Fall 2018

Group B: Polar Coordinate Whiteboard Writer

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MEMS 411: Mechanical Engineering Design Project
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Executive Summary

From the initial funding of $250.00, our group attempted to make a polar coordinate whiteboard writer that was to be used in educational settings. Market for polar coordinate whiteboard writer is a blue ocean. Having a successful prototype will allow us to find a niche place in a market that shares border with the global education market.

The challenges that polar coordinate whiteboard writer faces are inherently different from those of Cartesian ones. Our group spent 4 months to create a prototype of polar coordinate whiteboard writer. Each member aimed for development of specific skills that other members did not have. At the same time, we made various discussions to combine our ideas. We studied and applied various fields of related to engineering which include science, machinery, and circuitry.

Our three performance goals were the following: (1) be able to draw 3 different size circles, (2) be under 3 kg, and (3) be able to survive a 1.5 m drop test. Our result was the following: (1) was able to draw different size circular figures, (2) was 2 kg, and (3) internals did survive the drop test while externals did not. Although our prototype is not perfect, we have all the foundations to make it work, if given more time and funding. If given the opportunity to do so, we will apply higher level knowledge of vibrations and machinery onto our prototypes.

The final product is within our reach. Therefore, furfur research, development, and funding in the prototype and the product will surely make polar coordinate whiteboard writer come true and make it ready to spread across the globe.

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1 INTRODUCTION

There already exist many automated whiteboard writers based on Cartesian coordinate system to have market of them; the marker moves lefts and right, and up and down. The XY plot is well known, and easily understood. However, the market for whiteboard writers based on polar coordinate system is still a blue ocean. The polar coordinate system feels odd to those that are used to the Cartesian coordinate system. Making movements and drawing figures in polar coordinates have unique challenges compared with those in Cartesian coordinates; even drawing straight lines will be a challenge. Despite the challenges and disadvantages, polar coordinate system has its own strengths. Many objects in around us and the world make polar movements; there are figures like circles and spirals, and there are movements like signals, pivot joints and planetary motion. Representing these movements in equations of Cartesian coordinates are lengthy and complex; in polar coordinates, the equations are drastically simplified. Therefore, we will make a whiteboard writer based on polar coordinate system; we will make a small contribution to the market. We will make a whiteboard writer that is fully functional in the polar coordinate system. Domination of the polar coordinate system will be our top priority. At the same time, our machine will not lack the functions of a typical whiteboard writer. It will be out of the vision once it completes its drawings. It will be precise and concise in its drawings. It will clean up after itself. It will be portable and convenient. It will be affordable. Most importantly, it will function.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

2.1.3 Related Codes and Standards

In this design, we mainly consider two reasons for safety. One is about sharpness and another is electricity.

2.1.3.1 IEEE Guide for AC Motor Protection - IEEE Std C37.96™-2012 (Revision of IEEE Std C37.96-2000)

This is the one standard about proper motor use and protection provides us with baseness when we select and apply motors on the prototype. It regulates low-voltage and medium-voltage motors, which fall into the moto category we use. Its motor starting conditions and ambient conditions is helpful for us to use the motor properly.

2.1.3.2 Sharp edge test in 16 CFR 1500 49 Code of Federal Regulations (CFR) Consumer Product Safety Commission

This is the one code about sharpness avoids possible hazardous penetration into human body parts that might happen during use. The code is from legal regulation institute. It has all the rules about our potential operations such as insertion. We can also get the access to how to frame edges properly, etc.

2.2 User Needs

2.2.1 Customer Needs Interview

Table 1: Customer Needs Interview

Product: Polar Coordinate Whiteboard Writer
Customer: Ian Taylor

Notes: We asked some questions about the basic concepts that Ian wants to develop in this whiteboard writer. The interview took about 30 minutes.

Address: Jolley 111, Washington University Danforth Campus Date:
September 7, 2018

Question	Customer Statement	Interpreted Need	Imp.
Basic movement	Has to be used in a polar system, drawing circles on the whiteboard. Writer needs to move aside to avoid disturbing the vision after drawing.	polar coordinate movement avoid disturbance	5 4
Additional function	The writer is able to erase on the whiteboard.	Eraser attachment	4
Safety	Don’t move too fast. Don’t be too shaped	Rotational Speed Safety	2 3
Material	No preference. Don’t be too heavy Within 100 bucks, 150 for max.	Safety Cost	3 2
Portability	Be able to attach to a standard whiteboard. Not super compact, but something could be carried around.	Portability	3

2.2.2 Interpreted Customer Needs

Table 2: Interpreted Customer Needs

Need Number	Need	Importance
1	polar coordinate movement	5
2	avoid disturbance	4
3	Eraser attachment	4
4	Safety	3
5	Portability	3
6	Cost	2
7	Rotational Speed	2

2.3 DESIGN METRICS

2.3.1 Target Specification

Table 3: Target Specification

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	4, 5, 6	Total weight	kg	5	1
2	2, 5	Length of arm	cm	70	30
3	1, 4	Rotational speed of writer	rad/s	0.314	0.628
4	4	Sharp edge test in 16 CFR 1500 49 Code of Federal Regulations (CFR) Consumer Product Safety Commission	binary	Pass	Pass
5	4	C37.96-2012 - IEEE Guide for AC Motor Protection	binary	Pass	Pass

2.4 PROJECT MANAGEMENT

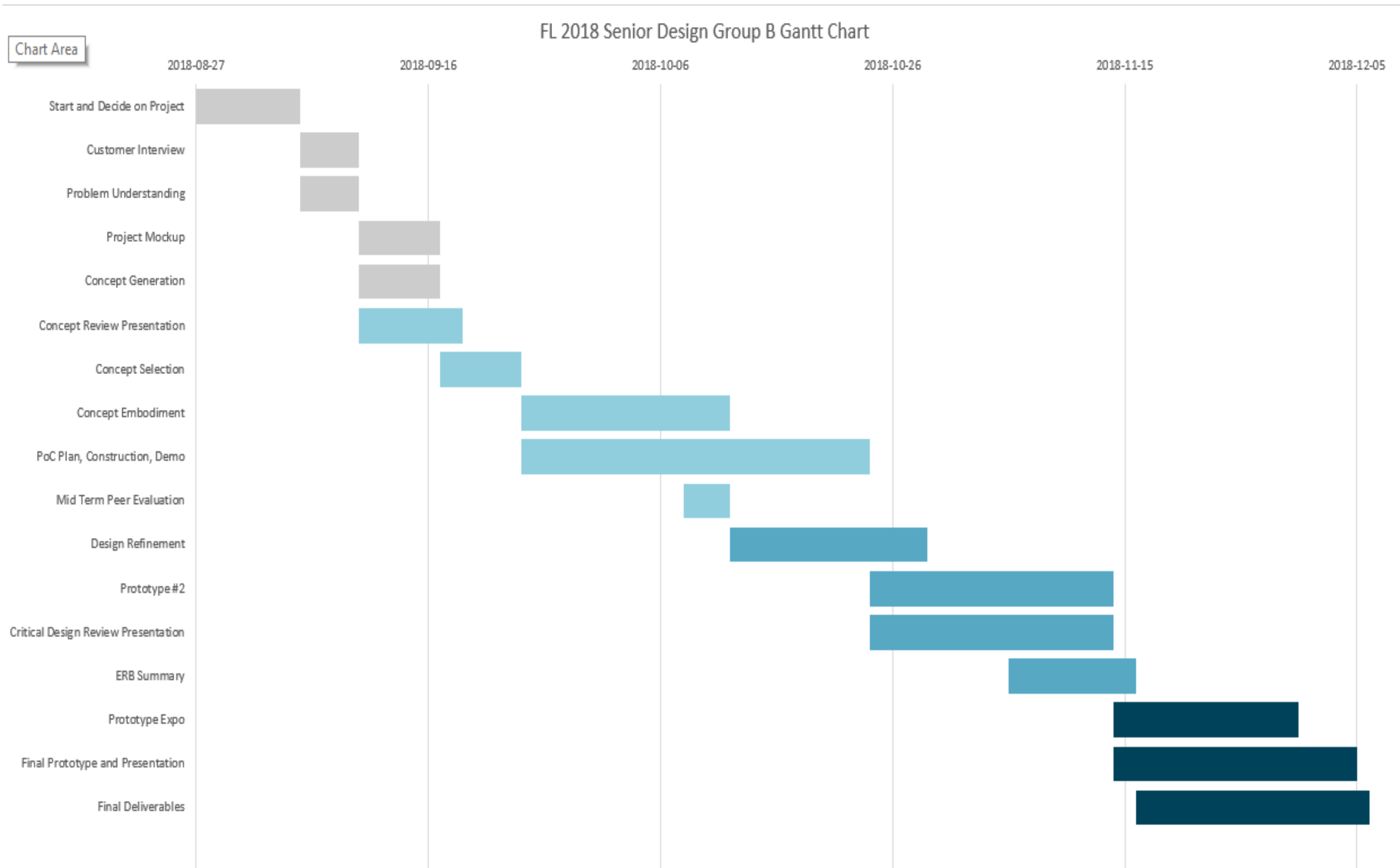


Figure 1: Gantt Chart

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

The mockup helps us to understand the design better by reminding us some potential trouble the user might meet with. We firstly wanted one track only. But after we implemented the mockup, we figured out that the marker pen rotated around the track due to torque caused by the friction between the pen and whiteboard. Thus, we decided to add one more track so that the torque could be eliminated. We were considering to use magnet for attaching the equipment onto the whiteboard. But we then figured out that with a electrical motor added, the force generated from the magnet is not capable of holding the prototype so we came up with another idea by using a vacuum hooker.

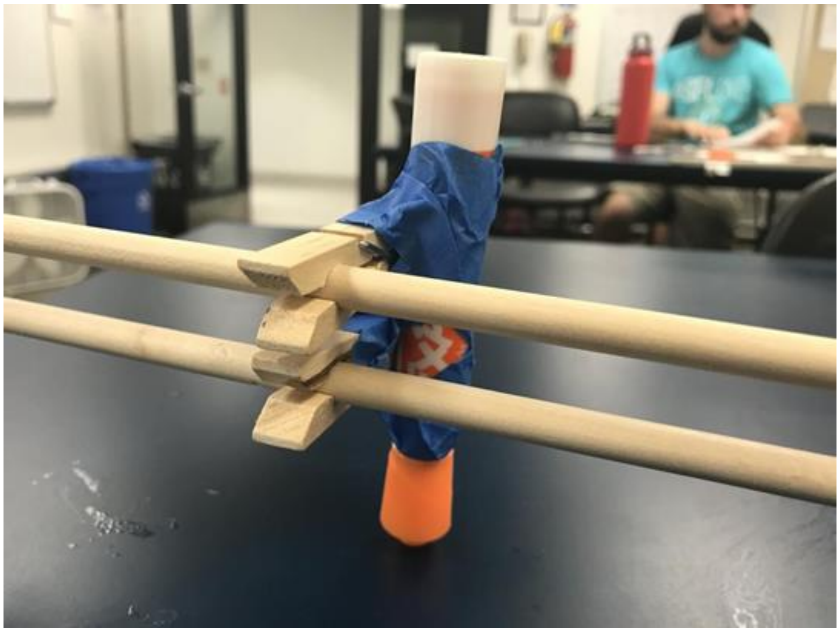


Figure 2: photograph of mockup's radial motion mechanism

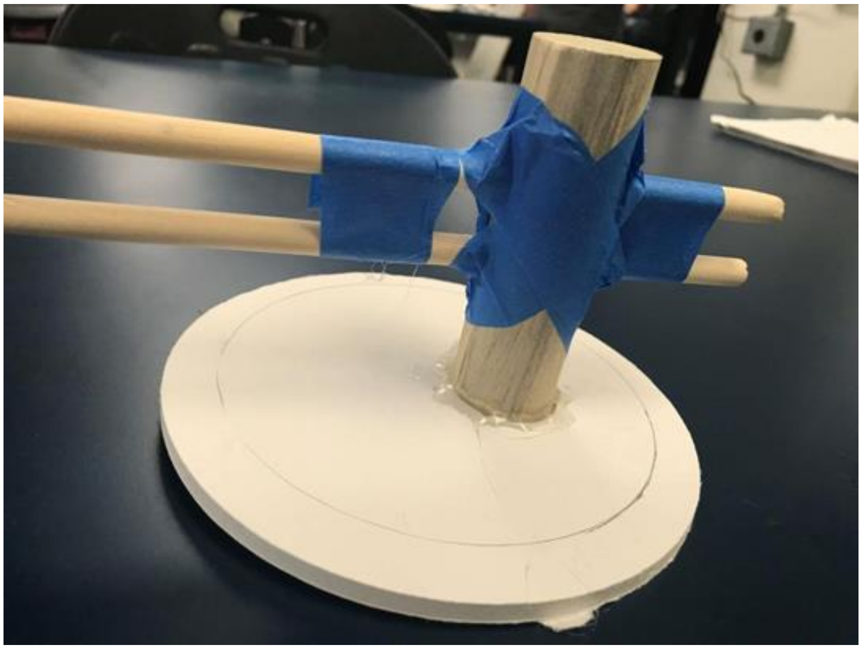


Figure 3: Photograph of mockup's tangent motion mechanism

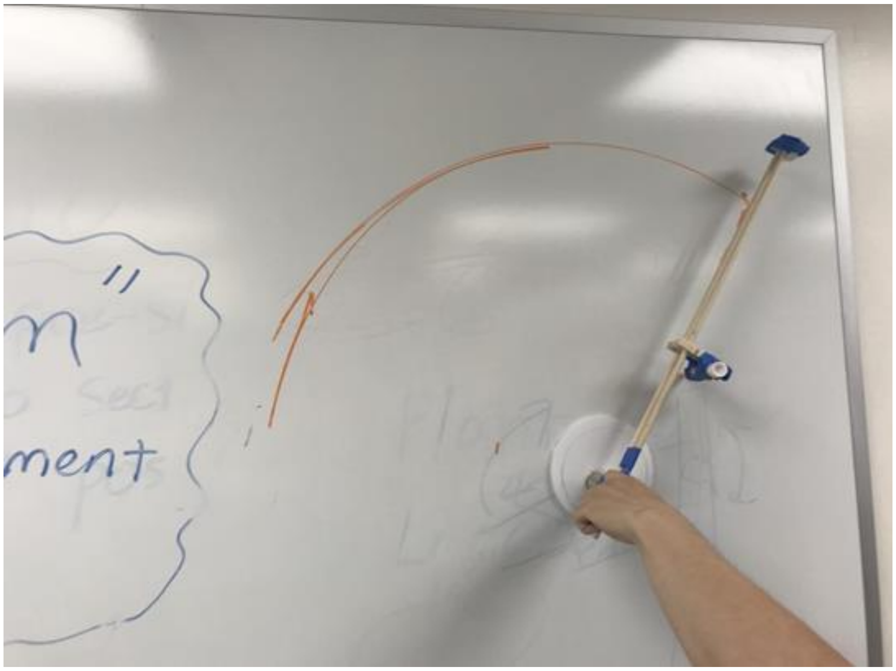


Figure 4: Photograph of mockup-whiteboard interaction at third position

3.2 FUNCTIONAL DECOMPOSITION

3.2.1 Function Tree

Basic in the customer needs we come up a function that can complete the needs.

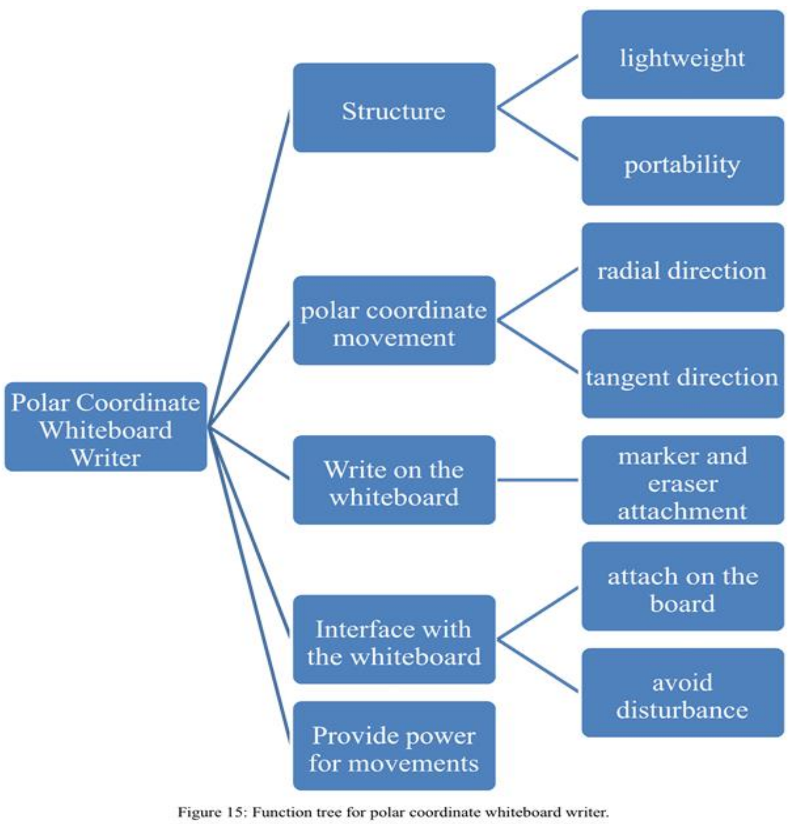
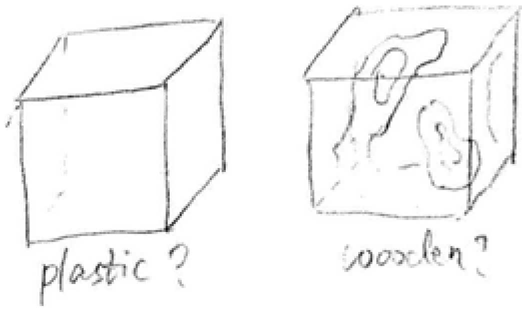
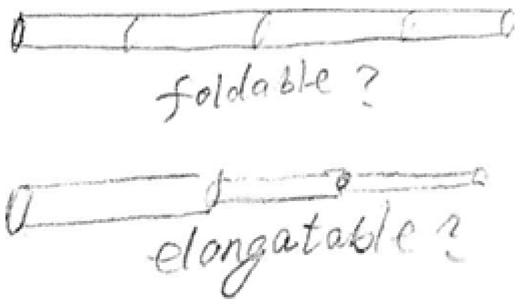
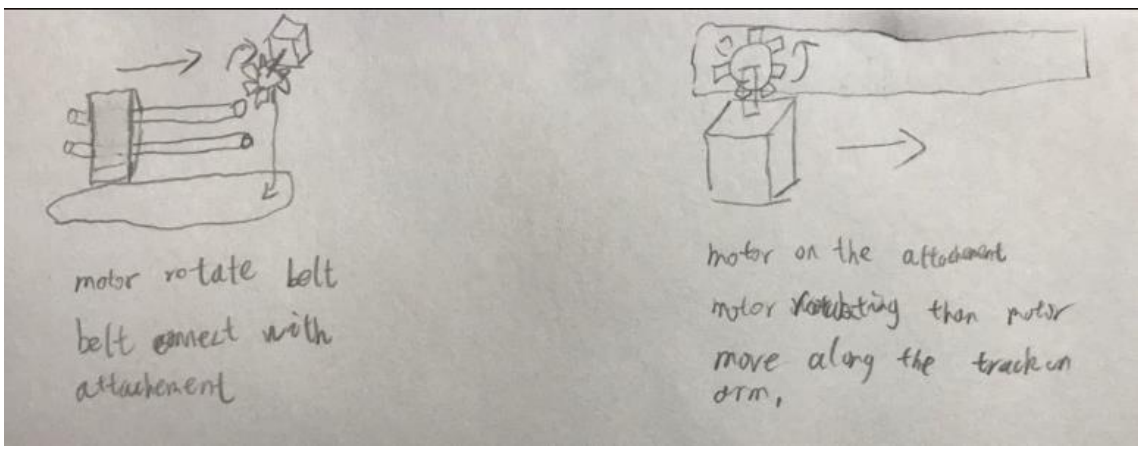
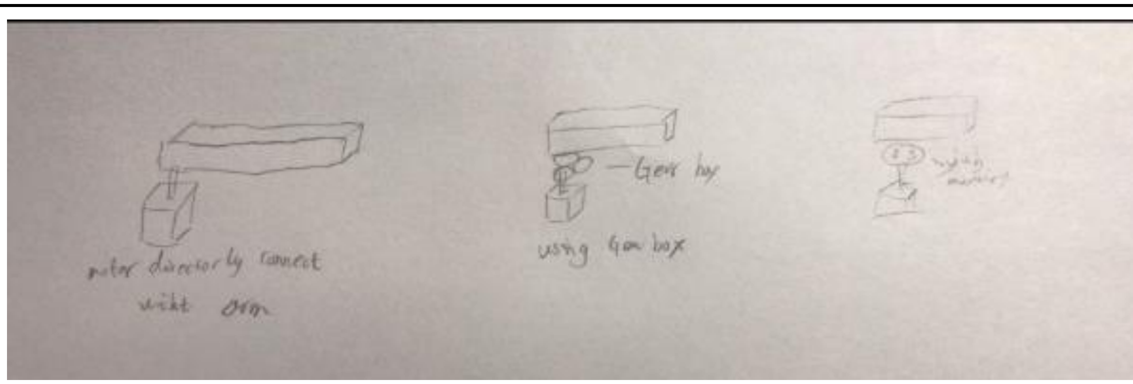
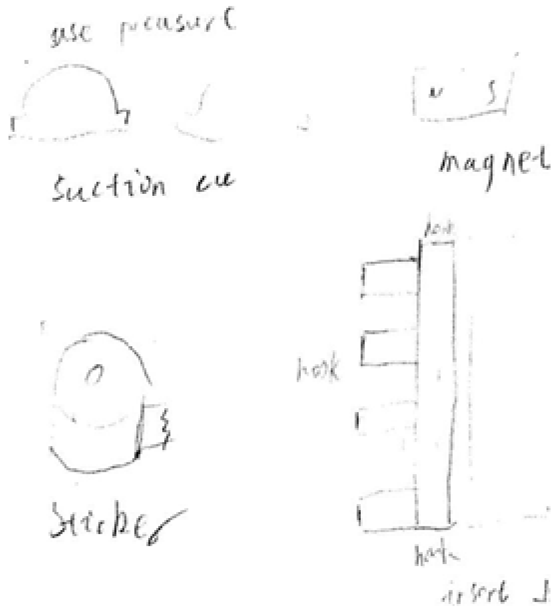
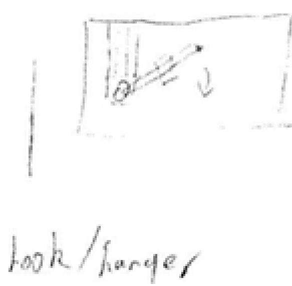
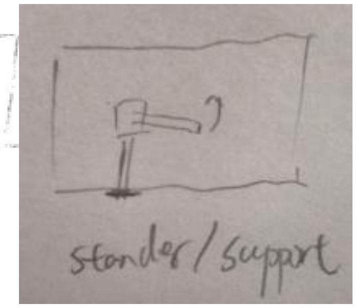
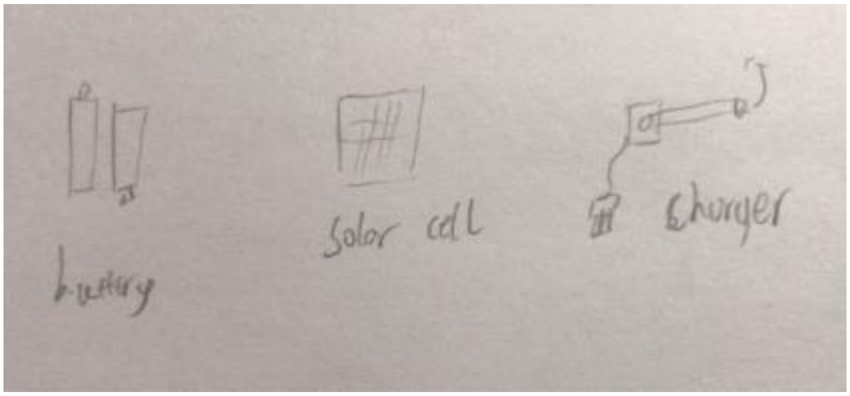


Figure 5: Function Tree

3.2.2 Morphological Chart

Table 4: Morphological Chart

1.Light Weight	
2.Portability	
3.Radial direction movement	
4.Tangent direction movement	

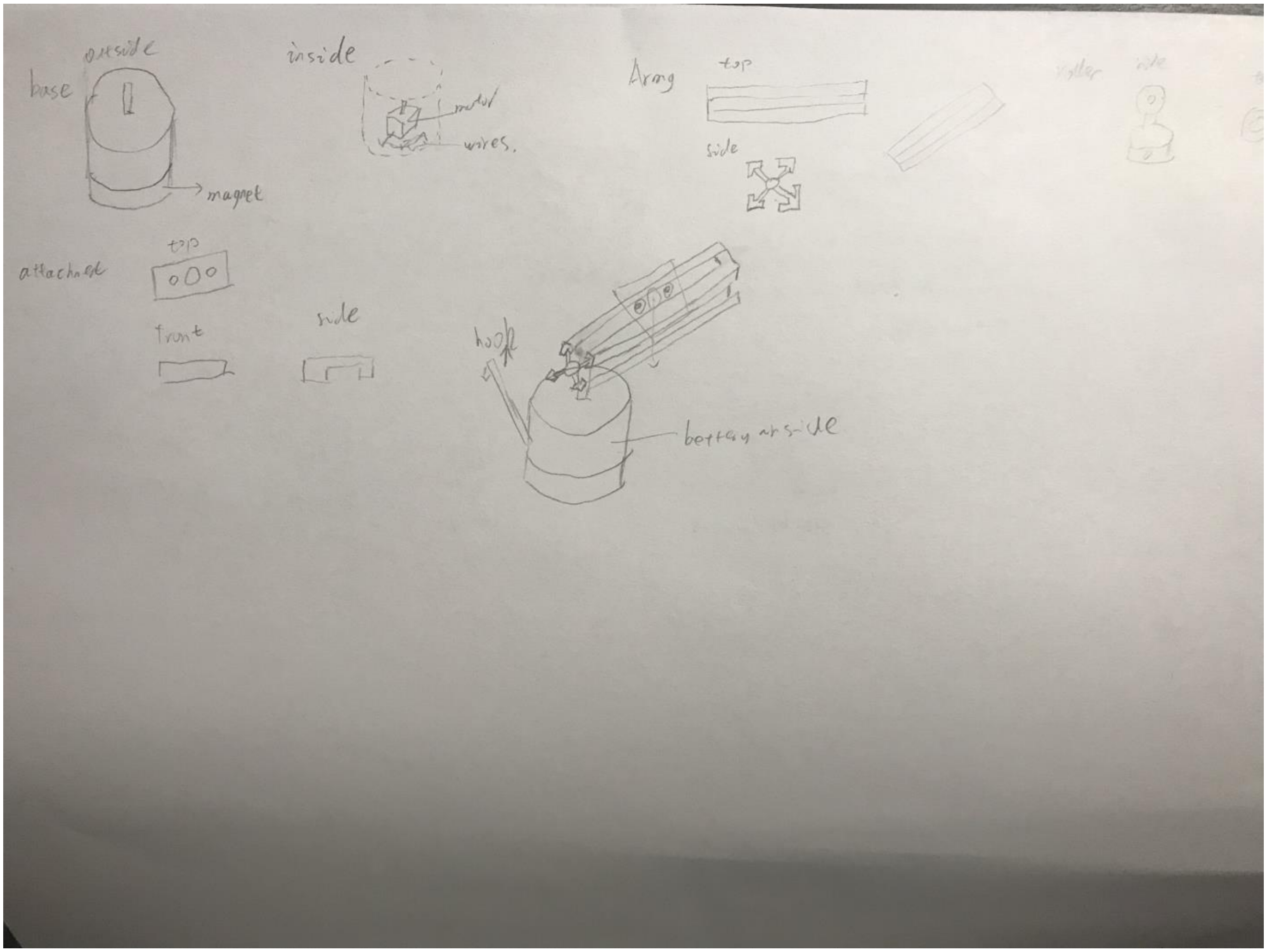
5.Attachment	
6.Attach on the board	
7.Avoid disturbance	
8.Power	

3.3 ALTERNATIVE DESIGN CONCEPTS

3.3.1 Alternative Design Concept #1

Concept Name: “Free move whiteboard writer”

Group Member: Zexin Han



Description: A base is made of magnet, which used to attach to the white board. The motor is used to rotate the arm to make an angular movement. And the hook is for avoid too much vibration by the movement. The attachment box and the motor in side it will produce the radial movement along the arm. And the pen will have screw at the end to insert the slot on the box.

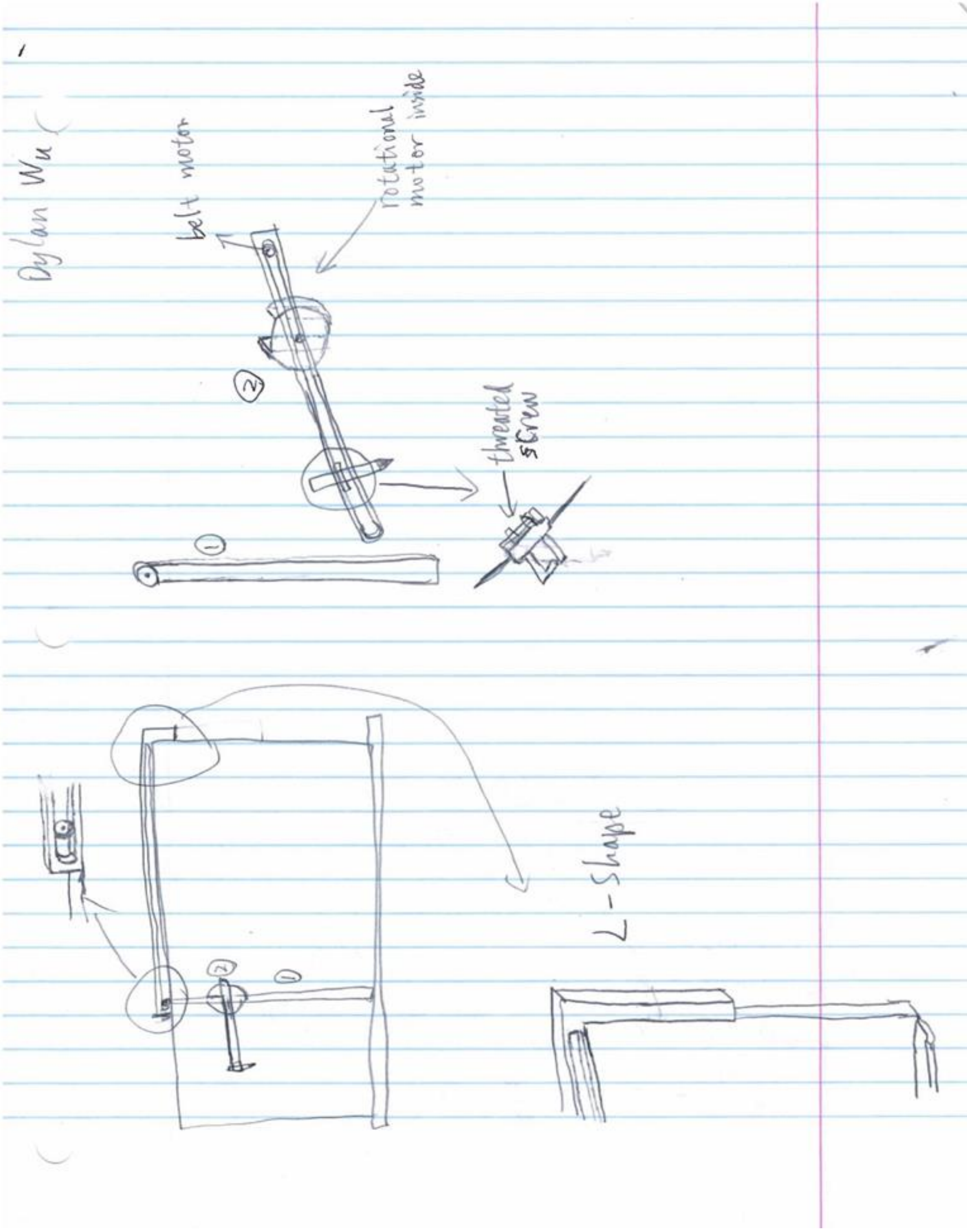
Solutions:

1.Wooden
2.Motor with gear
3.Motor with track
4.Slot
5.Magnet
6.Hook/Hanger
8.Battery

3.3.2 Alternate Design Concept #2

Concept Name: “L-Shape Whiteboard Writer”

Group Member: Dylan Wu



Description: this design contains a L-shape track which is hanged on the top of the whiteboard. The vertical track would move horizontally along the track. And the writer could move along the vertical track by timing belt. The arm of writer would rotate by the stepper motor.

Solutions:

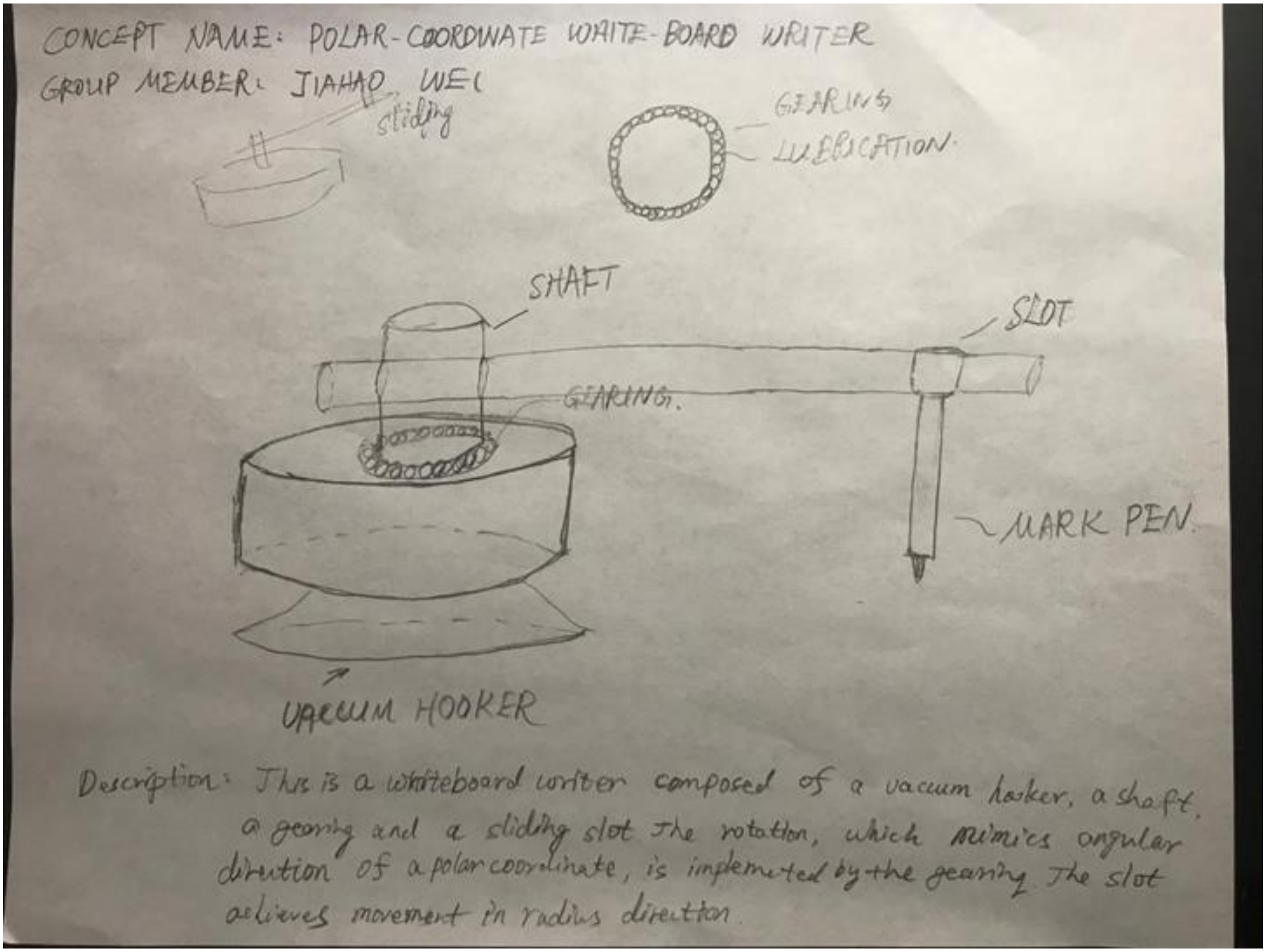
1. Aluminum
2. Motor with gear
3. Motor with track
4. Slot
5. Clamp
6. Magnet

7. Hook/Hanger
8. Battery

3.3.3 Alternate Design Concept #3

Concept Name: "Polar-coordinate whiteboard writer"

Group Member: Jiahao Wei



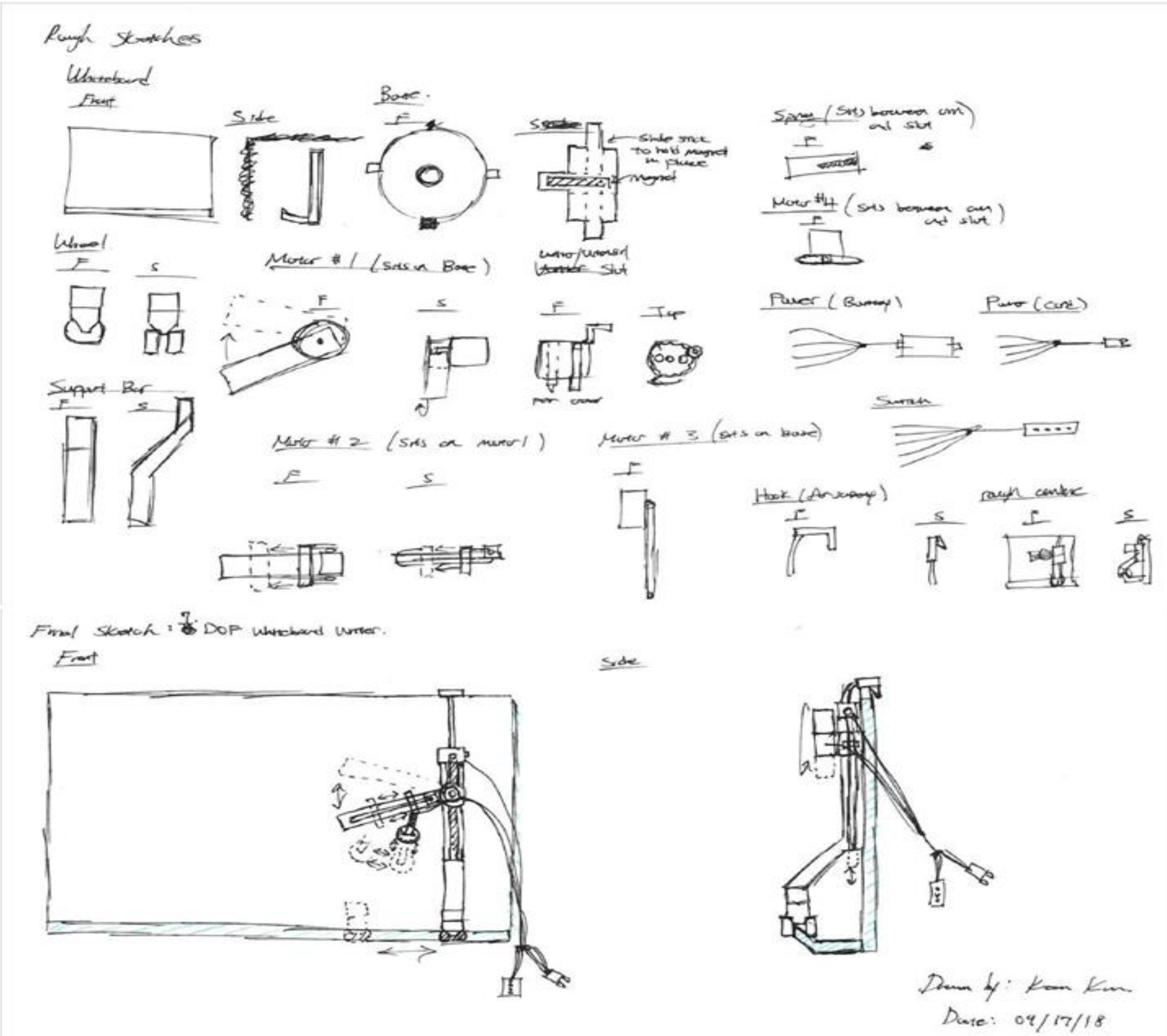
Description is shown on the picture already.

Solution:

1.Wooden/Plastic
2.Motor with gearing
3.Track fixed on the motor shaft
4.Slot
5.Vacuum
8.Battery/AC power

3.3.4 Alternate Design Concept #4

Concept Name: “7 Degrees of Freedom Whiteboard Writer”
Group Member: Keon Kim



Description: The machine is held in place on the whiteboard by friction between machine and whiteboard, friction between hook and back of the board, and magnetic attraction between magnet and whiteboard. The machine aims for 7 degrees of freedom. Global X movement by the wheel. Global Y movement of the base by the motor. Global Φ movement of the arm by the motor. Primary R movement of the utensil slot by the motor. Local Φ movement of the utensil slot by the motor. Local R movement of the utensil slot by a compressed spring. Global change on utensil done by the utensil slot. All motors are controlled by an external switch. All motors are powered by external power sources such as batteries or power cord.

Solutions:

1. Wooden
2. Motor with gear
3. Motor with track
4. Slot
5. Magnet
6. Hook/Hanger
7. Stand
8. Wheels
9. Plug

4 Concept Selection

Here we adjusted reasonably after discussion compared with the initial user needs based on the design process.

4.1 Selection Criteria

Table 5: Analytic Hierarchy Process

	Light Weight	Portability	Radial Direction	Tangential Direction	Marker & Eraser	Attach on Boards	Avoid Disturbance	Row Total	Weight Value	Weight (%)
Light Weight	**1.00**	0.33	0.11	0.11	0.33	0.14	0.20	2.23	0.02	2.18%
Portability	3.00	**1.00**	0.33	0.33	0.20	1.00	0.14	6.01	0.06	5.89%
Radial Direction Move	9.00	3.00	**1.00**	0.20	0.20	1.00	1.00	15.40	0.15	15.09%
Tangential Direction	9.00	3.00	5.00	**1.00**	0.33	1.00	0.33	19.67	0.19	19.27%
Marker & Eraser	3.00	5.00	5.00	3.00	**1.00**	**0.33**	0.20	17.53	0.17	17.18%
Attach on Boards	7.00	1.00	1.00	1.00	**3.00**	**1.00**	0.20	14.20	0.14	13.92%
Avoid Disturbance	5.00	7.00	1.00	3.00	5.00	5.00	**1.00**	27.00	0.26	26.46%
							Column Total:	**102.04**	**1.00**	**100%**

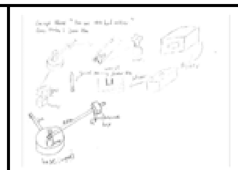
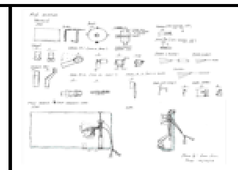
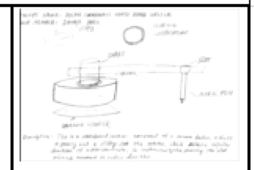
ONLY change the lower-left triangle of the matrix
Right 3 columns will be automatically calculated

Row criterion is ________ than/as column criterion

Numerical ratings:
- 9 -- Extremely more important
- 7 -- Very strongly more important
- 5 -- Strongly more important
- 3 -- Moderately more important
- 1 -- Equally important
- 1/3 -- Moderately less important
- 1/5 -- Strongly less important
- 1/7 -- Very strongly less important
- 1/9 -- Extremely less important

4.2 Concept Evaluation

Table 6: Weighted Scoring Matrix

		Alternative Deisgn Concepts							
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Light Weight	2.18	5	0.11	1	0.02	3	0.07	3	0.07
Portability	5.89	1	0.06	5	0.29	3	0.18	3	0.18
Radial Direction Move	15.09	3	0.45	3	0.45	5	0.75	1	0.15
Tangent Direction	19.27	3	0.58	3	0.58	2	0.39	5	0.96
Marker and Eraser Attach	17.18	3	0.52	3	0.52	3	0.52	3	0.52
Attach on Boards	13.92	3	0.42	3	0.42	2	0.28	5	0.70
Avoid Disturbance	26.46	2	0.53	2	0.53	3	0.79	2	0.53
	Total score	**2.132**		**2.280**		**2.176**		**2.568**	
	Rank	**4**		**2**		**3**		**1**	

4.3 Evaluation Results

Based on the results from our AHP, the 6 selection criteria, from highest weight percentages to lowest weight percentages, were "Radial Direction (20.8 %), "Tangential Direction (20.8 %)," "Marker and Eraser (16.7 %)," Lightweight (16.7 %)," Portability (12.5 %)," and "Attach on Board (12.5 %)." We evaluated our designs with the AHP and the weighted scoring matrix; the 4 designs, from highest score to lowest score, were "Polar-coordinate whiteboard writer (3.250)," "Free move whiteboard writer (3.084)," "7 Degrees of Freedom Whiteboard Writer (3.083)," and "Dylan's Alternate Design Concept (2.916)." Through evaluations, our group decided that design "Polar-coordinate whiteboard writer" was the best design for our project. In the 6 criteria – Lightweight, Portability, Radial Direction, Tangent Direction, Maker and Eraser, and Attach on Board – design "Polar-coordinate whiteboard writer" achieved scores of 0.50 (2nd), 0.38 (2nd), 0.21 (4th), 1.04 (1st), 0.50 (1st), and 0.63 (1st), respectively. The best design had the second highest score in "Lightweight" because making use of suction cups greatly reduced the total mass of the system; the lightest design also made use of the hook to reduce the 26 total required weight. The best design had the second highest score in "Portability;" reasons were similar to those of "Lightweight." The best design had the lowest score in "Radial Direction" because of lack of motors that functioned in radial direction; other designs had motors that functioned in radial direction. The best design had the highest score in "Tangent Direction" because the design had focus on the base where the tangent direction motor would be placed; other designed had varying focuses at various locations of the machines. The best design had the highest score in "Marker and Eraser;" all designs had the ability to write and erase. The best design had the highest score in "Attach on Boards" because it made great use of suction cups; other designs used magnets which had limitations on attachable surfaces.

4.4 Engineering Models/Relationships

4.4.1 Model #1

Gear Ratio

$$\frac{Driven\ pitch\ Diameter}{Driving\ pitch\ Diameter} = \text{Ratio}$$

The gear ratio are used to control the velocity and power. In this product. We decided to use gear to slow down the speed from the motor and transform the power.

$Fr = Ft\tan\phi$ $p = \frac{\pi d}{N}$

T=torque=rFt $P = \frac{N}{d}$

$W = power = \omega r\ Ft$

Ft is tangential force and Fr is radial force which does no work. r is radius and ω is the angular velocity. P is diametral pitch and p is circular pitch. N is the number of teeth.

The gear ratio is used to control the velocity and power. In this product. We decided to use gear to slow down the speed from the motor and transform the power. We also need to know how much force a gear will can transform when it connect to a motor. Those equation can help us to calculate out which type of motor we can use to support the whole product to rotation.
Source: https://curriculum.vexrobotics.com/curriculum/mechanical-power-transmission/gear-ratios.html

4.4.2 Model #2

$\sigma b = \frac{-My}{I}\ \delta max = \frac{FL^3}{3EI}$

M=−F(L−x)

M is the moment and F is force. σb is the shear stress and δ is the deflection on the beam.
This model is for analyzing the force act on the arm part of our design. If we want to move the pen or any attachments to the end of the arm, we need to know how strong the arm will be. And we also need to know the deflection will happen at the end to make sure it will not influence the drawing. And we need to know the moment of the rotation of the origin point.
Source： http://www.strucalc.com/normal-stress-bending-stress-shear-stress/

4.4.3 Model #3

$F_{suction} = P_{air} \times Area$

Assume the suction cup is exhausted, the air pressure would apply a force on the contact area. Where P_{air} is the air pressure, and Area is the contact area of the suction cup.

$V_{weight} = Weight\ of\ the\ whole\ project$

The vertical shear force on the contact area would be equal to the weight of the project

$\sigma_{normal} = M \times r\ I$

This equation indicates the normal stress of the contact surface due to the weight. M is the resultant moment about the contact surface, r is the radius of the suction cup, and I is the inertia of the circular cross section. After the static conditions, the dynamic conditions would be added. Because of the rotational motion of the arm, the interface between the suction cup and the whiteboard would experience a torsional stress

$\tau_{torsion} = Tr/J$

Where T is the twisting moment of the writer, r is the distance from the mass center to the rotation center axis, and J is the polar moment of inertia of area.
This model will help to analyze the interface stress between the project and whiteboard.

source： http://www.strucalc.com/normal-stress-bending-stress-shear-stress

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

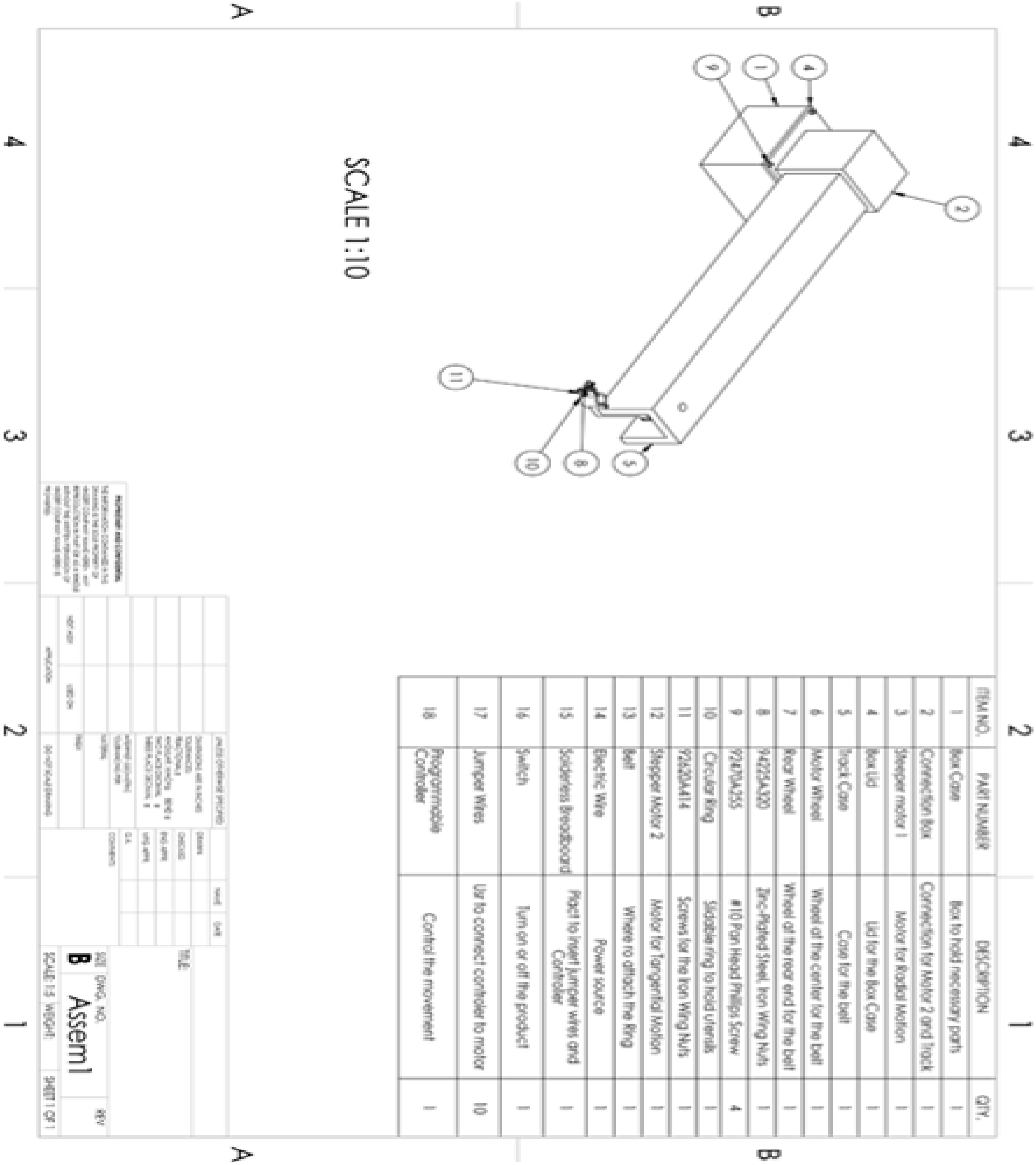


Figure 6: CAD embodiment of White Board writer with BOM and balloons

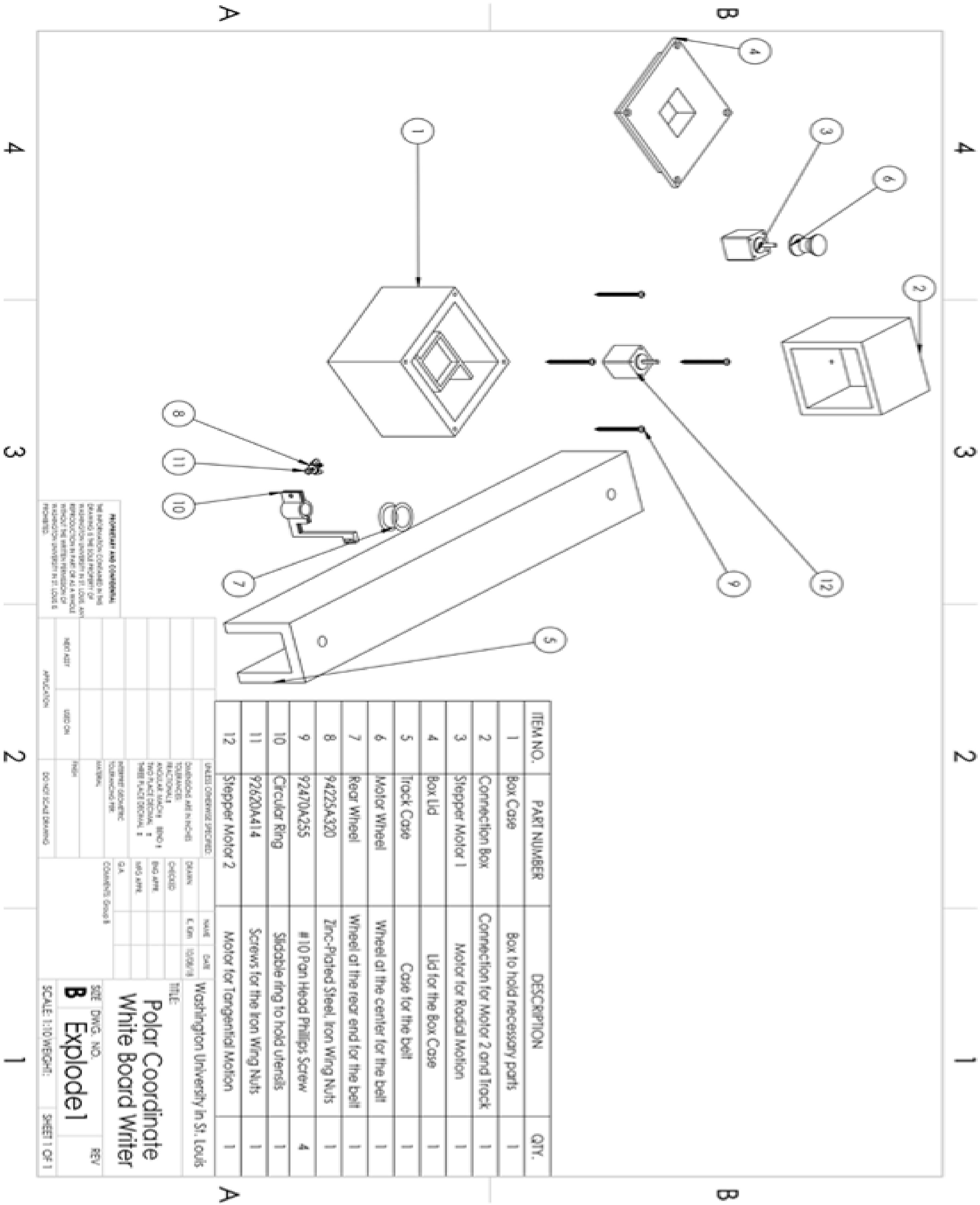


Figure 7: Exploded view of CAD embodiment of White Board writer with balloon callout

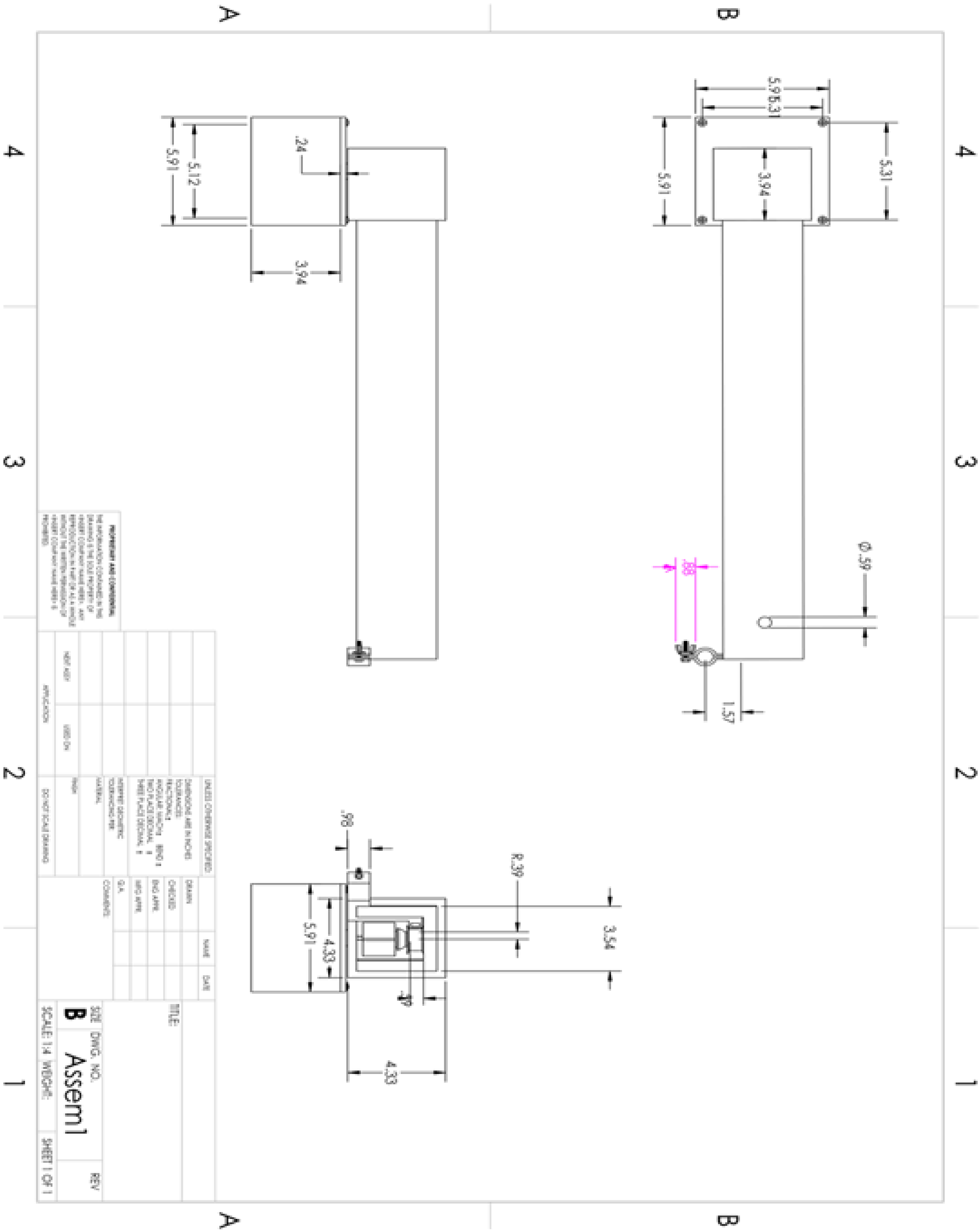


Figure 8: 3 views of CAD embodiment of White Board writer with dimensions

Table 7: Initial parts lists of prototype components

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Motor	Pololu	2257	Black	$2.95	6	$17.7
2	Nut	Zinc	94225A320	7/16 inch	$0.5	10	$5
3	Screw	Grainger	92620A414	¾ inch	$0.106	10	$1.06
4	Screw	Homedepot	92470A255	½ inch	$2.57	6	$15.42
5	Screw	Mcmaster	92314A257	3/8 inch	$9.43	1	$9.43
6	Suction cup	Amazon	N/A	½ inch	$6.95	2	$13.9

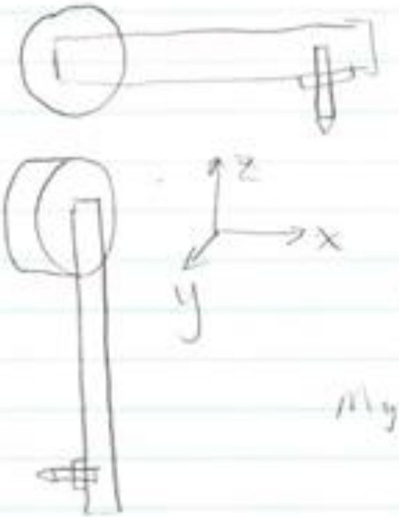
Total Price: $53.31

5.2 Proof-of-Concept

5.2.1 Prototype performance goals:

1. Mass of the product at most 3 Kg
2. Be able to draw 3 different size of circle
3. Drop from 1.5 meter without broken

5.2.2 Design rationale for PoC components(Next Page)



Static state,
the loads at whiteboard

$R_x = 0 = R_y$

$R_z = mg$ where m is the total mass of the project.

Here we're given $m = 3kg$

$R_z = 29.4\,N$

$M_y = mg \times C_x$ where C_x is the distance from center of mass to the whiteboard, could be found in the Solidwork analysis

$= 29.4N \times 0.1m$

$= 2.94\,N \cdot m$

Holding Torque is the torque that makes motor rotate.
Holding Torque For Stepper motor 17HS19-2004S1 is 59 N·cm

$T_{HT} = 59\,N\,cm \times \frac{1m}{100cm} = 0.59\,N \cdot m$

the maximum shear stress due to this holding torque

$$\tau_{HT} = \frac{16\,T_{HT}}{\pi d^3} = \frac{16 \times 0.59}{\pi\, 0.15^3} = 890.32\,Pa \qquad [1]$$

where d is diameter of the circular basement, it's 15 cm

the maximum bending stress on the whiteboard is

$$\sigma_{max} = \frac{32 \cdot M_y}{\pi d^3} = \frac{32 \times 2.94}{\pi (0.15)^3} = 8873\,Pa \quad [2]$$

For the suction cup, because it can't be perfectly vacuum. so the air pressure apply on the cup is assumed as $\frac{1}{2}$ of standard. Here we assume that suction cups are not deformed too much.

Max. Force acted on $= \frac{1}{2} P_{air} \times Area$

$= \frac{1}{2} \times 101325 \times \pi (\frac{0.15}{2})^2 = 895.3\,N$

Citation of Eqn. [1] and [2]: Torsion of Shafts,
www.engineeringtoolbox.com/torsion-shafts-d_947.html

6 WORKING PROTOTYPE

6.1 OVERVIEW

When we measured the weight of the PoC prototype it is kind of too heavy. Se we changed material of arm. We used two aluminum rod to replace the wood arm box. And we also redesign the large box which used to hold the wires and motor. We make the size of box much larger and changed material to light wood. We also designed two new holder for the timing pulley. One of the holder has place to hold the small motor which used to rotate the timing belt.

6.2 DEMONSTRATION DOCUMENTATION

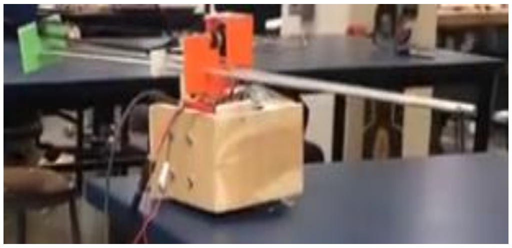


Figure 9: Prototype pic1

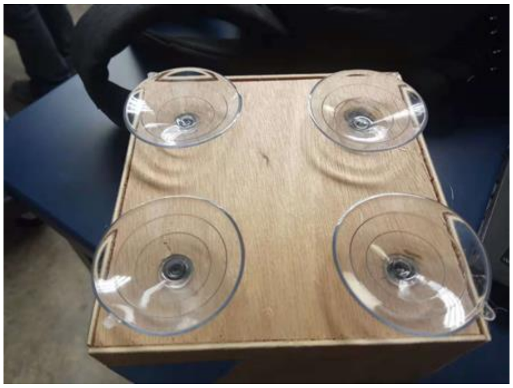


Figure 10: Prototype pic2

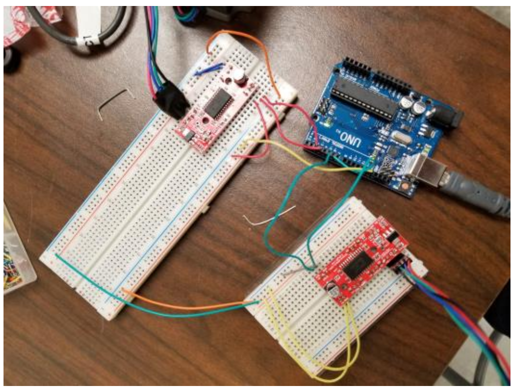


Figure 11: Prototype pic3

6.3 EXPERIMENTAL RESULTS

Our First performance goal is the Mass of the product be at most 3 kg. We have done a great job on this goal. In the PoC prototype, our whiteboard writer weight is greater than 3 kg. So we make the changes on arm and the box holder. We replaced the heaviest part, the wood arm, by two aluminum rod. We also used couple 3D print part to replace the wood which successfully reduce the total weight. The final weight is about 2 kg, which is much light then we thought.

Our second performance goal is making the writer to be able to draw three different size of circle. We failed this goal, but we still success on half of the goal. We make it be able to doing the motion on table but not on the white board. The biggest problem is that we did not find a way to overcome the gravity. When we put on the white board, it can only rotate a small angle. We assume the motor is not strong enough to against the gravity. And the wire will block the movement of arm. When it finish one circle the pen will hit on the wire and stop.

Our third goal is that let the white board writer drop from 1.5 meter high without broken. The result of the drop test is not complete success. The final prototype is not damaged, but the box holder is little bit all apart. The reason is the connection between each wood is not strong enough. We used nail to make the wood board assembly together. But it not works well. But other part of the prototype is not damaged. The connection between shafts is stable. The motor frame protect the motor well.

7 DESIGN REFINEMENT

7.1 FEM STRESS/DEFLECTION ANALYSIS

a) We used the middle mesh density to analyze the arm. We assuming the fixed point is the green part in the figure 1. And the left purple force is the weight applied by motor which is about 10 N. the force on right is the attachment and the holder's weight. We assume it is 5 N. Once the holder moves to the end of the arm, it will influence the fixed point most. The simulation is different from the real world. The weight may not apply the point we assume in the solidworks. And we only analysis a part of it without considering the influence from other motion. But this still help us notice the limitation of the design.

b) This is the arm of the rotation. The simulation is assuming the pen move to the end of the arm.

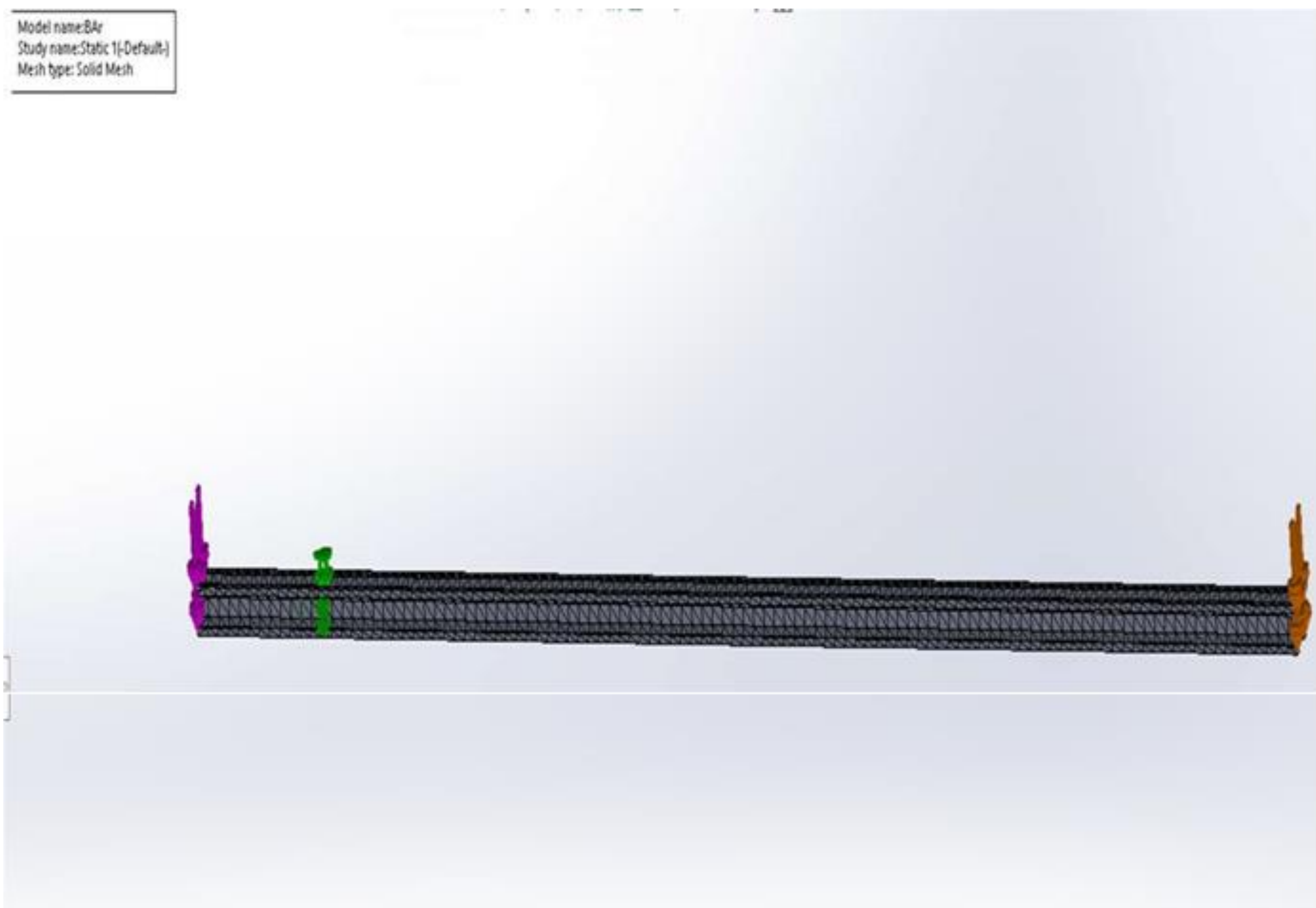


Figure 12: Analysis with mesh, loads and boundary conditions

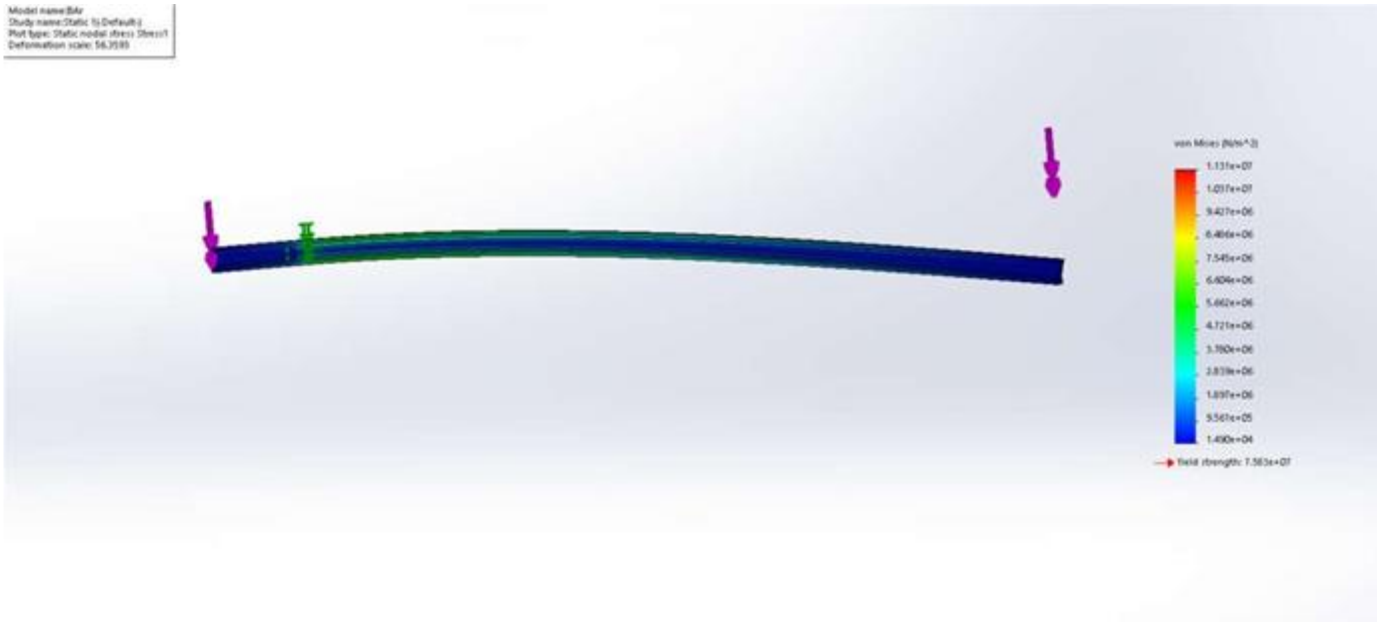


Figure 13: Solidworks Stress Analysis

c.) The safety factor= The ultimate stress / The applied stress

The max stress from the simulation is 1.1310^{7}N/m^{2}. The material we used is Aluminum 2024. The yield stress is 0.5810^{7} N/m^{2}

The safety factor is 2 in this project.

7.2 Design for Safety

a) Risks identification:

1) Risk Name: device falls from whiteboard

Description: the whiteboard writer is attached to the whiteboard vertically by suction cups. If the suction cups are not vacuum properly, the writer could fall from whiteboard. The smoothness of whiteboard surface might effect the severity of this risk.

Impact: 5. It is one of the most important concern of our design, the failure of vertical attachment between device and whiteboard could cause property damage and injuries.

Likelihood: 2. We use 4 heavy duty suction cups to secure the device.

2) Risk Name: arm breaks

Description: the long arm experiences the twist and bending very frequently. Do not apply the force on the arm when push the device onto the whiteboard or pull out the device

Impact: 4. If the arm breaks, the device will be unfunctional. It causes injuries and damages.

Likelihood: 2. The material we used for the arm is aluminum, which is strong enough for our device. The arm might break when it is carried with the lecturer.

3) Risk Name: motor drivers overheat

Description: if short circuits occurs in the system, the driver chip would be overheated and burnt. And the power input

should be within working range of the motors and drivers.
Impact: 2. It could make device stop working.
Likelihood: 3. It occurs in our prototype, we probably need to get a lower power supply and review our wiring.

4) Risk Name: shafts break
Description: the device has two smaller shafts with the timing belt and pulleys, one big shaft with basement rotational stepper motor. Shafts experience a relatively large stress when the motors rotate.
Impact:3. If the shafts break, the belt and pulleys would fall and cause potential damages. These small items might hurt people as well.
Likelihood: 1. The material of the metal shaft is strong enough to prevent this risk.

5) Risk Name: timing belt breaks
Description: the timing belt is made of rubber, so the property yields with the room temperature. It cannot work properly in the extreme temperature. To make the tooth of belt fit into the pulley, the belt has to be pulled very tightly, which also increase the risk.
Impact: 2. The failure of belt would make device stop working. It would make belt bounce out of the device and cause damages
Likelihood: 2. We apply a butt joint plus hard glue joint at the ends of belt to prevent this risk.
b) Risk Assessment Heat Map

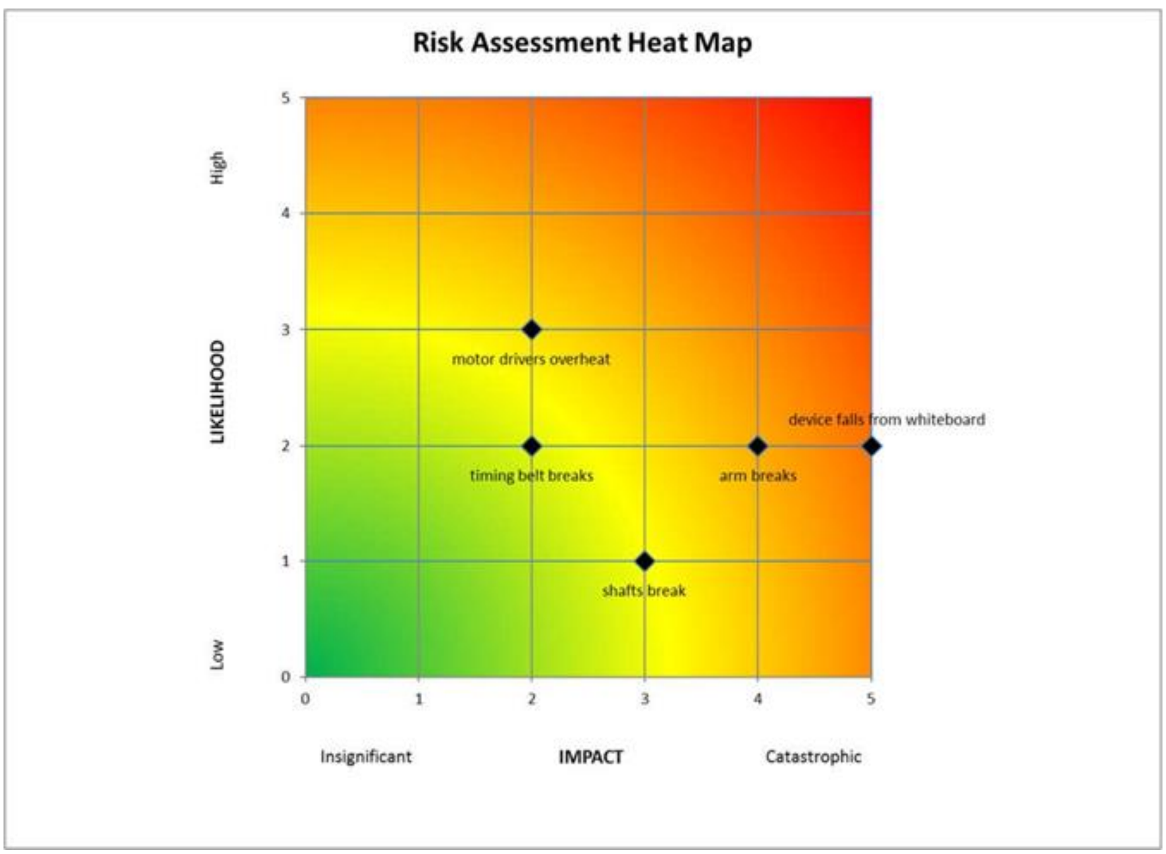


Figure 14: Risk Assessment Heat Map

c) The Heat Map shows a red-orange color on the falling risk point, so the falling risk is the highest priority. This risk is located at the right edge of the map which means the impact of falling risk is very serious. The next highest priority is the arm breaking risk, the point is located within the orange color range. The point of motor driver overheats locates within the yellow-orange color range. It is the third highest priority. Next is the of risk on the shafts, whose point lies on the yellow color area. The last one is the risk on the belt, whose point lies on the green color area.

7.3 DESIGN FOR MANUFACTURING

Draft Analysis

Draft analysis gives us an intuition of how to take a part of the manufacturing tool more easily. In this analysis, the part is pulled along the direction which is marked on the figure 1. To achieve such easier pull-out step, draft angle analysis is applied. The angle is applied in order to create some leans either inward or outward a little bit so the part would take less effort for taking out.

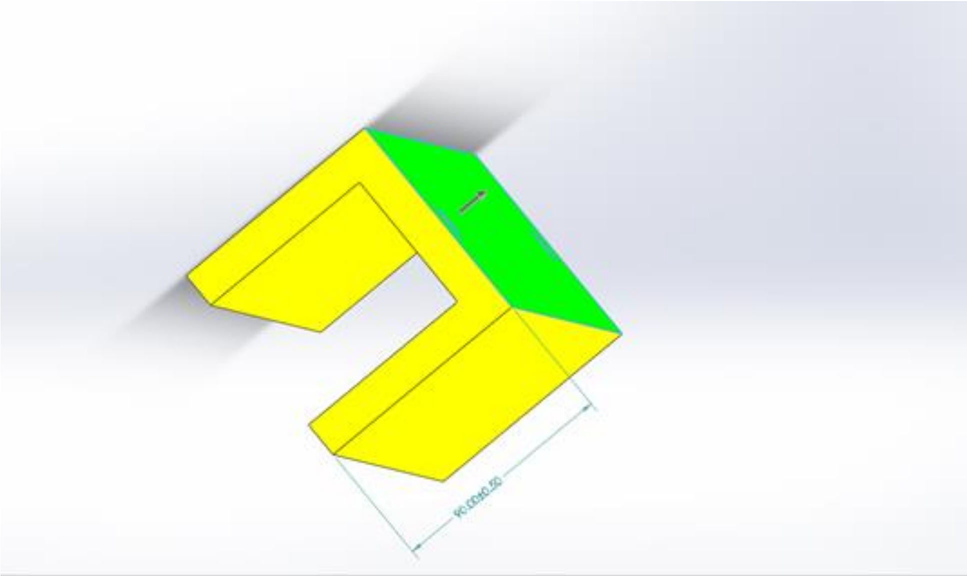


Figure 15: Analysis before drafting

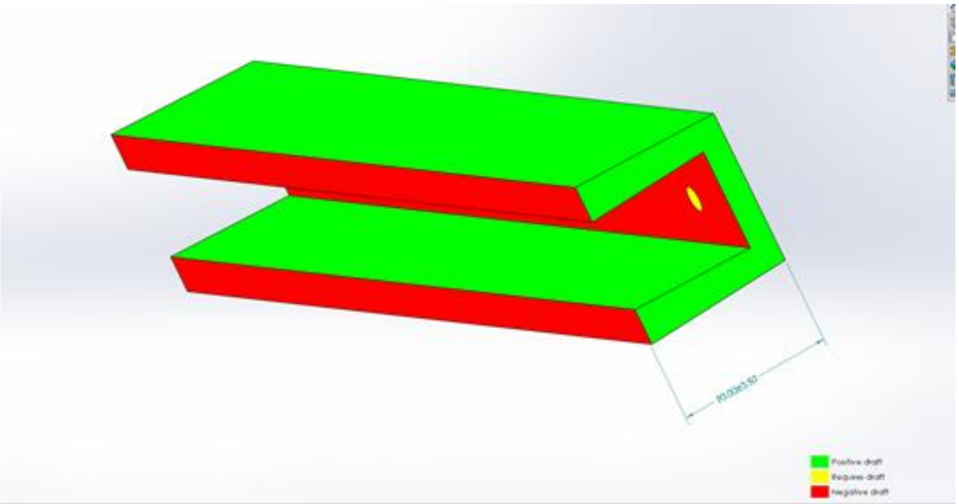


Figure 16: Analysis after drafting

DFM Analysis

DFM analysis is used for making the part more realistic for manufacturing. It usually includes criterion such as Hole/Depth diameter ratio, mill sharp internal corners, etc. Some of the problems that Solidworks point out are useful, but some are not. For example, one useless prompt is that for the design of track with holes, it says usually the ratio between the depth of the track and the diameter of the hole is around 3. But this does not apply in our design. One useful example is that it gives us a remind that straight sharp right angle is difficult to achieve in real industry, so I used fillet and chamber function so that it looks more realistic. Figure 3 and 4 show the results after DFM analysis for the track drafted track part and the wheel part. The good news is that the wheel passed all the tests, thus nothing needs to be changed.

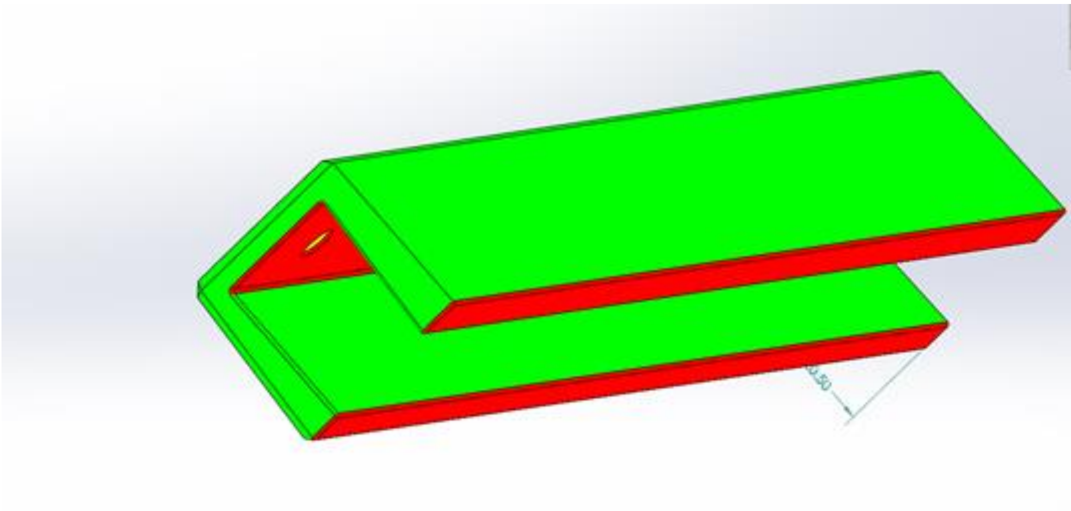


Figure 17: Edited track after DFM analysis

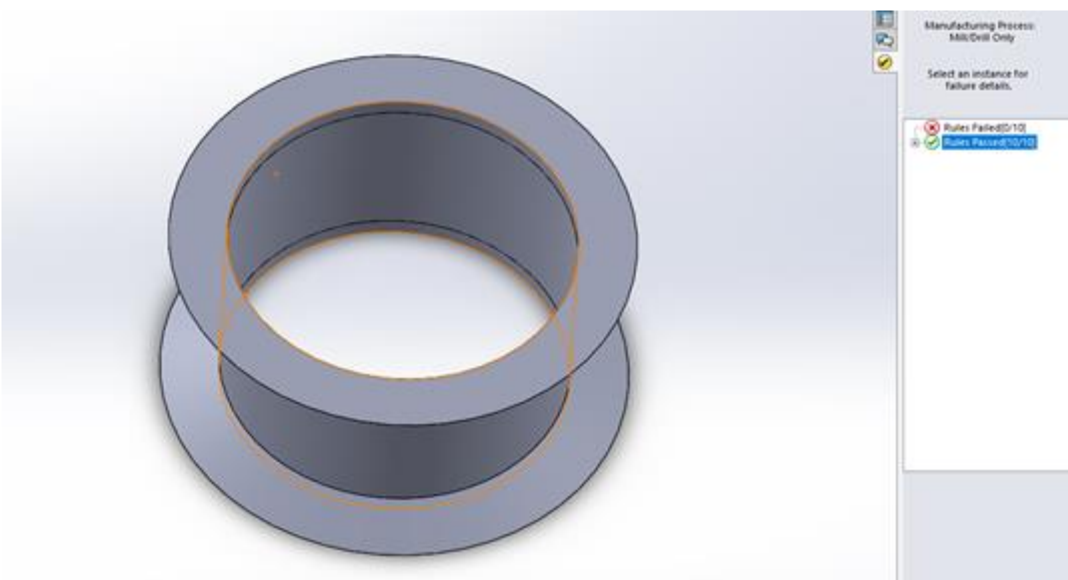


Figure 18: wheel (no need for DFM fabrication)

7.4 DESIGN FOR USABILITY

a) Vision

There are two main factors regarding vision impairment that affect the usability of our product: color blindness and dyslexia. Color blindness affects the usability of our device because our device because our devices may have switches and LEDs to control motor motion and indicate the running of the motor, respectively. There can be additional indicating devices such as writings or different colors to enhance usability. Dyslexia affects the usability of our device because our product does not have a user-end code that creates a simple input-output interaction. The user will have to modify the code to fully utilize the machine to meet the user's desired functions.

b) Hearing

Hearing impairments have no significant influence on the usability of the machine unless the user has a vision impairment. The user may use either his or her vision or hearing to see whether the machine is running or not. The machine will make rotations at set speeds. Even with implementations of safety devices, getting in the way of machine's path while the machine is running may cause problems for both the machine and the user.

c) Physical

Physical impairments greatly affects the usability of our product. We designed the product, based on the end-user interviews, to be portable. If the user cannot carry our product around, attach onto the wall, and detach from the wall, the product is not usable. Therefore, if the user has a physical impairment that prevents him or her from performing those actions, the product usability is greatly decreased. At the same time, similar to the reasoning for hearing, a user with a physical impairment may not be able to adjust the code to meet the user's needs.

d) Language

Language has significant impact on the usability of the machine. Language has no impact on the actual running of the machine, but language has significant impact on the coding of the machine; the indicators may be in color, and the manual may be written in different languages. The machine uses Arduino and its code to intake signals and makes output; the Arduino codes is a computer code with English as a base language. Therefore, it is critical that user has enough of proficiency in English to understand Arduino codes. The code may be simplified to be user-friendly, and comments can be added in different languages, but there are limitations.

e) Control

Control impairments have some impact on the usability of the machine. Although the machine does not move dangerously fast, the user should be aware of the path the machine moves in. At the same time, taking off the machine requires some focus; the machine attaches onto the wall with vacuum suction cups. Taking these off may create sudden downward forces on the hands; a sudden downward force may cause the user to drop the machine. Once it stays on the wall, the machine stays on the wall for a long time, and the machine does not run past certain speeds.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

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

The final project result generally aligns with its initial project description but with some extent of degradation. The problems are as follows:

Firstly, it cannot achieve drawing a intact circle on the whiteboard because when the writer goes up, the torque provided by the big step motor is not able to overcome the gravitational force and the torque caused by gravity.

Secondly, the belt that allows motion along the track gets loose while working, because there is some vibration existing and there is not an effective glue/fixation to stop the track from moving along the holes on the orange part.

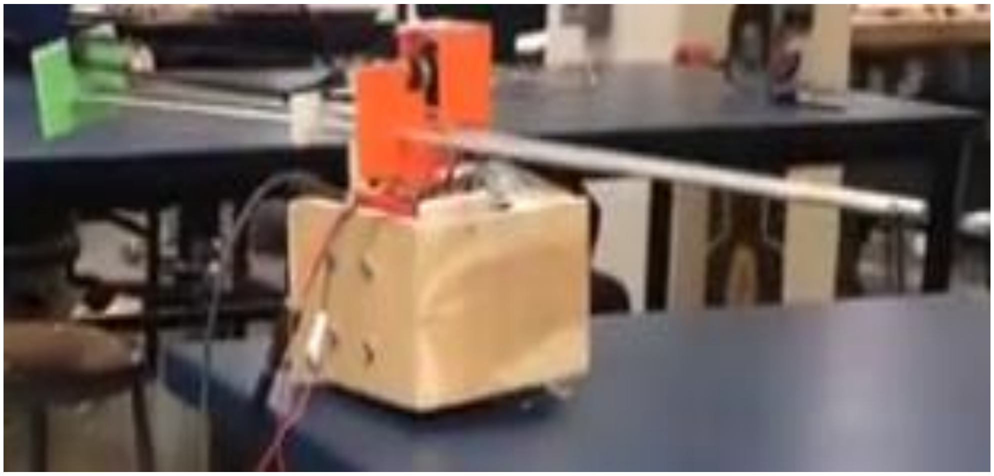


Figure 19: Final Test

Thirdly, the drop test is not super successful even if all the parts inside the box are protected well. The box itself is too fragile because it is assembled by separate pieces. We tried to use 3-D print technology at the beginning to print out the box. But it turned out that the box is too big for the platform to hold. And since this part is too big, sometimes the machine became overheated and stopped automatically.

8.1.2 Was the project more or less difficult than expected?

The project was more difficult than we originally expected.

Firstly, there is some difficulty caused by inadequacy of equipment. We originally planned to use the laser cut to cut and shape the wooden pieces. But the device was broken so we need to cut the box manually, which is also part of the reason for the box failing in the drop test.

Secondly, fixation is always a problem. There are only a few convenient ways for fixing under the lab condition, such as hot glue and very simple drills. But hot glue is not feasible for medal. And it would look not attractive if we shot the glue too much on our design. A more effective way of fixing is worth more consideration in the future design work.

Thirdly, there is some more detailed unexpected trouble. For example, the way we wrap up the coils, especially the coils around the rotation part, turned out to be ineffective. We should have adopted the way that engines use. Simply connecting the wires, which is the way we use in the project, will cause the coils outside become shorter and shorter.

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

We should have spent more time on investigating an efficient way for fixation. Because even though we did not think of it too much at the beginning, if caused unanticipated trouble on the product. We should also have spent more time on the box design and how to allocate the space inside the box so that we could have made the box smaller and more suitable for 3-D printing.

We should also have spent more time on deciding which motor we wanted to use by more calculation and simulation analysis. The chip of the control system also needed more time to understand so that we could have avoided burning and damage of it.

The part that required less time was the belt mechanism. We at first wanted to achieve a mechanism like a printer using belt and gears. But it turned out to be too tedious and even a much simpler belt with two gears at both ends worked fine.

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

There is nothing significantly easier than we expected. Some unexpected difficulty is usually caused by details. For example, assembling the orange part and the motor shaft involves with very careful part-selection process and accurate design for the Solidworks model of the orange part.

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

Every design in the class is good. Given three-four weeks' more time, our design would be a great one. Every design has its pros and cons. Our chosen design is easy to start and tackle. But there are a lot of details to pay attention to in the process of working.

8.2 Design Resources

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

We decided the codes by thinking about relevant components of the product piece by piece. We considered that we will be using AC motor so the codes for AC motors will apply in this case. It flashed in our mind that we also needed to consider the possible danger caused by sharpness when reading Dr. Potter's example, so we decided to use that code, too. The two codes we are using are IEEE Guide for AC Motor Protection - IEEE Std C37.96™-2012 (Revision of IEEE Std C37.96-2000) and Sharp edge test in 16 CFR 1500 49 Code of Federal Regulations (CFR) Consumer Product Safety Commission.

However, when we were working on the prototype, we didn't refer t

o the two codes too much because the motor we are using does not require that high voltage. Additionally, there was little sharpness trouble appeared.

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

We missed how to wrap up the coils around the rotary motors. We did have expectation on other trouble that may appear, but this is the difficulty we did thought of encountering.

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

Simulation on the torque rotating the track in gravitational field could have given us more quantitative intuition on the design so that we could made a better decision for motor selection.

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

We would firstly made a more detailed schedule. And before starting the actual project, we want to use CAD/CAE design tools to simulate our design. We want pay more attention to the motor selection step and get it done as soon as possible so that we would still have opportunity to change to another motor if time permits. We would not assume the hot glue could adhere everything so before relying on it, we would come up with alternative methods for fixation.

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

We will change the motor. We think a strong step motor might work better in our situation. And we will change the driver too. Because the motor need more power to overcome the gravity, the diver may get overheated easily. We might working more on our base box. Make the box a little bit bigger and find a better material to make it can be assemble tightly. The old one just fall apart because the wood board is too thin.

8.3 TEAM ORGANIZATION

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

All team members have plenty of skills and we learned a lot from each other. As talked in the previous section, simulation skills using Solidworks will benefit a lot to the project. At the same time, further knowledge and experience in machinery that have to handle both vibration and gravity would have helped us finalize our project.

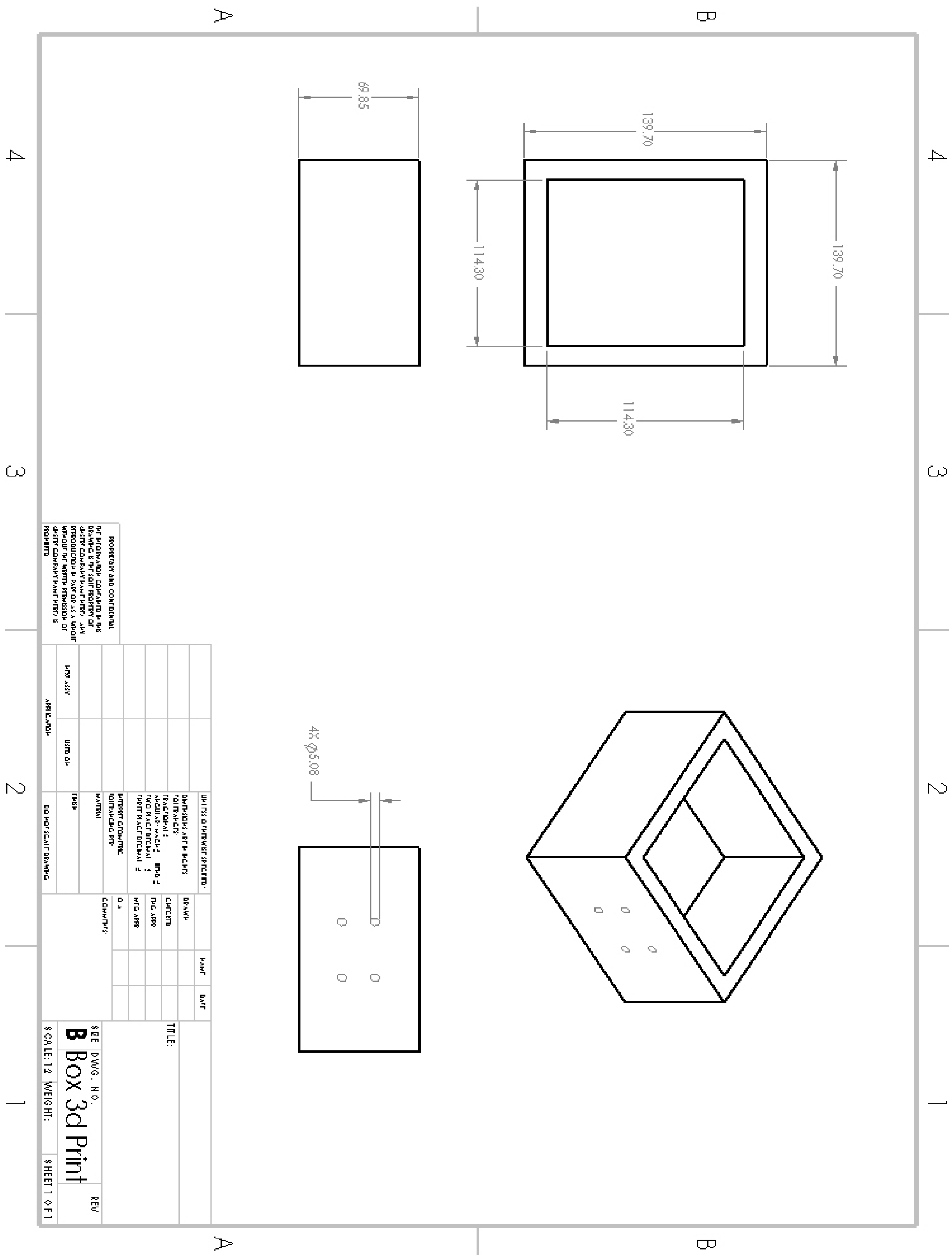
8.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

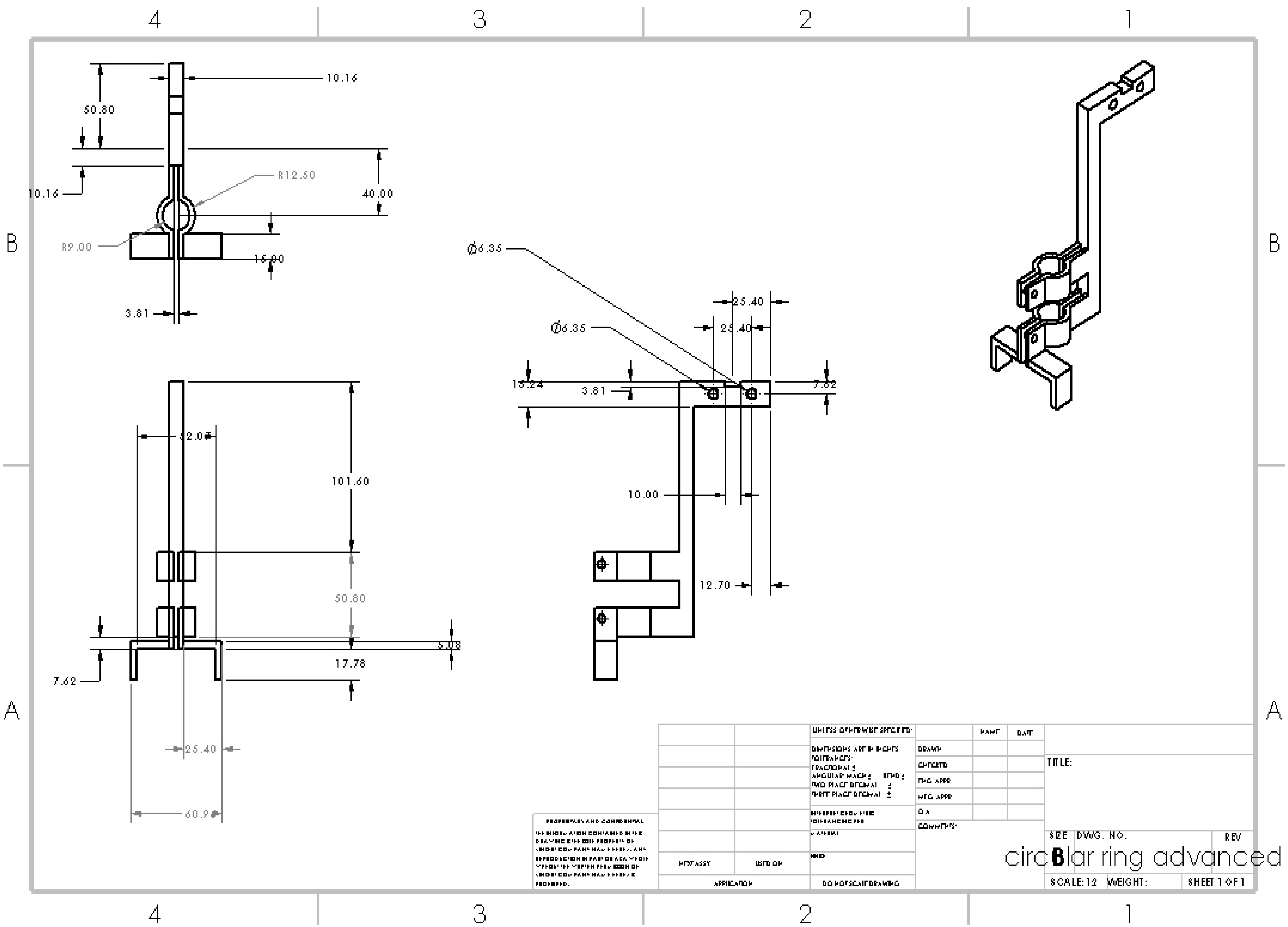
We also want to design a device that could work both in polar coordinate and Cartesian coordinate. We call it "all purpose" whiteboard writer.

APPENDIX A – COST ACCOUNTING WORKSHEET

Polar Coordinate Whiteboard Writer					
Group B					
Item	Description	Source	Quantity	Unit Price	Total Price
Aluminum Round Rod	3/8 in. x 36 in.	HOMEDEPOT	2	5.28	10.56
Red Oak Plywood Project Panel	1/2 in. x 2 ft. x 4 ft	HOMEDEPOT	1	15.5	15.5
Machine Screw	#4-40X3/4"	HOMEDEPOT	10	1.68	16.8
Machine Screw	#10-25X1"	HOMEDEPOT	2	2.05	4.1
Screw Nut	#4-40	HOMEDEPOT	10	0.89	8.9
Wing Nut	#10-25	HOMEDEPOT	2	1.09	2.18
Stepper Motor Driver	VELLEMAN 3A	MicroCenter	2	19.99	39.98
Breadborad	ADAFRUIT HALF-SIZE	MicroCenter	2	4.99	9.98
Stepper Motor Driver	Gikfun EasyDriver Shield	Amazon	4	5.98	23.92
Timing Belt	5 Meter GT2	Amazon	1	13.99	13.99
Stepper Motor Mount Bracket	Steel Black Nema 23	Amazon	2	5.49	10.98
Universal Aluminum Mounting Hub	1/4″ Shaft, #4-40 Holes	Pololu	2	3.975	7.95
Stepper Motor	NEMA 23	Pololu	1	39.95	39.95
Stepper Motor	NEMA 17	Pololu	1	16.95	16.95
Arduino Shield	UNO R3	Pololu	1	24.95	24.95
Total:					246.69

APPENDIX B – FINAL DESIGN DOCUMENTATIO

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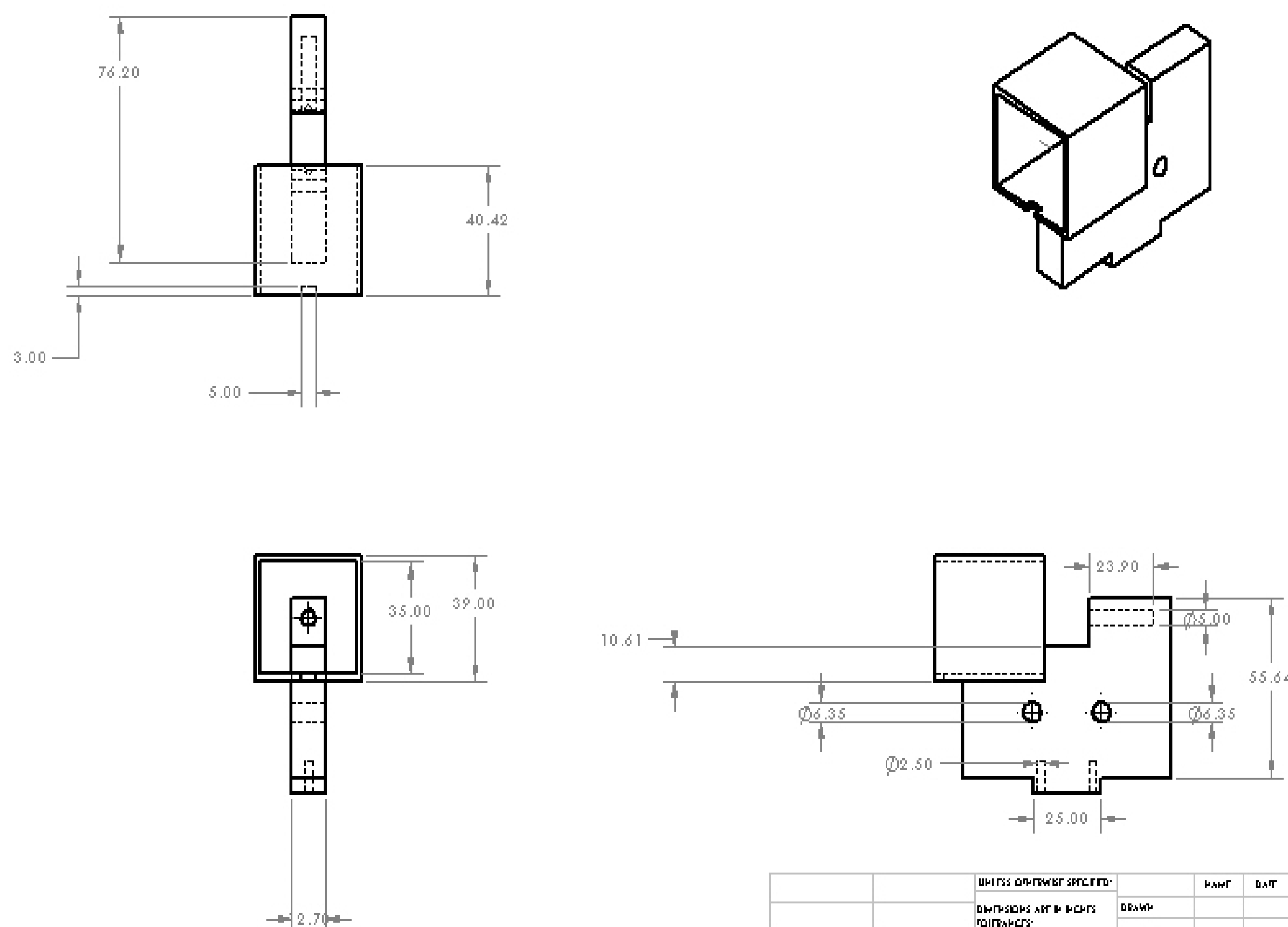

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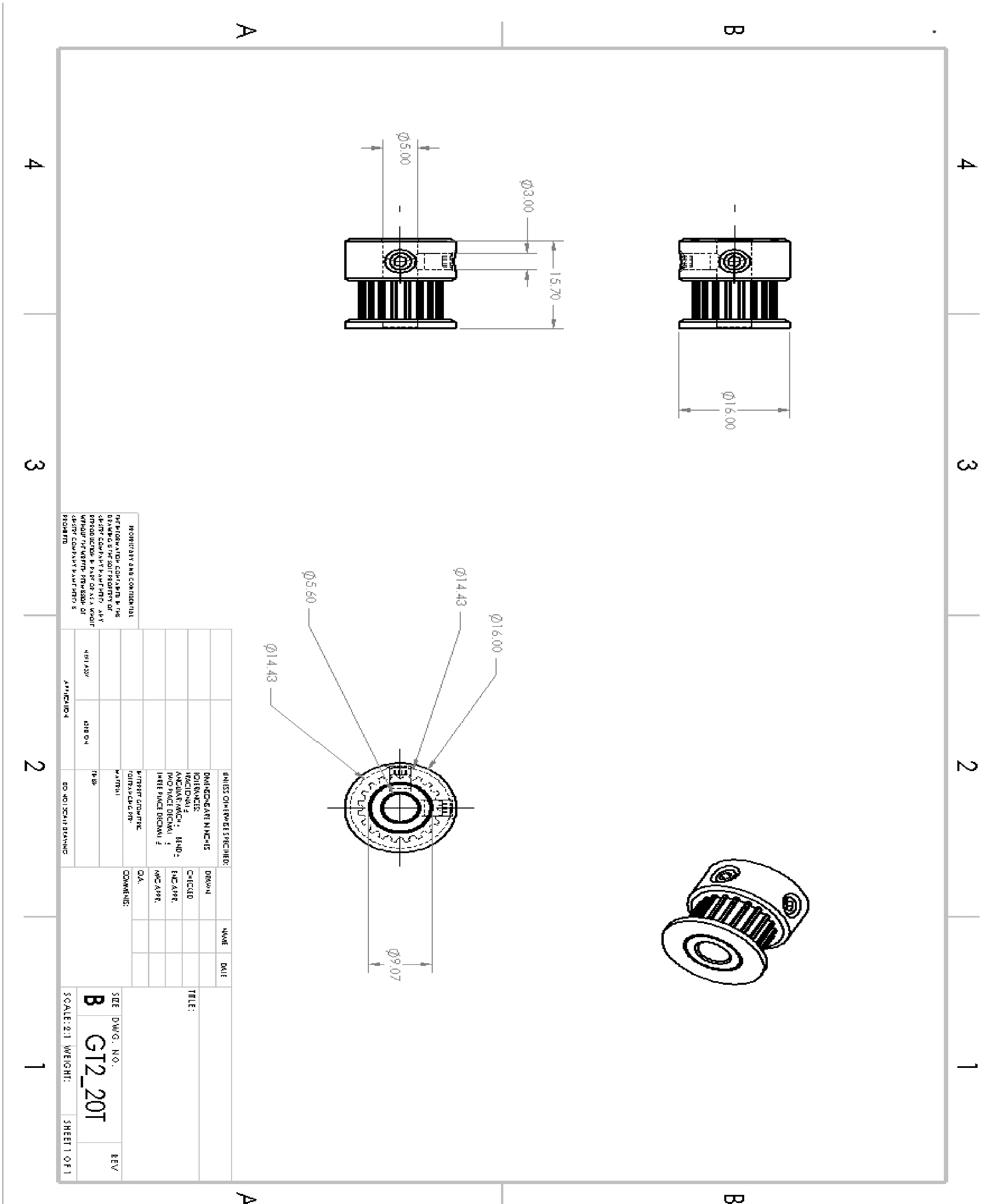
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