Fall 2018

The Photosynthesizer - Automated Plant Imaging System

Alan Chung
Washington University in St. Louis

Oscar Chavez
Washington University in St. Louis

Daniel Tyszka
Washington University in St. Louis

Alexander Stoddard
Washington University in St. Louis

Washington University in St. Louis

SCHOOL OF ENGINEERING & APPLIED SCIENCE

Executive Summary

The purpose of our project is to develop an automated system for photographing plant samples. The motivation for this was to aid in the research of parasitic mildew on several species of plants, by automating data collection for more efficient field study. Our assignment was to create this device based on the needs of our customer following an interview. In the design process, we generated many ideas for the creation of the device, some of which drew inspiration from already existing devices. From ideas for individual functional components, we generated several ideas for the device as a whole, and from this, we methodically deduced the best type of device for our goals, based on the strengths and weaknesses of these choices. Once we decided on the overall design, we set forth to analyze and refine our design through quantitative means of analysis. Subsequently, we constructed a proof-of-concept prototype to demonstrate the merit behind our design idea. After assessing this prototype, we built a working prototype, which was evaluated on its ability to fulfill the design goals set forth in our problem statement. From this, the design was refined until it reached its final state.

The device we constructed consists of a wooden frame that spans a 3m x 3m square. In each of the corners, a vertical post sticks up, each one with a motor attached at the bottom. These motors are used to control four strings that suspend a camera above the ground. By programming our motors to coordinate their movements, we can control the movement of the camera to create an automated process for photographing the ground inside the square, akin to a puppeteer putting on a show. Finally, the lightweight wooden frame of the device consists of multiple modular pieces that can be broken down for ease of storage and repositioning, then reassembled when necessary.

MEMS 411: MECHANICAL ENGINEERING DESIGN PROJECT
FALL 2018

Group J – The Photosynthesizer

Oscar Chavez

Alan Chung

Alexander Stoddard

Daniel Tyszka

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1 INTRODUCTION

We are Alexander, Oscar, Alan, and Daniel, four engineering students who have created a product called The Photosynthesizer. Dr. Rachel Penczykowski is a professor and biologist at Washington University in St. Louis, studying the concentration of powdery mildews that grow on a plant species called *Plantago lanceolata*. In assessing the impact of climate on parasitic growth, she manually takes multiple photographs throughout the afternoon, documenting her research in an organized, but time-consuming, manner. We hope to provide for her an automated camera system that can procure data for Dr. Penczykowski on its own, thereby saving her time and/or yielding much more relevant research.

From talking with Dr. Penczykowski about her needs regarding the device, we determined three main goals for our prototype:

1. Photograph a 3-meter by 3-meter grid of land, at a reasonable quality, to effectively determine the presence and concentration of parasitic mildew.
2. Complete a cycle of automated photographs in 20 minutes or less.
3. Run at least twice before requiring a change of battery.

In order to meet these goals, we could not just blindly approach the problem – rather, we needed to incorporate some elements involving calculation into our design. One such element was the spindle used to wind the string controlling the camera mount. We had to design it in such a way that the torque on the motor was minimized – that is, we controlled the diameter of the shaft so that we could have the motors pull the string with adequate torque. The coordination of the motors would have to be calculated using trigonometry and coding, and the corner posts, as we discovered during the test of our working prototype, would need to have bracings, which require analysis of the geometry of the angles involved to properly create.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

Existing Designs:

1.a 3D-Printed Raspberry Pi Skycam for Drone-Free Aerial Video

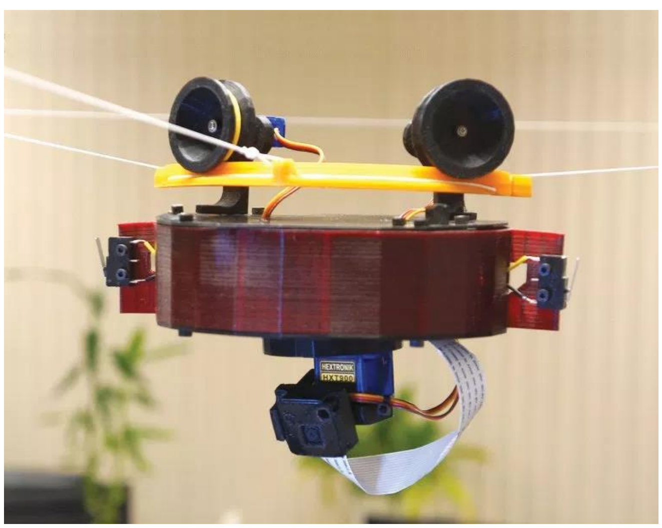


Figure 1 Image of miniature Skycam

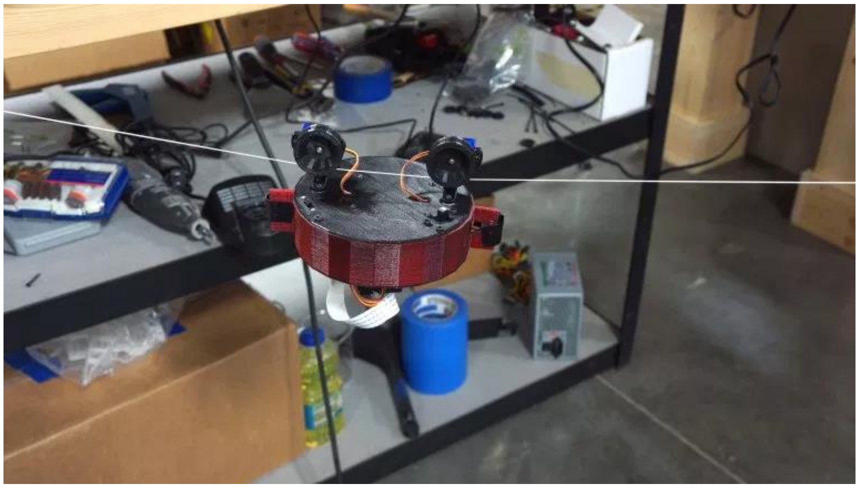


Figure 2 Skycam aerial view, seen from above

1.b Website Link:

https://makezine.com/projects/3d-printed-raspberry-pi-skycam/

1.c Description:The mini Skycam is a small robot that works very much like a much larger full scale Skycam. The mini SkyCam uses small servo motors to move the robot across a string and control the tilt of the camera. All the structural components in the skycam are created by the use of a 3D printer. Unlike the SkyCam which is able to move in a x, y,z coordinate plane ,the Mini-SkyCam in only capable of movement across a single line. The electronics of the system are controlled by a Raspberry pi, which uses a pre-programed code to manage its components. The system uses a Program called coder to control the movement of the mini-skycam. The program is able to move the Mini- SkyCam across the string, as well as the rotation and tilt of the camera.

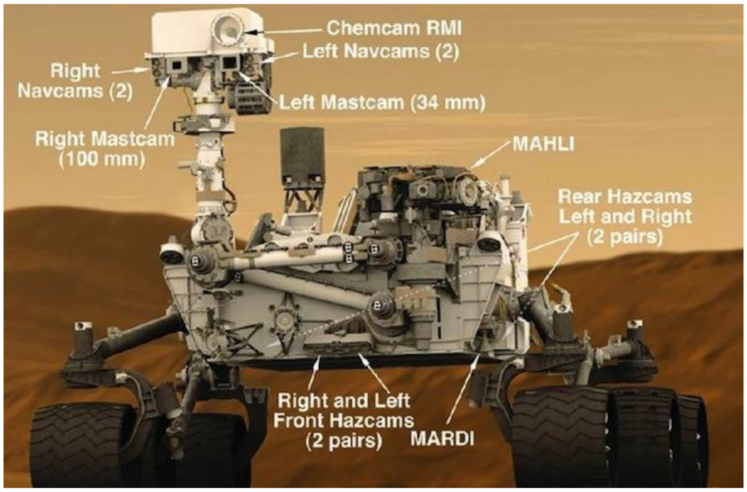


Figure 3 Features of the Curiosity Mars rover

Figure 4 An image of a meteorite captured by Curiosity

1.b
Website Link:
https://www.nasa.gov/multimedia/podcasting/curiosity20130613.html
Image 1
https://www.wired.com/2012/08/curiosity-mars-rover-cameras/
Image 2: https://mars.nasa.gov/resources/curiosity-rover-finds-and-examines-a-meteorite-on-mars/

1.The Curiosity is a car sized rover that explored the surface of Mars. Mounted in the Rover are 17 alternate cameras used to take pictures of the surface as well as navigating rover. The rover uses 6 wheels to navigate along the surface of the red planet, with each wheel being about the size of a small car wheel. Near the wheels there are four cameras to help Engineers navigate the surface of the planet. While there are other various cameras the the rover, the camera which has the capability of taking images of the ground is the Mastcam, as can be seen in Figure 4 above. The camera has the capability to extending over the 2 meters from the rover, tilting +90, - 90, as well as rotating 180 degrees, being able to take photos of the landscape, itself and the ground terrain. The rover has a computer software that is capable to stitching photos together and compiling them to create a single photo.

1.a Overhead Camera Rig

Figure 5 A DIY overhead camera rig

1.b Website link: https://www.instructables.com/id/DIY-Overhead-Camera-Rig/

1.c Description: The overhead camera rig creates an enclosure of sorts that allows for a camera suspended above a subject on a flat surface to have its position adjusted in three dimensions. It seems to be able to move the camera almost anywhere within the confines of its frame, and keeps the camera securely in place in its proper position. This device is human-powered; in order to adjust the position of the camera, its user must loosen the knobs that secure it in place, then manually move the camera to its intended position, and finally tighten the knobs to firmly secure the camera in its new position. Another function of this device is it can hold rolls of paper that can provide background and/or lighting options for the camera shot. This device is small enough that no remote activation for the camera is necessary, as its user can just reach in and use the camera at will.

Pre-Existing Patents

1.a

Patent Number: No. 9964836

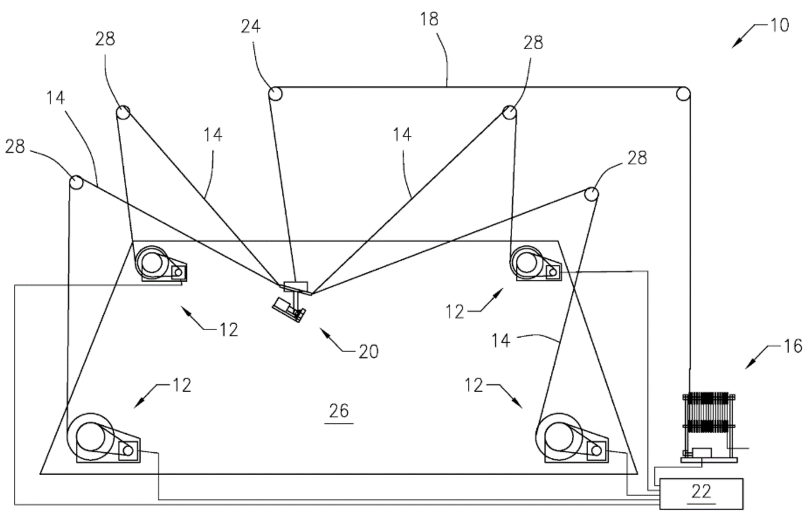


Figure 6 Wiring setup of the SkyCam

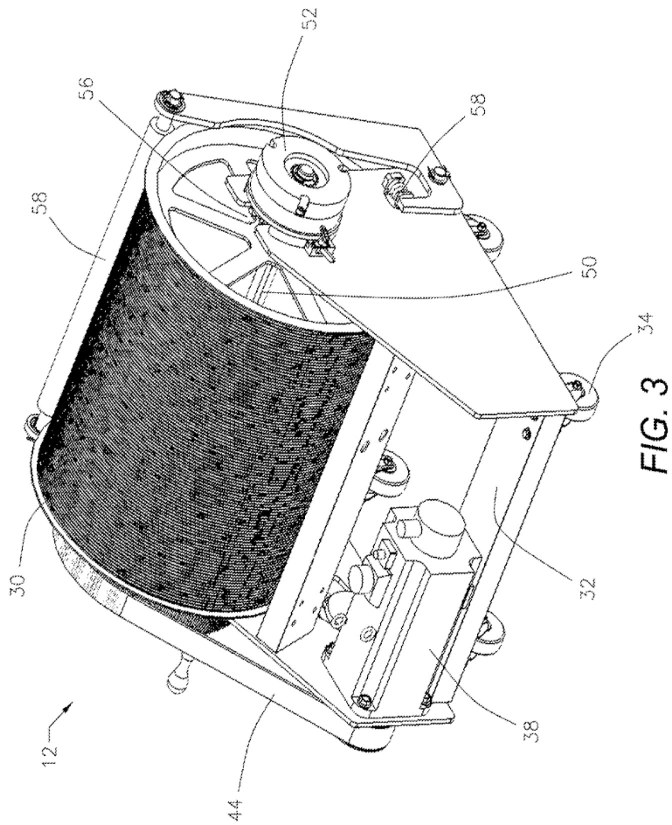


Figure 7 The motor and spindle of the SkyCam

1.b: Description.

The patents describes the system that is use reels and cables to provide a camera floating above head. A computer system will communicate to reels to feed cables and position the camera in the in the x,y,and z coordinate plane. A mechanical Gimbal would be use to determine the tilt and rotation of the camera The main use of the camera would be for large broadcasting purposes, such as sporting events productions and entertainment events.

2.a. Patent Number: No US5453933A

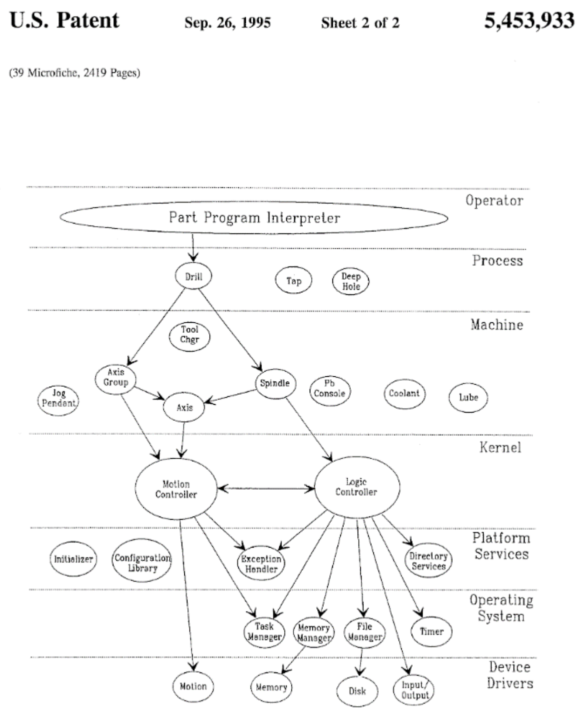


Fig.2

Figure 8 A function tree of a CNC machine

2.b Description

The CNC (computer numerical control) machine is a controlled system tool that has the capability to move in the x,y,z planes for shaping workpieces of metal. Operators have the ability to input codes for the machine perform a machining tasks. CNC have the abilities to make very quick and accurate movements. The CNC Also has the ability to use CAD (computer-aided design) software to provides paths for the machine to follow when creating 2D or 3D objects.

Standards:

1a. The standards to be used in this project will be the IEEE 1625-2008-IEEE Standard for Rechargeable Batteries in Multi-Cell Mobile Computing Devices and IEEE NESC, Handbook, and Preprint Set-0-2007 National Electrical Safety Code (NESC) + Handbook +2012 preprint proposals set

1b. The IEEE 1625-2008 will be a useful standard for this project because this standard covers the design analysis for rechargeable battery systems. A preferred requirement by the consumer was that the ground photographer is automated and the ideal way to make something automated while remaining within the budgetary restrictions is to run the system off of a rechargeable battery pack(s) that will control the motion of the ground photographer along with the movement of the camera to photographing. This standard outlines the analysis for reliability and quality of multi-cell battery systems which is essential to avoid the battery failing or not being able to deliver enough power to the system. This leads into the second standard, the NESC standard. This standard outlines the safety measures to be taken when installing, operating and maintaining a system that involves electrical wires and conductors. This will be essential to reducing risk of injury through electrical shock and overloading the system at any point. Overloading the system or incorrect wiring could fry circuit boards or other electrical components that can be difficult or costly to replace.

2.2 USER NEEDS

Table 1: User Needs Interview

Product: Plant Camera (PC)
Customer: Dr. Rachel Penczykowski

Address: McDonnell 407, Washington University Danforth Campus
Date: September 7, 2018

Question	**Customer Statement**	**Interpreted Need**	**Importance**
Weight Limit	It should be easy for one person to carry about 50 meters, but they drive to their sites so it doesn't need to be super light.	The PC is relatively easy to transport	4
Cycle Time	30 minutes would be ideal	The PC can be set up, run, and broken down in 30 minutes	4
Target Dimensions	Each plant is in a segment of 10cm by 10cm, for which she uses rope spun around a PVC tube as a reference. She showed it to us on 9/7/2018. The plants grow best when there is not a lot of tall vegetation, so they do well in periodically mowed fields or roadsides. The plants are usually not higher than 30 centimeters. There should be at least 30 centimeters between the top of the plant and the camera lens.	Use of a reference for scale would be helpful. The camera lens must be at least 60-70cm above ground.	3 4
Capture Area	We want the camera to take images along a regular grid that could be repeatable among the sites. Ideally this would be a few meters by a few meters.	The PC must capture an area of 3m x 3m	5
Weather Conditions	Needs to survive in high humidity; does not need to survive in the rain	The PC must be humidity-resistant	3
Storage/Transport	Ideally the setup could be partially broken down. It does not need to fit into a backpack, but ideally it is somewhat modular.	The PC must break down into, at minimum, a few modular components.	4
Camera Type	The camera currently in use is a Nikon D3400. Buying a new camera for the experiment is also an option. The camera needs to be able to capture the presence of parasites on the plants. A phone camera could also be an option.	The PC needs a camera with good enough resolution to see fine details on the plants.	5

Controls	This should be an automated system so that we can collect other data that must be collected in the field while the camera collects data that can be analyzed later from photographs	The PC must be automated.	5

Table 2: Interpreted Customer Needs

Need Number	Need	Importance
1	The PC is relatively easy to transport.	4
2	The PC can be set up, run, and broken down in 30 minutes.	4
3	Use reference for scale in photographs	3
4	The camera lens must be at least 60-70cm above ground.	4
5	The PC must capture an area of 3m x 3m.	5
6	The PC must be humidity-resistant.	3
7	The PC must break down into, at minimum, a few modular components.	4
8	The PC needs a camera with good enough resolution to see fine details on the plants.	5
9	The PC must be automated.	5

2.3 DESIGN METRICS

Table 3: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total weight	kg	<30	<20
2	5	Base area	m^2	6.25	9
3	4	Height	cm	60	70
4	2	Time per cycle	minutes	<30	<20
5	3	Uses a reference for photograph scale	binary	No	Yes
6	1, 7	Disassembled volume	m^3	<1	<0.5
7	9	Is automated	binary	Yes	Yes
8	6	Works in high-humidity environment	binary	No	Yes
9	8	Captures fine details	binary	Yes	Yes

2.4 PROJECT MANAGEMENT

Assignment	Task	late Aug	early Sep	mid Sep	late Sep	early Oct	mid Oct	late Oct	early Nov	mid Nov	late Nov	early Dec
	Form a group	X										
Understanding	Brainstorm project ideas	x										
	Determine a project		x									
	Research existing products		x									
	Research codes and standards		x									
	Interview the customer		x									
	Weigh importance of needs		x									
Concept Gen.	Functional diagram			x								
	Morphological chart			x								
	Generate potential sketches			x								
Concept Select	Create a scoring matrix			x	x							
	Choose a concept			x	x							
System Design	Make a rough parts list				x	x	x					
	Order parts					x	x	x				
	Make a formal pre-CAD sketch					x						
	Make a CAD model						x					
Detail Design	Construct initial prototype						x					
	Test initial prototype						x	x				
	Improve safety							x	x			
	Improve usability							x	x			
Final Production	Construct final product									x	x	
	Present final product											x

Figure 9: Gantt Chart used to organize team efforts, taken from early November

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

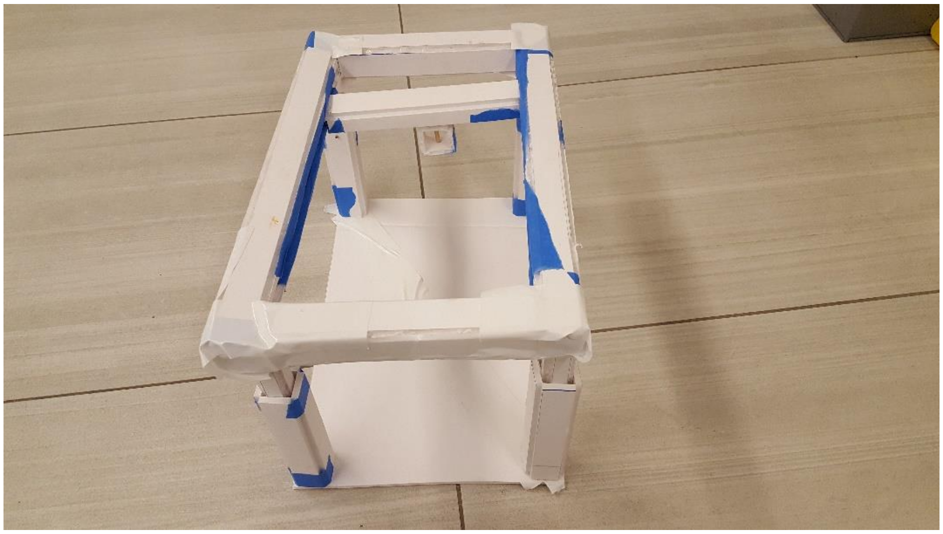


Figure 10 Initial mockup prototype

The mockup influenced the thoughts about the design because as a group, we realized that the current mockup would be bulky and difficult to breakdown. The mockup would also be heavy so there needs to be revisions to reduce the weight of the object. There are a significant amount of moving parts that would need to move in unison with each other or there could be potential issues that could cause the machine to malfunction such as the two wires on either side of the central rod not pulling and releasing at the same rate which would cause the metal to bend or the wires to break.

3.2 FUNCTIONAL DECOMPOSITION

Function Tree

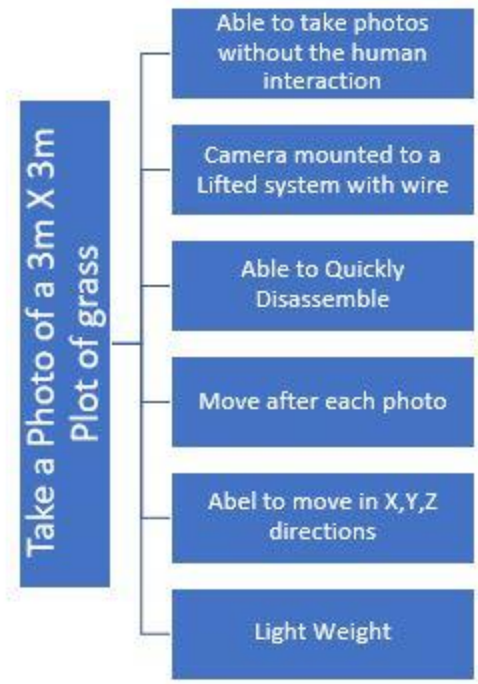


Figure 11 Function Tree

Morphological Chart

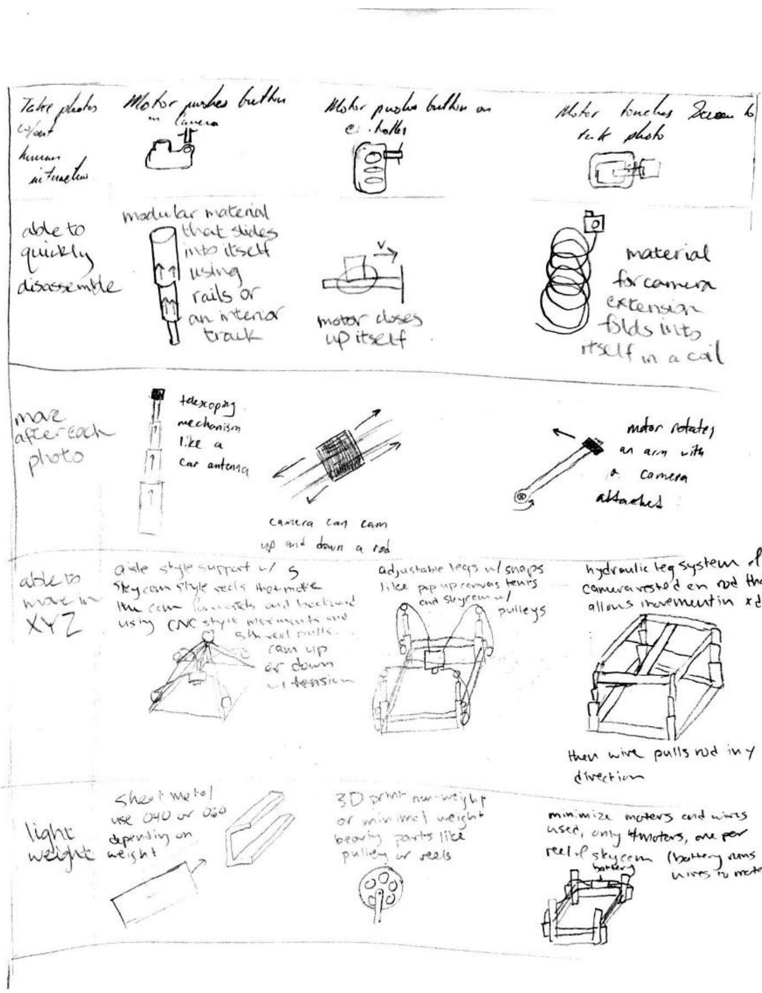


Figure 12 Morphological Chart

3.3 ALTERNATIVE DESIGN CONCEPTS

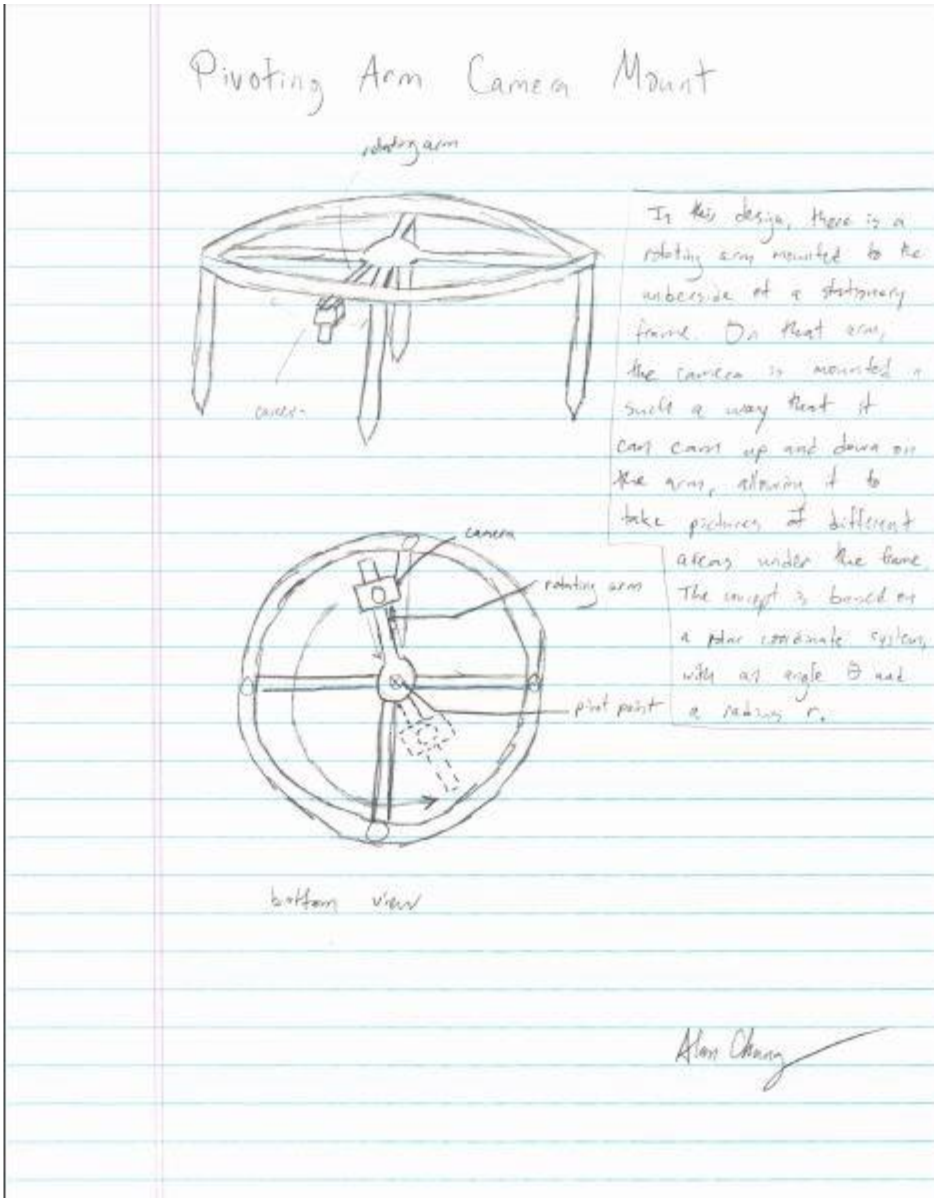


Figure 13 Conceptual drawing - Alan Chung

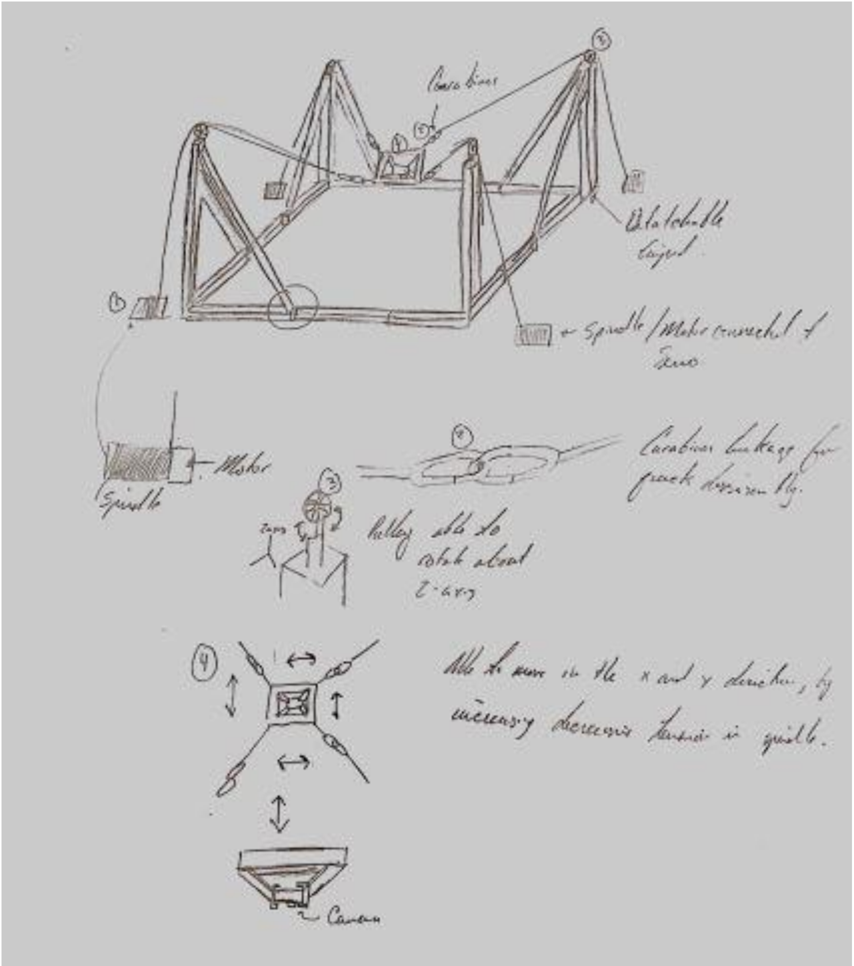
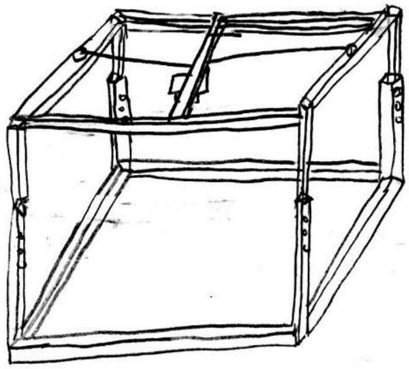


Figure 14 Conceptual drawing - Oscar Chavez

Figure 15 Conceptual drawing - Alexander Stoddard



The system uses an empty cube that contains a system w/ snaps that model that of a pop up camping tent. The camera will have a strepping aparatus that will mount it to central beam. The camera is free to move forwards and backwards. There are two wires that connect to the central rod that will pull the central rod left and right.

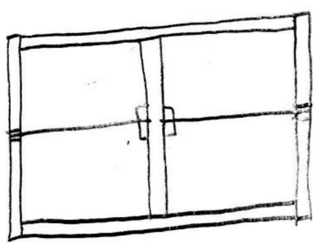


Figure 16 Conceptual drawing - Daniel Tyszka

4 CONCEPT SELECTION

4.1 SELECTION CRITERIA

	Dissasembly/ Setup time	Able to move in X,Y,Z Directions	Light Weight/ Compactability	Power Usage	Ease of Programming	Cost	Row Total	Weight Value	Weight (%)
Dissasembly/ Setup time	1.00	0.11	0.20	3.00	1.00	1.00	6.31	0.09	8.74%
Able to move in X,Y,Z Directions	9.00	1.00	3.00	7.00	7.00	5.00	32.00	0.44	44.30%
Light Weight/ Compactability	5.00	0.33	1.00	1.00	3.00	1.00	11.33	0.16	15.69%
Power Usage	0.33	0.14	1.00	1.00	0.33	1.00	3.81	0.05	5.27%
Ease of Programming	1.00	0.14	0.33	3.00	1.00	0.11	5.59	0.08	7.73%
Cost	1.00	0.20	1.00	1.00	9.00	1.00	13.20	0.18	18.27%
						Column Total:	72.24	1.00	100%

Figure 17 Matrix for comparing selection criteria

4.2 CONCEPT EVALUATION

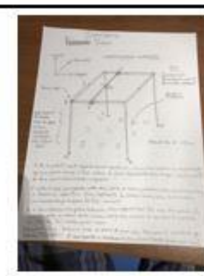
		Alternative Design Concepts							
									
Selection Criterion	Weight (%)	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Dissasembly/ Setup time	20%	1	0.00	4	0.01	1	0.00	3	0.01
Able to move in X,Y,Z Directions	30%	2	0.01	5	0.02	4	0.01	1	0.00
Light Weight/ Compactability	20%	3	0.01	4	0.01	2	0.00	3	0.01
Power Usage	10%	4	0.00	2	0.00	3	0.00	5	0.01
Ease of Programming	10%	3	0.00	2	0.00	4	0.00	5	0.01
Cost	20%	4	0.01	3	0.01	2	0.00	5	0.01
	Total score	0.029		0.041		0.029		0.035	
	Rank	3		1		3		2	

Figure 18 Matrix for comparing concepts

4.3 EVALUATION RESULTS

In the weighted scoring matrix, we discovered that our best design choice would be concept B. In the matrix, we said that its disassembly and setup time would get a 4 out of 5 due to its relative simplicity to take apart, though its assembly will prove to be more challenging. During assembly, some of the wires may be complicated to put in tension, or it may be difficult to mount the camera in the correct orientation. The criteria to move in the x, y, and z direction was rated as a 5 because we figured it would be relatively simple to get the camera to move in all three axes using the lines to pull the camera – it comes down to a relationship between the four lines' movement relative to one another. Ease of programming received a 2 because we felt that this mechanism will need to be coded by a programmer of at least intermediate experience, who has prior experience with electronics.

4.4 ENGINEERING MODELS/RELATIONSHIPS

Equations to be used for this project:

Eq. 1: $v = \frac{x}{t}$

This equation states that the velocity (v) is the desired distance that the camera must move (x), divided by the amount of time that it is moving (t). This equation will be useful for this project because the speed of camera will relate to the time the battery is running. Since the battery will be supplying the power to the motors to move the camera, more of its charge will be used if the camera takes a longer time to reach its destination.

Eq. 2: $\rho = \frac{p}{A}$

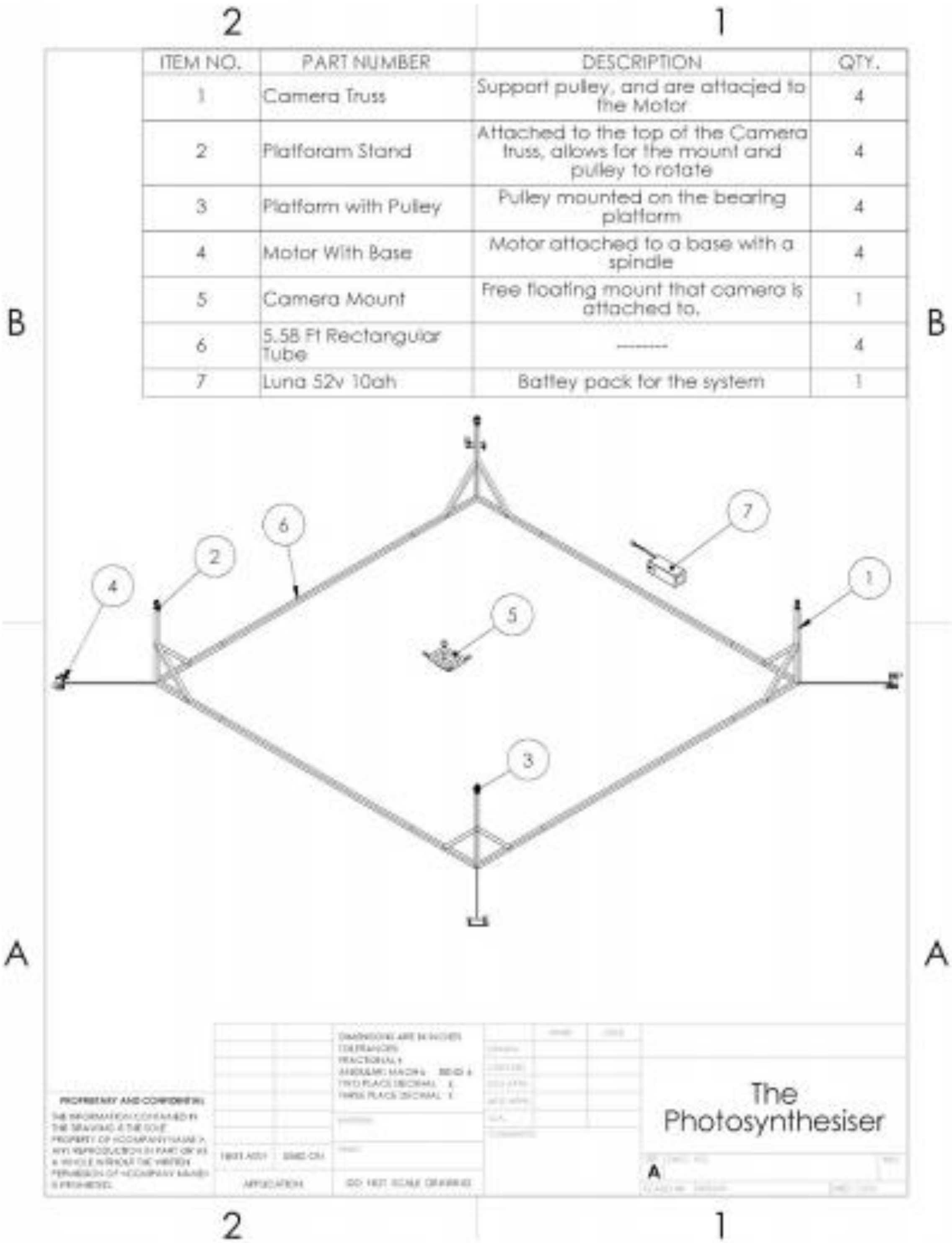
This equation defines the density (ρ) of the powdery mildews as the number of plants infected (p) divided by the area photographed (A). This equation will be useful in determining the potency of the powdery mildew on the plants, which is the main area of focus. If the density is low, then there may be no need to photograph the area and more time can be spent on areas with higher density of mildew.

Eq. 3: $Q = It$

This equation defines charge (Q) of the battery as the current used in the circuit (I) multiplied by the time (t) that the circuit is being run. This equation is essential because it gives an estimate of how long the battery can run before needing to be recharged. It goes without saying that it would be a major inconvenience if the battery were to fully deplete in the middle of photographing, as the system would have to be moved and the pictures would need to be retaken.

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Camera Truss	Support pulley, and are attacjed to the Motor	4
2	Platforam Stand	Attached to the top of the Camera truss, allows for the mount and pulley to rotate	4
3	Platform with Pulley	Pulley mounted on the bearing platform	4
4	Motor With Base	Motor attached to a base with a spindle	4
5	Camera Mount	Free floating mount that camera is attached to.	1
6	5.58 Ft Rectangular Tube	---------	4
7	Luna 52v 10ah	Battey pack for the system	1

Figure 19 Initial CAD drawing of prototype

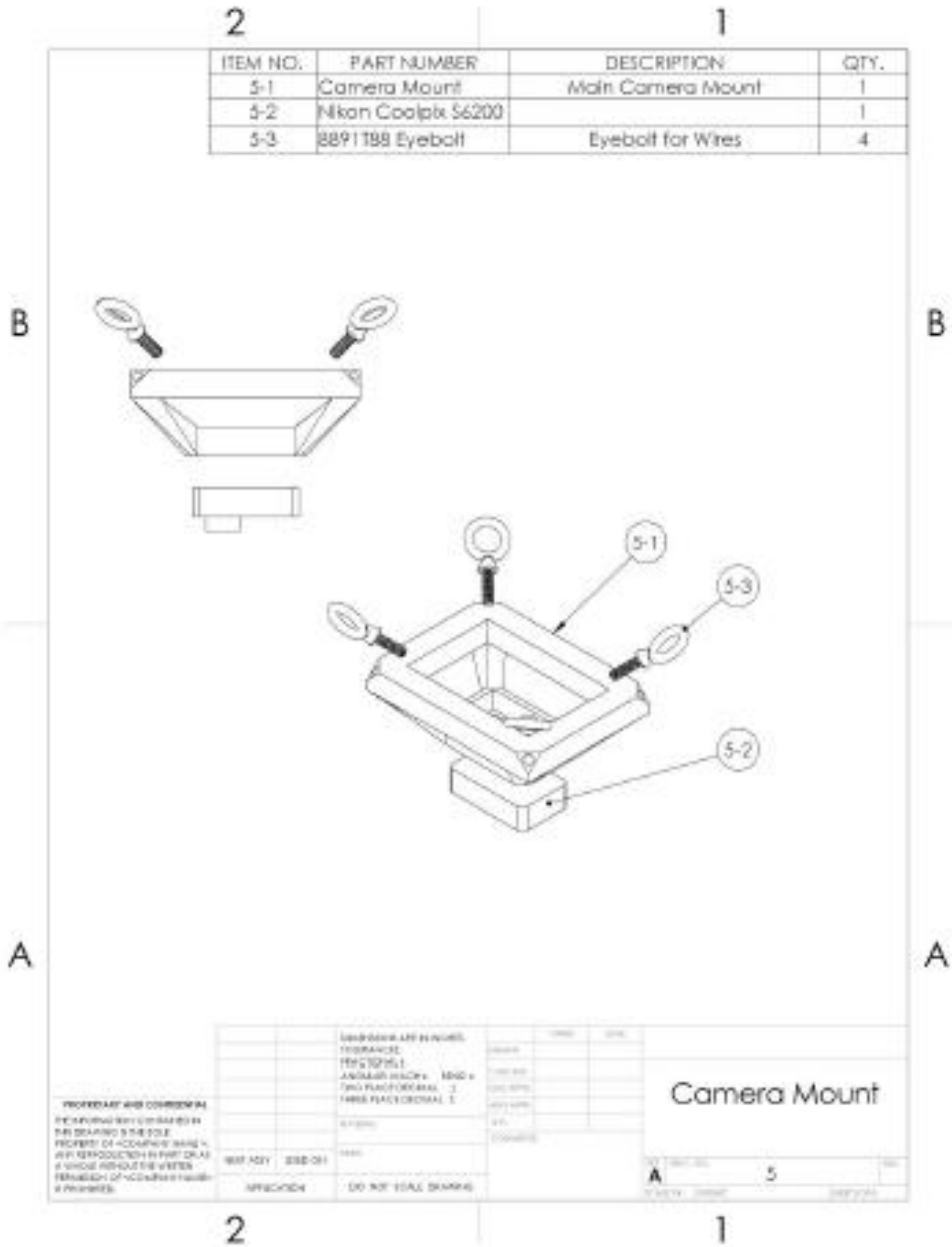


Figure 20 CAD drawing of camera mount

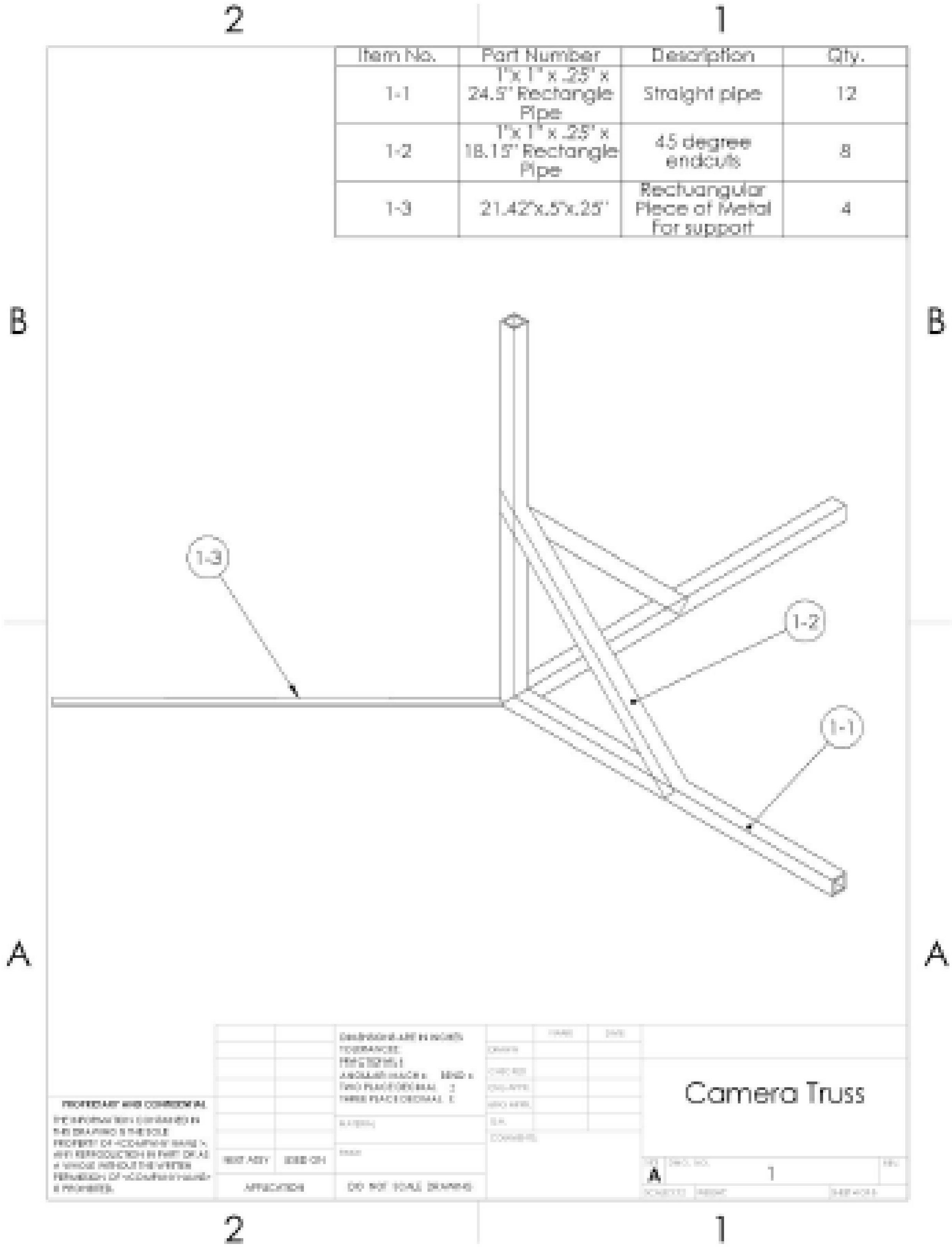


Figure 21 CAD drawing of one of the camera trusses

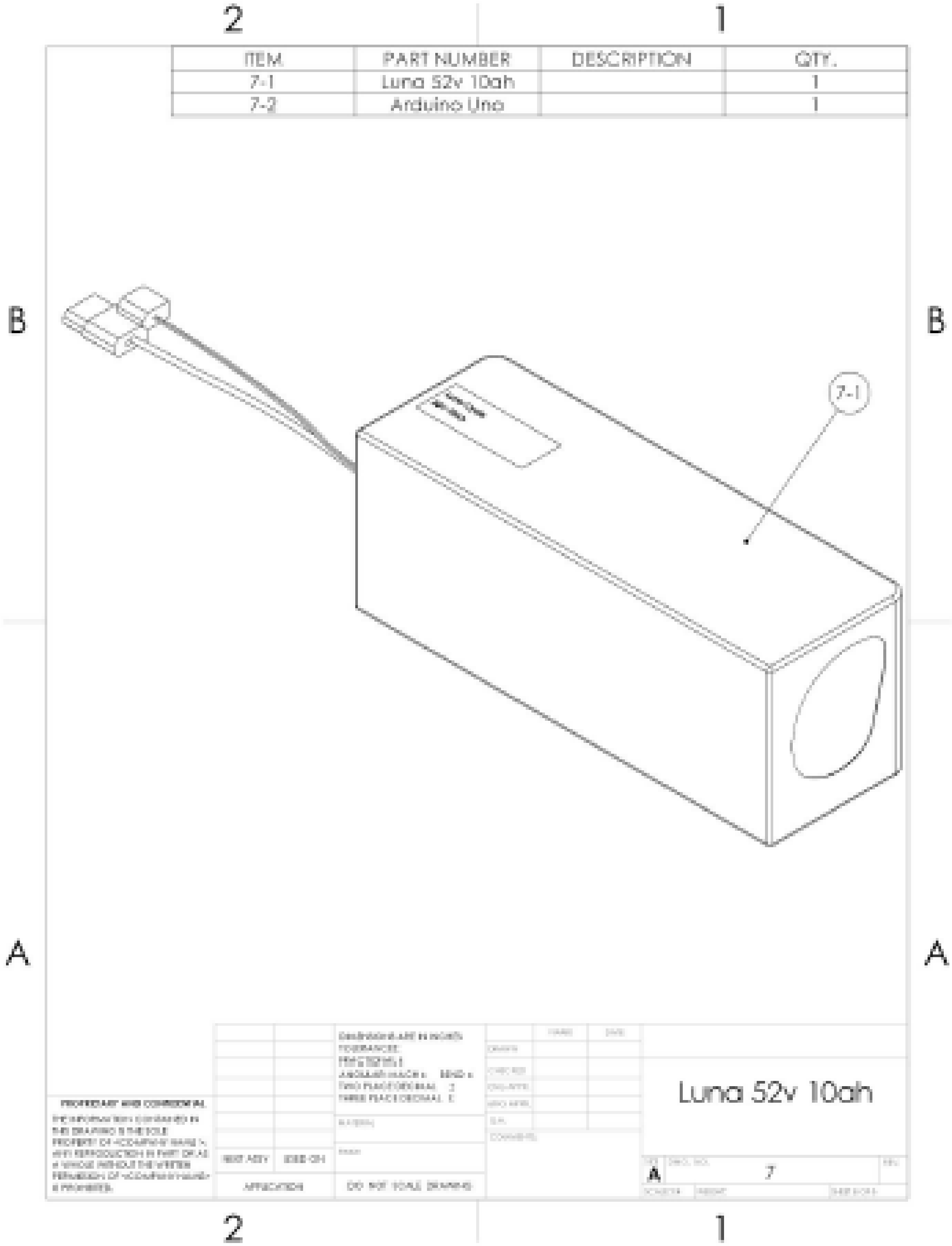


Figure 22 CAD drawing of battery

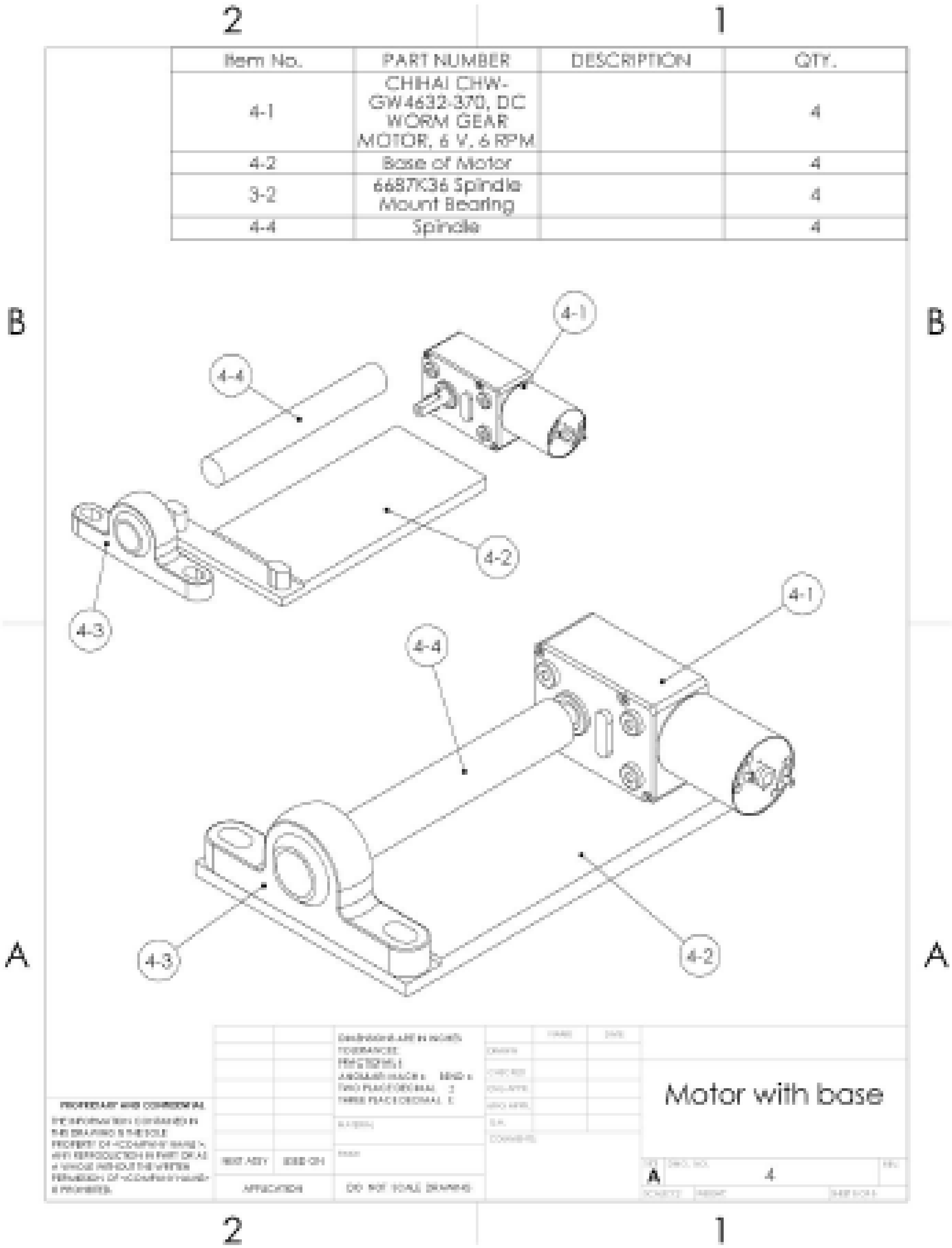
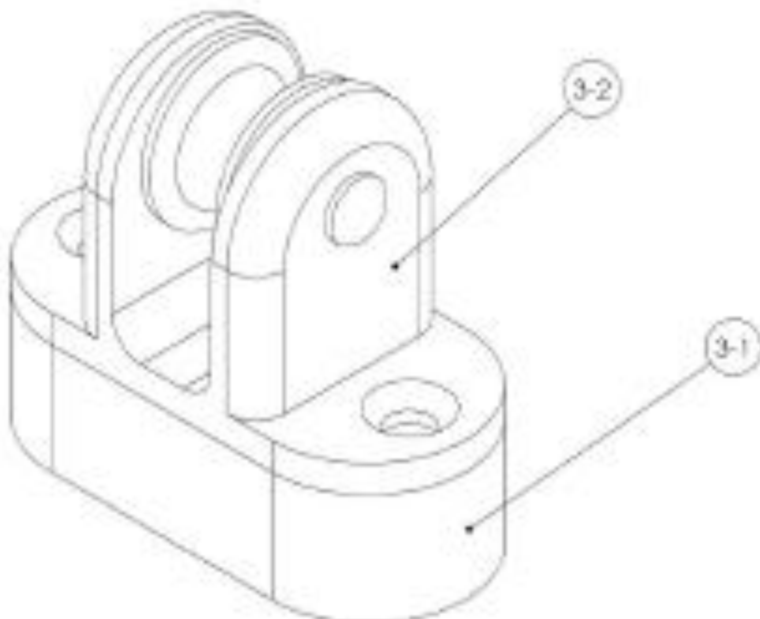


Figure 23 CAD drawing of motor and spindle

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
3-1	Rotating Platform	---	4
3-2	3071T21 Pulley	---	4
3-3	Medium-Strength Class 8.8 Steel Hex Head Screw Zinc-Plated, M4 x 0.7 mm Thread, 20 mm Long	---	8
3-4	Medium-Strength Steel Nylon-Insert Locknut Class 8, Zinc-Plated, M4 x 0.7 mm Thread	---	8
3-5	Zinc-Plated Steel Split Lock Washer for M4 Screw Size, 4.4 mm ID, 7.6 mm OD	---	8



Platform with Pulley

A 3

NEXT ASSY USED ON

APPLICATION

DO NOT SCALE DRAWING

PROPRIETARY AND CONFIDENTIAL

Figure 24 CAD drawing of pulley

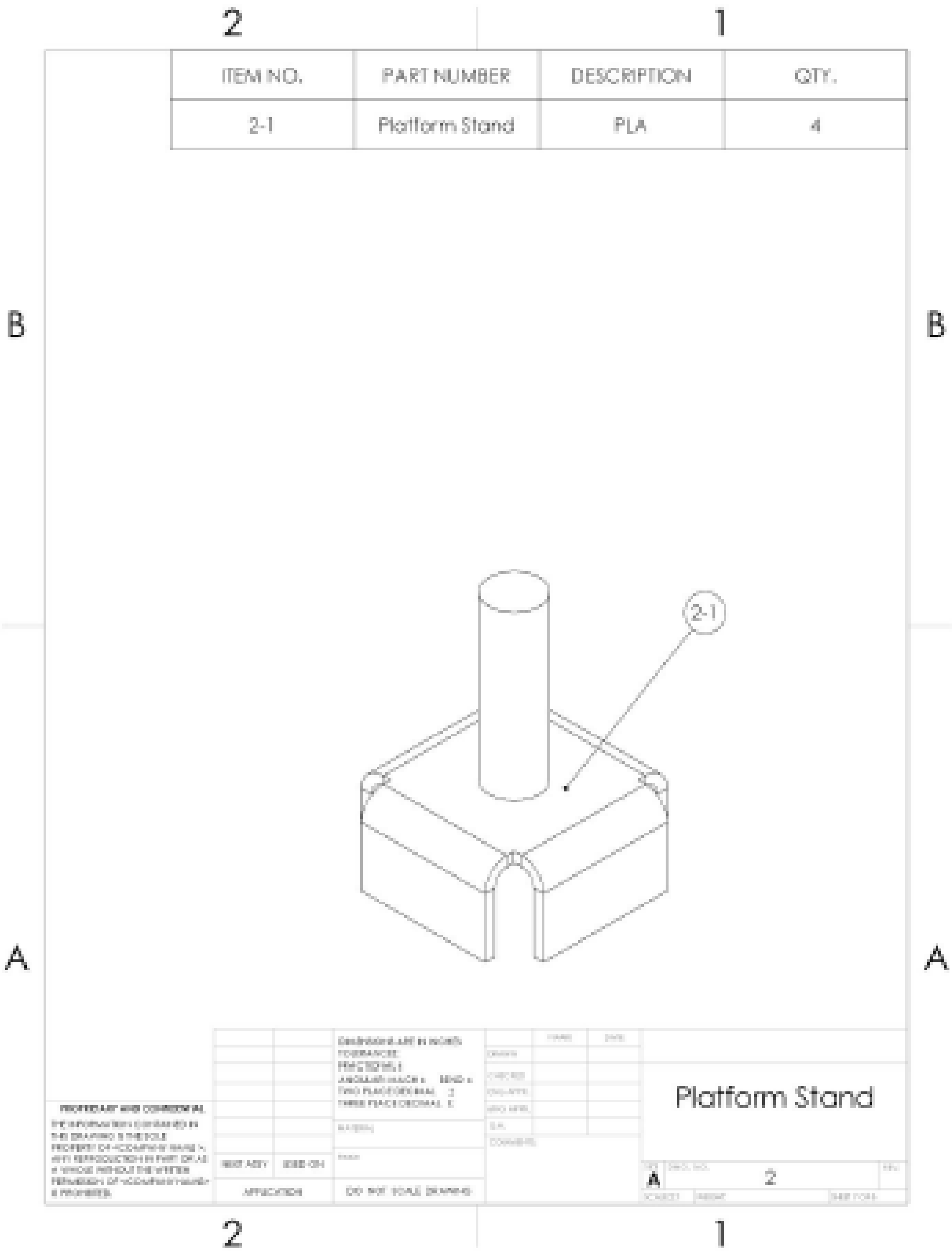


Figure 25 CAD drawing of pulley platform

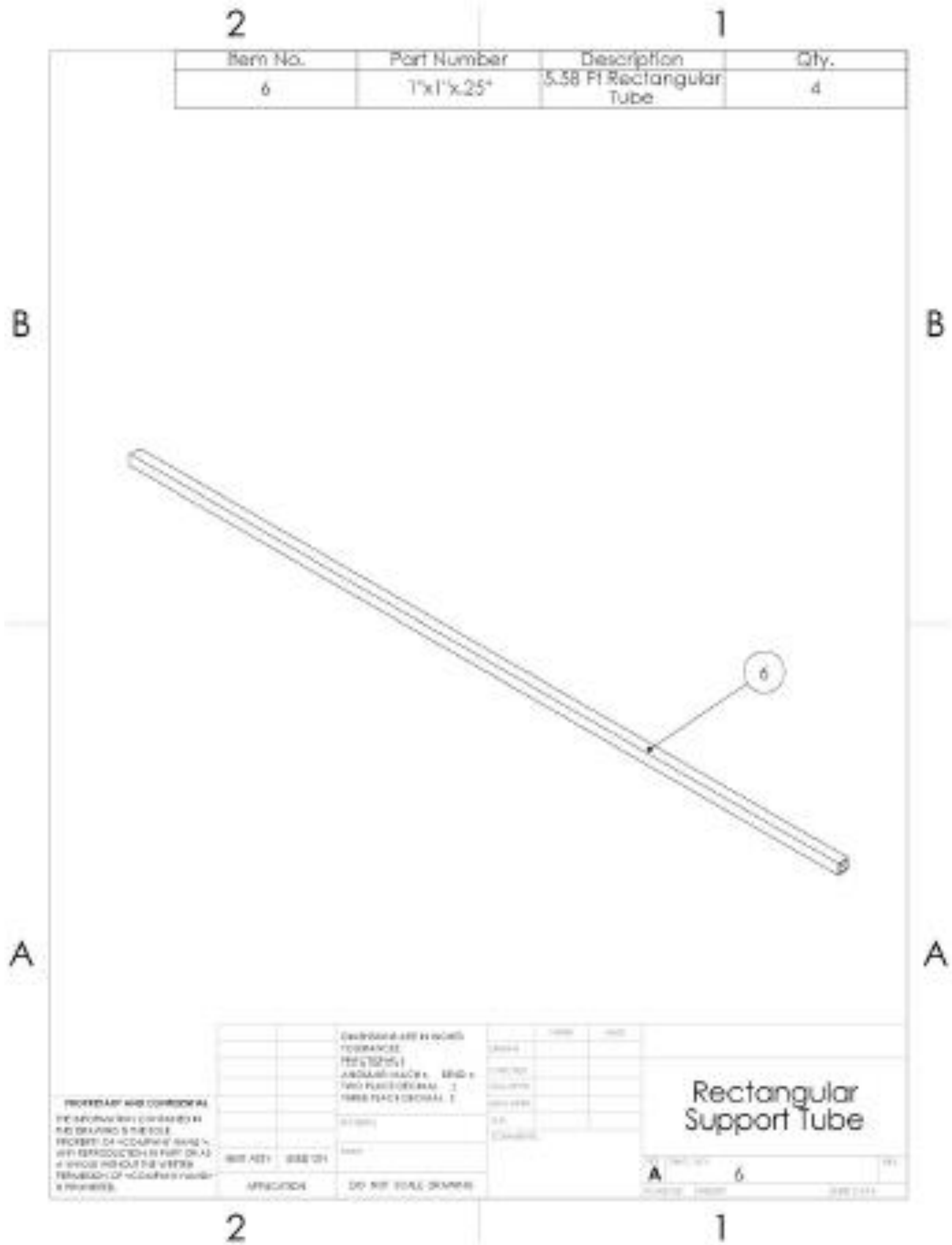


Figure 26 CAD drawing of a support tube

5.2 PROOF-OF-CONCEPT

Our prototype performance goals are as follows:

1. It can be cycled in a span of 20 minutes.
2. It will photograph every part of a 3m x 3m square of ground to a quality that allows the user to determine the presence of powdery mildew.
3. It will run at least 2 cycles before requiring a change of battery.

Design Rationale

Our Photosynthesizer relies upon vertical poles, from the tops of which cables extend and are put in tension to support a suspended camera between the poles. The vertical position of the camera above the ground is held constant, while the horizontal coordinates (x [left-right] and z [up-down]) can be adjusted. Since the camera of constant mass is not moving, it is not accelerating, meaning that it exhibits zero net force. This gives way to statics equations that we have simplified to 2 dimensions. For the sake of simplicity, we assume the cables to be massless. Physics allows us to solve for the maximum tension T1 in one of the ropes. It is a function chiefly of the x coordinate, where the parameters S, L, m, and g can be hardcoded into the equation without difficulty. Pulleys will be lodged onto the tops of the poles, and a spindle will be wrapped around the pulley as a cable in tension that keeps the camera suspended in air. The size of the pulley affects the torque; a bigger spool requires more torque but fewer turns. After tension and torque are computed, it is important to identify the electrical components required for the automated motion of the camera. The batteries and motors chosen depend upon the voltage and current required by this system. Ultimately, what remains to be done is the ordering of parts, construction of the system, computer programming of the automation, testing, refinement, and submission.

Calculations Underlying Design Rationale

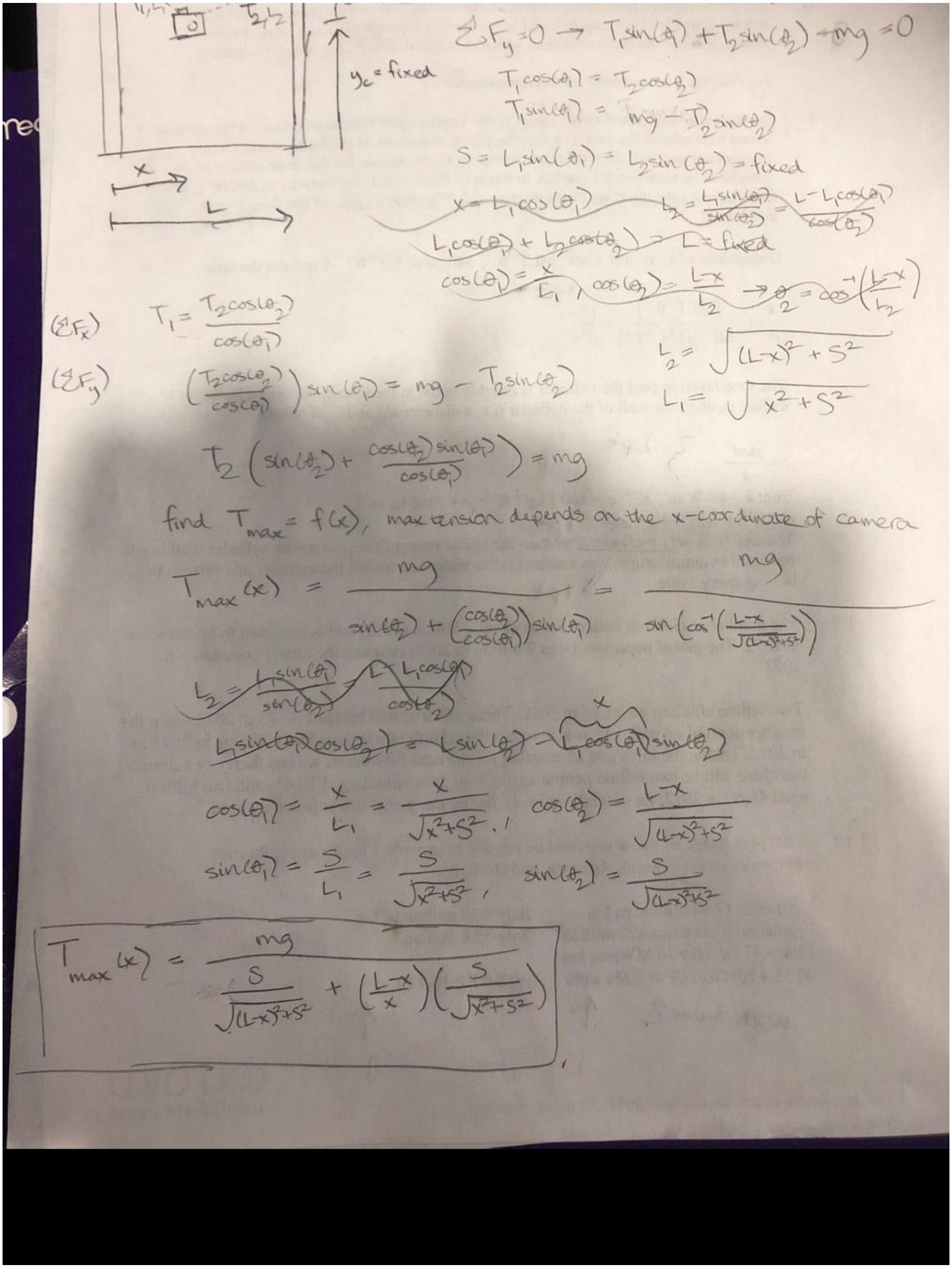


Figure 27 Derivation of equation used to calculate torque

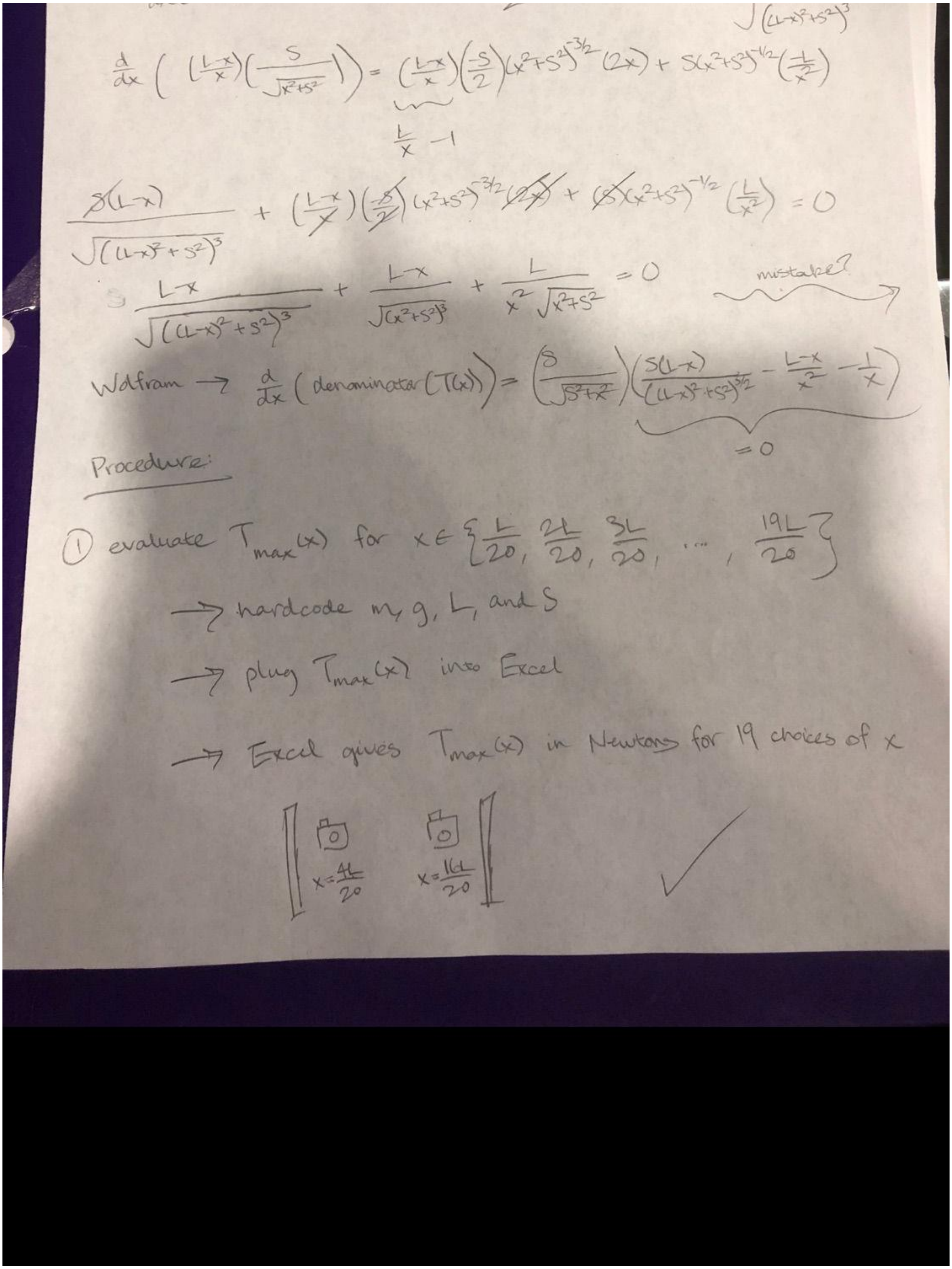


Figure 28 Derivation of equation used to calculate torque

Excel Calculations for Maximum Torque

pos x	neg x	s	pos tan-1	neg tan-1	real angle pos x	real angle neg x	T1	T2	radius1	r2	r3	torque 1	torque 2	torque 3
0	-3	0.6	0	-1.37340077	1.570796327	0.19739556	9.81E-17	1.5696	0.002	0.0025	0.003175	1.96108E-19	2.45134E-19	3.11321E-19
0.1	-2.9	0.6	0.16514868	-1.36677835	1.405647649	0.20401798	0.258236	1.538209	0.002	0.0025	0.003175	0.000516471	0.000645589	0.000819898
0.2	-2.8	0.6	0.32175055	-1.35970299	1.249045772	0.211093333	0.499406	1.544203	0.002	0.0025	0.003175	0.000998811	0.001248514	0.001585613
0.3	-2.7	0.6	0.46364761	-1.35212738	1.107148718	0.218668946	0.72355	1.57938	0.002	0.0025	0.003175	0.0014471	0.001808875	0.002297271
0.4	-2.6	0.6	0.5880026	-1.34399748	0.982793723	0.226798848	0.930714	1.634901	0.002	0.0025	0.003175	0.001861429	0.002326786	0.002955018
0.5	-2.5	0.6	0.69473828	-1.33525135	0.876058051	0.235544981	1.120953	1.702634	0.002	0.0025	0.003175	0.002241905	0.002802381	0.003559024
0.6	-2.4	0.6	0.78539816	-1.32581766	0.785398163	0.244978663	1.294325	1.7758	0.002	0.0025	0.003175	0.002588651	0.003235813	0.004109483
0.7	-2.3	0.6	0.86217005	-1.31561394	0.708626272	0.255182391	1.450904	1.849072	0.002	0.0025	0.003175	0.002901808	0.003627261	0.004606621
0.8	-2.2	0.6	0.92729522	-1.30454428	0.643501109	0.266252049	1.590773	1.9184	0.002	0.0025	0.003175	0.003181546	0.003976932	0.005050703
0.9	-2.1	0.6	0.98279372	-1.29249667	0.588002604	0.278299659	1.714029	1.980746	0.002	0.0025	0.003175	0.003428058	0.004285073	0.005442042
1	-2	0.6	1.03037683	-1.27933953	0.5404195	0.291456794	1.820789	2.033836	0.002	0.0025	0.003175	0.003641579	0.004551974	0.005781007
1.1	-1.9	0.6	1.07144961	-1.26491746	0.499346722	0.305878871	1.911192	2.075964	0.002	0.0025	0.003175	0.003822385	0.004777981	0.006068036
1.2	-1.8	0.6	1.10714872	-1.24904577	0.463647609	0.321750554	1.985404	2.105839	0.002	0.0025	0.003175	0.003970809	0.004963511	0.006303659
1.3	-1.7	0.6	1.13838855	-1.23150371	0.432407776	0.339292614	2.043626	2.122474	0.002	0.0025	0.003175	0.004087253	0.005109066	0.006488514
1.4	-1.6	0.6	1.16590454	-1.21202566	0.404891786	0.35877067	2.086104	2.125105	0.002	0.0025	0.003175	0.004172208	0.00521526	0.00662338
1.5	-1.5	0.6	1.19028995	-1.19028995	0.380506377	0.380506377	2.113139	2.113139	0.002	0.0025	0.003175	0.004226277	0.005282847	0.006709215
1.6	-1.4	0.6	1.21202566	-1.16590454	0.35877067	0.404891786	2.125105	2.086104	0.002	0.0025	0.003175	0.004250211	0.005312763	0.006747209
1.7	-1.3	0.6	1.23150371	-1.13838855	0.339292614	0.432407776	2.122474	2.043626	0.002	0.0025	0.003175	0.004244948	0.005306184	0.006738854
1.8	-1.2	0.6	1.24904577	-1.10714872	0.321750554	0.463647609	2.105839	1.985404	0.002	0.0025	0.003175	0.004211679	0.005264598	0.00668604
1.9	-1.1	0.6	1.26491746	-1.07144961	0.305878871	0.499346722	2.075964	1.911192	0.002	0.0025	0.003175	0.004151929	0.005189911	0.006591187
2	-1	0.6	1.27933953	-1.03037683	0.291456794	0.5404195	2.033836	1.820789	0.002	0.0025	0.003175	0.004067672	0.00508459	0.006457429
2.1	-0.9	0.6	1.29249667	-0.98279372	0.278299659	0.588002604	1.980746	1.714029	0.002	0.0025	0.003175	0.003961491	0.004951864	0.006288867
2.2	-0.8	0.6	1.30454428	-0.92729522	0.266252049	0.643501109	1.9184	1.590773	0.002	0.0025	0.003175	0.0038368	0.004796	0.00609092
2.3	-0.7	0.6	1.31561394	-0.86217005	0.255182391	0.708626272	1.849072	1.450904	0.002	0.0025	0.003175	0.003698144	0.00462268	0.005870803
2.4	-0.6	0.6	1.32581766	-0.78539816	0.244978663	0.785398163	1.7758	1.294325	0.002	0.0025	0.003175	0.003551599	0.004439499	0.005638164
2.5	-0.5	0.6	1.33525135	-0.69473828	0.235544981	0.876058051	1.702634	1.120953	0.002	0.0025	0.003175	0.003405269	0.004256586	0.005405864
2.6	-0.4	0.6	1.34399748	-0.5880026	0.226798848	0.982793723	1.634901	0.930714	0.002	0.0025	0.003175	0.003269802	0.004087253	0.005190811
2.7	-0.3	0.6	1.35212738	-0.46364761	0.218668946	1.107148718	1.57938	0.72355	0.002	0.0025	0.003175	0.003158759	0.003948449	0.00501453
2.8	-0.2	0.6	1.35970299	-0.32175055	0.211093333	1.249045772	1.544203	0.499406	0.002	0.0025	0.003175	0.003088407	0.003860509	0.004902846
2.9	-0.1	0.6	1.36677835	-0.16514868	0.20401798	1.405647649	1.538209	0.258236	0.002	0.0025	0.003175	0.003076418	0.003845522	0.004883814
3	0	0.6	1.37340077	0	0.19739556	1.570796327	1.5696	9.81E-17	0.002	0.0025	0.003175	0.0031392	0.003924	0.00498348

Figure 29 Excel sheet used to optimize design for applied torque

(source file found at https://wustl.instructure.com/files/130849/download?download_frd=1)

Proof-of-Concept Prototype

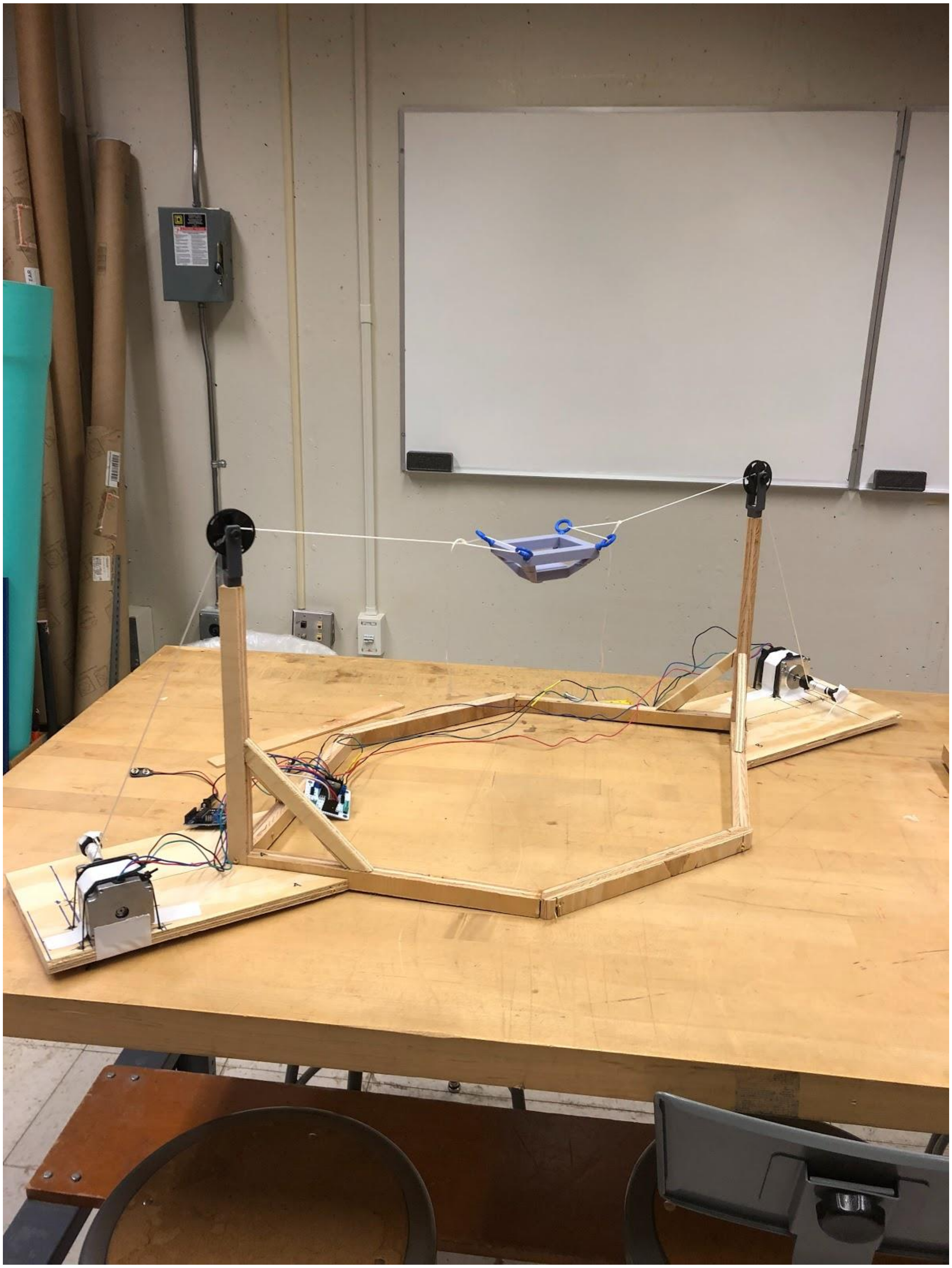


Figure 30 Proof-of-concept prototype

6 WORKING PROTOTYPE

6.1 OVERVIEW

Our PoC prototype was a scaled down and drastically simplified version of what we needed for our working prototype. The most significant change was that for the working prototype, rather than having two end poles (allowing for linear movement in between the poles), we had four poles at the corners of a 3m x 3m apparatus (allowing for movement in the x-y plane). Additionally, the working prototype had another functionality in that it could be taken apart and reassembled – the PoC had no such functionality.

6.2 DEMONSTRATION DOCUMENTATION

Figure 31 Working prototype, seen from above

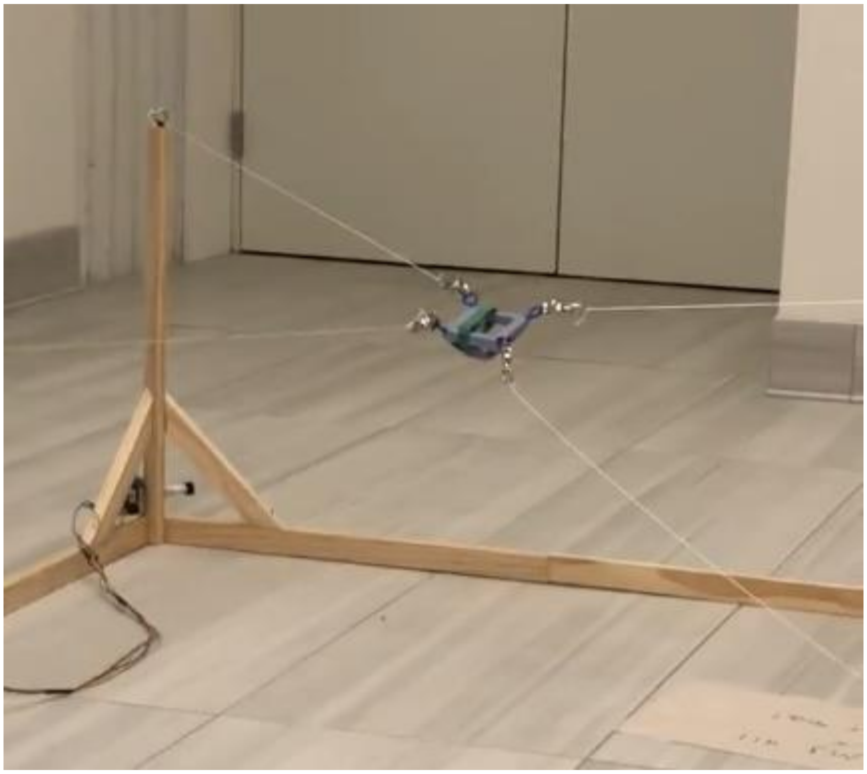


Figure 32 Working prototype in action

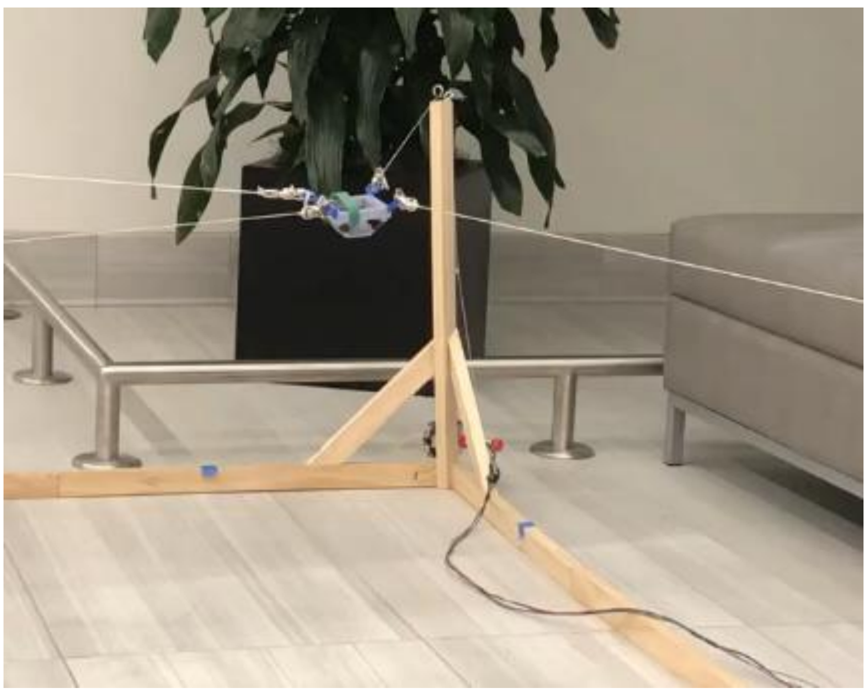


Figure 33 Test run of working prototype

6.3 EXPERIMENTAL RESULTS

***Performance Goal #1** – Cycle in span of 20 minutes*

In our testing of this prototype, we were able to determine that it could cycle through the entire 3m x 3m area in under 20 minutes. Our code at the time of presenting the working prototype had very limited functionality, and it did not account for tension that would suspend the camera fixture. This resulted in the fixture dragging along the ground as it moved from one point to another due to having too much slack in the strings. However, testing revealed that at the speed that the device moved the camera fixture, 20 minutes would be an ample amount of time to cycle through the entire area**.**

***Performance Goal #2** – Photograph 3m x 3m area to a quality allowing a user to determine presence of mildew*

We were unable to meet this performance goal at the time of evaluation due to not having a camera that was capable of automatically taking pictures at set intervals, which was our approach to automating the process of photographing the area. Upon testing, however, our prototype was able to achieve a range of motion that encompassed nearly the entire 3m x 3m area, and an automated camera would be able to capture the whole area if the movement was programmed correctly. While it had the capacity to move a camera to the necessary positions to capture the entire area, we were unable to test the photographing functionality.

***Performance Goal #3** – Battery lasts for at least 2 cycles before needing to recharge*

The battery we used in our prototype more than exceeds this performance goal. From a full charge, this battery seems to be able to handle tens, if not hundreds, of test runs before fully depleting the battery. Through a multitude of test runs in the process of refining our code for the prototype, the battery has not needed to be charged at all – surprisingly, the lights on it still indicate that it has roughly half of its charge remaining after the expo on 11/30. 9-volt batteries could potentially be used if the original battery is not available, but we have not done any testing to determine the life of a 9V battery on the prototype.

7 DESIGN REFINEMENT

7.1 FEM STRESS/DEFLECTION ANALYSIS

a.

For this FEA analysis, our group decided it would be best to study the pulley of our system to verify if it is able to handle the maximum force of 4.65 N that is exerted on the pulley by the camera mount system. The bottom surface of the pulley base is fixed because it will be placed flat on a surface and thus prevented from moving. The holes in the pulley base are also fixed because they are mounted with bolts. A fine mesh was used on the model to due to various number of curves that are present in the surface. Contact sets were created with the cylindrical bearing within the pulley an and the base to allow the two rotate. The FEA will analyze the base of the mount well, but will also have issues with the rotating pulley. This is due to the force being applied over a single wire, translating force to a single line over the pulley. However, SolidWorks applied the force throughout the surface of the pulley, creating slightly inaccurate results.

b.

i.

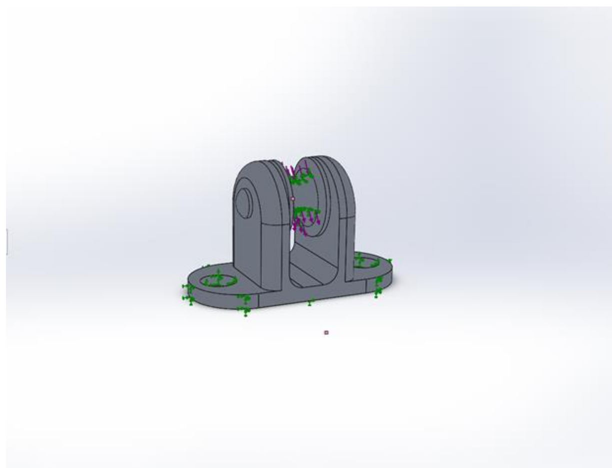


Figure 34 Unloaded pulley model

ii.

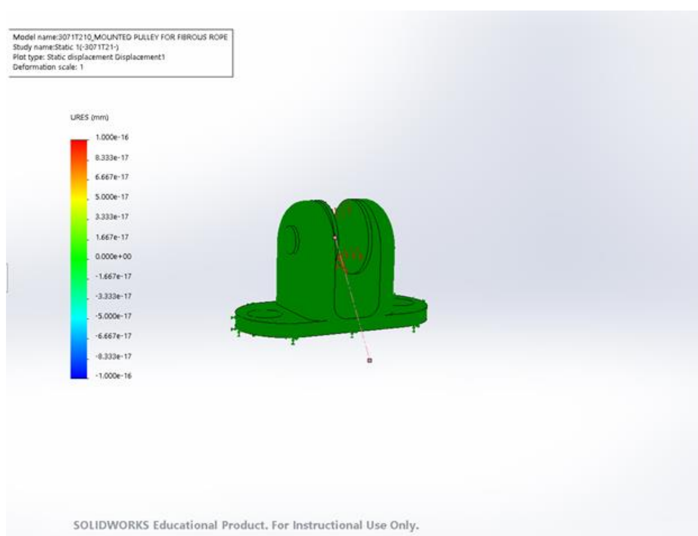


Figure 35 Pulley analyzed for Von Mises stresses

c.

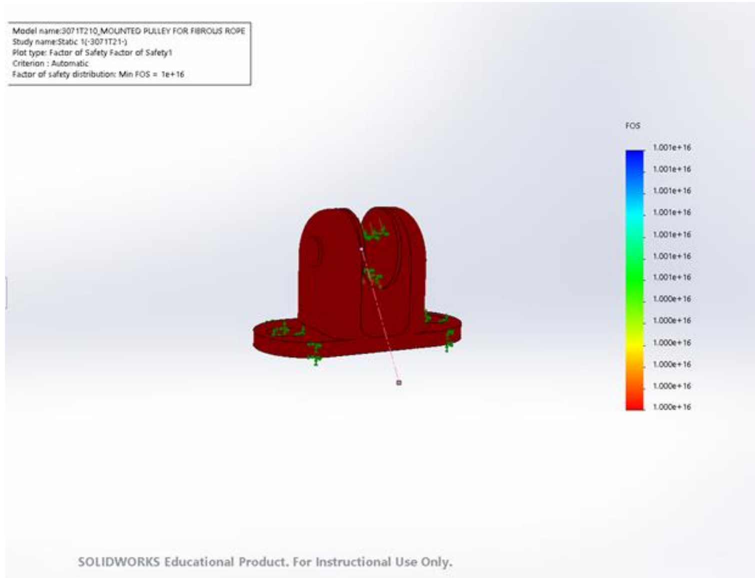


Figure 36 Pulley analyzed for factor of safety

The minimum factor of safety as determined by FEA analysis is 1E16, which reveals that a much larger magnitude of force can be applied to the model before having to consider the possibility of failure. The amount of deflection that would cause a significant problem would be determined by what part of the model we are analyzing. If the Y shape of the base is being analyzed, 1mm of deflection inward on either side of the model would be enough to prevent the pulley from rotating. If the cylinder inside of the pulley was moved in any direction by 1mm, it would be enough, once again, to prevent the pulley from rotating. If the pulley collapsed from within by .5 mm, the pulley would again be prevented from rotating. For our pulley analysis there was very little to no deflection, allowing for rotation with our applied for of 4.65N.

7.2 DESIGN FOR SAFETY

Risk #1: Weather
Description: Inclement weather could short circuit or otherwise damage the device.

Impact: 4 - Rain could lead to short-circuiting. This opens up a myriad of complications, from component failure to fire.

Likelihood: 3 - Generally speaking, weather conditions are relatively stable. Rain usually won't appear out of nowhere on a sunny day, but there is a risk of rain when the device is used on a cloudy day.

Risk #2: Improper assembly
Description: If improperly assembled, the device could come apart

Impact: 2 - If the device comes apart, the user would just have to reassemble it. The device is fairly rugged; falling apart due to improper assembly should not cause much, if any, damage.

Likelihood: 2 - Through simplicity of design and user instruction, we aim to allow the user to properly assemble/break down the device with ease. That being said, everyone makes mistakes.

Risk #3: Pinching
Description: If someone sticks a body part (e.g. a finger) into a connecting/moving part, there is a risk that they will be pinched.

Impact: 4 - With enough tension in the lines, it may be possible to break a finger or worse if someone's finger is caught between the spindle and the line.

Likelihood: 1 - It's not very likely for someone to accidentally pinch themselves using this device, but it can happen if they aren't careful.

Risk #4: Hitting edge
Description: The device could damage itself if a motor pulls the camera mount too far, i.e. into one of the posts.

Impact: 4 - The camera mount and/or the post could get damaged to varying degrees of severity from colliding with one another.

Likelihood: 2 - We aim to, with the use of programming, index the motor positions to where this does not occur, but our code may not be perfect. This could be mitigated, however, by putting physical blockers on the lines to prevent the camera mount from smashing into the poles.

Risk #5: Motor burnout
Description: If there is too much load on the motors, they can burn out.

Impact: 5 - The device will become unusable until the defective motor is replaced.

Likelihood: 3 - The motor specifications should provide ample torque for the loads from our design, but loads on the lines could come from external forces, such as wind or snagging onto foliage, which could potentially overload the motors.

Risk #6: Structural failure
Description: Some chance events (e.g. someone falling onto the device) may result in structural failure
Impact: 5 - The device will physically break and become unusable until repaired.
Likelihood: 1 - If the user employs caution and common sense, this should not happen.

Heat Map

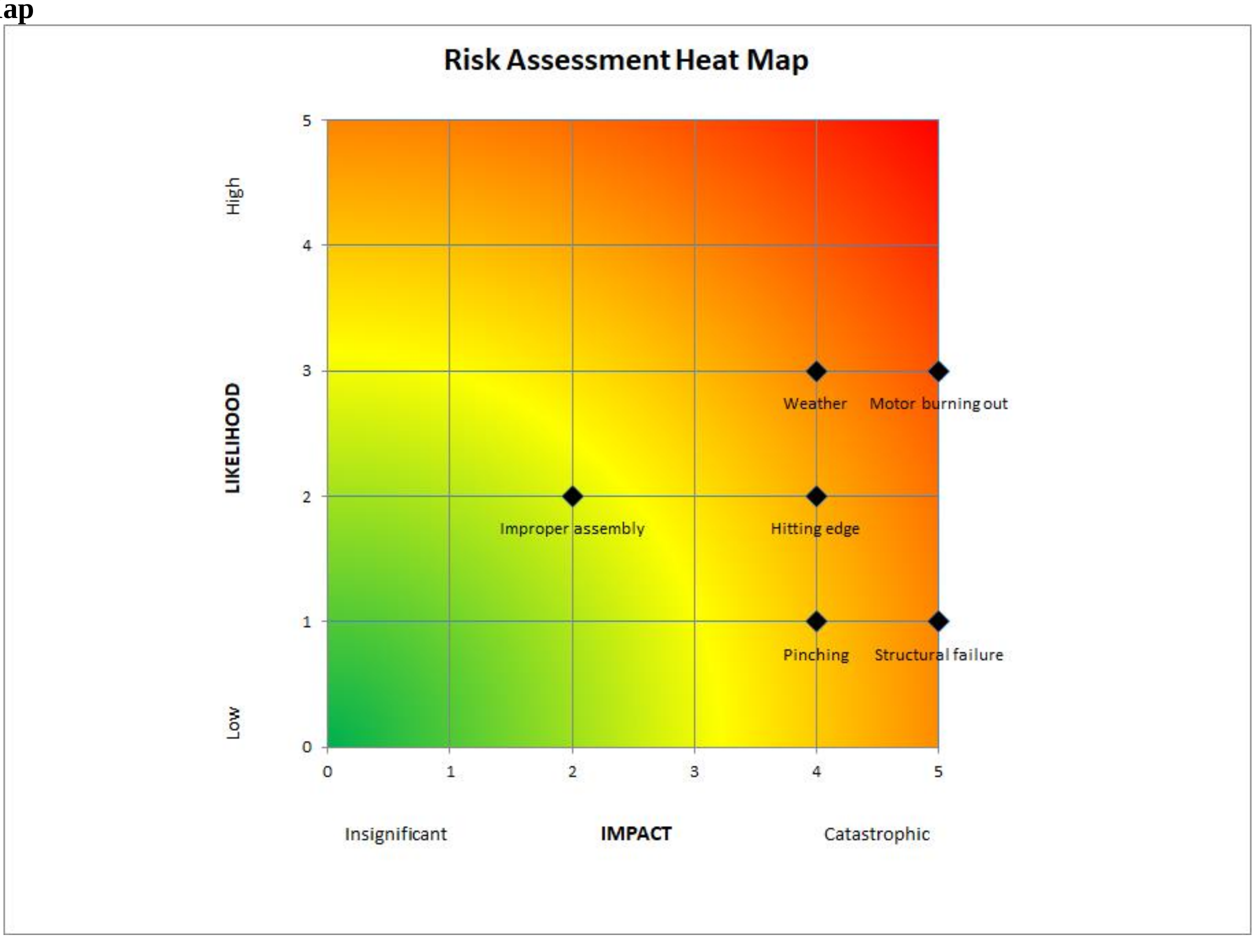


Figure 37 Risk assessment heat map

According to the heat map, the order of priority for the issues should be, from highest to lowest priority:

5 > 6 > 1 > 4 > 3 > 2

The highest priority issues are those involving failure of components, which will lead to the device losing functionality. Motor burnout is the most likely out of these issues, which can happen if something causes excessive load for one or more of the motors on our device. Our motors took up the largest part of the budget, so we should design our device to protect them as best as possible. With this in mind, we look at the next issue, which is weather. Granted, this device in its current design *cannot*, and *should not*, be used during weather conditions where there is a risk of moisture damaging the device and/or causing short-circuits, but there is the off chance that unexpected weather developments can cause problems for the device. Next up is the risk of structural failure from external forces such as, for example, somebody tripping and falling on the device. We designed our frame to be fairly sturdy, and this should at least mitigate some of the damage from such an event occurring. Subsequently, the risk of damage from running into the posts is worth noting, but it can be mitigated by mechanical design and/or coding that will prevent impact. The final two issues stem from human error, and we will attempt to simplify the design and provide ample warning to protect the user from harm.

7.3 DESIGN FOR MANUFACTURING

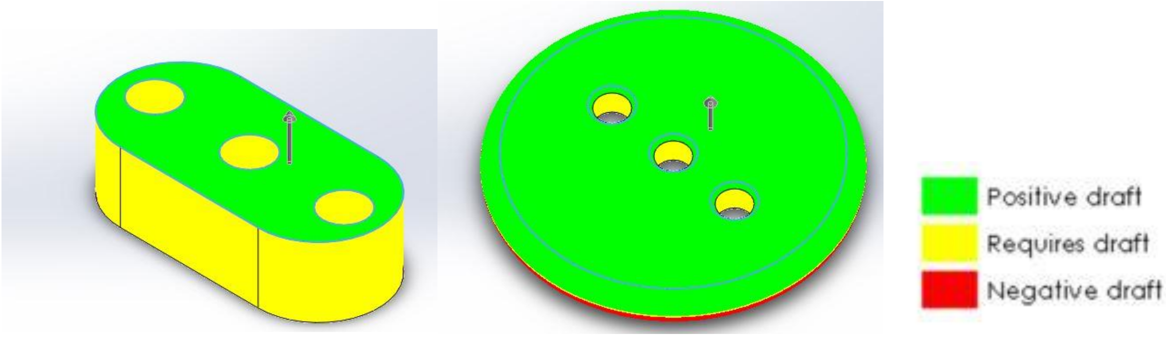


Figure 38 Analysis of draft for manufacturing

The original design involved some necessary revisions because of the sharp angles involved in the rotation stage. These issues were addressed and fixed by the making the stage a rotated platform with rounded edges. The holes in the center were then chamfered to reduce the sharp edges within the stage.

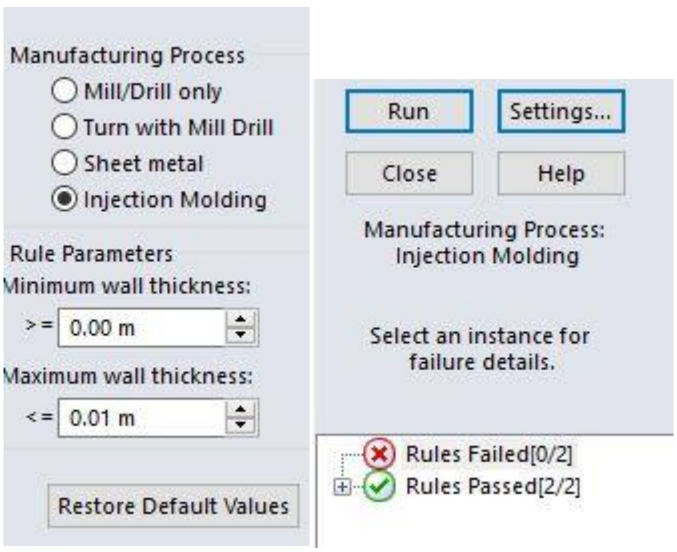


Figure 39 Analysis for rotation stage in injection molding

This is the analysis for the rotation stage in the injection molding system. By editing the maximum wall thickness, the rotation stage shown above does not have any failing conditions.

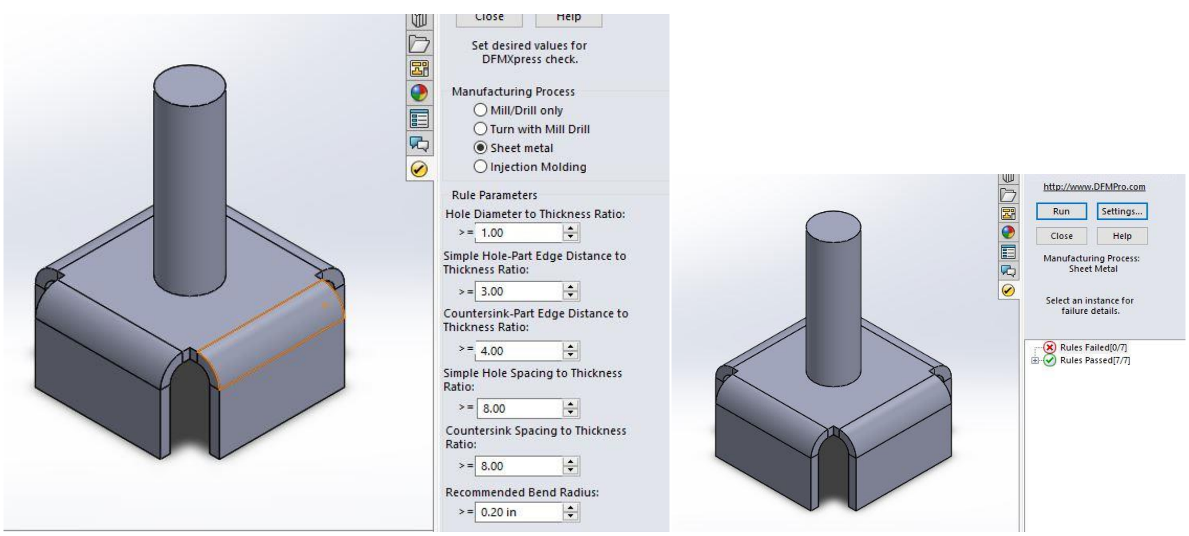


Figure 40 Analysis of leg cap

This is the analysis for the leg cap that the rotation stage is going to attach to legs. The rotation stage will attach this to the legs on each corner and running the analysis using sheet metal leads to no failing conditions for the manufacturing process.

7.4 DESIGN FOR USABILITY

1) **Vision impairment -** Our design is large enough that vision impairment such as presbyopia and myopia should not be an issue; we could also make it so that user-interactive buttons are large and have high contrast with their backgrounds. We can accommodate for red-green color blindness by avoiding these colors in our design, since we will be using this in proximity to plants, which are green.
2) **Hearing impairment -** Our design does not have any features that rely on the user hearing and/or interpreting sounds. The goal of the design is to be autonomous upon setup - there are no audio cues that would be problematic for someone with a hearing impairment. Perhaps if a motor were to malfunction, it would make a discernible noise that could be used to diagnose the issue, but this is not an intended feature of the design.
3) **Physical impairment -** We aim to have our design be as light as possible without sacrificing structural integrity; this way, the components can be carried more easily to accommodate users with physical ailments. In addition, we aim to simplify the mechanisms for connecting each of the components together to make it easier for someone with arthritis, for example, to assemble.
4) **Language impairment -** We could create a set of instructions (i.e. an instruction booklet) and/or put signage on our device that utilizes pictures to work around a potential language barrier. By relying more on pictures to demonstrate actions required to operate the device, we can bypass any potential difficulty a non-English speaker may have.
5) **Control impairment -** We could put signage on the device warning the user to not use it while under the influence of control-impairing substances. To address the issue of user fatigue, the interface should be simple enough to be understood by a fatigued user, and the device should also be rugged enough to withstand any heavy-handed user blunders.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

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

The Final design project does align with the initial project description, but partially. While The Photosynthesizer does have the capability to take picture of mildew in grass as instead, it is not able to take the photos of the entire 3 x 3 meter plot. We were able to completely setup and disassemble The Photosynthesizer in less than 10 minutes with ease and is one goal that we were able to achieve without an issue.

8.1.2 Was the project more or less difficult than expected?

The project happened to turnout much more complicated than expected. While we did have small issues while designing the frame and the mechanical components of the experiment, they were very simple to fix and to resolve. A small issue that we had was when deciding which motors would suit our model the best without having over engineering. A great difficulty was faced in the electrical setup of the wiring of four stepper motors to the proper powersource as well as to the driver that control the motors. Major issues were also found in programming of the motors, without any previous arduino experience it was fairly steep learning curve.

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

One part of the design that our group should have spent more time is the electrical. While dozens up dozens of hours were spent on attempting to resolve the issues with the electrical components, and the coding, more time was still required. For example a fine tuning of the code was required to help the camera levelize when taking photos, and much better cable management may have been instilled. One part of the project where we felt we spent too much time on was the frame. The frame was relatively simple to build compared to the time we spent designing. Many oversimplifications were done during the construction, and produced not issues during testing.

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

The frame has to be the most difficult and simplest component to make. The frame being made out of wood was simple to cut down to required length and assembled. The most difficult part of the frame was building the supports at the corner of each beam. Because the vertical beam which had the string attached to them were at two angles to the base board, two angles were required to cut the supports flush to the vertical beam. This resulted in various research, and was finally resolved with the help of Professor Woodhams.

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

If the group were to design a different concept, if would first and foremost be one in which the electrical component is much more simplified, and one in which we are not fighting the force gravity at all times. We think it would be much simpler to create a system that functions almost like a CNC machine which is able to move in the x and y direction by the use of two motors,and has supports that sustain the frame from the ground. Or if were were to continue to use a wire system, were would break the plot down into 1 x 3 meter plot and only move the camera in the y direction, where people would then shift the system over to take pictures of the rest of the plot.

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?

To find relevant codes and standards, our group decided on features of our design that could have an applicable code and/or standard, and searched accordingly. Namely, we found standards for electrical components that would be useful for ensuring that our design remains safe to operate. Naturally, because they were standards for electrical components, they had little bearing on the mechanical aspect of our conceptual design.

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

We believe that the most important and critical information was the amount of weight that stepper motors are able to maintain when there is current flowing through the coils. Our group managed to calculate the amount of weight that was to be supported by the motors when there was no current, but when it was discovered that by running the program the motors became difficult to rotate we began adding more weight. We believe that this caused for the stepper motor teeth to begin to grind down and cause a motor failure.

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

It would have been great to use an engineering software to analyze the circuitry of the of system. A program such as PSpice, would have allowed us to determine steppers or motors were going to function in our electrical system properly without any malfunctions. It would have been a great opportunity to use a strain gauge to understand the amount of torque that our system was outputting when loaded with current. It would have also been a great opportunity to determine by how much our motors degraded.

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

If the course were to be able to be done for a second time, a project with much simpler electrical and easier coding would have been chosen. For this current project there were too many factors that made it difficult to create a fully working model. If this model were to be done again, a different design prototype would be chosen.

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

To begin with, if there were more time and money, the first upgrade would have to be the motors. With upgraded motors it would be possible to mount a DSLR and prevent the eroding of the motor teeth. These motors would not have to be stepper motors, but rather a different motor that has the capability of using memory controls to know what position its gear is at. A second upgrade would have to come in the form of wires. A great amount of budget was spent on wiring alone. More organized wire was offered, but was much more expensive.

8.3 TEAM ORGANIZTION

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

Our team members' skills complemented each other, allowing us to divide up labor on the project and work more efficiently. Skills ranging from woodworking, mathematical modeling, and coding, to leadership and planning all helped our team move forward with the project. However, we lacked skills in dealing with electronics and circuits – this part of the project is beyond our area of expertise and we had to learn as we went forward, but eventually reached a point where electrical issues prevented us from continuing to develop the project in the time allotted.

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

It does not appear that the design experience has inspired our group to attempt other design projects. At least, not as part of the same group.

APPENDIX A – COST ACCOUNTING WORKSHEET

Column1	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Stepper Motor	https://www.pololu.com/product/1476	1476		$24.95	4	$99.80
2	1" X 2" x 6' Wood	https://www.menards.com/main/building-materials/lumber-boards/boards/1-x-2-select-pine-board/1031563/p-1444444783172.htm	1031563	Wood	$2.80	10	$28.00
3	Eye Bolts			Steel	$1.15	12	$13.80
4	Battery	https://www.amazon.com/gp/product/B01337QXMA/ref=oh_aui_detailpage_o08_s00?ie=UTF8&psc=1	YB1208300-USB	Black, Rectangular	$49.99	1	$49.99
5	Motor Driver Module	https://www.amazon.com/gp/product/B0166QZ5HO/ref=oh_aui_detailpage_o06_s00?ie=UTF8&psc=1	A4988		$9.99	4	$39.96
6	Inland Uno R3 MainBoard	https://www.microcenter.com/product/486544/uno-r3-mainboard	UNO R3 BOARD		$7.99	1	$7.99
7	Elenco 22 Gauge Solid Hook-Up Wire	https://www.microcenter.com/product/404659/22-gauge-solid-hook-up-wire-25-foot-6-color-kit	WK-106		$17.99	2	$35.98
Total:							$275.52

Figure 41 Cost Accounting Worksheet

APPENDIX B – FINAL DESIGN DOCUMENTATION

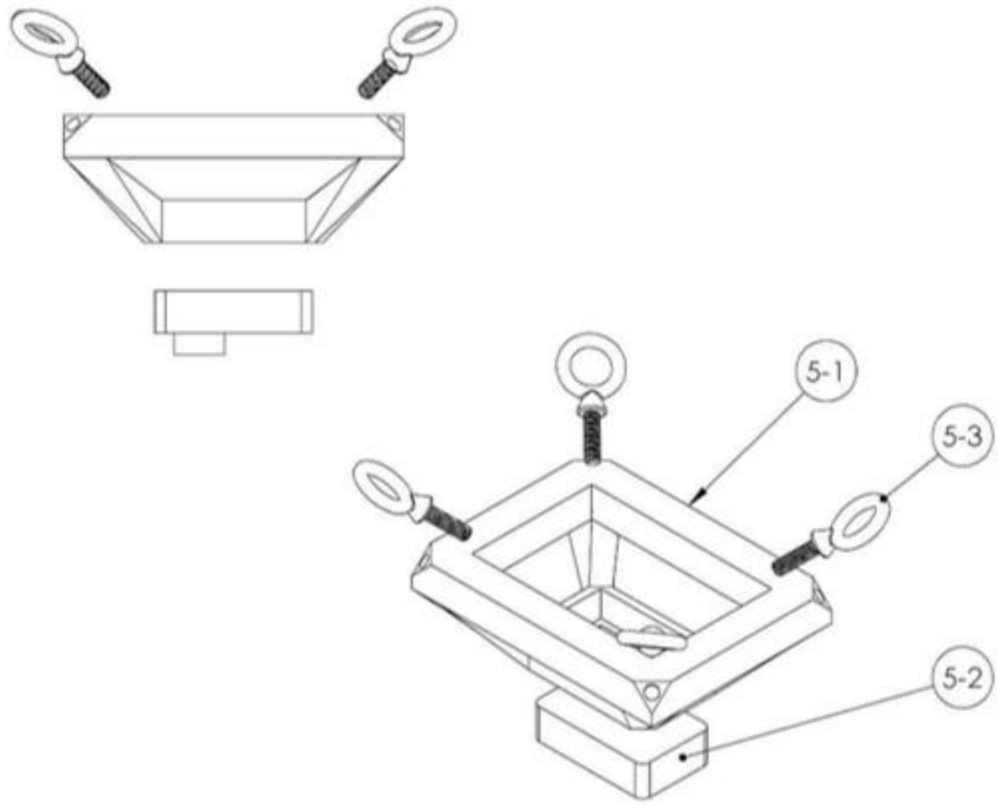


Figure 42 Camera Mount

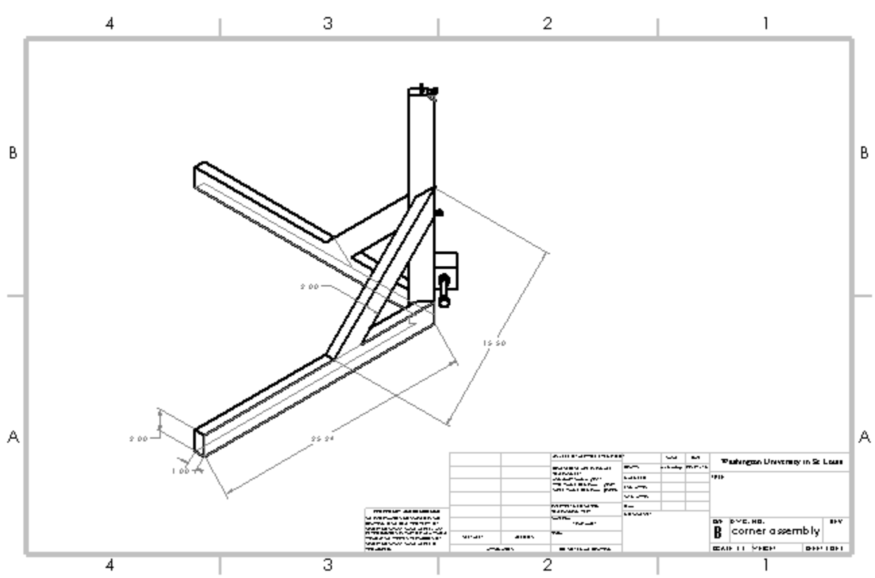


Figure 43 Camera truss

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Used materials and information provided in MEMS 411 lecture.