h + S_{y2} \times L_3 - S_{y1} \times L_2 = 0$$

4.3.3 Design III

As shown in the following figure, the Throwing arm's center of mass is away from the rotating rod. Therefore, to balance forces and moments acting on the supports, the arm must be designed in a way that is more dense on the right (in red). The reason for this design is to balance negative torque, help with rotations counter torque, and minimize the power required from the DC motor.

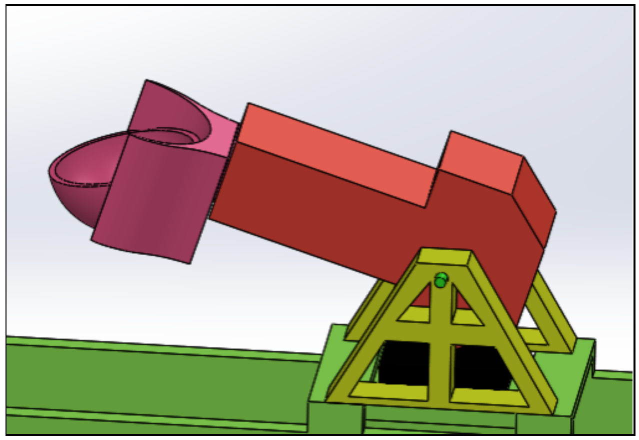
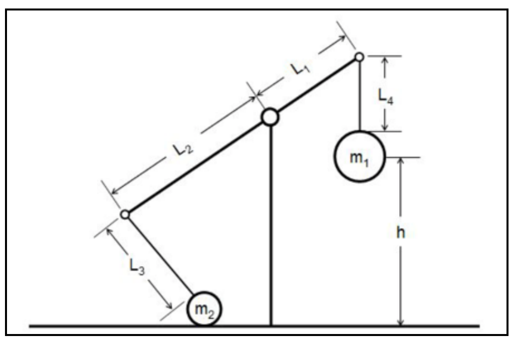


Figure 8: Mass distribution of the arm

This logic can also be seen in trebuchet design in the following figure. Instead of m1 in trebuchet, our design is denser on the right side.



5 Mechanical Design Analysis

5.1 Finite Element Analysis

5.1.1 Design I

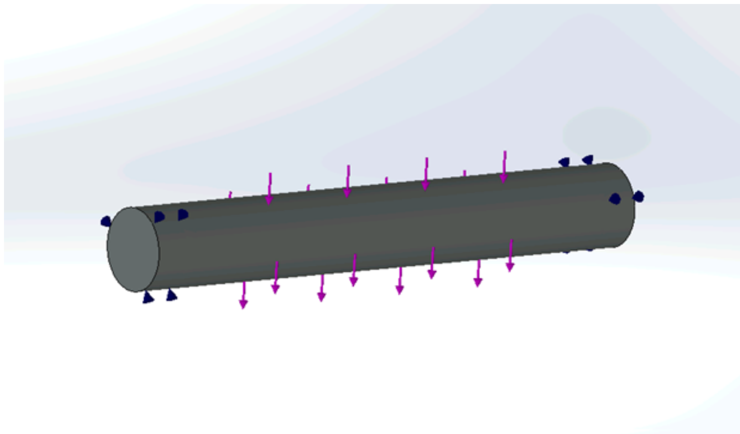


Figure 9: Design I Force Setup

A FEA analysis was performed on the drive shaft of the proposed tennis ball launcher concept and the heat maps can be found in Appendix B. Bearing fixtures were set up on the edge of each shaft to imitate its final design. The force was applied perpendicular to the axis of the shaft to mimic the friction force applied from the ball. The summary table can be seen below.

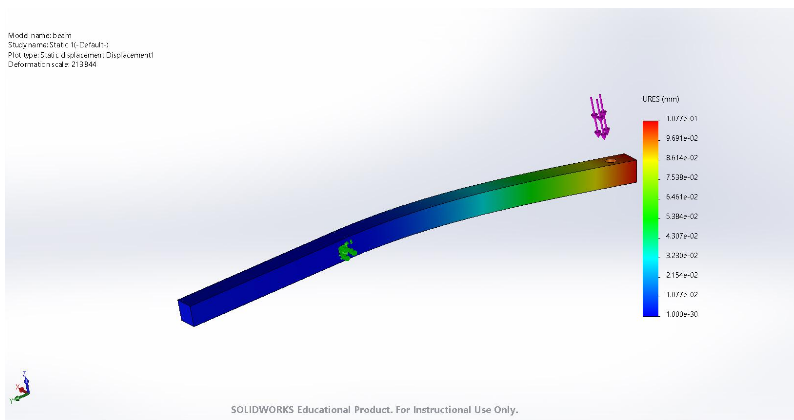
Table 10: Design I Results Summary

Parameter	Simulated Results	Analytical Solution
Displacement/Deflection	0.9104mm	1.66mm
Yield Strength	2.206x10^8 Pa	N/A
Strain	3.401 x 10^-04	N/A

The analytical and simulated results were comparable for the deflection of the drive shaft as shown in the table above. The next following section will discuss material selection to ensure the concept will perform as intended.

5.1.2 Design II

For the finite element analysis, I have imported the CAD model into the simulation section of the Solidworks in order to analyze displacement, stress, and strain of the throwing arm to make sure the throwing arm can tolerate the weight of the ball and other forces on it. Thus the results are added below



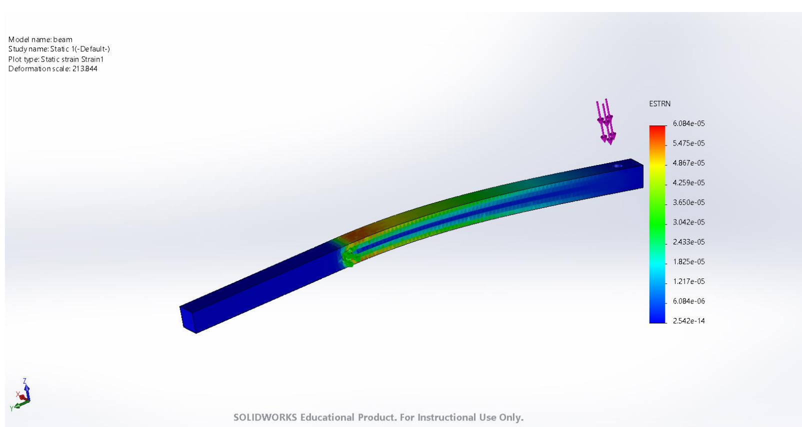


Figure 11a: FEA of the beam

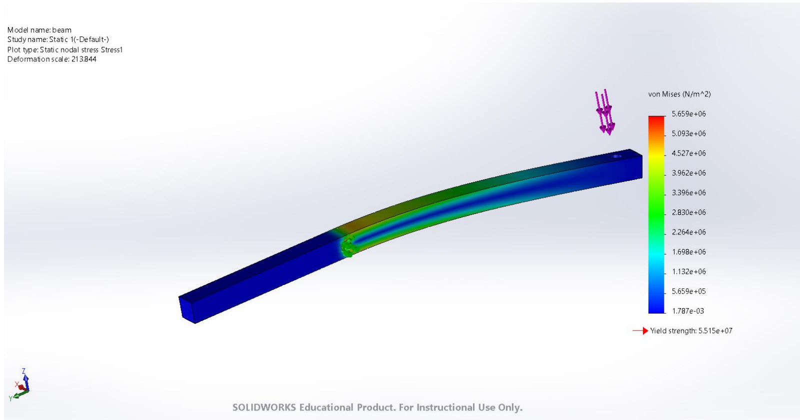


Figure 11b: FEA of the beam

5.1.3 Design III

After performing FEA analysis in Solidworks for this design, results for stress, deflection, and strain are calculated and presented in the following table. For a more detailed analysis of figures refer to Appendix B under "Design III".

Name	Type	Min	Max
Stress	VON: von Mises Stress	6.425e+00N/m^2	4.204e+04N/m^2
Displacement	URES: Resultant Displacement	0.000e+00mm	1.308e-05mm
Strain	ESTRN: Equivalent Strain	2.640e-10	2.620e-07
Factor of Safety1	Max von Mises Stress	1.927e+04	1.261e+08
Factor of Safety2	Max von Mises Stress	1.927e+04	1.261e+08

Figure 12: FEA analysis Results

5.2 Simulation & Validation

Assembly files from three designs were exported into Matlab Simscape. Simscape helps with developing physical models and simulate them. Results from the second lab are presented in the following table. In addition, codes and figures of our Simscape designs are included in Appendix D.

Lab 2: Results

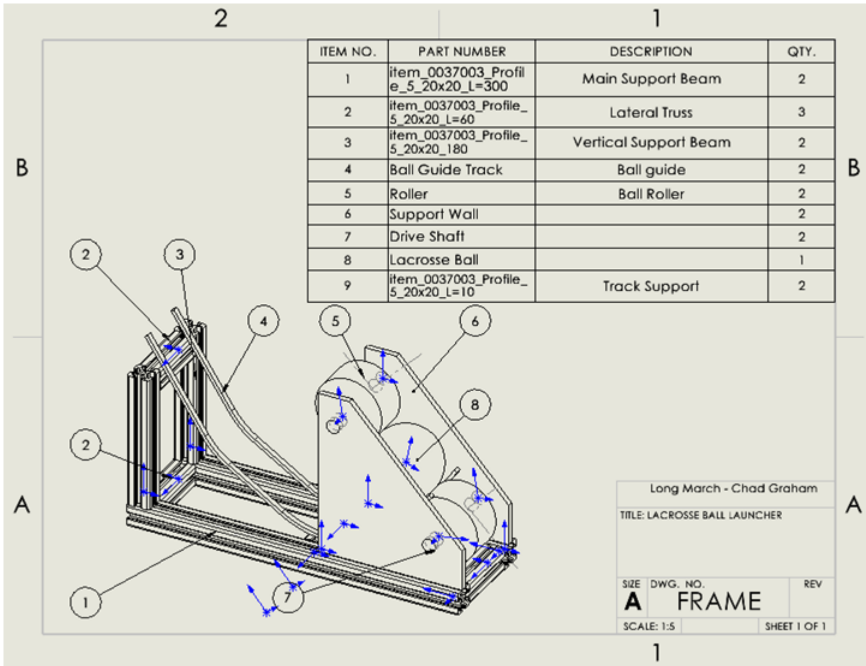
	Angular Velocity (After 10 second)	Angular Acceleration (After 10 seconds)
Base Model	-4.53811	-10.3749
Geometry 2	4.7461	9.0776
Geometry 3	-4.5887	-10.1299
Material (rho) 2	4.6073	9.9035
Material (rho) 3	4.516	10.4963
Inertia 3	0.7689	0.0415
Solver (auto)	4.5023	10.5475
Solver (ode15s and time 0.001s)	4.5023	0.5475
Damping (8e-4)	4.8418	7.8544
Damping(8e-1)	-4.45E-04	9.93E-05
Torque (100)	23.2331	-15.7428
Torque (1)	4.4613	10.675

Figure 13: Results Obtained from lab 2

6 Manufacturing

6.1 Bill of Materials

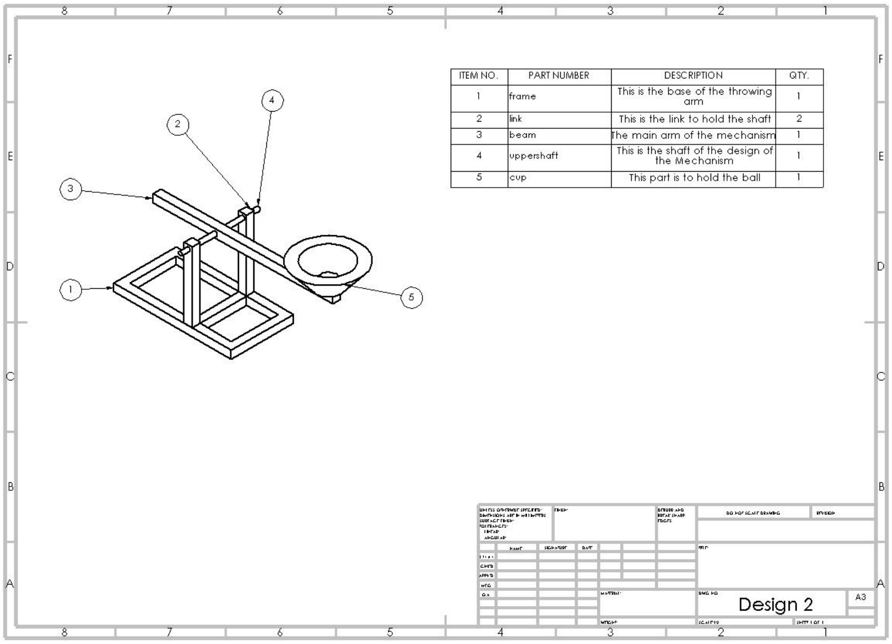
6.1.1 Design I



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	item_0037003_Profile_5_20x20_L=300	Main Support Beam	2
2	item_0037003_Profile_5_20x20_L=60	Lateral Truss	3
3	item_0037003_Profile_5_20x20_180	Vertical Support Beam	2
4	Ball Guide Track	Ball guide	2
5	Roller	Ball Roller	2
6	Support Wall		2
7	Drive Shaft		2
8	Lacrosse Ball		1
9	item_0037003_Profile_5_20x20_L=10	Track Support	2

Figure 14: Bill of Materials for Design I

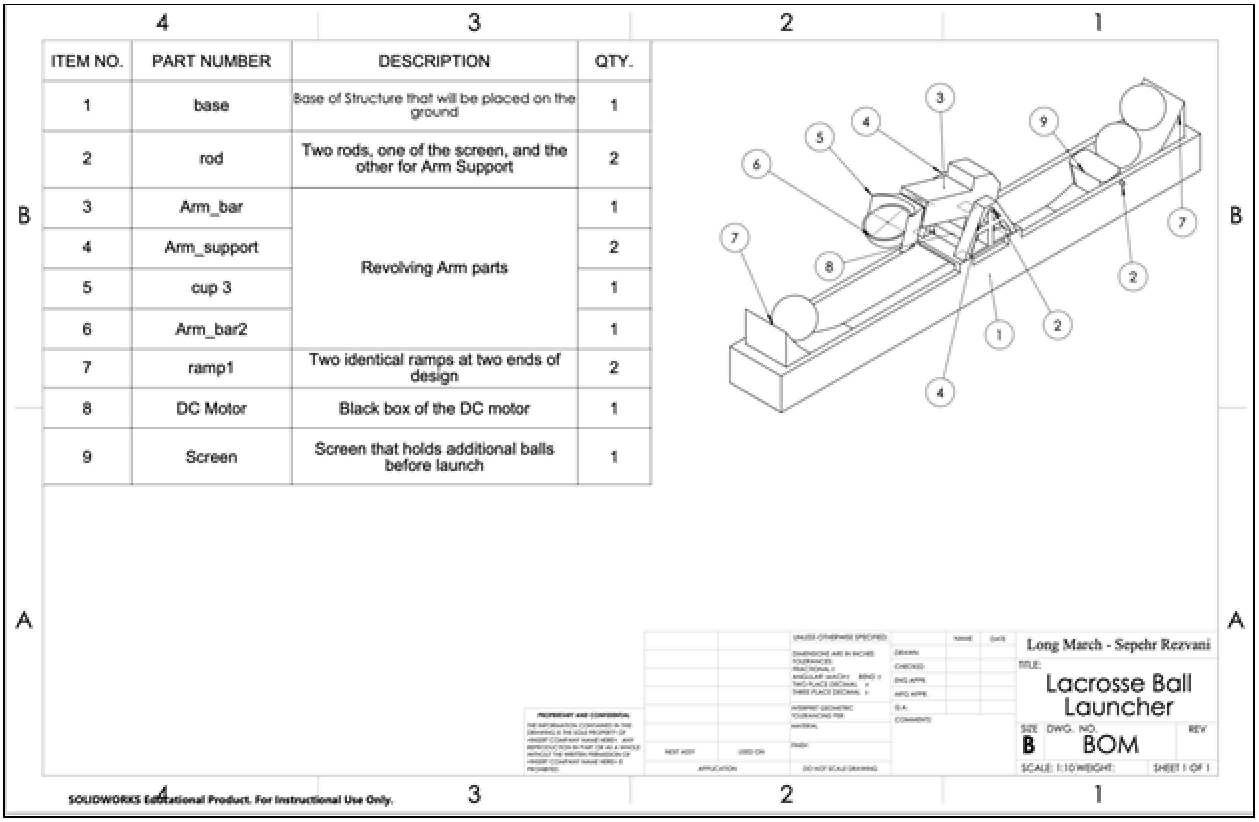
6.1.2 Design II



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame	This is the base of the throwing arm	1
2	link	This is the link to hold the shaft	2
3	beam	The main arm of the mechanism	1
4	uppershaft	This is the shaft of the design of the Mechanism	1
5	cup	This part is to hold the ball	1

Figure 15: Bill of Materials of Catapult Arm

6.1.3 Design II



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	base	Base of Structure that will be placed on the ground	1
2	rod	Two rods, one of the screen, and the other for Arm Support	2
3	Arm_bar	Revolving Arm parts	1
4	Arm_support		2
5	cup 3		1
6	Arm_bar2		1
7	ramp1	Two identical ramps at two ends of design	2
8	DC Motor	Black box of the DC motor	1
9	Screen	Screen that holds additional balls before launch	1

Figure 16: Bill of Materials for Design III

6.2 Material Selection

6.2.1 Design I

The main structure will be constructed from aluminum extrusion due to its incredible yield strength, availability, and affordability. The Ball Guide Track is made out of stainless steel. The driveshaft was selected to be made out of 1045 Cold Drawn Steel due to its corrosion resistance and superior yield strength. The rollers will be made out of high-density rubber to maintain a high coefficient of friction with the lacrosse ball to minimize slip.

6.2.2 Design II

There are many choices for selecting the proper material for the components of the second design. First of all, we have tried to use one material for the whole system in order to reduce the cost of manufacturing and maintenance of the throwing arm project. Thus using static analysis results which are added in the appendix we have decided to use aluminum alloy 6061 as the main material for manufacturing the second design. The approximate cost of the design according to the quantity of the material used is around $200-$250 dollars

6.2.3 Design III

As shown in table (Design III) in Appendix A under "BOM and Cost Breakdown", the materials selected are based on the purpose of parts in the design. For example, “Titanium Ti-8Mn, Annealed” is used for the “Arm_support” part due to the high stress applied to this part. For other parts like ramps, where very little load is applied, simpler and cheaper materials were selected. Another factor considered for the material selected is their availability in the Solidworks database, in some special instances, better materials could be selected if they were available in Solidworks.

6.3 Fabrication Methods

6.3.1 Design I

This iteration was purposely designed for ease of manufacturing in mind. Each material is readily available from local suppliers such as Proax, McMaster Carr, and others. Basic hand tools will be used to fabricate the simple frame structure and the drive shaft can be ordered from McMaster Carr to fit the design. Extrusion can be cut with a simple saw and constructed with nuts and bolts.

6.3.2 Design II

Depending on the material that we select for the second design we have different options for manufacturing the components for example if the material is selected to be PLA then the manufacturing method would be 3D printing. For this project if the material is aluminium alloy the manufacturing method is selected to be CNC machining however we have an option to move forward with 3D printing method for the Cap in the second design thus since the shape of this component would cost more using CNC machining

6.3.3 Design III

As mentioned in the previous section, materials were selected based on their importance and cost. Referring to Appendix A, these main portions of our budget would be allocated to the main arm and its supports. All materials are available and can be purchased with our limited budget.

7 Decision Matrix

A weighted objective chart (WOC) is used as a means of comparing various alternatives by ranking them based on a list of criteria . The weighted table work is that the user pre-rank the important stuff each of the comparison criteria in advance then ranks each design option based on how well it fulfills each of the criteria. The list of criteria for our project is shown below:

In the following, different values are assigned to each score so that the higher score has a better advantage to our design for example if the cost of the design is less then its score would be higher. The list of criteria with the corresponding values is shown below.

	Criteria						
Score	Ease of Assembly [min]	Cost [$]	Manufacturibility	Modularity (Design flexibility)	Number of parts	Material Availibility (Shipment time [day])	Durability [month]
1	>90	>450	1	1	>18	>9	<1
2	80-90	400-450	2	2	16-18	8-9	1-3
3	70-80	350-400	3	3	14-16	7-8	3-5
4	60-70	300-350	4	4	12-14	6-7	5-7
5	50-60	250-300	5	5	10-12	5-6	7-9
6	40-50	200-250	6	6	8-10	4-5	9-11
7	30-40	150-200	7	7	6-8	3-4	11-13
8	20-30	100-150	8	8	4-6	2-3	13-15
9	10-20	50-100	9	9	2-4	1-2	15-17
10	<10	<50	10	10	<2	<1	>17

Figure 17: Decision Matrix

Finally, the criteria and the corresponding score are finalized and now we have assigned a weight to each criterion .it should be noted that the total weight should be 100%. Then we have compared all three concepts using a score for each criterion and added a value

(is equal to score *weight) for each criteria. Finally, the accumulated values are compared in the following table

			Design I		Design II		Design III	
Criteria	Weight	Justification for Weights	Score	Value	Score	Value	Score	Value
Ease of Assembly [min]	5%		7	0.35	9	0.45	9	0.45
Cost [$]	30%		7	2.1	6	1.8	7	2.1
Manufacturibility	15%		7	1.05	8	1.2	8	1.2
Modularity (Design flexibility)	10%		5	0.5	8	0.8	10	1
Number of parts	15%		4	0.6	7	1.05	9	1.35
Material Availibility (Shipment time [day])	20%		7	1.4	5	1	9	1.8
Durability [month]	5%		9	0.45	7	0.35	9	0.45
				0		0		0
				0		0		0
				0		0		0
	100%	Total Values		6.45		6.65		8.35

Figure 18: Selected Design

Ultimately this led our team to select Design III as our mechanical concept. It yielded the highest overall score by a significant amount. Though selected, the design will continue to be iterated and optimized to properly integrate the motor and drive system.

8 Member Contributions

Chad Graham - Design I (Mechanical design, analytical calculations, FEA, BOM, material selection, cost breakdown. report, etc.), report format layout, grammar correction, and organization.

Arash Pour-Zargar- completed design 2 on the FBD design as well as FEA, material selection, BOM, and creation of the report template as well as the decision matrix

Sepehr Rezvani - Design III and report+formatting: Including Solidworks parts, drawings, and one final assembly file. FEA was done on Throwing Arm support, BOM and final cost estimation was completed as well.

Darwin Chang - Report. Ensuring compatibility and Importing of the Solidworks model into the Simulink/simscape models to be able to create the Model for the three designs. Simulated the models and fixed model errors present in the importing process. Obtained the results for Lab 2 shown in appendices E. Report Grammar, and Formatting

9 References

[1] K. WÓJCICKI, K. PUCIŁOWSKI, and Z. KULESZA, “Mathematical Analysis for a New Tennis Ball Launcher,” *Acta Mechanica et Automatica*, vol. 5, no. 4, pp. 110–119, 2011.

[2] “Polymer Properties Database,” *Rubber Elasticity*. [Online]. Available: https://polymerdatabase.com/polymer%20physics/RubberElasticity.html. [Accessed: 20-Jun-2021].

3] K. WÓJCICKI, K. PUCIŁOWSKI, and Z. KULESZA, “Mathematical Analysis for a New Tennis Ball Launcher,” *Acta Mechanica et Automatica*, vol. 5, no. 4, pp. 110–119, 2011.

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10 Appendices

Appendix A: Analytic Calculations

Load Validation Design I:

$$N = \frac{E \cdot s \cdot \Delta l}{2r} = \frac{(4.0\times10^{6} Pa)(5.94\times10^{-4} m^{2})(0.003m)}{2\cdot(0.0315m)} = 113.1N$$

S = Contact area during deformation

$$s = 2 \cdot \pi \cdot r \cdot h = 2 \cdot \pi \cdot (0.0315m) \cdot (0.030m) = 5.94 \times 10^{-4} m^{2}$$

The area of deformation was determined by considering the surface area of a dome with the height equal to one half of the deformation height (3mm).

$\triangle$l = deformation height

The deformation height is determined from the spacing between the two rollers. The rollers were separated by the diameter of the ball minus 6 mm to ensure a constant pressure is maintained.

R = radius of the ball

E = Young's Modulus

Since the material of a lacrosse ball is not consistent, vulcanized rubber (a common component in lacrosse balls) was selected to represent the material properties. 4.0MPa was determined for our calculations[CHAD 2].

The coefficient of friction was found from an online resource to be 0.73[CHAD 3].

$$T = \mu \cdot N = (0.73)(113.1N) = 82.561N$$

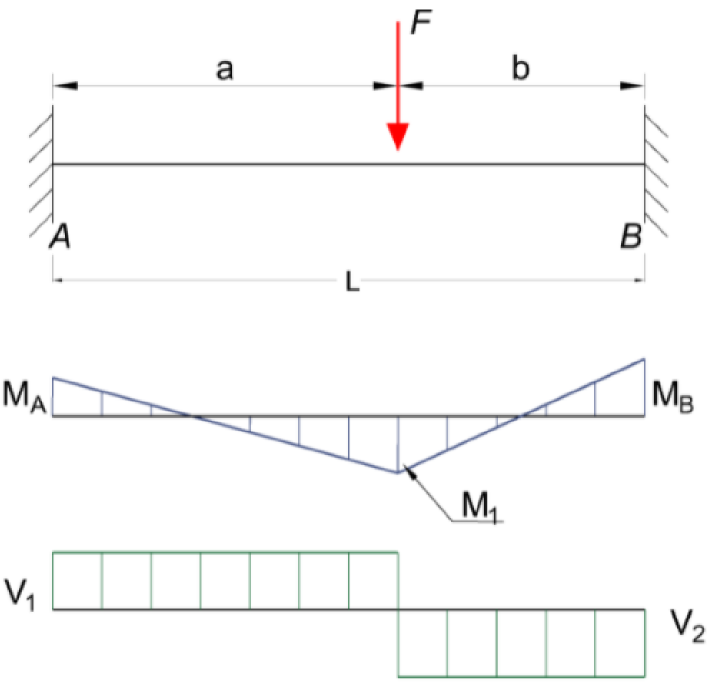


Figure 19: Bending Moments Graph

The moment of the fixed ends of the beam was determined as follows.

$$M_A = M_B = \frac{-Fa^3}{L^2} = \frac{(113N)(0.0426)^3}{(0.0852)^2} = 0.00120345Nm$$

The moment of the center of the beam was determined as follows.

$$M = \frac{2 \cdot F \cdot a}{L^3} = \frac{2 \cdot (113)(0.0426)}{(0.0852)^3} = 1.20345 \times 10 - 5Nm$$

The deflection was calculated for the top of the shaft at its extremity as follows.

$$\delta_{beam} = \frac{F \cdot a^6}{3 \cdot L^3 \cdot E \cdot I} = 1.66311386 \times 10 - 4m$$

Kinematics of Design I:

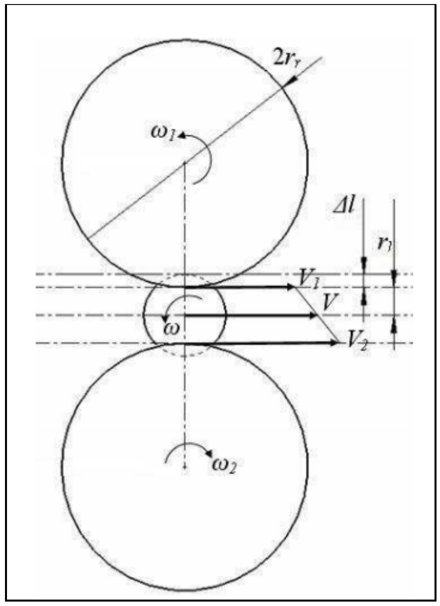


Figure 20: Tennis Ball Launcher Cross Section

$$V = \frac{V_1+V_2}{2}\varpi \cdot r_{roller} = \frac{V_2-V_1}{2}$$

$$V = \frac{(\omega_1+\omega_2)\cdot r}{2}$$

Energy Loss

Consider the kinetic energy of the rollers at the moment the ball is thrown.

$$\Delta E = E_1 - E_2 = \frac{1}{2} \cdot I_{roller}[(\omega_1^{\ 2} + \omega_2^{\ 2}) - (\omega_{10}^{\ 2} + \omega_{20}^{\ 2})]$$

Where; $I_{roller} = \frac{1}{2}mr^2$

For the ball it can be assumed that its initial kinetic energy is zero, while the final energy, in this case immediately after the throw, depends on its linear and rotational speeds of the rollers.

Since both rollers will have the same angular velocity the angular velocity of the ball can be assumed to be zero.

Thus; $$\Delta E = \frac{1}{2} \cdot mV^2 + \frac{1}{2} I_{ball} \omega^2$$

Where; $$I_{ball} = \frac{2}{3} mr^2$$

Therefore the initial kinetic energy of the plant required to launch the ball using the equations above can be shown as:

$$E = \frac{1}{2} I_{roller} (\omega_1^{\ 2} + \omega_2^{\ 2}) + \frac{1}{2} mV^2 + \frac{1}{2} I_{ball}$$

Making the assumption that angular velocity before and after the launch are the same:

$$\frac{\omega_{10}}{\omega_{20}} \simeq \frac{\omega_1}{\omega_2}$$

Then, the initial rotational speeds of the rollers, needed to throw the ball with the required linear and rotational velocities can be calculated, as:

$$\omega_0 = \omega + \sqrt{\frac{1}{2} I_{ball} \omega^2}$$

BOM and Cost Breakdown

Component	Configuration	Material Cost (USD/Assembly)	Manufacturing Cost (USD/Assembly)	Total Cost (USD/Assembly)
item_0037003_Profile_5_20x20_L=300	Default	2.91	12.75	15.66
Track	Default	4.66	7.90	12.56
Wheel	Default	4.36	7.21	11.56
item_0037003_Profile_5_20x20_180	Default	1.17	10.15	11.32
Ball	Default	6.06	4.27	10.33
item_0037003_Profile_5_20x20_L=60	Default	0.58	9.27	9.85
item_0037003_Profile_5_20x20_L=10	Default	0.10	8.54	8.64
Mounting Wall	Default	2.33	6.11	8.44
Drive Shaft	Default	0.30	20.83	21.13
Total		22.46	82.03	104.49

Figure 21: Cost Breakdown of Tennis Ball Launcher

Design I

Design III:

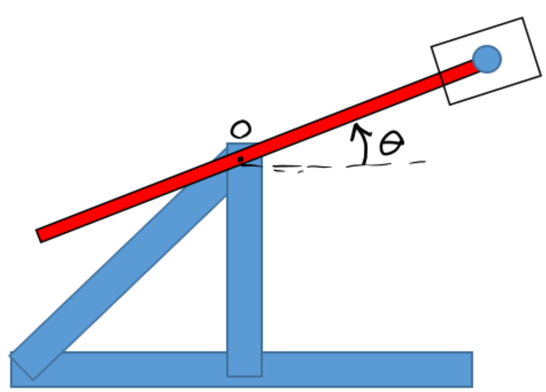


Figure 22: Cross Section of Catapult

The first step for static analysis is to have FBD of the Catapult throwing mechanism. I have added the FBD as follows

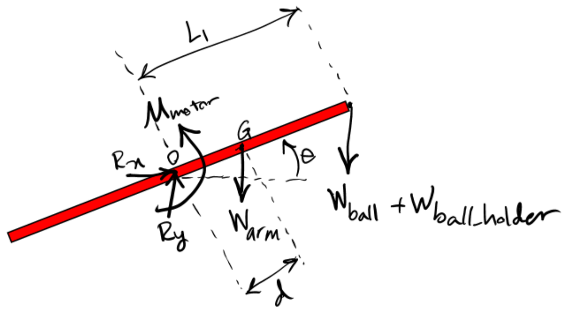


Figure 23: FBD Diagram of throwing mecahnism

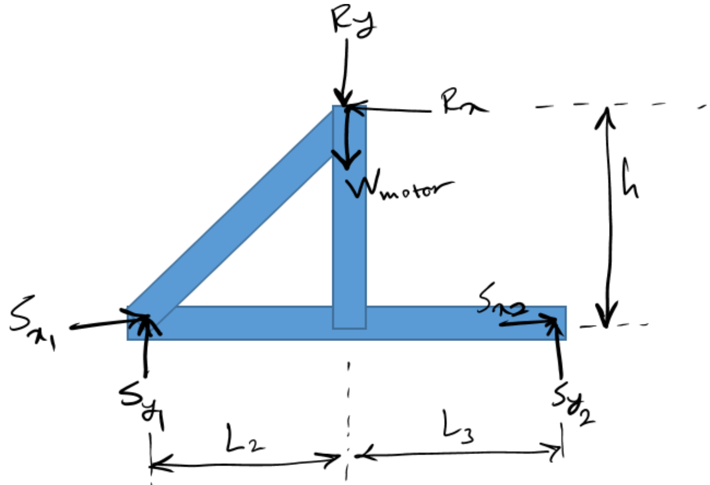


Figure 24: FBD fo the A frame

Sample Calculations assuming:

L1		0.15
d		0.05
W_arm		1.96
W_ball		1.42245
W_ball_holder		0.1962
h		0.11
L2		0.5
L3		0.9
W_motor		1.962

Theta (degrees)	Theta (radians)	Ry	M_motor,static	Sy1	Sy2
0	0	3.57865	0.3407975	3.561846	1.978804
30	0.523598776	1.72865	2.427739407	2.372561	1.318089
45	0.785398163	0.8062	1.042759544	1.779557	0.988643
60	1.047197551	1.51	1.006506	2.232	1.24
90	1.570796327	3.362	3.77667E-17	3.422571	1.901429

Figure 25: Sample Calculations

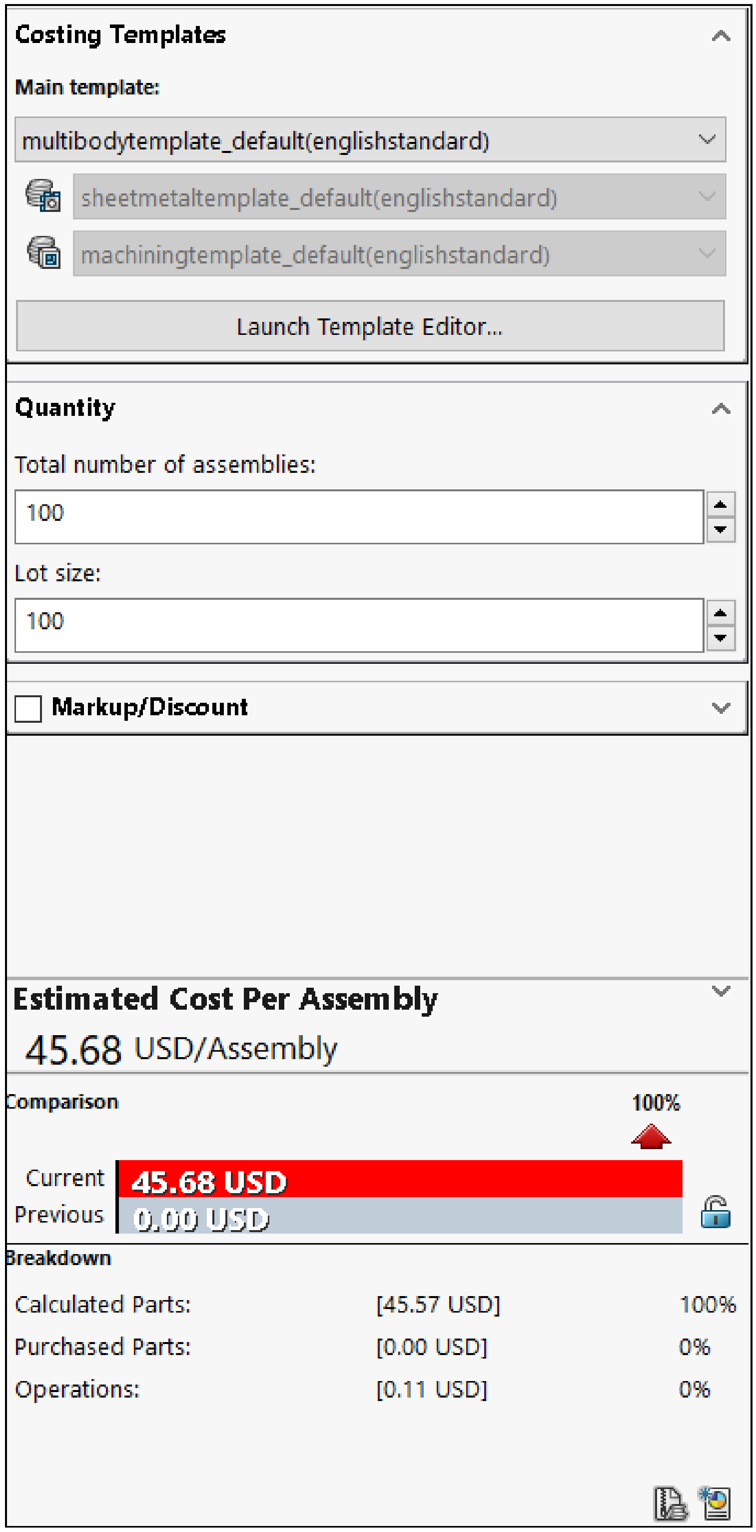
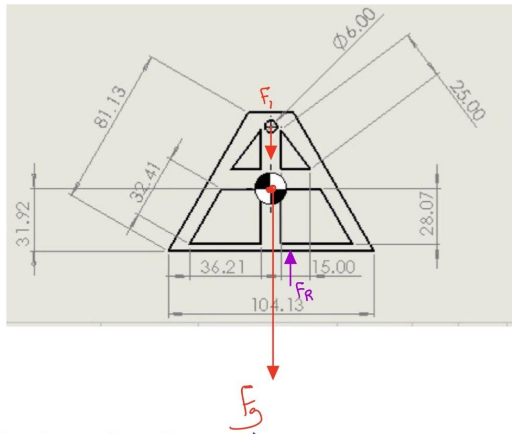


Figure 26: Cost Breakdown of Catapult System

Design III:



F_g: force due to gravity

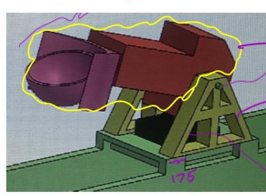
F_1: force applied to supports due to rotating arm

F_R: reaction forces on supports applied be the surface

$$F_g = m_{support} \times 9.81 = 242.2g \times \frac{1kg}{1000g} \times 9.81 = 2.38\ N$$

$$F_1 = \frac{m_{arm}}{2} \times 9.81 \Rightarrow F_1 = 6.74\ N$$

because there are 2 "supports"



$m_{arm} =$

$997.32 + 122.69 + 57.15 + 51.03 + 145 = 1373.19g$

Figure 27: FBD and calculations of Design 3

BOM and Cost Breakdown

Appendix B: Finite Element Analysis:

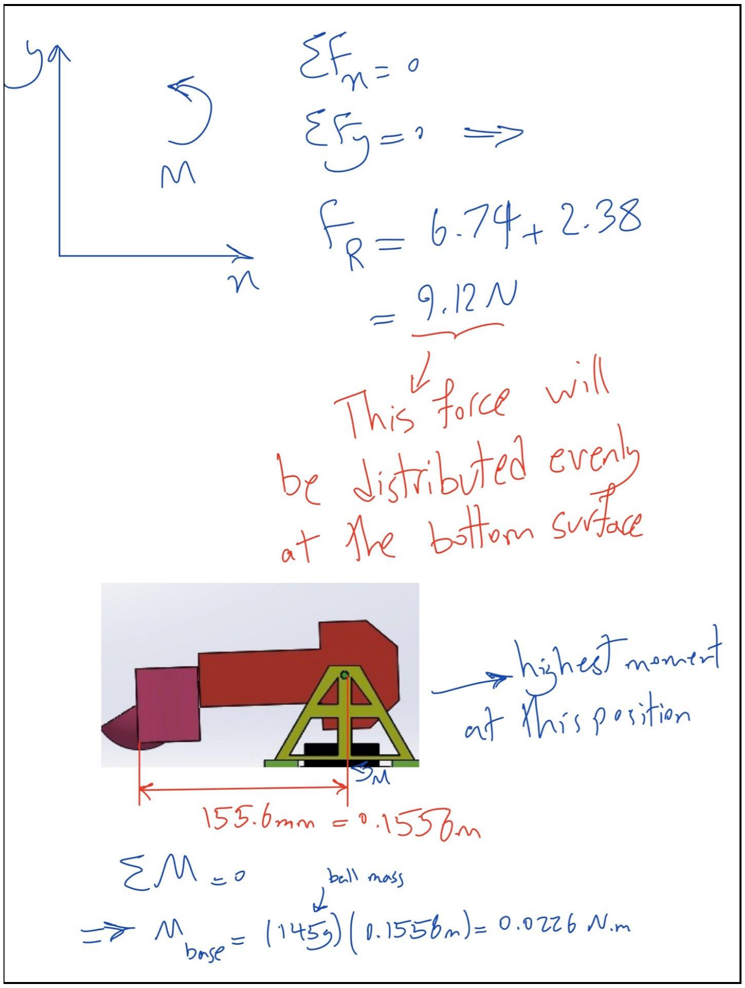


Figure 27: FBD and calculations of Design 3 cont.

Design I:

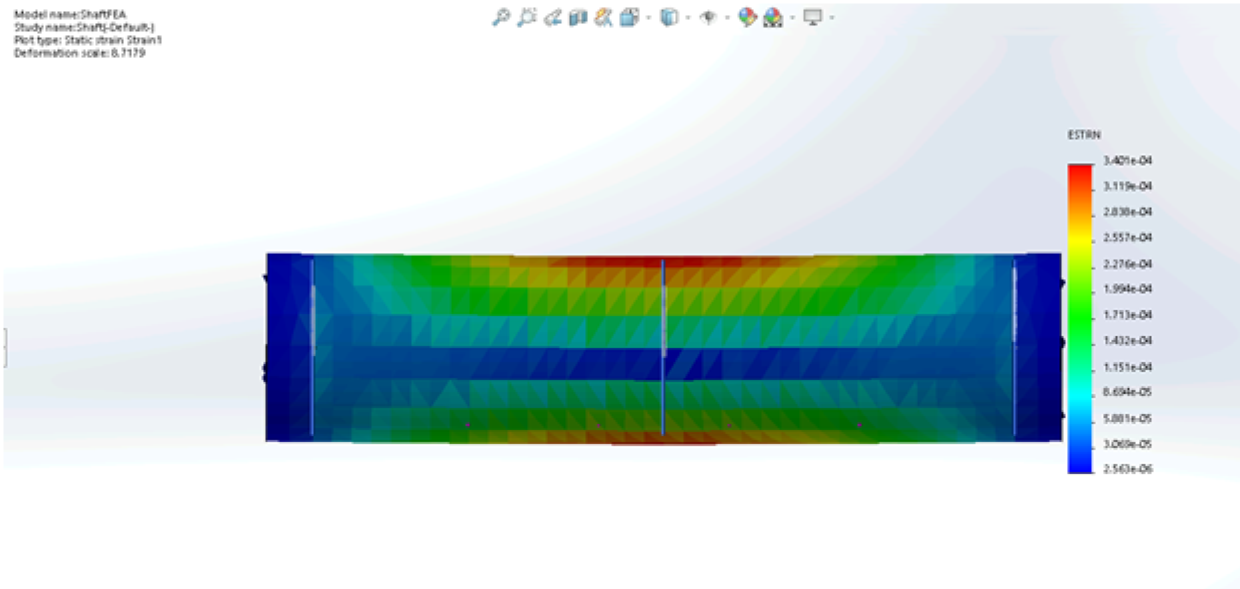


Figure 28: Design I Strain Heat map

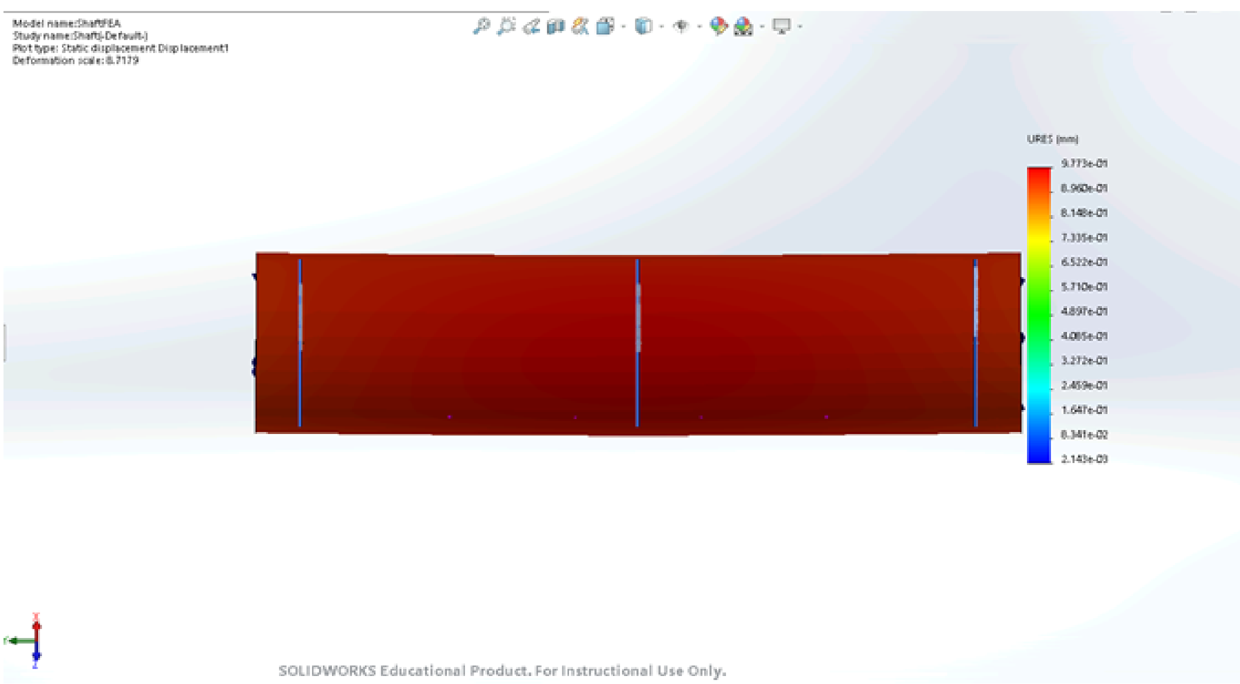


Figure 29: Design I Deflection Heat Map

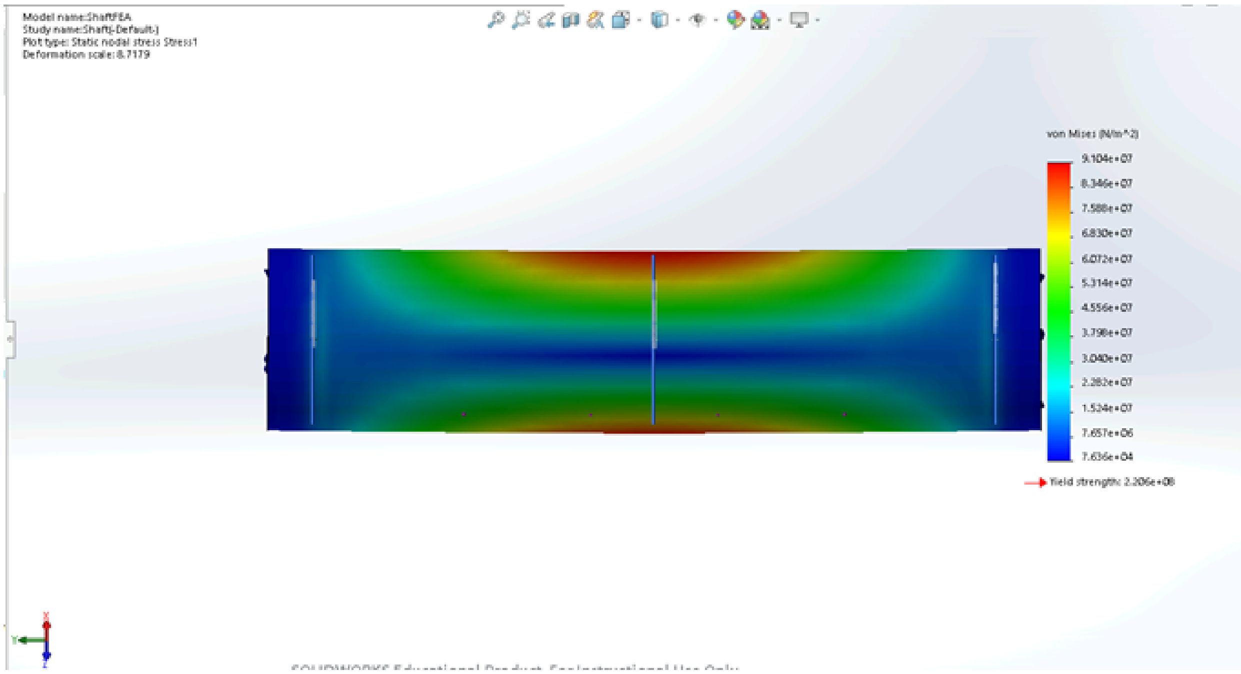


Figure 30: Design I Von Mises Stress Heat Map

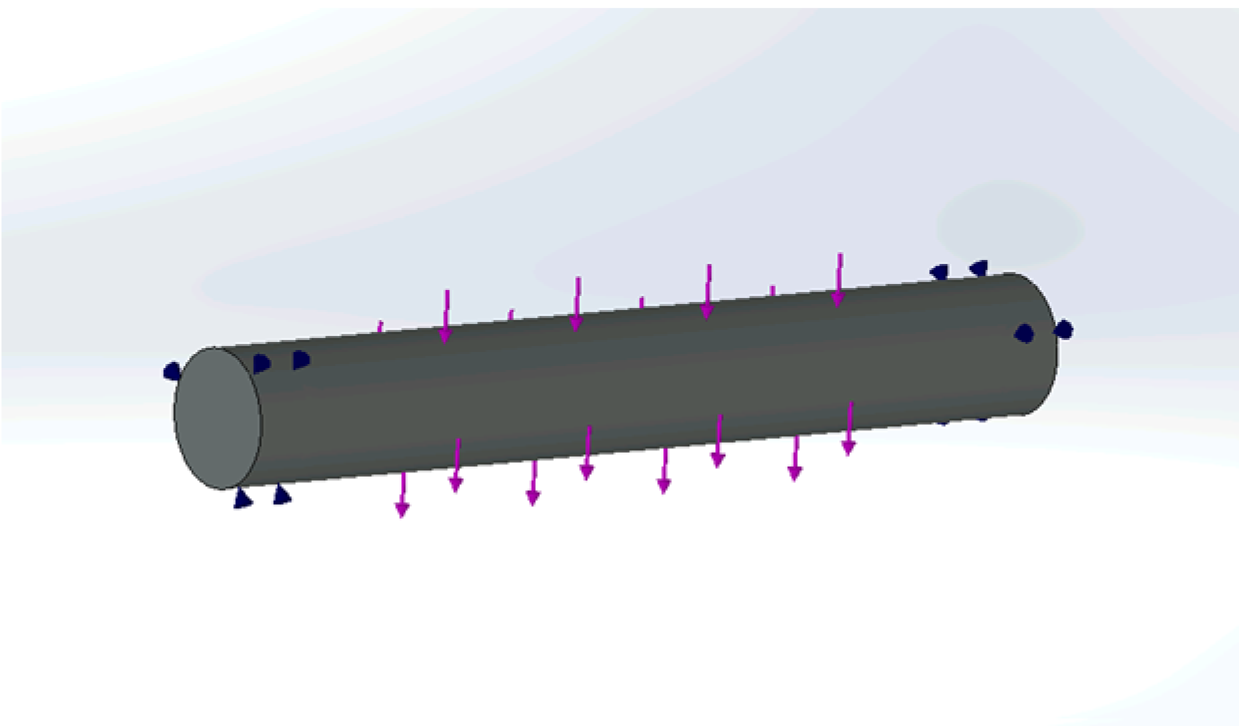


Figure 31: Design I Force Setup

Design III:

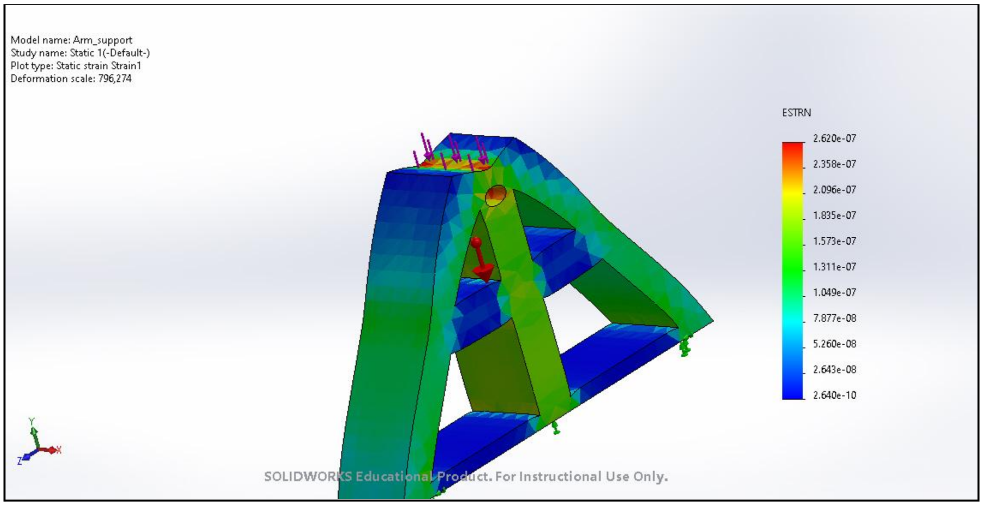


Figure 32: Design III Strain

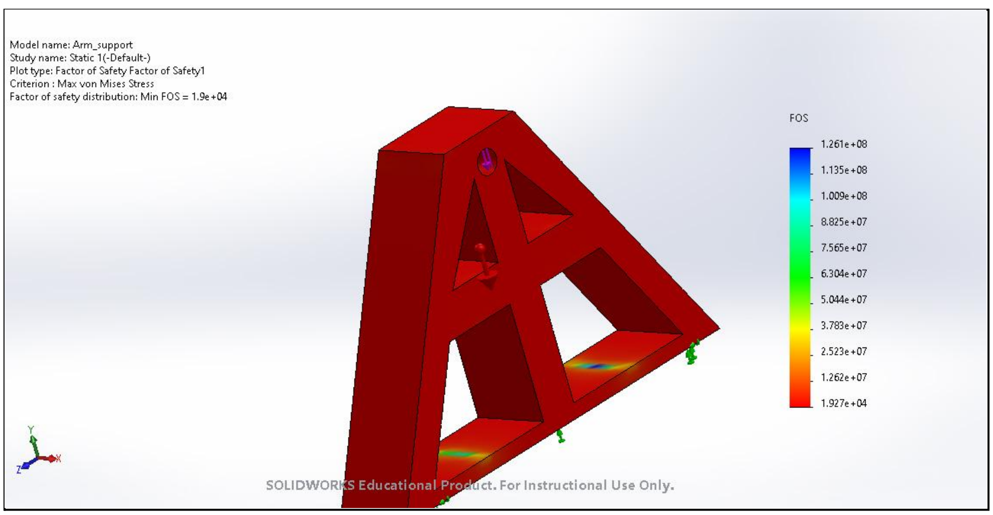


Figure 33: Design III Safety Factor

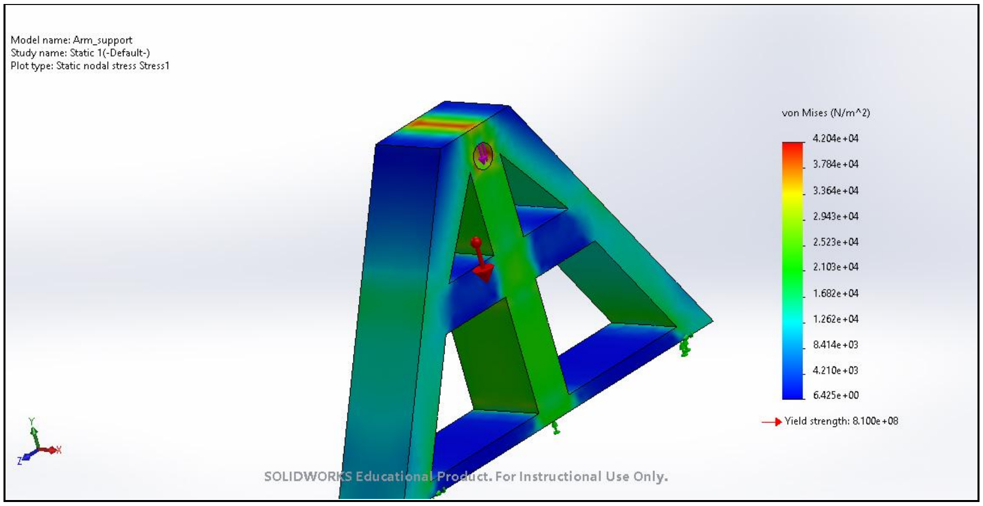


Figure 34: Design III Von Mises Stress Heat Map

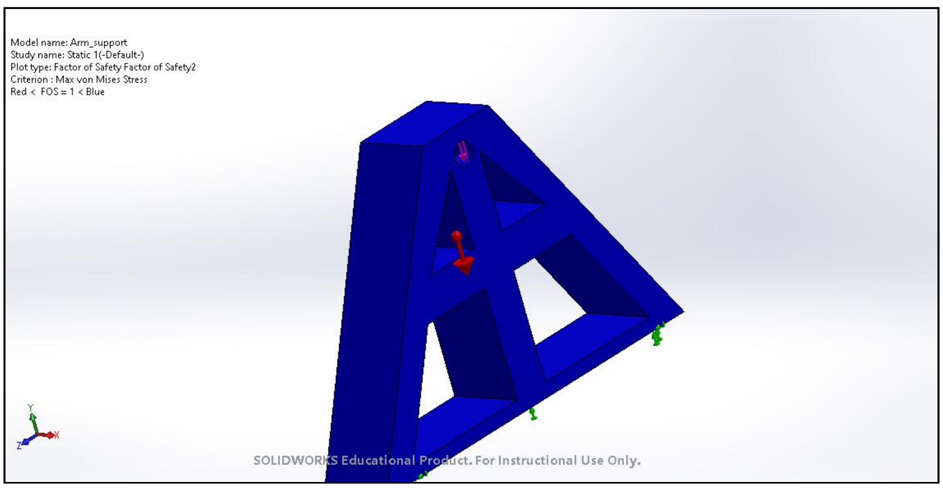


Figure 35: Design III Safety factor 2

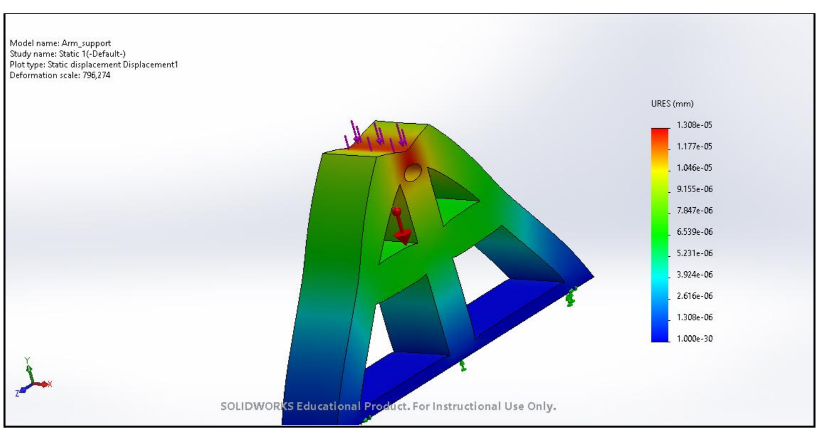


Figure 36: Design III Deflection

Appendix C: Simulink/Simscape Models

Model 1:

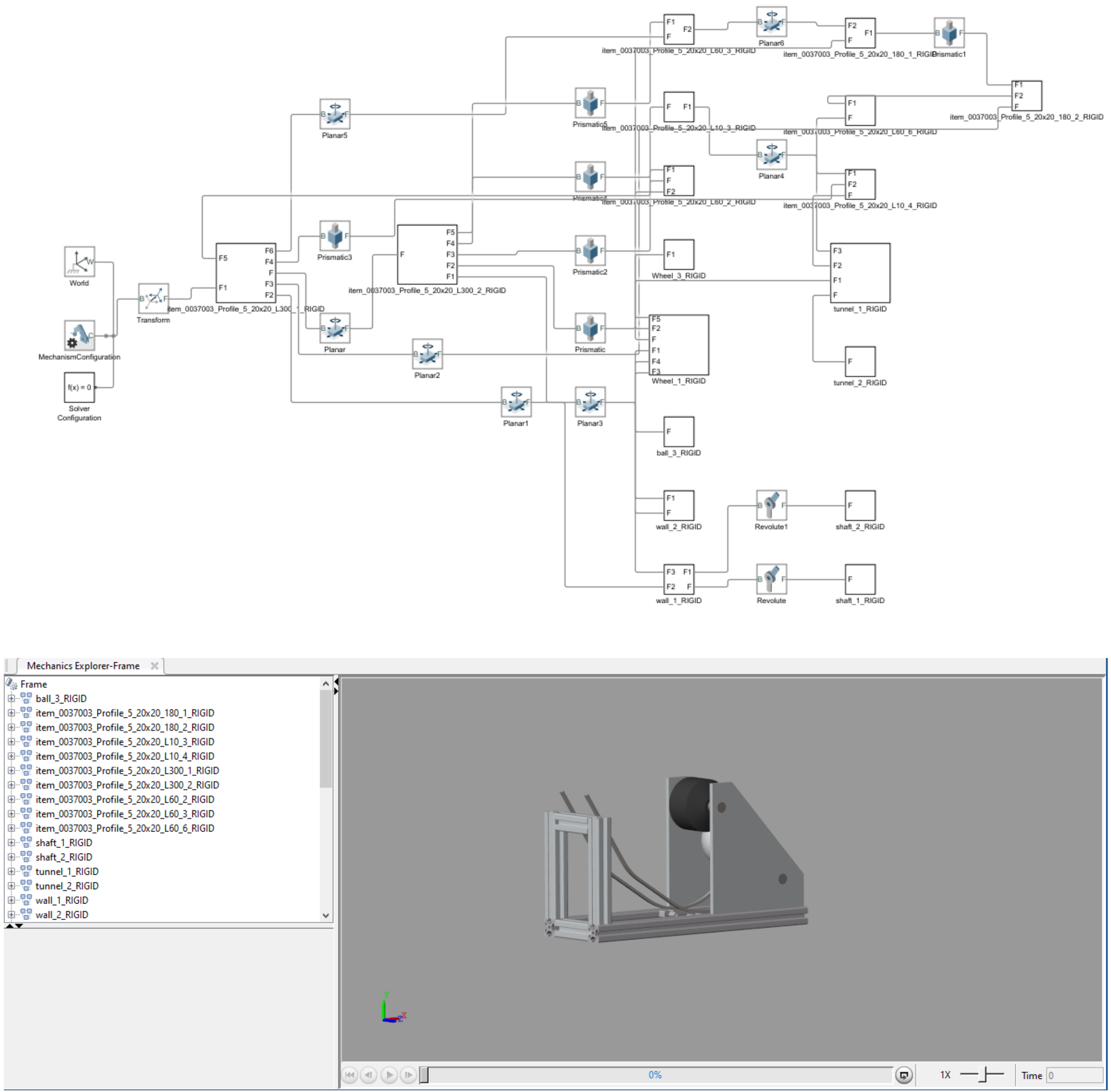
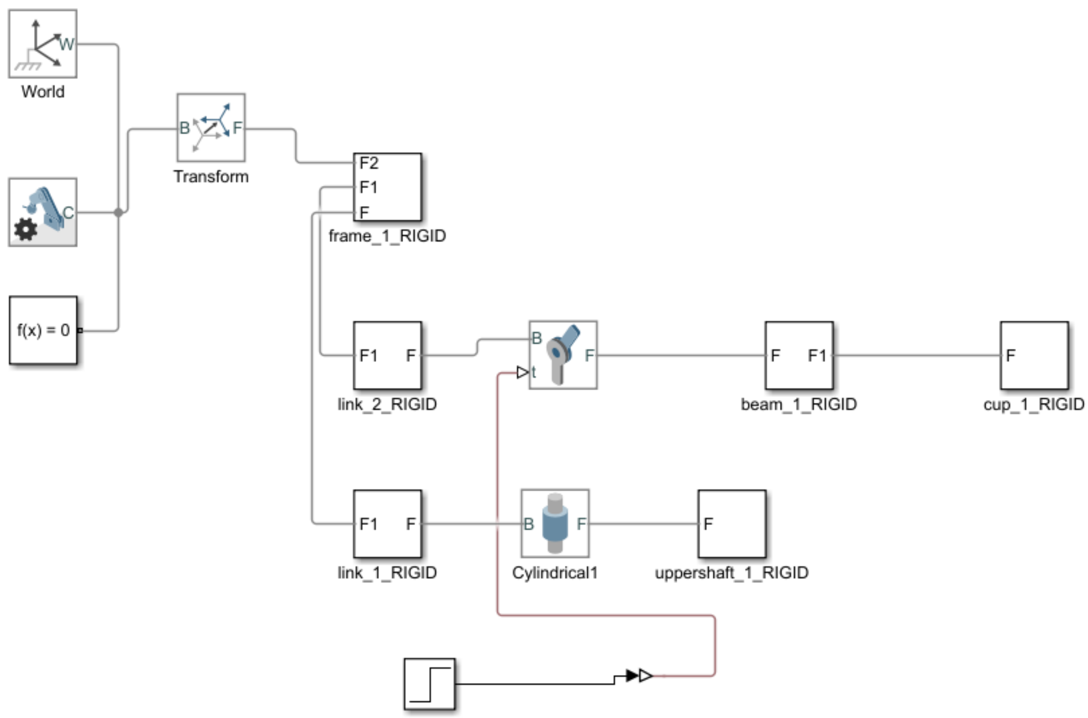


Figure 37: Simulink Model for Design 1: Tennis Ball Launcher

Model 2: Catapult Arm



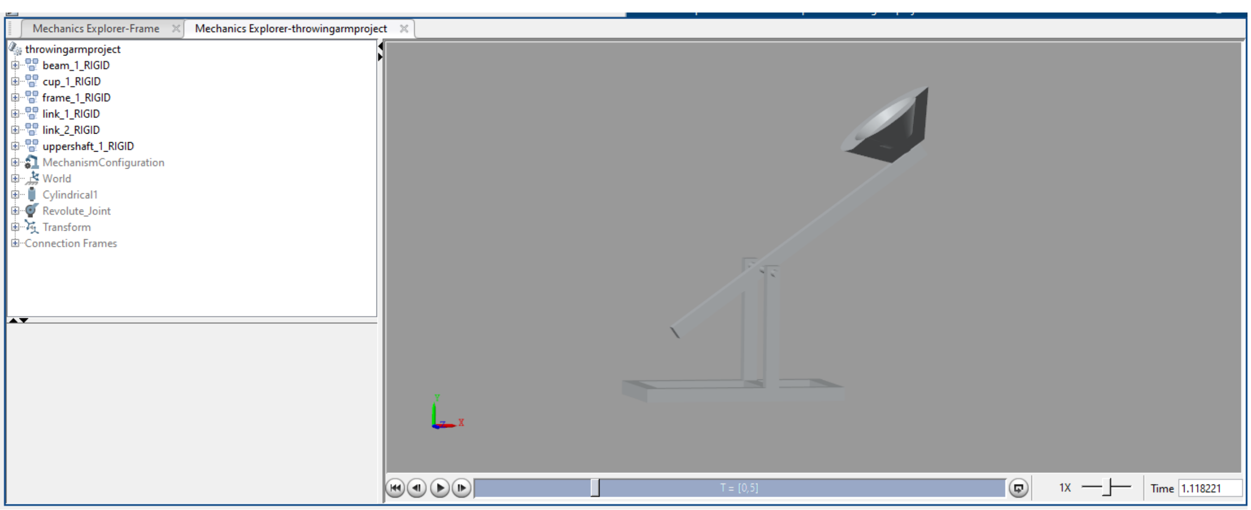
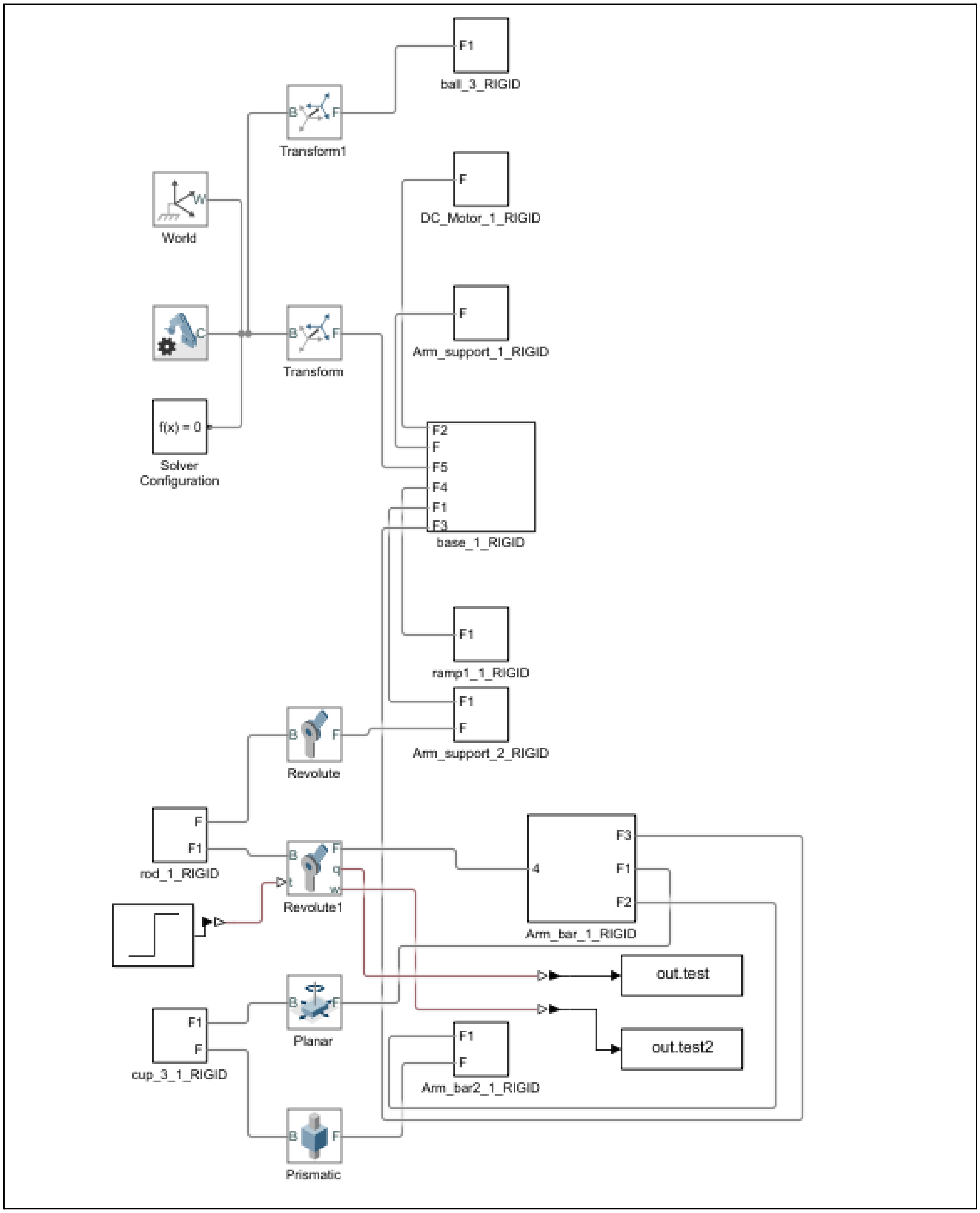


Figure 38: Simulink Model for Design 2: Catapult Launcher

Model 3:



F1
ball_3_RIGID
B
F
Transform1
F
DC_Motor_1_RIGID
W
World
C
B
F
Transform
F
Arm_support_1_RIGID
f(x) = 0
Solver
Configuration
F2
F
F5
F4
F1
F3
base_1_RIGID
F1
ramp1_1_RIGID
F1
F
Arm_support_2_RIGID
B
F
Revolute
F
F1
rod_1_RIGID
B
F
q
t
w
Revolute1
F3
4
F1
F2
Arm_bar_1_RIGID
out.test
out.test2
F1
F
cup_3_1_RIGID
B
F
Planar
F1
F
Arm_bar2_1_RIGID
B
F
Prismatic

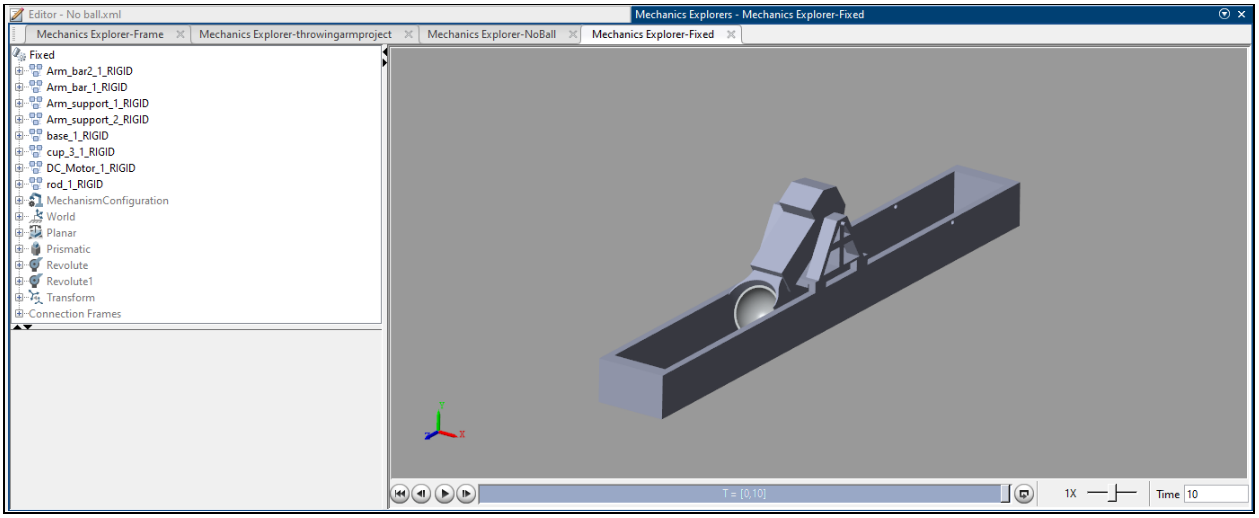


Figure 39: Simulink Model for Design 3: Lacrosse Ball Launcher

Appendix D: Detailed Drawing

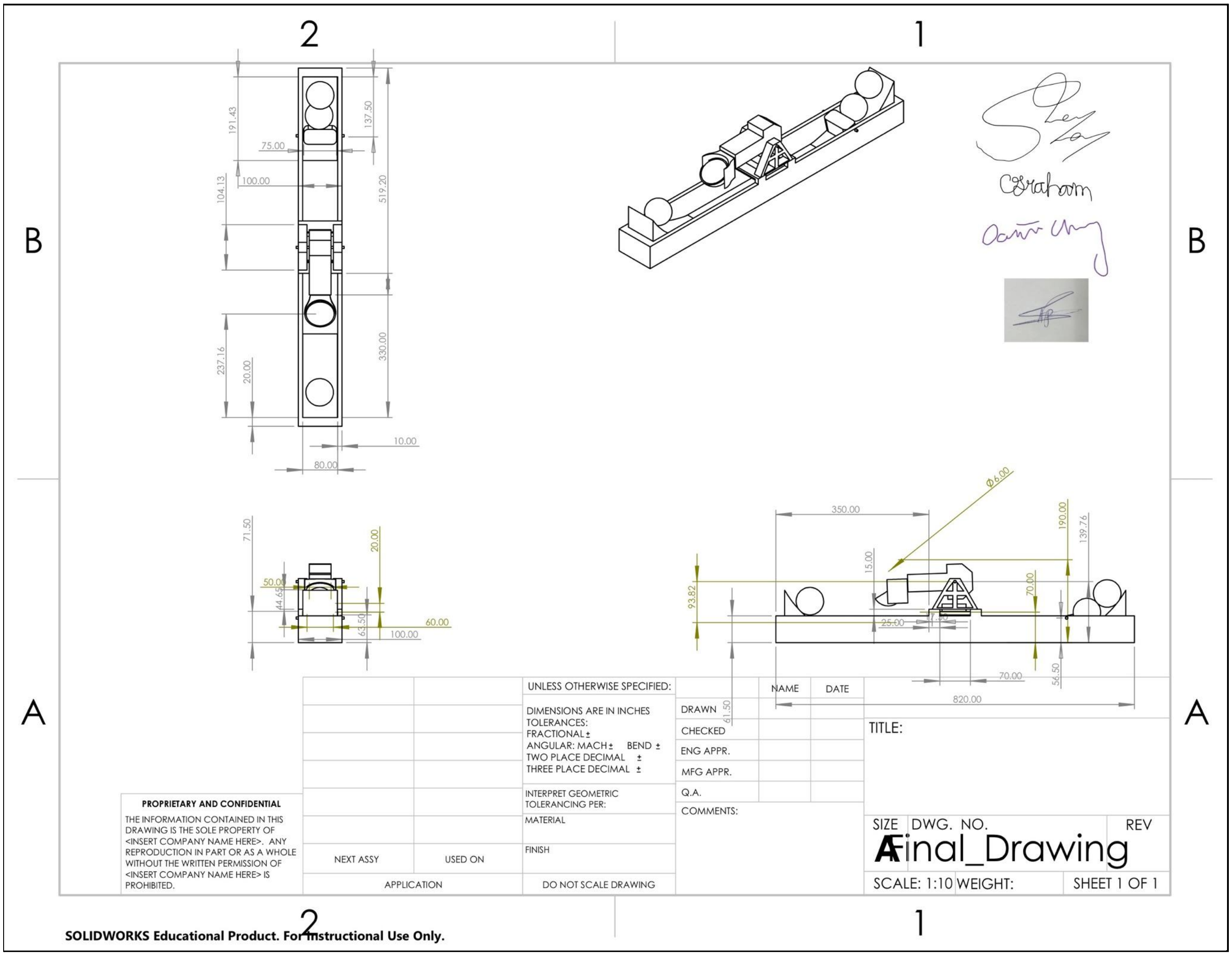


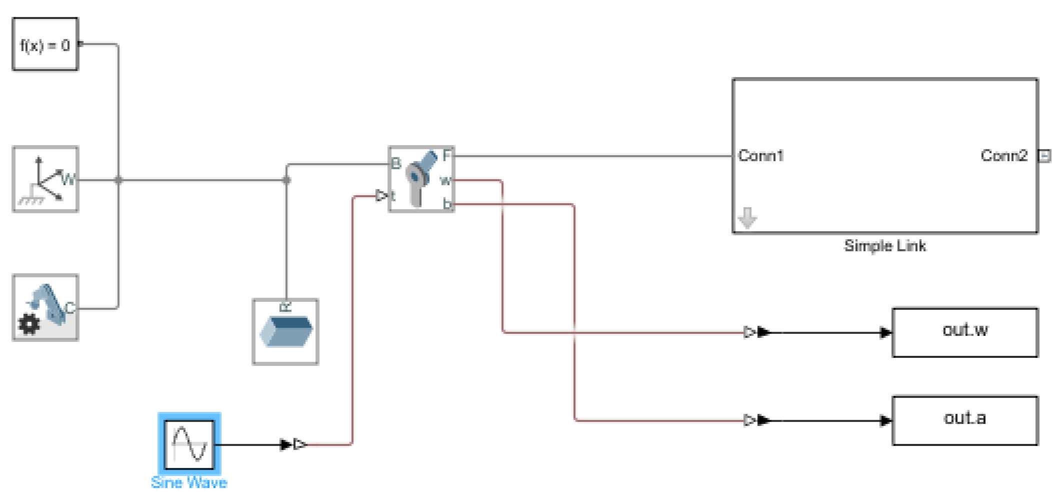
Figure 40 - Drawing of Design III Assembly Signed by Group Members

Appendix E: Lab 2 Code for Hand Calculations, Model, and Simulation

```
close all
clc

% Calculations for lab 2
rho = 2700;
length=1;
width=0.10;
thickness=0.10;
volume = length * width * thickness;
mass = rho * volume;
inertia_cent = (1/12)*(length^2 * width^2);
inertia = inertia_cent + (mass)*(length/2)^2;

% assumming start from rest, and bar is horizontal
gravity = 9.81;
energy=mass*gravity*sin(pi/2)*length;

velocity = sqrt((energy*2)/mass); %from kinematic energy
ang_velocity_90=velocity*length/2;
disp(ang_velocity_90)

ang_velocity_180=0; % returns to starting height
disp(ang_velocity_180)

ang_velocity_270=-ang_velocity_90; % same as 90 but opposite direction
disp(ang_velocity_270)

ang_velocity_360=0; % back to original direciton
```

```
disp(ang_velocity_360)


figure;
hold on;
plot(out.w);
plot(out.a);
legend('w', 'a')
disp(out.w(end));
disp(out.a(end));
```

Figure 41: Code for Lab 2 Calculations



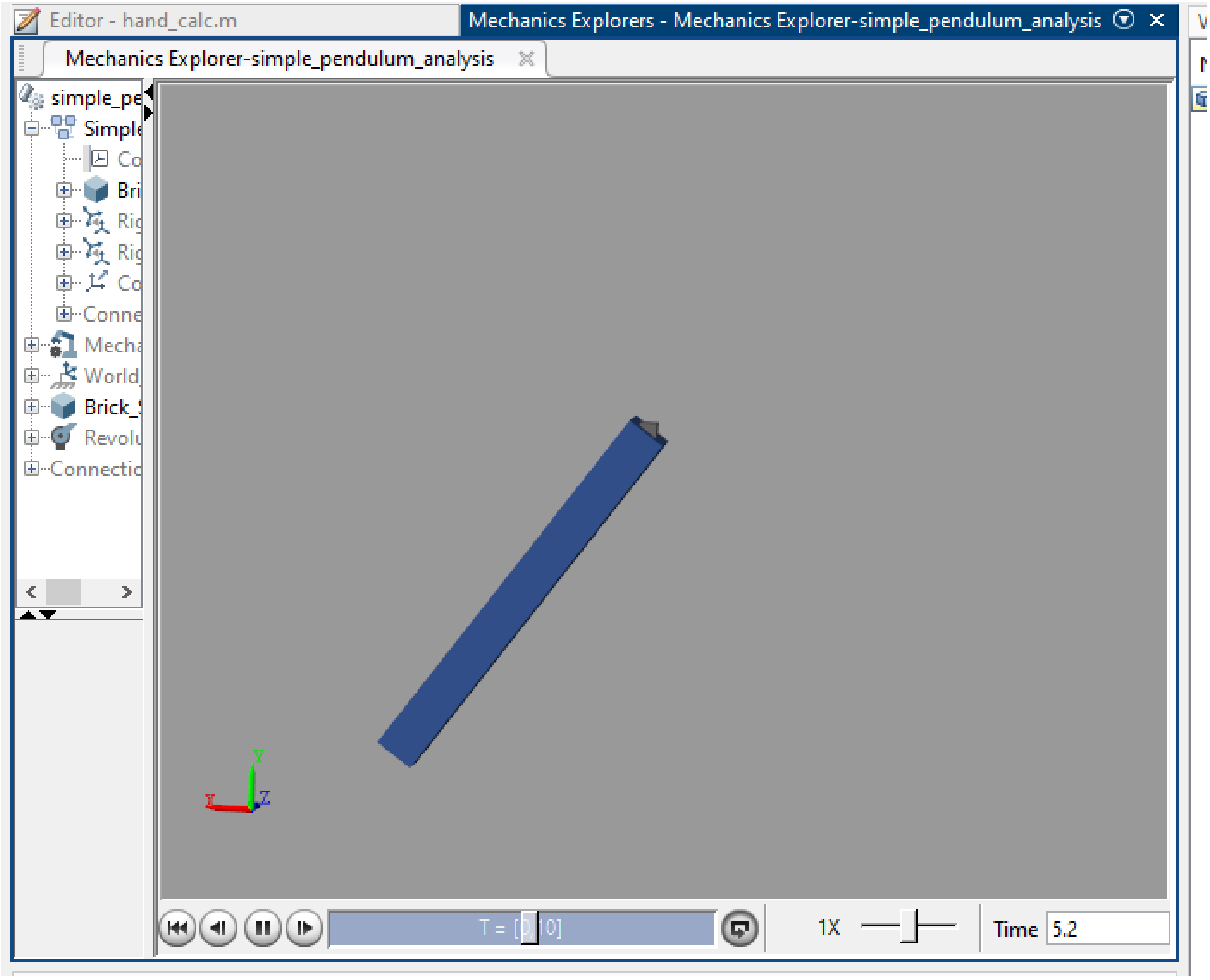


Figure 42: Simulink Model for Lab 2, pendulum arm