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MEMS 411: Creation of a 3-Axis Camera System for Various Imaging Modalities

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Washington University in St. Louis

JAMES MCKELVEY SCHOOL OF ENGINEERING

SP21 MEMS 411 Mechanical Engineering Design Project

3-Axis Camera System

The Lake Lab at Washington University in St. Louis faces challenges when setting up their camera systems for experiments. The Three Axis Camera system aims to optimize the experience by automating the movement and creating a user-friendly design. The current set-up requires the camera position to be adjusted manually and is "not liked" by most users. This wastes their time since the lab must set the location for the camera first and if the camera positioning is moved then the experiment will be ruined. Thus, the lab asked us specifically to help them automate these movements with our design and improve their experimental procedures and precision.

To solve this problem the camera will be attached to a motor which translates its rotational movement into linear motion through a lead screw. The lead screw is accurate to about 0.01mm which will allow the Lake lab to get precise focus. Furthermore, the motor is calibrated so the lab can reproduce any camera height through a user interface we coded. For the other directions, the device moves along smoothly in the x and y with rulers for recording set locations. In general, our design streamlines the current process and will allow the Lake lab to do perform reproducible and accurate experiments.

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1 Introduction

Group D will create a device to move a FLIR Blackfly USB 3.0 and possibly other cameras in the x, y and z dimensions. This project will be completed for the Lake lab at Washington University in St. Louis so that they can easily and accurately control the positioning of the FLIR camera during quantitative polarized light imaging (QPLI) and when growing collagen. The current solution requires manually adjusting a clamp. With this solution, the z-height cannot be reproduced exactly from experiment to experiment which throws the camera out of focus. The camera system will also be used to monitor collagen cell cultures. Currently, the cells are inspected visually to ensure that they grew correctly. Using the camera system, the cell cultures can be verified with the FLIR camera which provides a more accurate measure of completion. Ultimately, the three axis camera system will streamline the workflow for experiments in the Lake lab and save time when collecting data.

2 Problem Understanding

2.1 Existing Devices

The following are several devices that perform similar jobs to our design goal, but are either too expensive or do not meet all of the customer needs. Each device will be used to inspire the design process and give the team a jump start when designing the camera system for the Lake lab.

2.1.1 Existing Device #1: Automated Microscope System

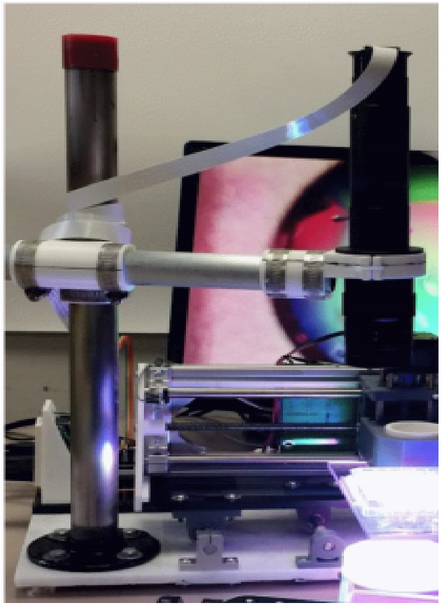


Figure 1: Automated Microscope System (Source:[1])

Demo: `https://rb.gy/ljgdho`

Description: The Automated Microscope (AMi) is a software controllable microscope which has been specially designed to image 12, 24 and 96 well plates. The AMi uses an Arduino to control the x, y and z movements and also uses Raspberry Pi to run Python scripts and save images. The AMi is also able to adjust the focus and shine light on the samples. This product is very similar to the camera system that the Lake lab needs; however, it is not designed to operate a FLIR camera or for the Lake lab's specific use case. The AMi also does not physically move the camera only the plate which the sample sits on. This is not the desired behavior, but the motion system could be adapted to move the camera in our design.

2.1.2 Existing Device #2: Ring Stand with Mechanical Clamp

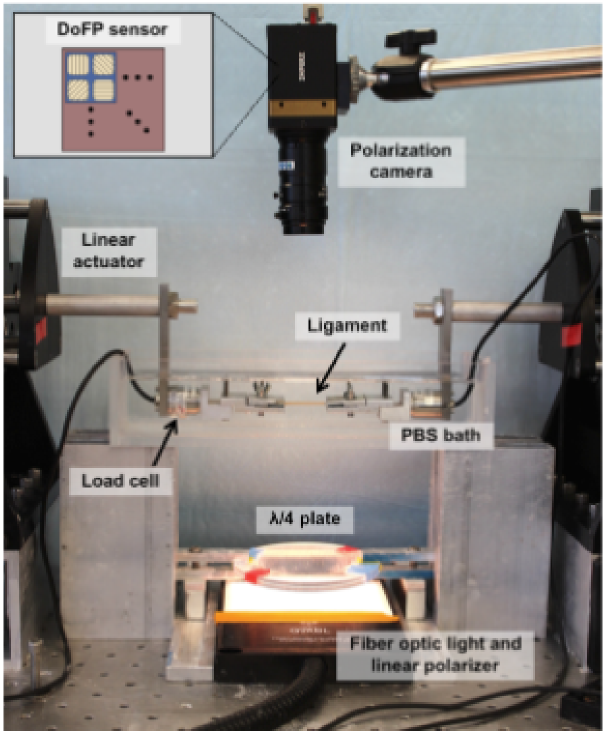


Figure 2: Automated Microscope System (Source: Lake Lab Website)

More Information: https://lakelab.wustl.edu/research/quantitative-polarization-imaging/

Description: The current solution the Lake lab uses a metal boom arm attached to a ring stand. The boom arm extends over the tissue sample as seen in Fig. 2. To change the focal point of the camera requires manually adjusting the height of the boom arm on the ring stand. This design idea achieves the goal but is inefficient. Despite that, this design is a good starting point to learn what works and what doesn't. The ring stand attaches to the optical table providing a stable base and the boom arm has a fixture for attaching multiple types of cameras. Both of these features are useful and could inspire the design of the next camera system.

2.1.3 Existing Device #3: Creality Ender 3

Figure 3: Creality Ender 3 3D Printer (Source: Creality Website)

Product Page: https://www.creality.com/goods-detail/ender-3-3d-printer

Description: At first glance a 3D printer might seem radically different from a camera imaging system; however, its core function is fine control of x, y and z motion. The creality Ender 3 3D printer uses 3 stepper motors, 1 lead screw and 2 belts to control the motion of the extruder. The motion system of a 3D printer is exactly the same as the design criteria except it has a filament extruder instead of a camera. The Creality 3D printer is a budget 3D printer that could help to pick parts and inspire the motion system for the final product.

2.2 Patents

2.2.1 Patent 1: 9V rechargeable battery (US7029788B2)

This patent is for a rechargeable 9V battery. Similar to other 9V batteries, this patent is for a battery containing 7 column cells of nickel and cadmium or nickel metal hydride. However, this patent has walls with cutouts to create more space for the battery cells. This allows the battery to maximize its capacity within a standard battery size. This device will likely be used to power the Arduino and some steppers in the design.

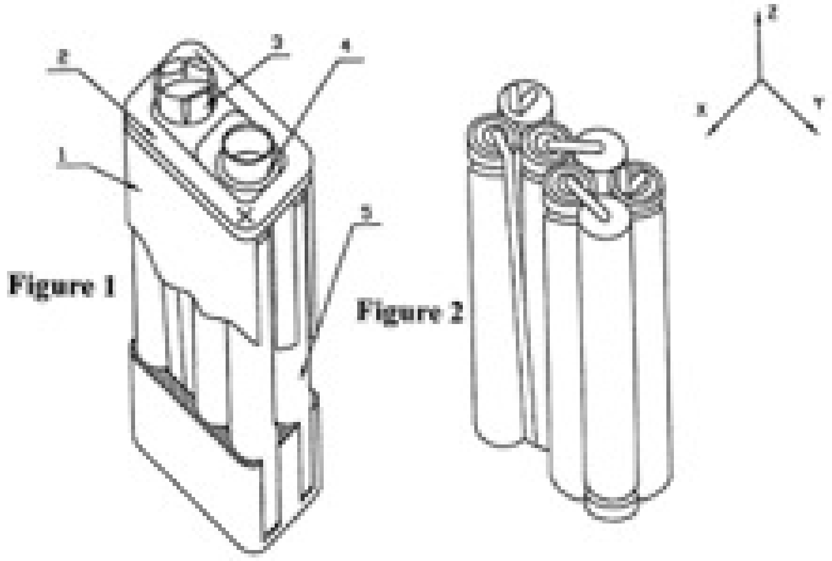


Figure 4: Patent Images for rechargeable battery

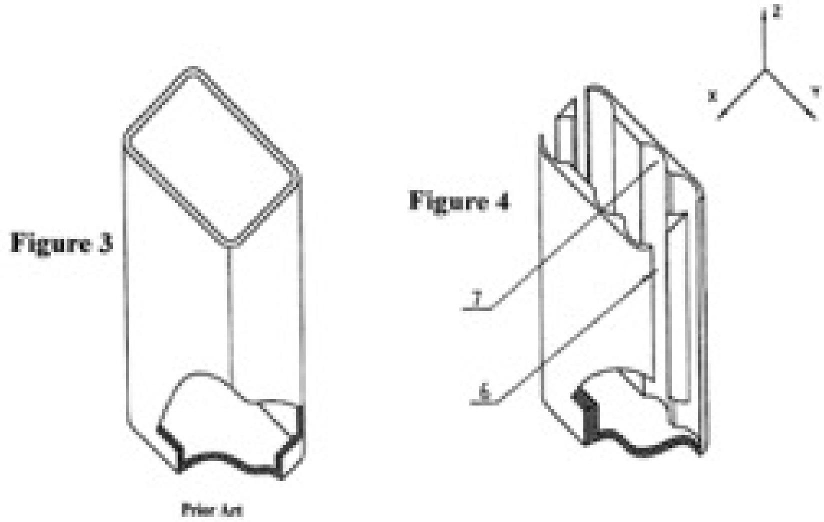


Figure 5: Patent Images for rechargeable battery shell

2.2.2 Patent 2: Automated Microscope System (US20020015224A1)

This patent is for an automated microscope with a separate light source and at least one controller and one power source. This microscope system allows the microscope to be moved in the x, y and z planes at user determined speeds. This system allows for greater stability of the microscope when in use, allowing an improved focus on the object being analyzed.

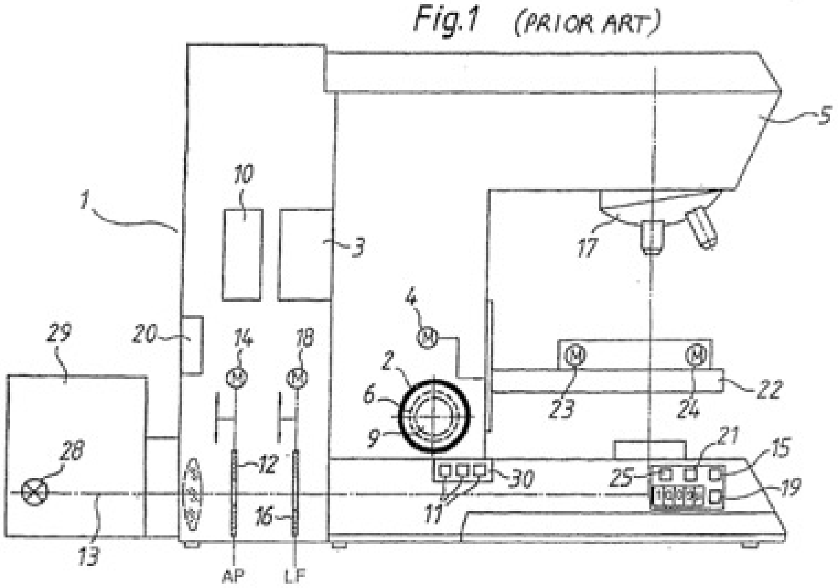


Figure 6: Patent Images for automated microscope system

2.3 Codes & Standards

2.3.1 ANSI/SLAS Microplate Standards (ANSI/SLAS 1 to 4 – 2004)

The Society for Laboratory Automation And Screening has created this standard with the American National Standards Institute for the footprint dimensions, height dimensions, bottom outside flange dimensions and well positions in well plates. These standards are important for our project design because the camera must be able to be moved over each well in a well plate being analyzed. If the camera does not have the correct x-y range then not every well can be imaged.

2.3.2 Rolling Bearings - Steel balls (ISO 3290-1:2014)

This International Standard defines the requirements for ball gauge, interval and surface defects in ball bearings. The camera stand we create must be able to move along the x, y and z axis. A large lead screw on the z-axis may not support the weight of the camera, lens and the rest of the stand. In order to distribute this force, we would need to add a rod with a ball bearing so that the device still rotates smoothly.

2.4 User Needs

For our design, we are working with the Lake lab at Washington University in St. Louis. The device will likely be used by multiple users, so our device will have to serve multiple purposes. The following outlines our interview with a member of the Lake lab and the design criteria/needs inferred from that interview.

2.4.1 Customer Interview

Interviewee: Leanne Iannucci
Location: Whitaker 350, Washington University in St. Louis, Danforth Campus
Date: February 5th, 2021
Setting: The client walked the team through what she wanted the device to be able to observe and focus on. She showed us the current set up and explained the wants of her and the other researchers. We talked to her about the several improvements and changes we could make to meet her demands. Previously, we had met with the client on December 10th so this interview only lasted around ~30 min.

Interview Notes:

Where will the device be?
- The device needs to be portable; there are two locations where the device will be used.

How do you want the device powered?
- Batteries might not be ideal, but acceptable. Plugging the device is probably the most convenient for me if I am running it for a full work day. I normally use it for around 1 hour but the longest it is set up for is like 8 hours.

Are there sizing specifics different than the current product?
- Not really. Similar sizing is fine, doesn't find it that important for my purposes.

How do you imagine operating the device?
- I want to be able to fine tune the location of the camera through a program on the computer already used. I want to have the option to come back to the same point at later points.

What are the current likes and dislikes of the product?
- I do not like the current set up. I do not like the manual design, so anything different would be good. There is an additional piece used for the lighting and if that could be added, great, but no problem otherwise.

Are there any specific materials you would prefer us to use/not use?
- I do not care that much. I do not want wood and was thinking 8030 as a possibility. Ideally, metal would be good.

How precise do the measurements have to be?
- I want to focus on a smaller plane. It will be used for 24 well plates and on slides as well. You can compare it with the EVOS life technologies microscope specs that is used to focus on the slides.

What is the range of motion required?
- I want it to move in xyz. The xy adjusts must be at least the size of the well plate. It probably will be bigger than the footprint of the 3D printer located in the lab.

What type of support does this device need to have?
- Basically, it should be similar to the current product where it supports the camera and microlens. I will send you the product number for both. I think it would be best if it fit into the board we have down right now.

What is your vision for this device?
- I am imagining a 3D printer and claw machine, so something in between. If you can figure out how to get the light fixture in your design, that would be great but not necessary.

2.4.2 Interpreted User Needs

Table 1 shows a table of the interpreted customer needs we determined from the customer interview and are ranked by importance.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	Can pan over 12-well plate	5
2	Must have saved locations	5
3	Must be portable	5
4	Support the camera and microlens	5
5	Fine control of x, y, and z positions	4
6	Run for a full workday	4
7	Made out of metal	3
8	Contain a light fixture	1

2.5 Design Metrics

These design metrics are loosely made from viewing the current project. We plan to return to the current device and set up to take measurements and more precisely get design metrics. These metrics are based on the interpreted customer needs discussed above.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	3,7	Total device weight	kg	5.5	4.5
2	1	x range	mm	128	200
3	1	y range	mm	86	100
4	2	Control Resolution	mm	< 2.0	< 1.0
5	6	Battery Life	hrs	24	∞
6	4	Max weight arm supports (camera + lens)	kg	TBD	5

Note the acceptable maximum weight the arm can support will be the mass of the camera plus the mass of lens which we are waiting to hear back from our customer on so for now it is TBD.

2.6 Project Management

The Gantt chart in Figure 7 gives an overview of the project schedule.

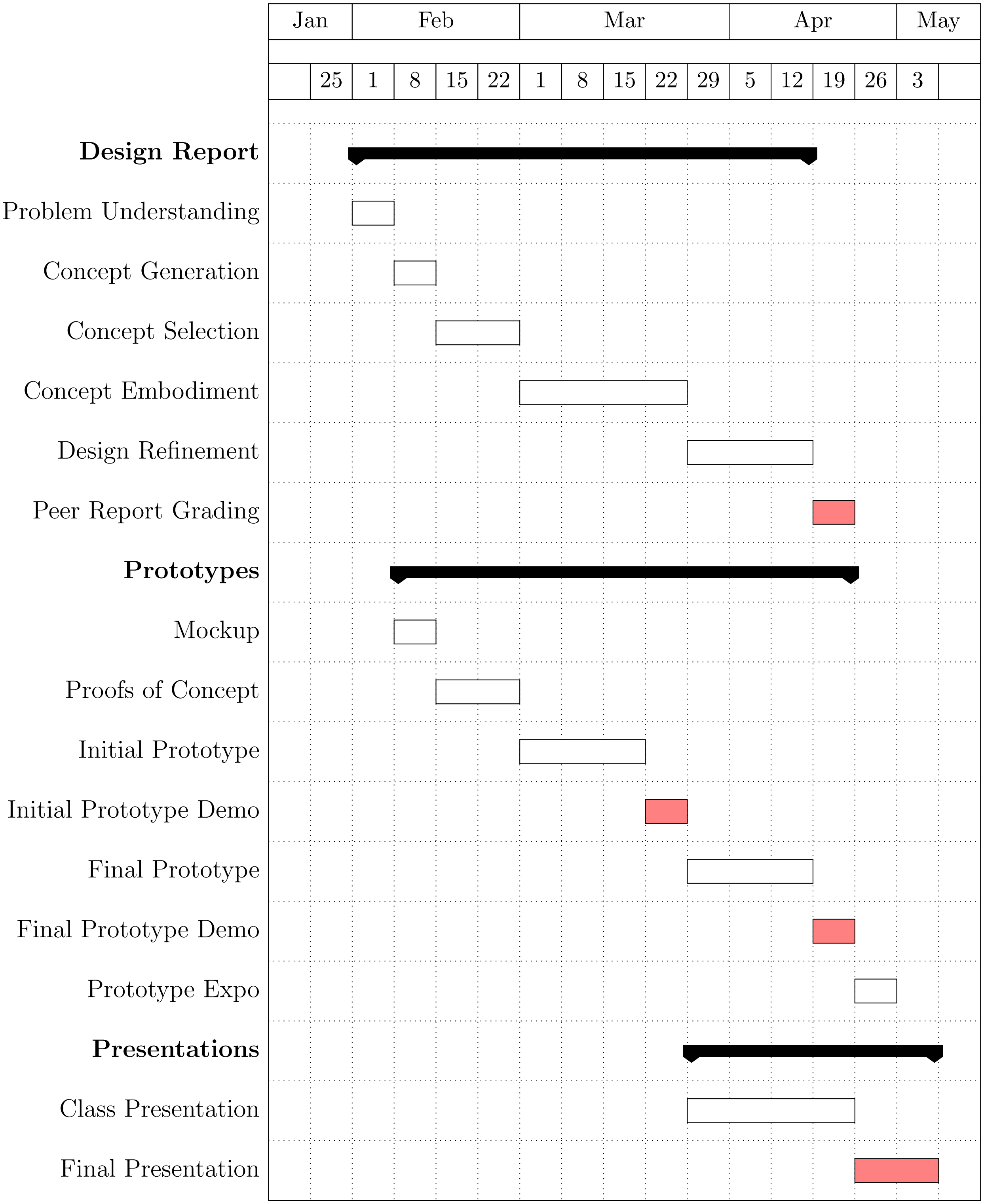


Figure 7: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

Building this prototype made us aware that the horizontal arm of the camera holder creates a large moment around the base of the device. We initially thought we would be able to place the wooden dowel in the foam to keep it vertical, but the horizontal arm of the screw kept tipping the device over. We realized that when we have stronger materials for our device, and a camera held at the end of the horizontal arm, that moment will only increase. The device will need to be held onto the lab bench with something strong, such as a screw on each corner, to prevent the camera from falling over. Our vertical arm will have to be made of a material strong enough not to break, as well. Additionally, by having one horizontal arm to move in the x and y axes, we would be able to simplify our design. However, this may lead to struggles when the user tries to move the camera over the rectangular well plates when analyzing samples.

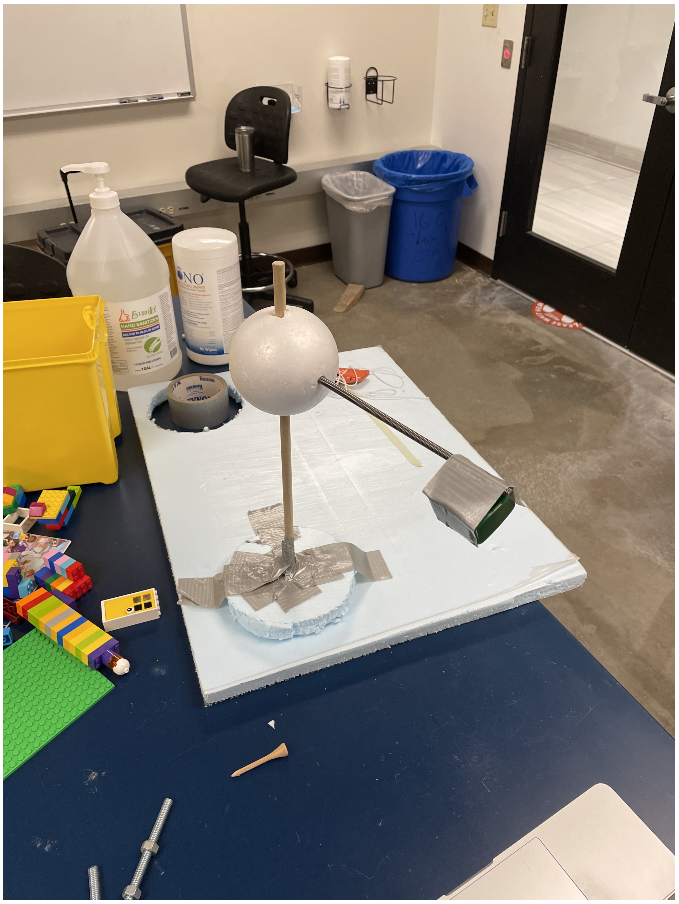


Figure 8: Prototype Isometric View

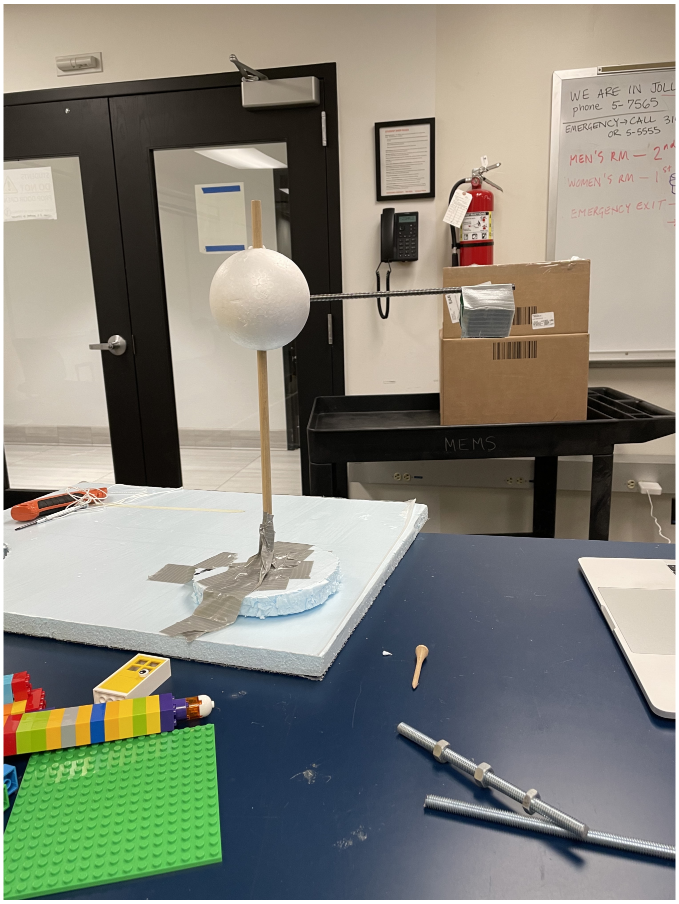


Figure 9: Prototype Side View

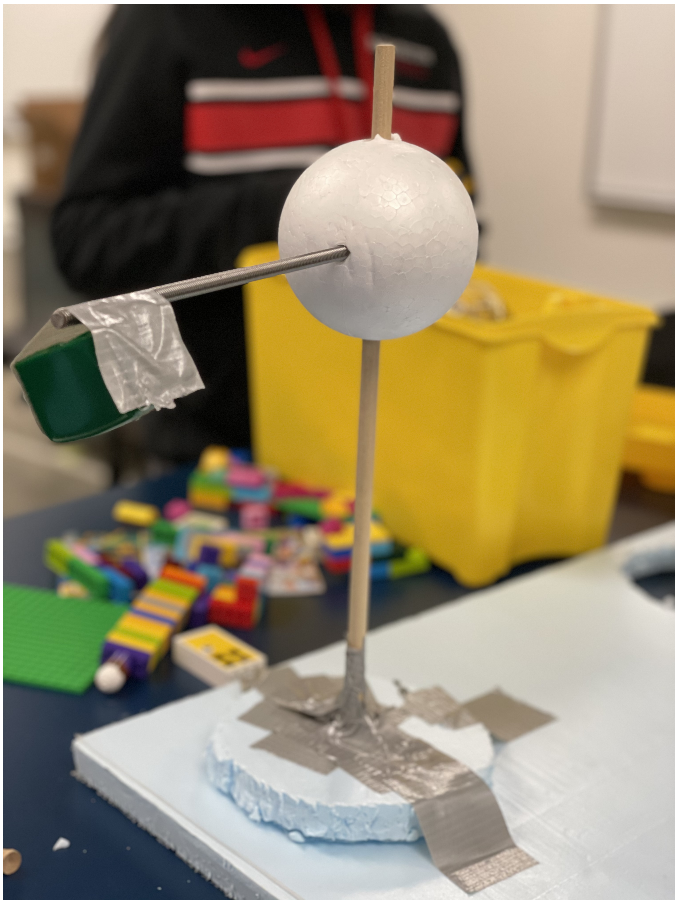


Figure 10: Prototype Front View

3.2 Functional Decomposition

Figure 8 shows the functional decomposition for the camera and microlens holder. The main function is broken up into smaller subfunctions that can be completed by a component or group of components.

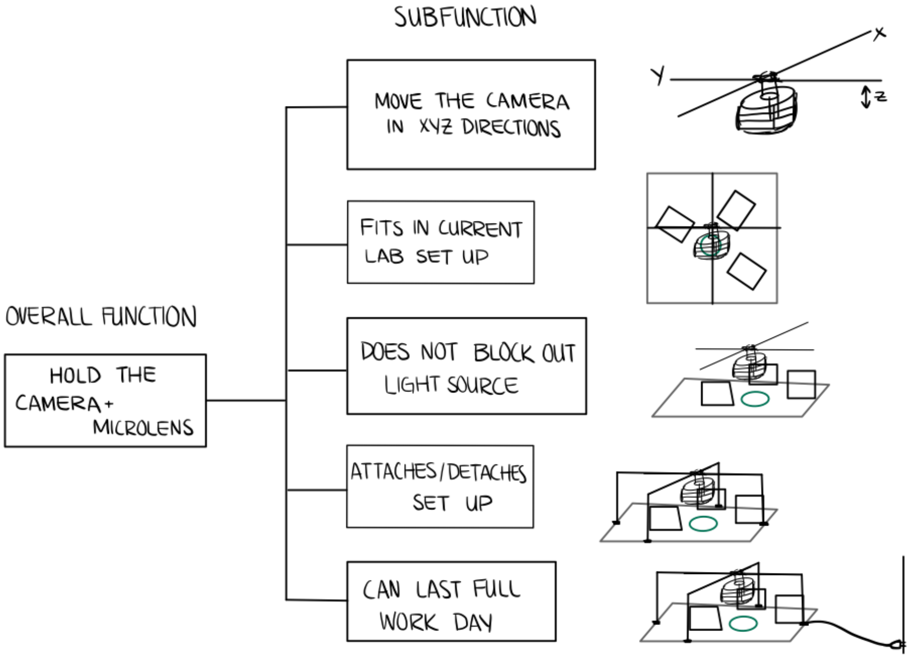


Figure 11: Function tree for camera and microlens, hand-drawn and scanned

3.3 Morphological Chart

Below is a morph chart with several ideas for how to implement the core user needs determined by the function chart and customer interview. These ideas will be compiled into a final design to create the 3-axis camera system for the Lake lab.

Figure 12: Morphological Chart for 3-axis camera system

3.4 Alternative Design Concepts

3.4.1 Cylindrical Coordinate Robot Arm)

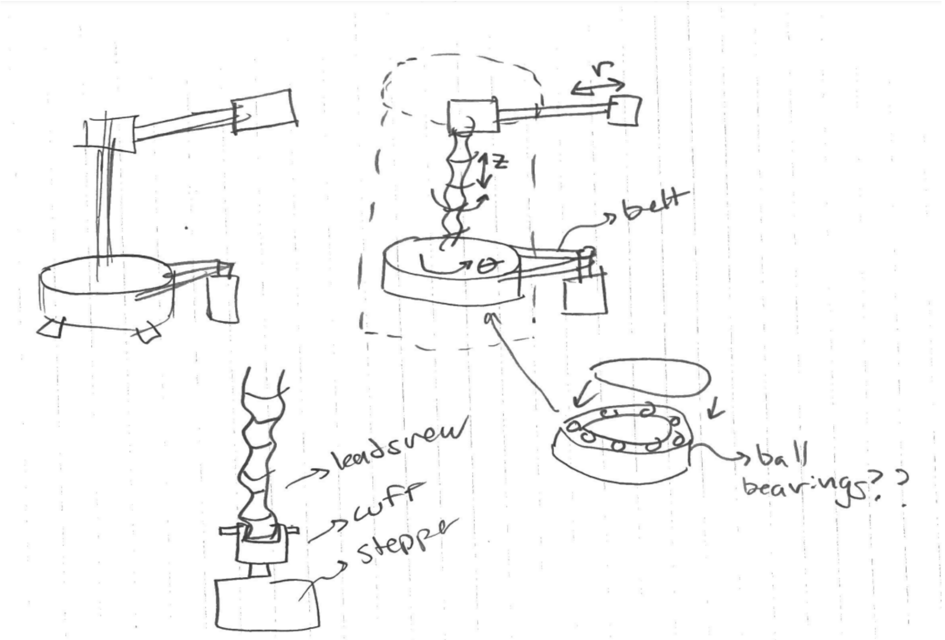


Figure 13: Preliminary sketch of a robot arm operating in cylindrical coordinates

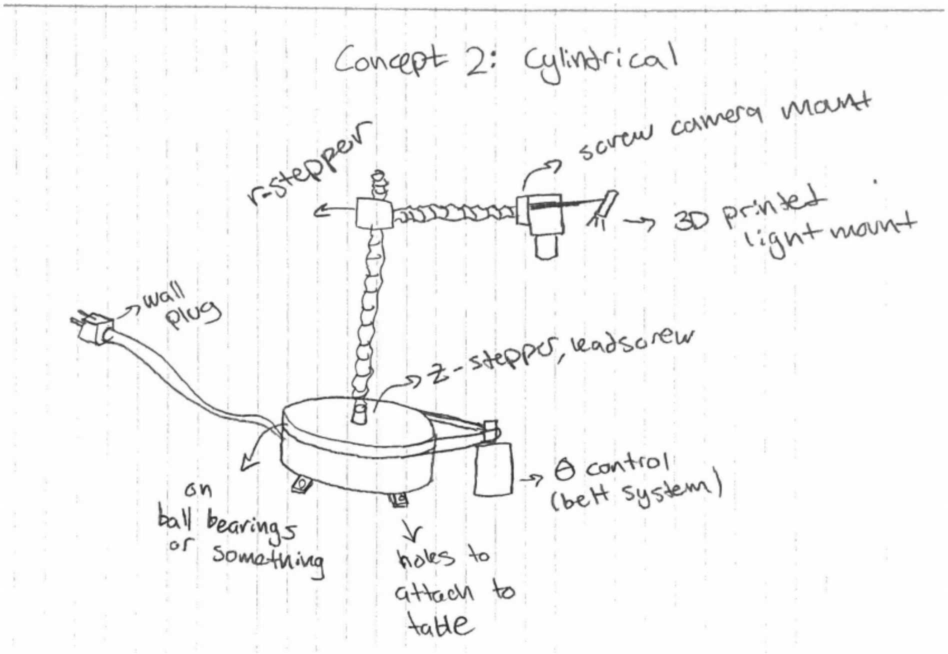


Figure 14: Final sketch of a robot arm operating in cylindrical coordinates

<u>Solutions from morph chart</u>:

1. Leadscrew for r and z axes, rotation via belt for theta axis

2. Gets power from wall
3. Holds light source with 3D printed attachment
4. Fastens to table at multiple points with screws
5. Holds camera with screw mount

Description: Each axis is controlled by an independent stepper motor. The steppers for the z and r axes (cylindrical coordinates) rotate lead screws which move the assemblies attached to the respective lead screw. The theta axis is controlled by a belt system which rotates the base of the entire system. Each stepper will be connected to wall power. From early mock ups the team determined that a large moment arm is generated by the camera arm so the base will be mounted to the table at several points with screws. Similarly, the camera will be attached the the r-assembly with a screw to provide a strong mounting force and allow for several types of cameras to be attached. Finally, a light holder will be 3D printed to fit over the camera and provide the optimal angle of light.

3.4.2 Motorized Camera Arm

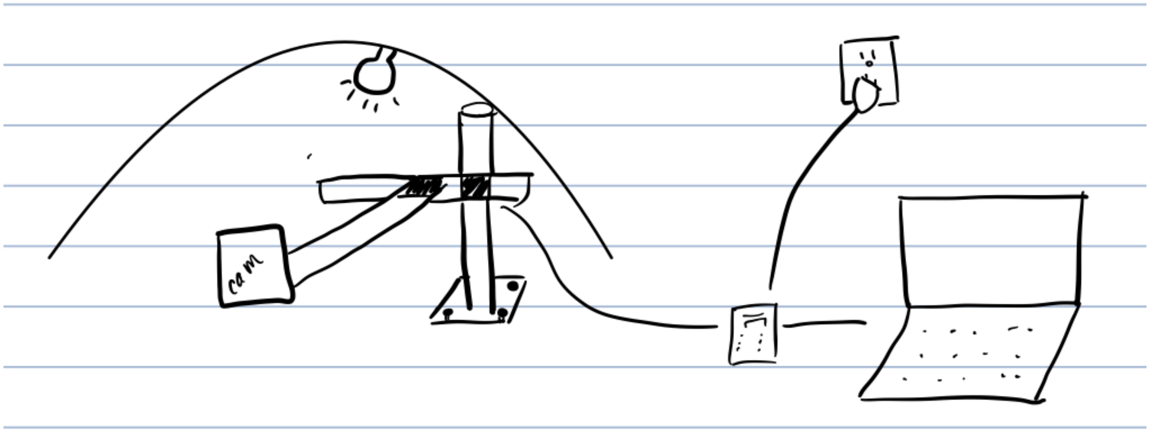


Figure 15: Preliminary sketches of Camera Stand Concept

Solutions from morph chart:

1. Motorized arms with lead screws
2. Separate structure to hold light source
3. Single base to fit in current lab setup
4. Plugged into wall outlet for power supply
5. Device is bolted onto the table with single base

Description: The device is plugged into the lab laptop and an arduino is used to program the vertical and horizontal arms so that the camera can be adjusted automatically. This allows the camera position to be replicated for studies lasting more than one day. It also allows the user to fine tune the vertical position of the camera for better focus on the tissue sample. The light source is attached to a separate structure to ensure it is at a 30 degree offset from the camera as well as to reduce the load on the camera stand. The device is plugged into the wall for power and bolted onto the table for maximum stability.

3.4.3 Table Mounted Camera System

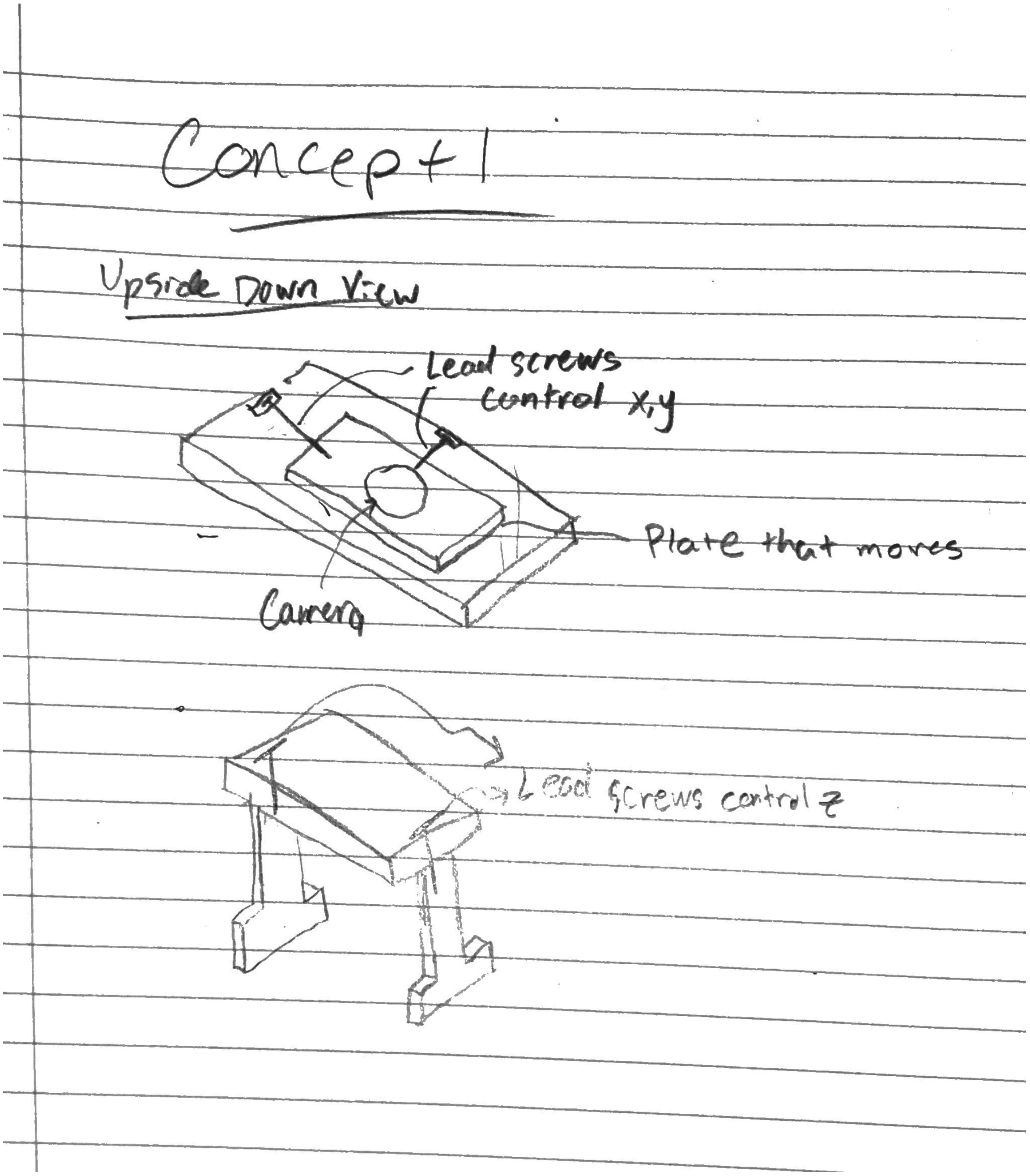


Figure 16: Preliminary sketches of Camera Stand Concept

Solutions from morph chart:

1. Camera moves in xyz directions
2. Device fits into current setup
3. Light source can be mounted on device
4. Device can be moved
5. Can be plugged into the wall

Description: The camera is attached to a plate that slides against a table-like structure. The plate is controlled by two lead screws that allow it to move in the xy plane. The height of the table is controlled by two lead screws (one for each leg). The device is controlled by an Arduino and powered by a wall outlet.

3.4.4 Table-like Camera Mount

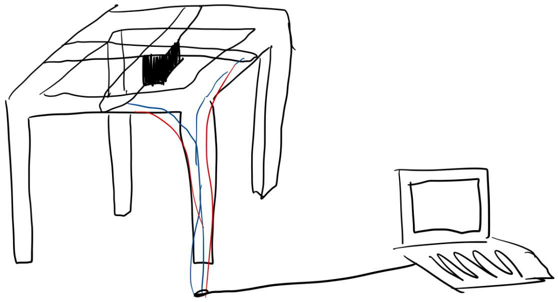


Figure 17: Preliminary sketches of Camera Stand Concept

Solutions from morph chart:

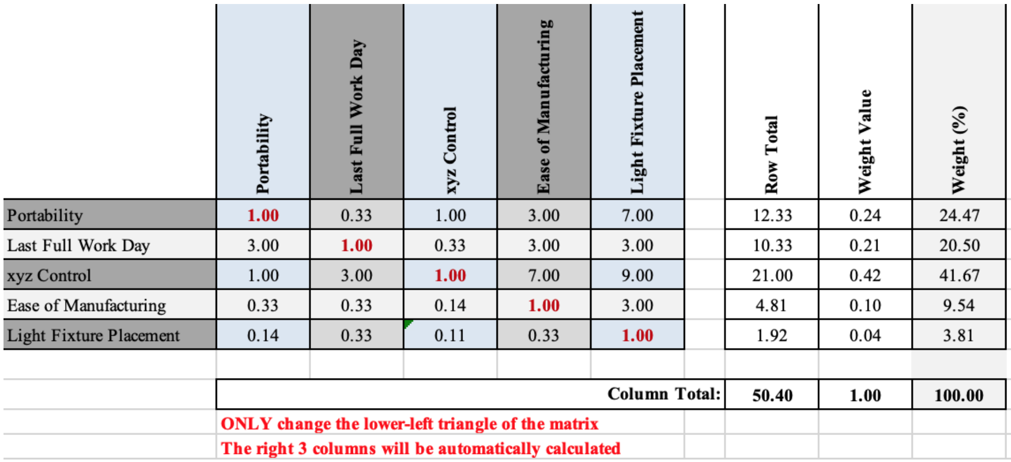
1. Unit sits on floor/table, multiple feet
2. Cartesian coordinate system
3. Arms controlled by lead screws
4. Reverse action, actively drive back
5. Battery (or connect to computer using a USB cable)

Description: The camera is attached to two rods that slide along what looks like a standard table without the top. The rods are manual and adjusted by the user. The height of the camera is lowered from its set up at the top.

4 Concept Selection

4.1 Selection Criteria

Within the realm of our design, we are not necessarily limited by certain group factors. Our project will be within budget and made from easily accessible materials. Thus, the selection criterion is similar to the needs of the customer but broaden to an overall design perspective.



	Portability	Last Full Work Day	xyz Control	Ease of Manufacturing	Light Fixture Placement		Row Total	Weight Value	Weight (%)
Portability	1.00	0.33	1.00	3.00	7.00		12.33	0.24	24.47
Last Full Work Day	3.00	1.00	0.33	3.00	3.00		10.33	0.21	20.50
xyz Control	1.00	3.00	1.00	7.00	9.00		21.00	0.42	41.67
Ease of Manufacturing	0.33	0.33	0.14	1.00	3.00		4.81	0.10	9.54
Light Fixture Placement	0.14	0.33	0.11	0.33	1.00		1.92	0.04	3.81
						Column Total:	50.40	1.00	100.00

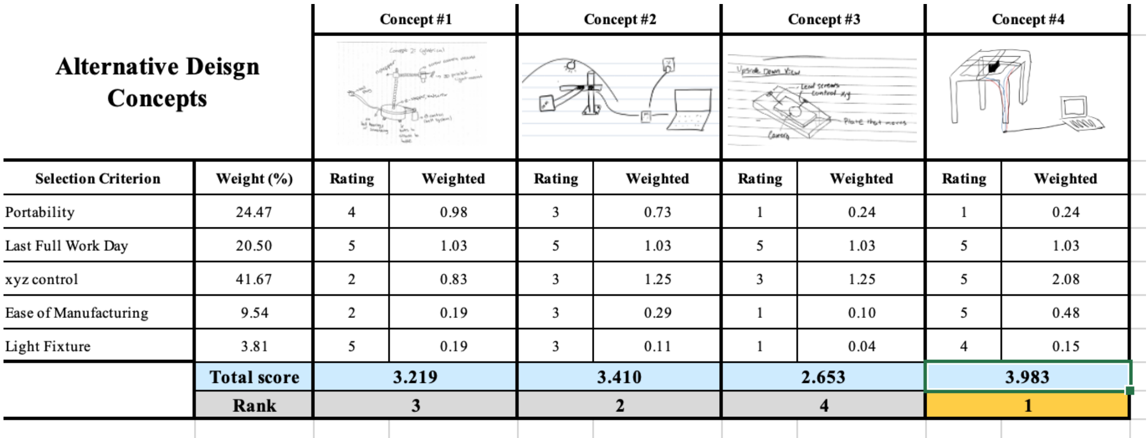
ONLY change the lower-left triangle of the matrix

The right 3 columns will be automatically calculated

Figure 18: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo.



Alternative Deisgn Concepts		Concept #1		Concept #2		Concept #3		Concept #4	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portability	24.47	4	0.98	3	0.73	1	0.24	1	0.24
Last Full Work Day	20.50	5	1.03	5	1.03	5	1.03	5	1.03
xyz control	41.67	2	0.83	3	1.25	3	1.25	5	2.08
Ease of Manufacturing	9.54	2	0.19	3	0.29	1	0.10	5	0.48
Light Fixture	3.81	5	0.19	3	0.11	1	0.04	4	0.15
	Total score	**3.219**		**3.410**		**2.653**		**3.983**	
	Rank	**3**		**2**		**4**		**1**	

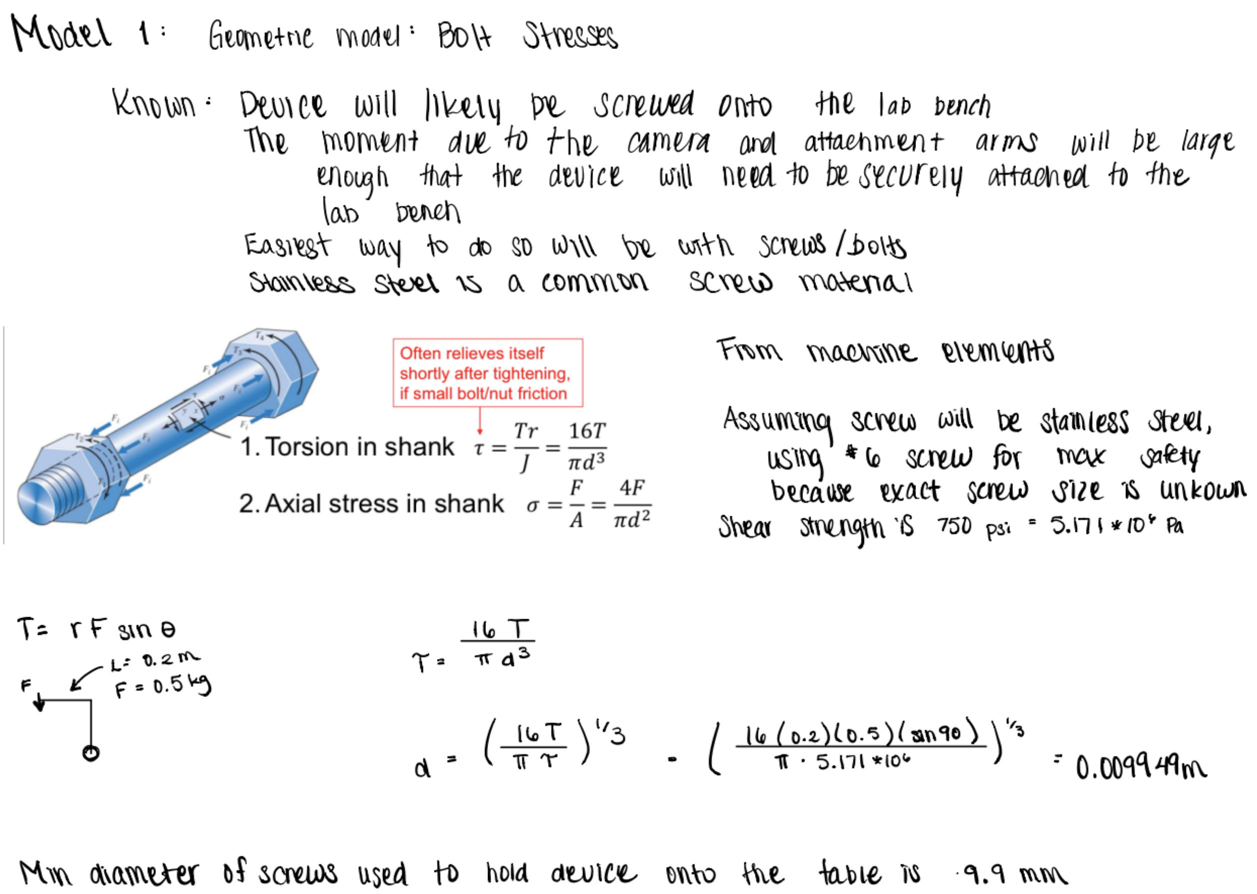
Figure 19: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

From the evaluation of each team members design using the analytic hierarchy process and weighted scoring matrix Concept 4 was chosen. It received a 1 for portability, 5 for lasting a full work day, xyz control and ease of manufacturing, and a 4 for having a light fixture. This design was given a 1 for portability because it is bulky and will be heavy. A 5 was awarded for the next three sections because the design is wall/computer powered, is constructed from 80/20 and has control of all 3 axes. The light fixture only received a 4 because the frame of the device blocks some of the light which is not ideal.

4.4 Engineering Models/Relationships

The following engineering models are applicable in ensuring that our device is functional and strong enough for real-world use.



Model 1: Geometric model: Bolt Stresses

Known: Device will likely be screwed onto the lab bench
The moment due to the camera and attachment arms will be large enough that the device will need to be securely attached to the lab bench
Easiest way to do so will be with screws/bolts
Stainless steel is a common screw material

Often relieves itself shortly after tightening, if small bolt/nut friction

1. Torsion in shank $\tau = \frac{Tr}{J} = \frac{16T}{\pi d^3}$

2. Axial stress in shank $\sigma = \frac{F}{A} = \frac{4F}{\pi d^2}$

From machine elements

Assuming screw will be stainless steel, using #6 screw for max safety because exact screw size is unkown
Shear strength is 750 psi = 5.171 * 10⁶ Pa

$T = rF\sin\theta$

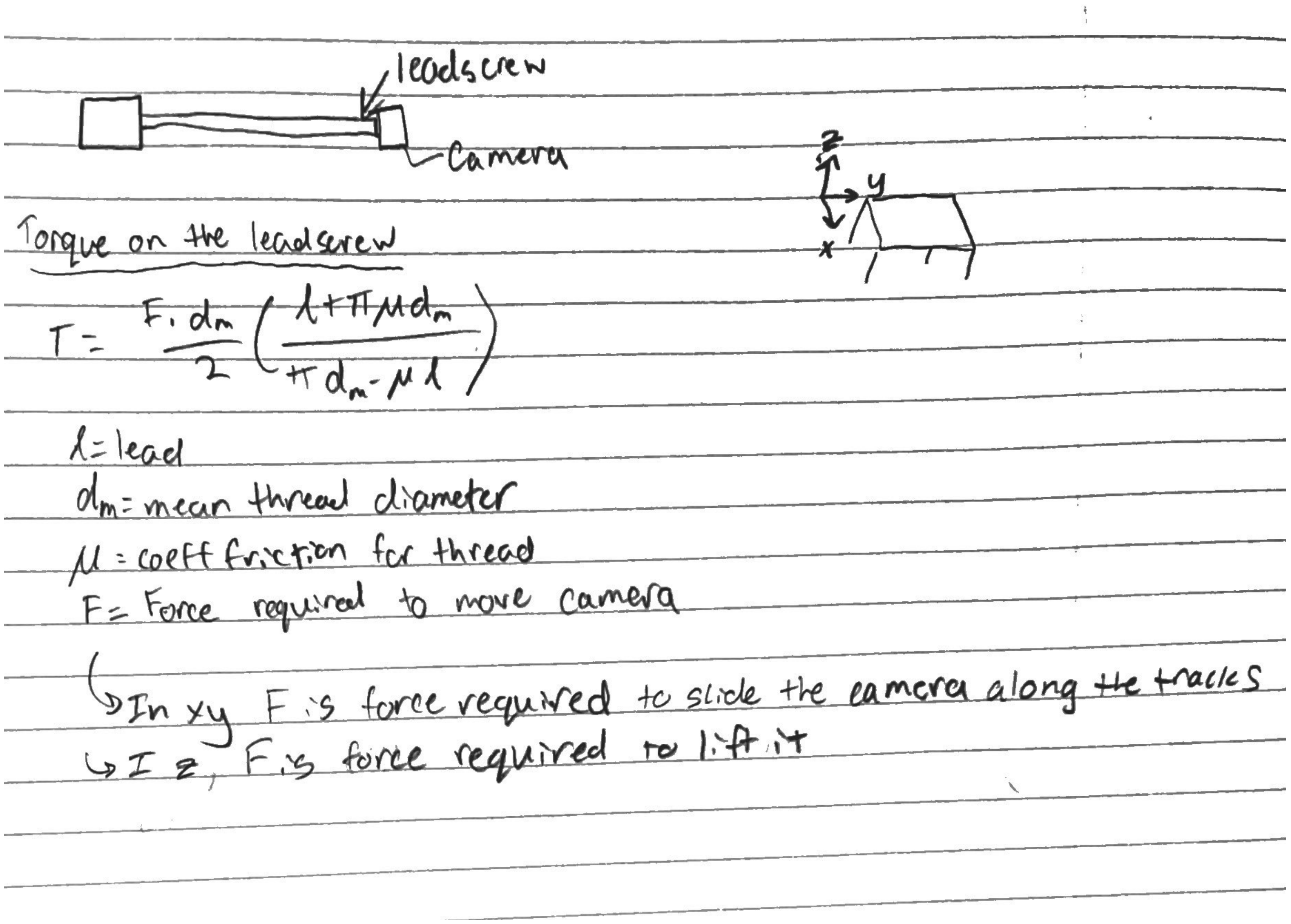
$\tau = \frac{16T}{\pi d^3}$

$d = \left(\frac{16T}{\pi \tau}\right)^{1/3} = \left(\frac{16(0.2)(0.5)(\sin 90)}{\pi \cdot 5.171 * 10^6}\right)^{1/3} = 0.009949\text{m}$

Min diameter of screws used to hold device onto the table is 9.9 mm

Figure 20: Engineering Model 1: Bolt Stresses

Description: The camera stand will be bolted onto the lab bench for a couple of the testing devices and will be mounted sideways for the Instron tensile testing. This will apply large amounts of force on the bolts used to attach the device to the lab bench. As a result, the bolts holding the camera mount onto the lab bench being used for any given form of testing must be strong enough to support both the camera and the mounting device without falling or slipping.
Source : [2]



Torque on the leadscrew

$$T = \frac{F \cdot d_m}{2}\left(\frac{\lambda + \pi \mu d_m}{\pi d_m - \mu \lambda}\right)$$

λ = lead
d_m = mean thread diameter
μ = coeff friction for thread
F = Force required to move camera
↳ In xy F is force required to slide the camera along the tracks
↳ I z, F is force required to lift it

Figure 21: Engineering Model 2: Lead Screw Torque

Description: The lead screw will be controlled by a stepper motor to move the camera around. It is important to determine the torque being applied to the lead screw so that we can use a strong enough stepper motor without adding extra weight to the device. The force required to move the camera would be different in x, y, and z so three different scenarios would have to be considered.
Source : [3]

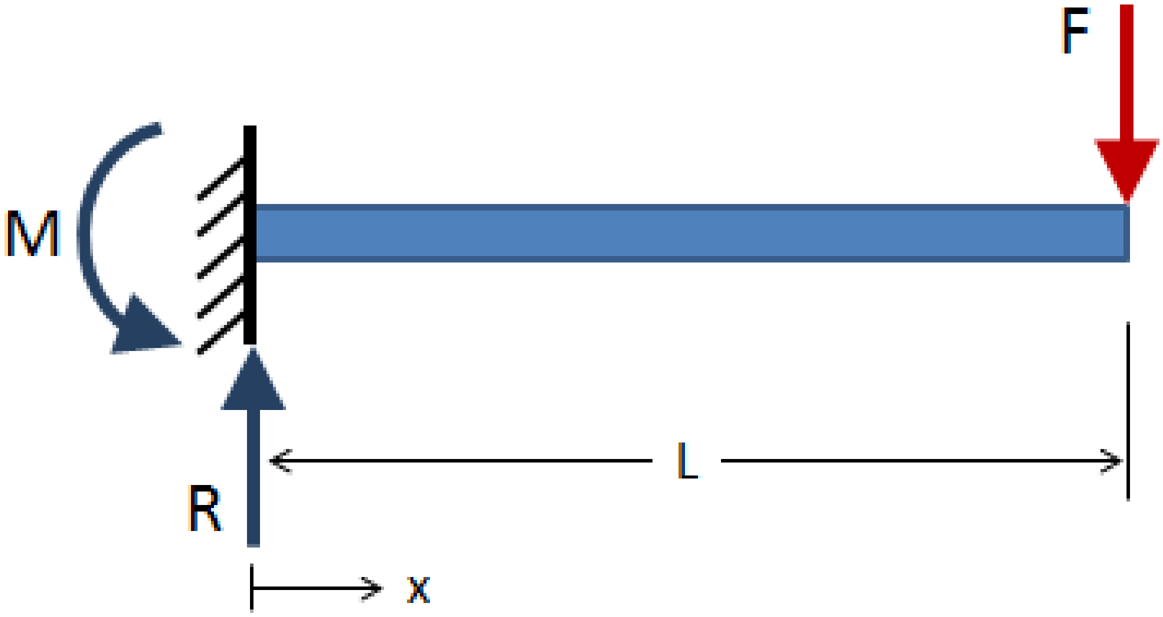


Figure 22: Engineering Model 3: A cantilever beam with applied force F, reaction Moment M and reaction force R

$$\sigma_x = \frac{-My}{I}$$

$$\delta_{max} = \frac{PL}{3EI}$$

Figure 23: Equations for normal stress due to a bending moment and the deflection of a beam under load P with Modulus of Elasticity, E, and Area Moment of Intertia, I.

Description: Beam bending theory will be extremely important to our camera system. It is likely that one of the arms will be hanging in space like in Figure 22 or maybe supported on two ends. The assumptions of linear, isotropic, and homogeneous are good assumptions because the construction materials will be steel and aluminum with a load (the camera or steppers) at the end. Furthermore, if there are large deformations then our system will simply not work so the small angle approximation will hold. The equations in Figure 23 will be useful equations for determine the deflection of each piece in our design and the stress due to the moment created by the camrea and lens.
Source : [4][5]

5 Concept Embodiment

5.1 Initial Embodiment

The following three views show the model from various angles and provide a bill of materials for constructing the 3 axis camera system. Note that the frame was removed for simplicity for the exploded view.

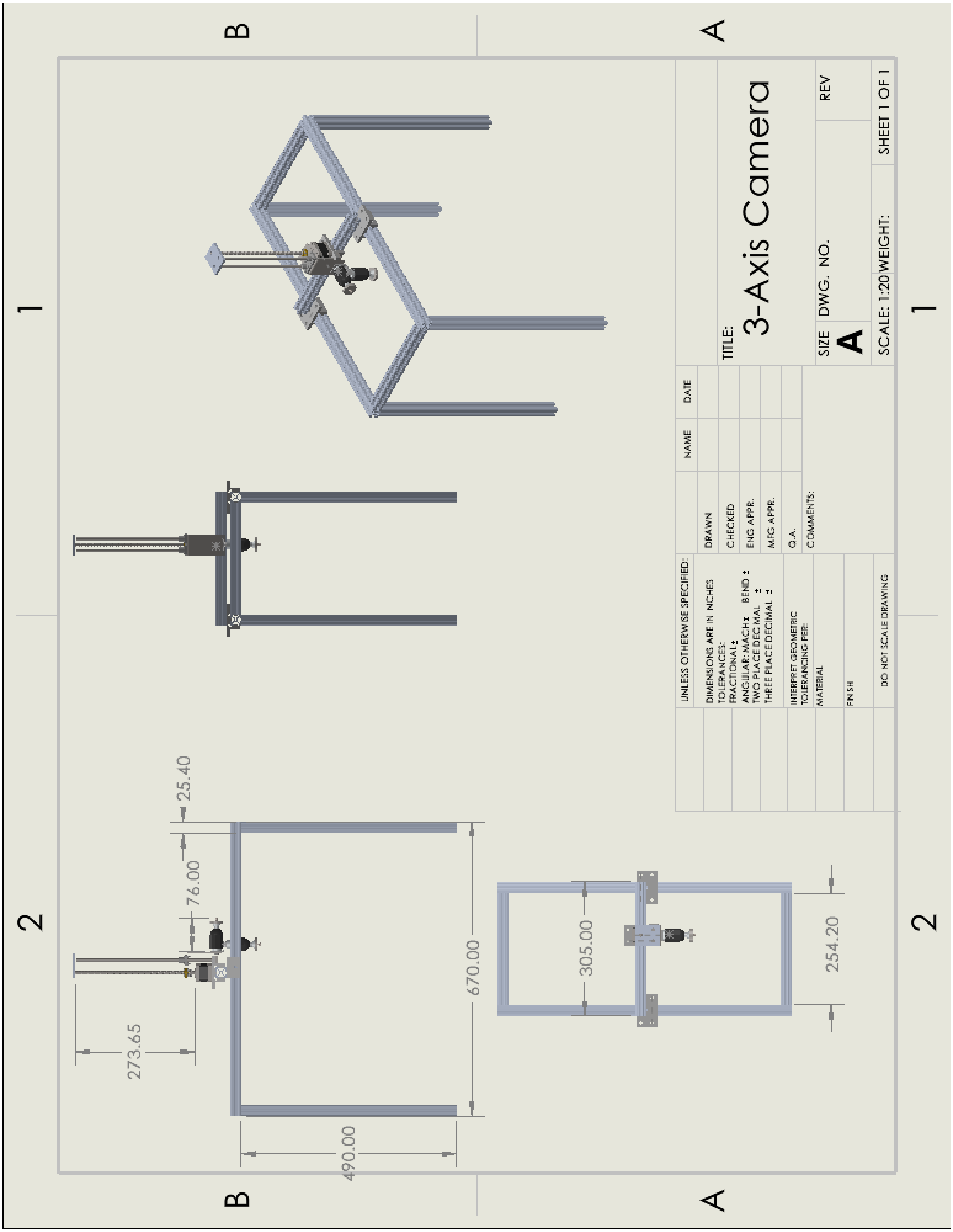
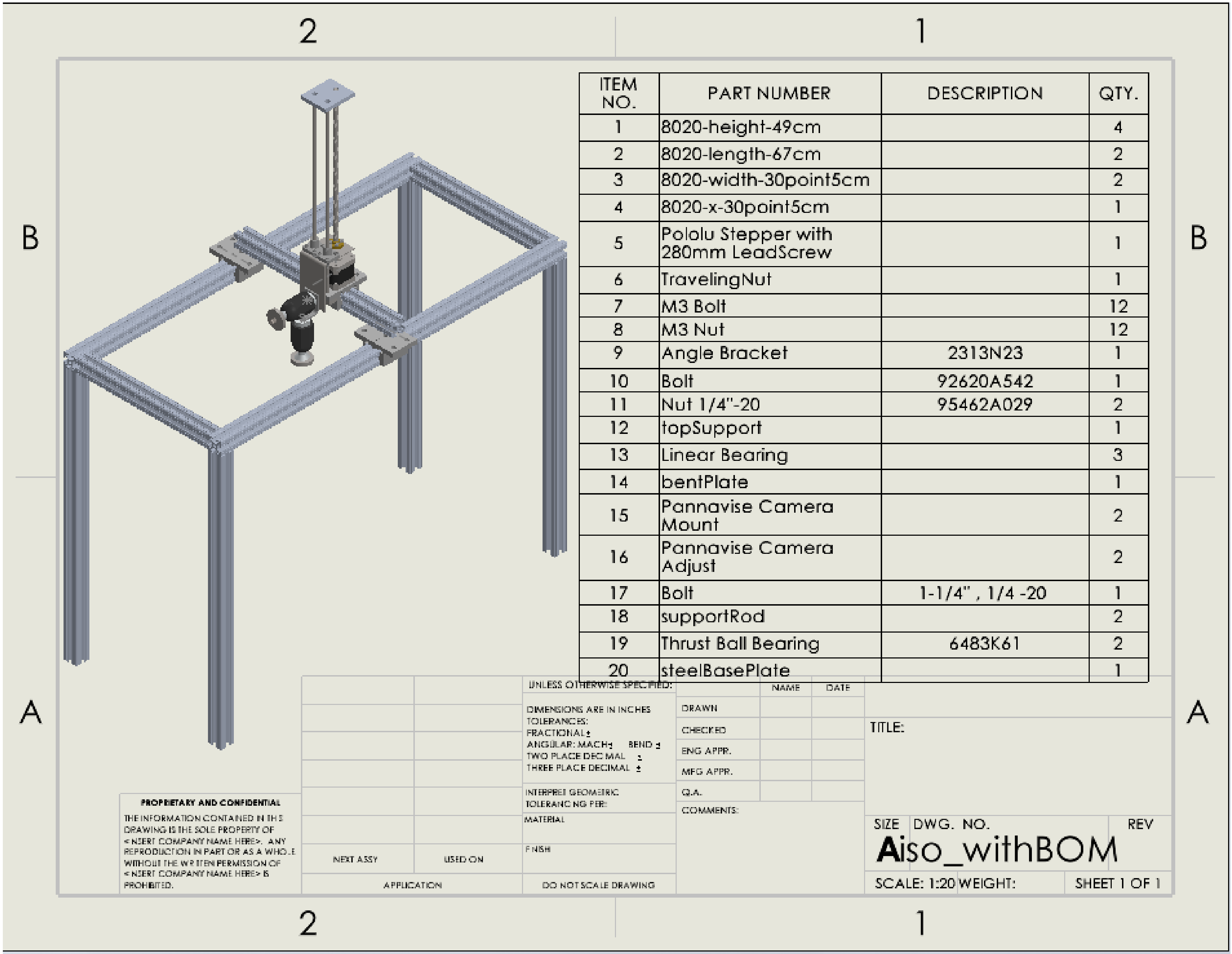


Figure 24: Assembled projected views with overall dimensions



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	8020-height-49cm		4
2	8020-length-67cm		2
3	8020-width-30point5cm		2
4	8020-x-30point5cm		1
5	Pololu Stepper with 280mm LeadScrew		1
6	TravelingNut		1
7	M3 Bolt		12
8	M3 Nut		12
9	Angle Bracket	2313N23	1
10	Bolt	92620A542	1
11	Nut 1/4"-20	95462A029	2
12	topSupport		1
13	Linear Bearing		3
14	bentPlate		1
15	Pannavise Camera Mount		2
16	Pannavise Camera Adjust		2
17	Bolt	1-1/4" , 1/4 -20	1
18	supportRod		2
19	Thrust Ball Bearing	6483K61	2
20	steelBasePlate		1

Figure 25: Assembled isometric view with bill of materials (BOM)

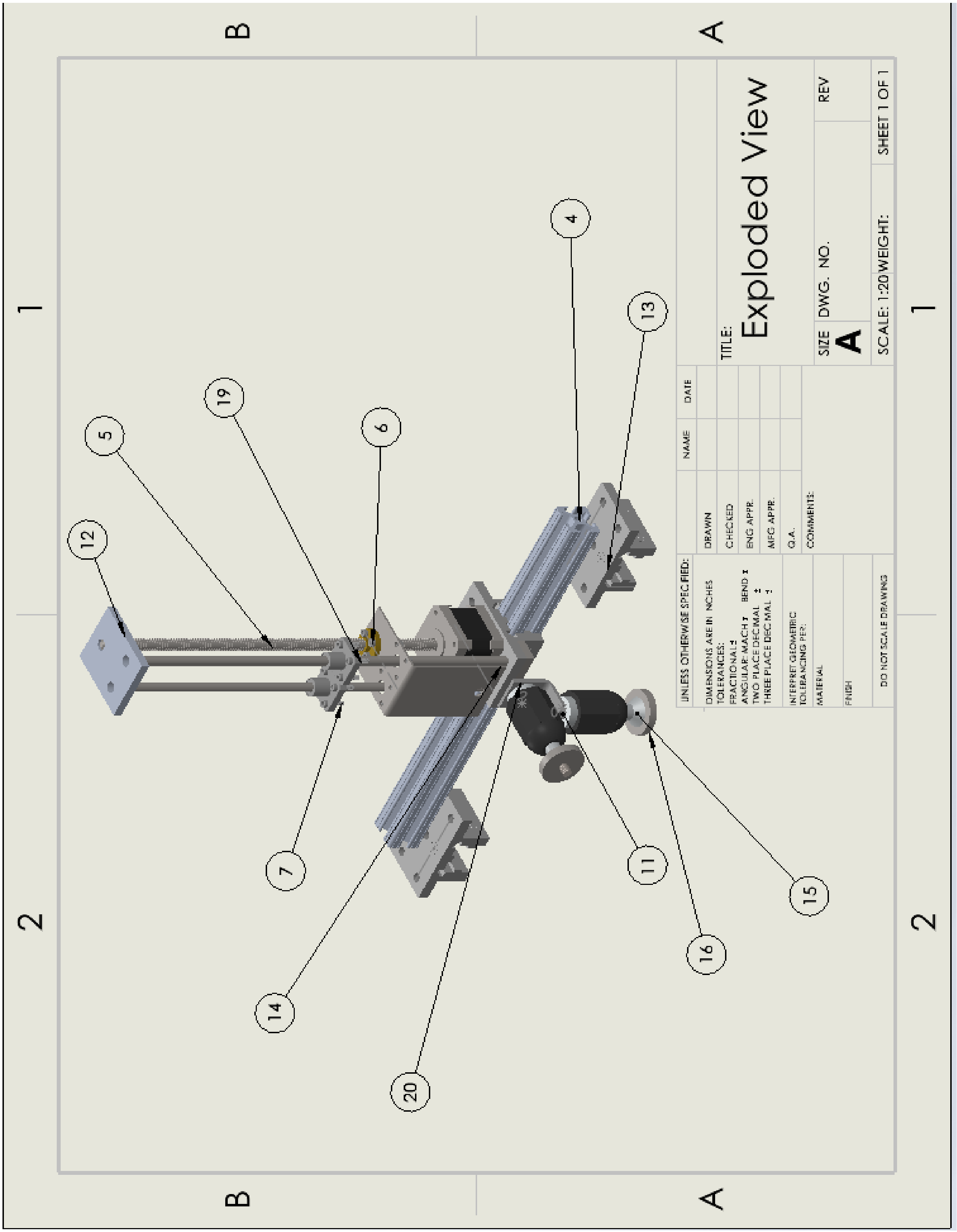


Figure 26: Exploded view with callout to BOM. Frame removed for simplicity.

5.1.1 Goals

1. The device can move a camera in the horizontal plane within a 0.1 x 0.25 meter envelope
2. The camera can be precisely (+/- 0.1 mm) positioned in vertical direction
3. The camera vertical position can be controlled from a computer interface

5.2 Proofs-of-Concept

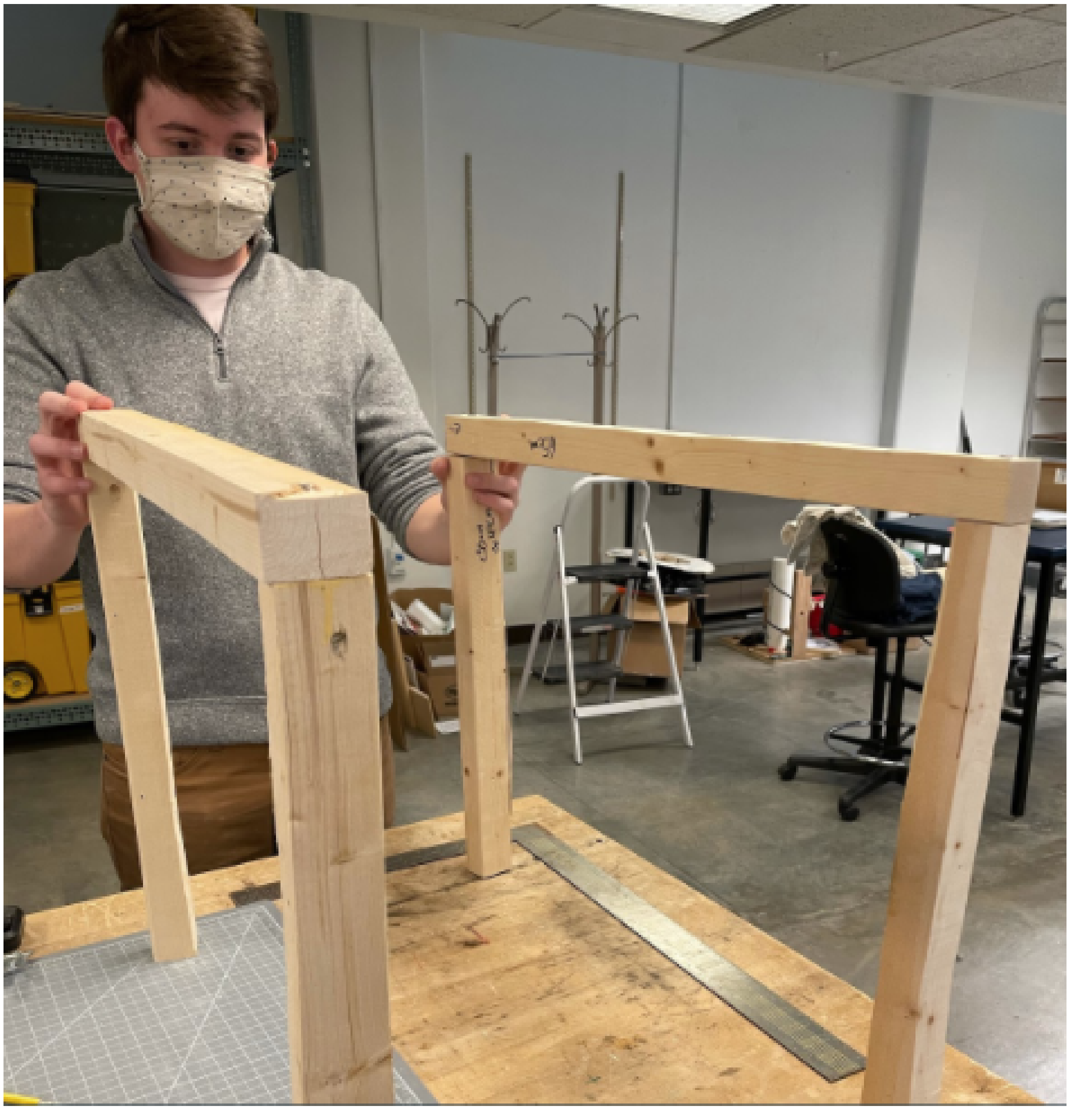


Figure 27: The proof of concept frame partially constructed

The team constructed a frame out of wood to test the various experiment setups and also used 8020 samples from the lab to test the linear motion and friction of the slide pads. The frame was built using measurements taken in the Lake lab.

5.2.1 Proof-of-Concept Testing

Through testing of the initial prototype, the team was able to finalize the structure holding the camera and micro-lens. After conversations with the client and analysis on moments, the final concept was created in CAD and partially in real life. A proof of concept was created using wood to act as the frame and random pieces of 8020 were used to test the x-y motion of linear sliders. The camera holding component was switched from a cross shape to a single bar to reduce the weight as the test frame was already very heavy. Our testing of the initial prototype also indicated that we would need to shorten the length of the legs in order to provide the desired range of motion. The testing also revealed that the stepper motor driver was under powered for the chosen stepper motor. This prevented the stepper from achieving its maximum torque. For the final, we shortened the legs, purchased a new stepper driver, and removed as much 8020 from the frame as possible.

5.2.2 Differences from Selected Concept

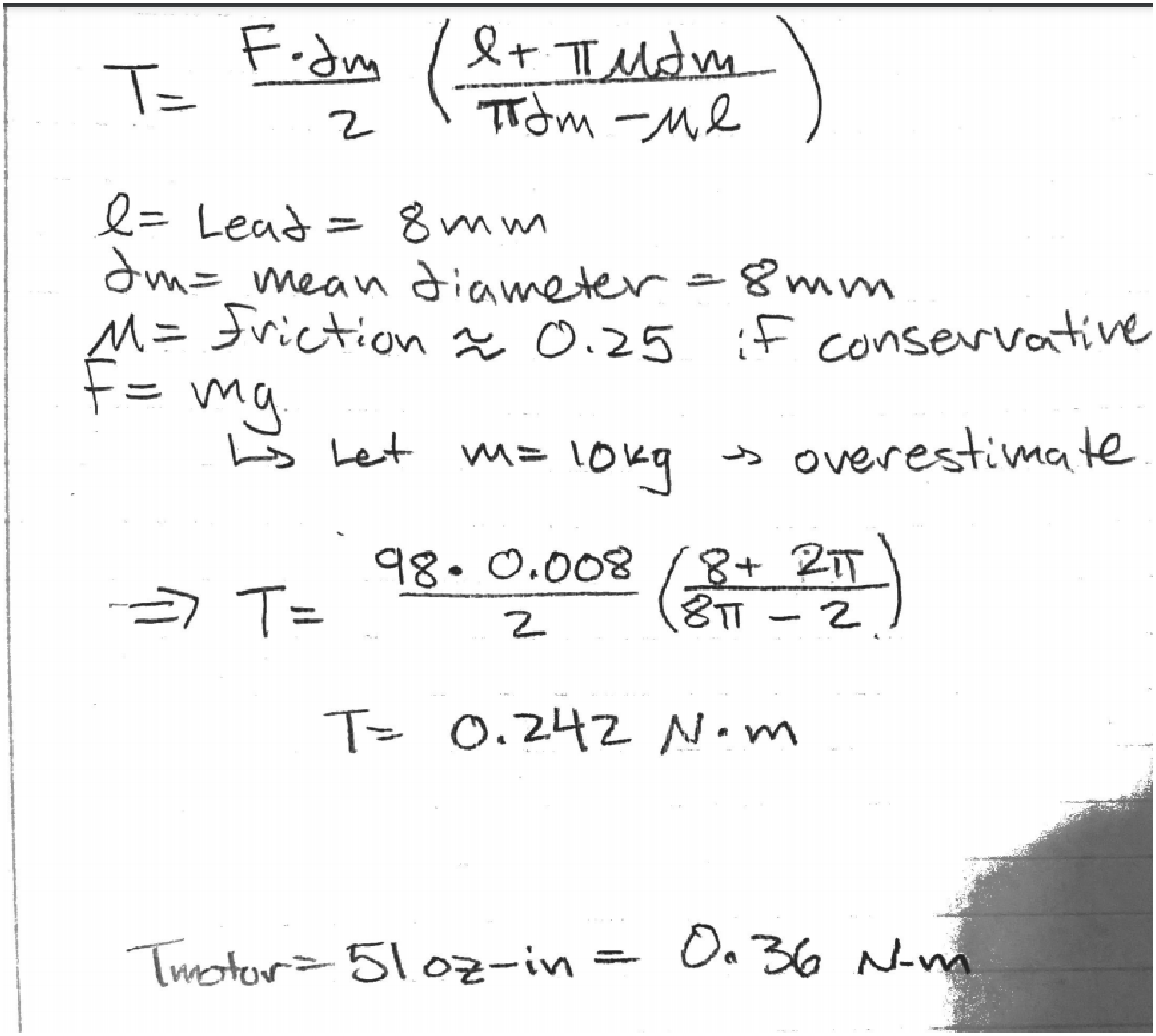
For our final design, several things were changed from the selected concept. The initial solution had lead screws in x, y, and z directions but after discussion with the customer the team decided there were too many complications. The team settled on a single lead screw to control the z-height and manual motion of x and y. With the idea to make a Cartesian robot, the team created a frame out of wood and test fit it in the various experiment conditions. Once completed, the team constructed the metal frame and tested the linear sliders given to us by the Lake lab. The linear sliders provided adequate x-y control, replacing the lead screws, and can be clamped down. Unfortunately, the components for the z-assembly could not be shipped in the given time frame so that was not tested fully. However, the CAD contains all the motion and it appears as if the design will work.

6 Design Refinement

6.1 Model Based Design Refinement

6.1.1 Lead Screw Torque Model

From the lead screw torque model the team was able to choose a motor based on the following calculation:



$$T = \frac{F \cdot d_m}{2}\left(\frac{l + \pi \mu d_m}{\pi d_m - \mu l}\right)$$

l = Lead = 8mm

d_m = mean diameter = 8mm

μ = friction ≈ 0.25 if conservative

$F = mg$

↳ Let $m = 10$kg → overestimate

$$\Rightarrow T = \frac{98 \cdot 0.008}{2}\left(\frac{8 + 2\pi}{8\pi - 2}\right)$$

$T = 0.242$ N·m

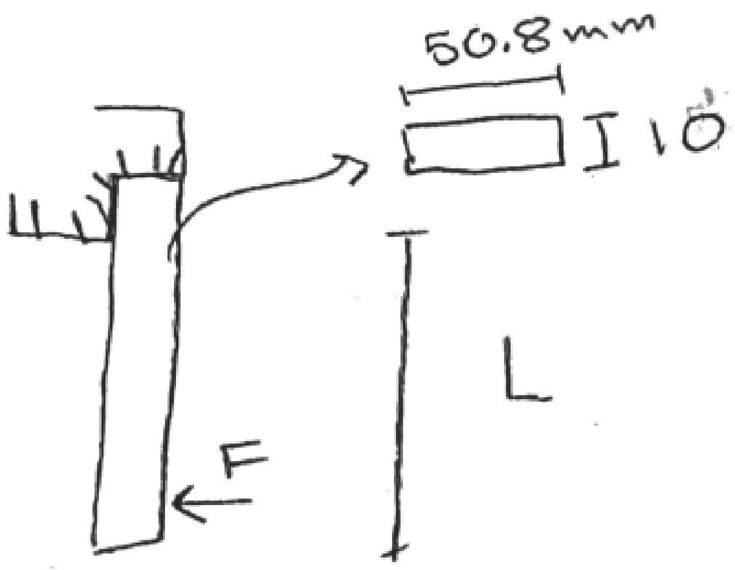
$T_{motor} = 51$ oz-in $= 0.36$ N-m

Figure 28: Math for lead screw torque

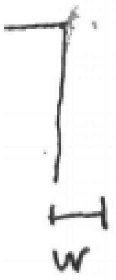
This model told us that our motor torque was greater than the torque necessary to raise a mass which was an overestimate. This gave us the confidence to purchase a motor early and begin testing. For this calculation the friction factor was chosen to be the maximum for dry steel even though we will lubricate the steel. The mass of the camera system was also overestimated as 10kg. All of this ensures our motor will have enough torque.

6.1.2 Deflection Model

For the final prototype, we added a 3D printed t-shaped piece to the stepper motor to hold the camera below the motion system. From the deflection model we calculated the deflection of the camera mount. If the mount bends too far in it will hit the plate where the stepper motor rests. This would cause the stepper motor to stall and would be catastrophic. Therefore, the maximum allowable deflection must be less than the gap that currently exists between the two.



$L = 1.5$ cm
$w = 2$ cm
$F \approx 5$N



-Deflection must be smaller than w
-Material is PLA
$\Rightarrow E = 3.5$ GPa

$$\delta_{max} = \frac{FL}{3EI}$$

$$\rightarrow I = \frac{bh^3}{12} = 4.233 \cdot 10^{-9}\ m^4$$

$$\delta_{max} = \frac{5 \cdot 0.15}{3 \cdot 3.5 \cdot 10^9 \cdot 4.233 \cdot 10^{-9}}$$

$$= 0.01687m$$

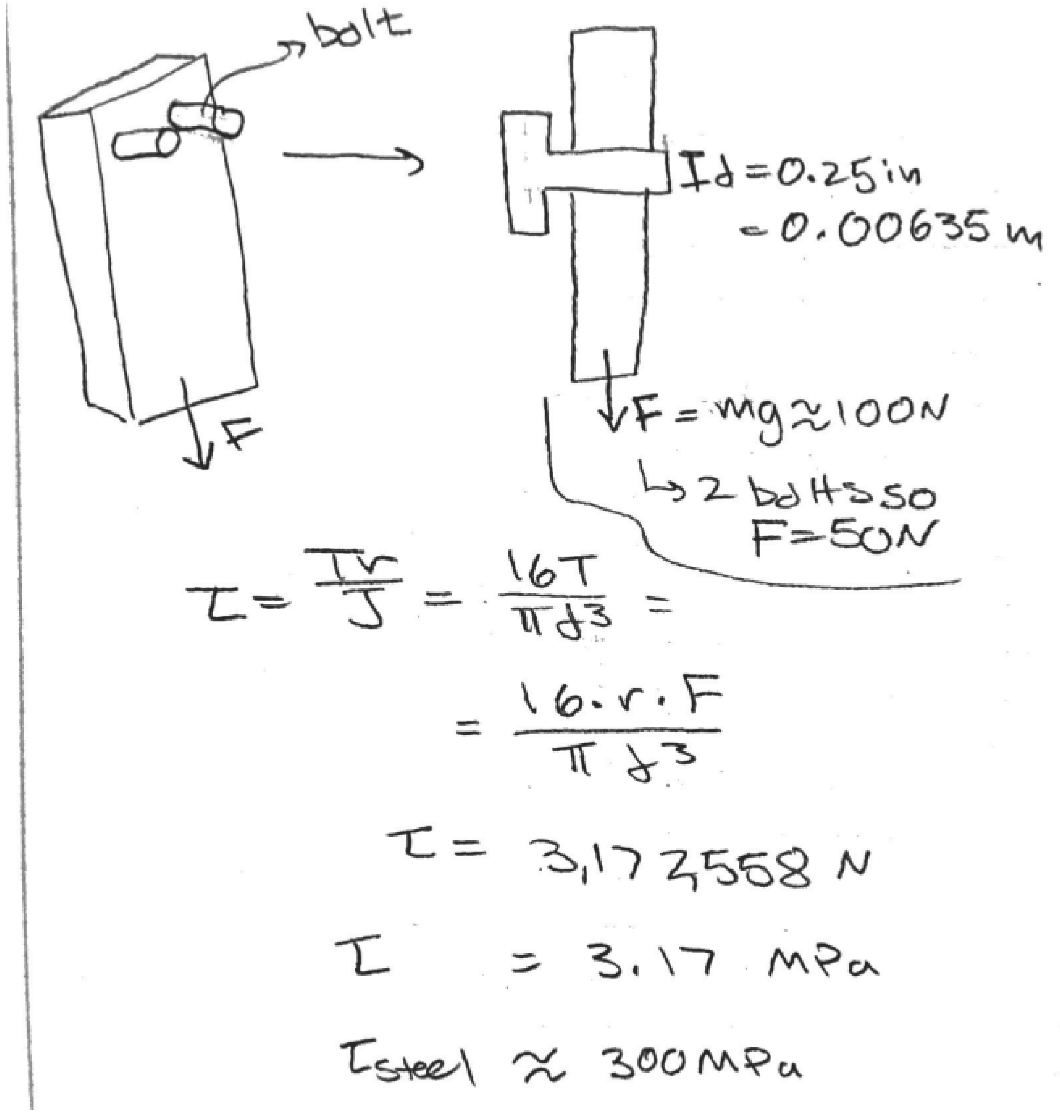
$$= 1.687cm$$

Figure 29: Math for beam deflection. L = length of beam. F = applied force. w = gap, I = area moment of inertia

From this math we see that the deflection is less, but not by much. We will likely machine a thin steel plate as a backer or print the camera mount to be thicker. This would increase the thickness from 10mm therefore decreasing the maximum deflection

6.1.3 Bolt Shear Stress

The camera mount and several other connections are supported purely by bolts. The camera mount is a critical component and cannot fail. Therefore, we calculated the shear stress in each bolt to be sure they would not fail.



$$\tau = \frac{Tr}{J} = \frac{16T}{\pi d^3} =$$

$$= \frac{16 \cdot r \cdot F}{\pi d^3}$$

$$\tau = 3,172,558\ N$$

$$\tau = 3.17\ MPa$$

$$\tau_{steel} \approx 300\ MPa$$

Figure 30: Math for bolt shear. Tau = shear stress, T = torque, d = diameter, F = applied force

The shear felt by the bolt was 100 time less than the shear strength of steel. The bolts failing will not be a problem.

6.2 Design for Safety

Below are the design considerations we made to keep everyone safe.

6.2.1 Risk #1: Electrical Fire

Description: The three axis camera system uses several off the shelf electronics components. The wire gauges and motor were chosen to be within the current limits of the system; however, the motor and wires do get hot sometimes. In fact, we had to buy thicker wires because the original ones melted plastic components in the build. If the wires were to burn that would be catastrophic and prevent the device from working and possibly hurt or kill people. That said, the wires were tested and this should not happen.

Severity: Catastrophic

Probability: Seldom

Mitigating Steps: To mitigate this risk we purchased wires that were much thicker than needed and also bought heat sinks to put on the electrical components. This allowed the current in the system to be high without melting components. The motor will just get hot, but it is not near any components and does not get hot enough to burn.

6.2.2 Risk #2: Stepper Motor Stall

Description: The stepper motor will continue to spin even if it hits an obstacle. The motor has no way to know if it is stuck or not. This will cause the motor to heat up because the torque is maxed out and torque is related to the current draw. If the motor stalls nothing really breaks, it just has the potential to break the project prematurely.

Severity: Negligible

Probability: Negligible – if code works

Mitigating Steps: To avoid motor stall the team added a limit switch at the base of the system. The motor will calibrate itself at the beginning of every run to know its true position. Once the position is known, the software will prevent the user from moving to the motor to an invalid position.

6.2.3 Risk #3: Frame Failure

Description: The frame is constructed from several pieces of 8020 that are all screwed together. If one of the screws comes undone or if a piece failed for any reason the entire structure would be compromised. The system would be considered broken even if the camera came out of level. A failure of this type would not be a huge safety risk but could lead to significant time loss. If the frame actually broke, it is very heavy and could hurt someone if it fell apart while being moved.

Severity: Marginal

Probability: Unlikely

Mitigating Steps: The frame was constructed with extreme redundancy. Every piece is attached at 2-3 points with as many screws as possible. The hardware was also chosen to keep everything square and tight. If something on the frame makes sound when it is picked up it likely means something is loose and needs to be fixed.

6.2.4 Risk #4: Mount Failure

Description: The project will accommodate several type of cameras that all use the same mounting hardware. This hardware fails sometimes (in fact the sample the customer gave us was a failed piece of mounting hardware). If the camera breaks that would be an expensive mistake. The camera + lens is also very heavy and could easily break a finger if it fell on someones hand.

Severity: Critical

Probability: Seldom

Mitigating Steps: The mounting hardware is bought from an outside manufacturer and the customer will be instructed to replace it after numerous uses. The customer is already used to this failure mode and should be prepared for it.

6.2.5 Risk #5: Project Falling off Table

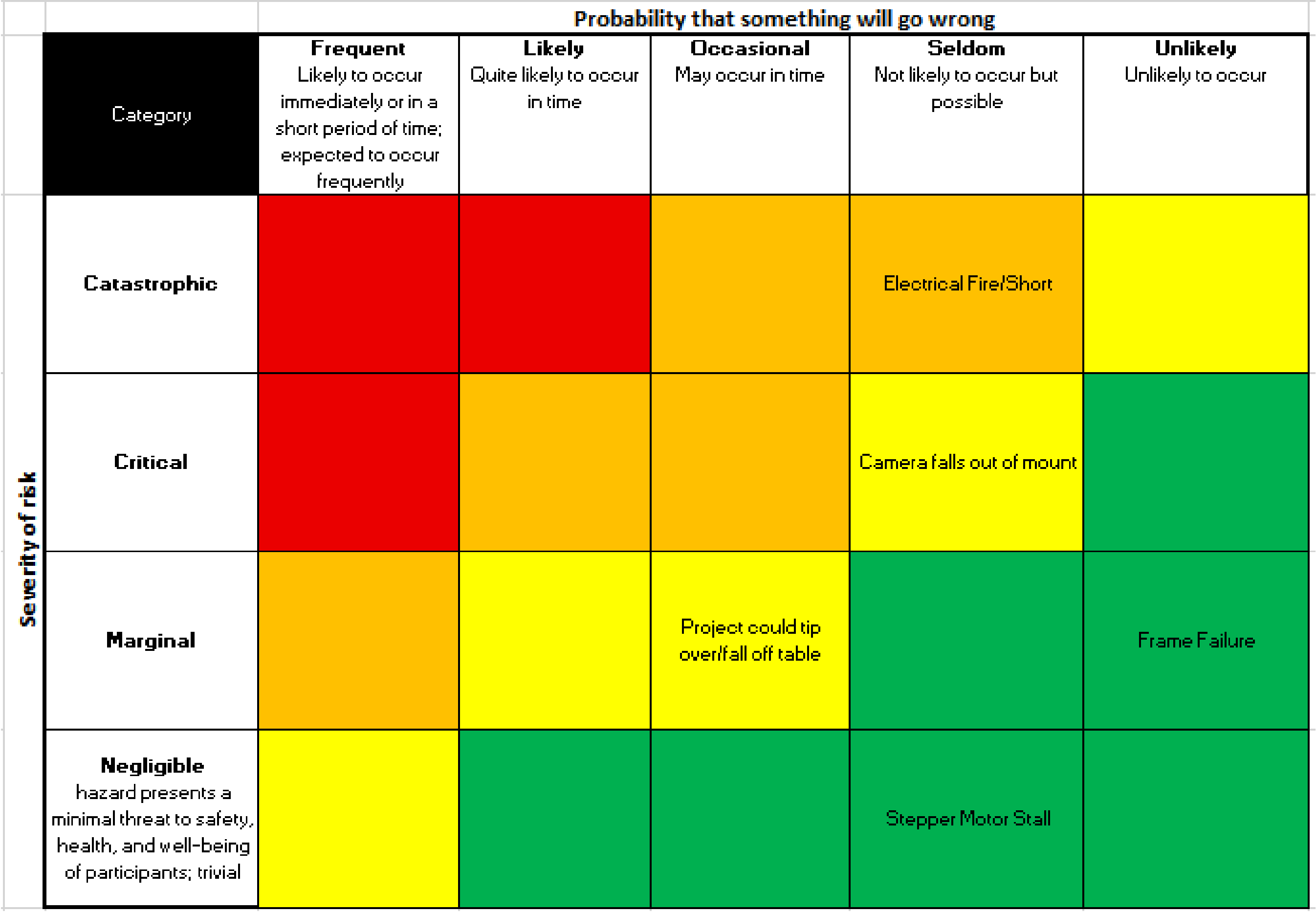
Description: The device is designed for several testing environments. Some of the environments utilize an optical table where the device can be screwed down; however, one or two use cases will require the device to free stand where it could be knocked over by humans. The stepper motor also creates strong vibrations which propagate through the frame and cause it to judder. This motion could eventually lead to the frame moving itself out of position or even falling off the table.

Severity: Marginal

Probability: Occasional

Mitigating Steps: The device will be screwed down as often as possible. Rubber feet are be used to increase the friction, reduce vibrations, and prevent the device from moving as much if it is bumped.

6.2.6 Risk Heat Map



Probability that something will go wrong

Severity of risk

Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Catastrophic	🟥	🟥	🟧	🟧 Electrical Fire/Short	🟨
Critical	🟥	🟧	🟧	🟨 Camera falls out of mount	🟩
Marginal	🟧	🟨	🟨 Project could tip over/fall off table	🟩	🟩 Frame Failure
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨	🟩	🟩	🟩 Stepper Motor Stall	🟩

Figure 31: Heat map of the safety risks described in section 6.2

6.2.7 Prioritization of Design Risks

Stepper motor stall and frame failure are risks that are mitigated extremely well. In fact, if the frame and software were done correctly, those risks should never happen. The most critical risk is an electrical fire or short. It would be very hard to tell if this is going to happen and would almost certainly cause a fire or break the device. Every wire was tested beforehand to make sure it doesn't heat up too much. If it did heat up too much it was replaced with a thicker wire. While the risk of electrical fire can be mitigated beforehand, the project falling off the table or breaking the mount is a failure mode we cannot entirely prevent. The parts used for the mount do break, and its hard to completely remove vibrations from the system. Therefore, we will instruct the customer that these risks exist and tell them how to prepare for them. In general, the device is very safe and much thought was put into keeping the customers safe.

6.3 Design for Manufacturing

Below are the parts and components required to manufacture our camera mount device.

Number of Parts: 28
Number of Fasteners: 30 not including 8020 fasteners, 100+ w/ 8020 fasteners

Theoretical Necessary Components

- Stepper motor and lead screw
- Traveling Nut
- Frame (9 Pieces)
- Linear slide bearings (x3)
- Adhesive backed ruler (x2)
- Top plate
- Support Rod Assembly
  - Support Rod (x2)
  - Linear Ball Bearings (x2)
  - Metal Plates and L-bracket (3 parts)
- Motor bracket
- Arduino
- Stepper Motor Driver
- Power Supply

The lead screw must be its own pieces because that is the central item of the project. Without the lead screw motion would not be possible. This also means the traveling nut is necessary as it allows the lead screw to transfer rotational motion into linear motion. The third essential item is the linear slider bearings. These pieces allow the project to be moved along the frame in the x and y directions. They could not be incorporated into another component and without them the friction would be a big hindrance to moving the project. The final essential component is the support rods. These rods relieve the bending moment created by the camera and allow the lead screw to rotate without binding. Without these rods the lead screw would lose accuracy and bend over time.

The design is already very close to the minimum number of components. The only clear way to reduce components would be to get a stronger support rod. This would reduce the rods and linear bearings by one. Furthermore, the platform which is attached to the lead screw currently is 3 pieces, but that could be reduced by making the entire piece out of sheet metal. This was not possible due to the manufacturing limitations of the machine shop, but in theory is an easy way to reduce pieces and manufacturing time. Also there are products to incorporate the stepper motor driver into the Arduino with a shield.

6.4 Design for Usability

6.4.1 Vision Impairment

Colorblindness will not affect this device. Only shades of grey will be used. If a user were trying to re-wire the device then color blindness would be important, but our device will be designed to be final when the customer receives it. If a user has poor eyesight for any reason, the UI might be hard to use if the text is small. To fix this the controls on the UI could be large and obvious to use (good design language).

6.4.2 Hearing Impairment

This should have a marginal impact on our device. Sound is not a feature of the device and it can be fully operated if a user is deaf. That said maybe a stepper gets stuck and the sound queue for that would go unnoticed by a deaf user. However, they could still notice the leadscrew not spinning, so this is not something we need to design around.

6.4.3 Physical Impairment

If a user was trying to perform maintenance, then a physical impairment would be a problem. However, the device will be robust and should not need to be attended to often. Also, the device will be operable from a UI (probably, nothing final yet) so if the user can use a mouse then operating the device should be no problem. Moving the device to a different testing environment could be impossible for some users; however, the strength of the frame cannot be compromised so that user would need to find help to move the device. Wheels or a carrying handle could be added to mitigate this problem.

6.4.4 Control Impairment

This should be a non-issue. The final product will not allow the user to operate the device in a manner that is unsafe or that the device is not capable of handling. The x, y, and z motion will be capped to the length of each lead screw so no one could unintentionally break the device with an erroneous input. The user might not type the right number into the UI, but if a user is too tired or drunk to type three numbers, they should not be performing rigorous scientific experiments anyway.

7 Final Prototype

7.1 Overview

Our final prototype looks much like the CAD embodiment in Fig 26. The final design was a Cartesian robot with a motorized z-axis that could be controlled through a computer program. The z-axis was tunable to sub-millimeter accuracy and the x-y axes could be positioned manually. The final design worked well and has a new home in the Lake lab.

7.2 Documentation

The prototype is made of 80/20, with four vertical legs connected by a rectangular frame. The stepper motor and lead screw are set on a horizontal bar that slides along the frame.

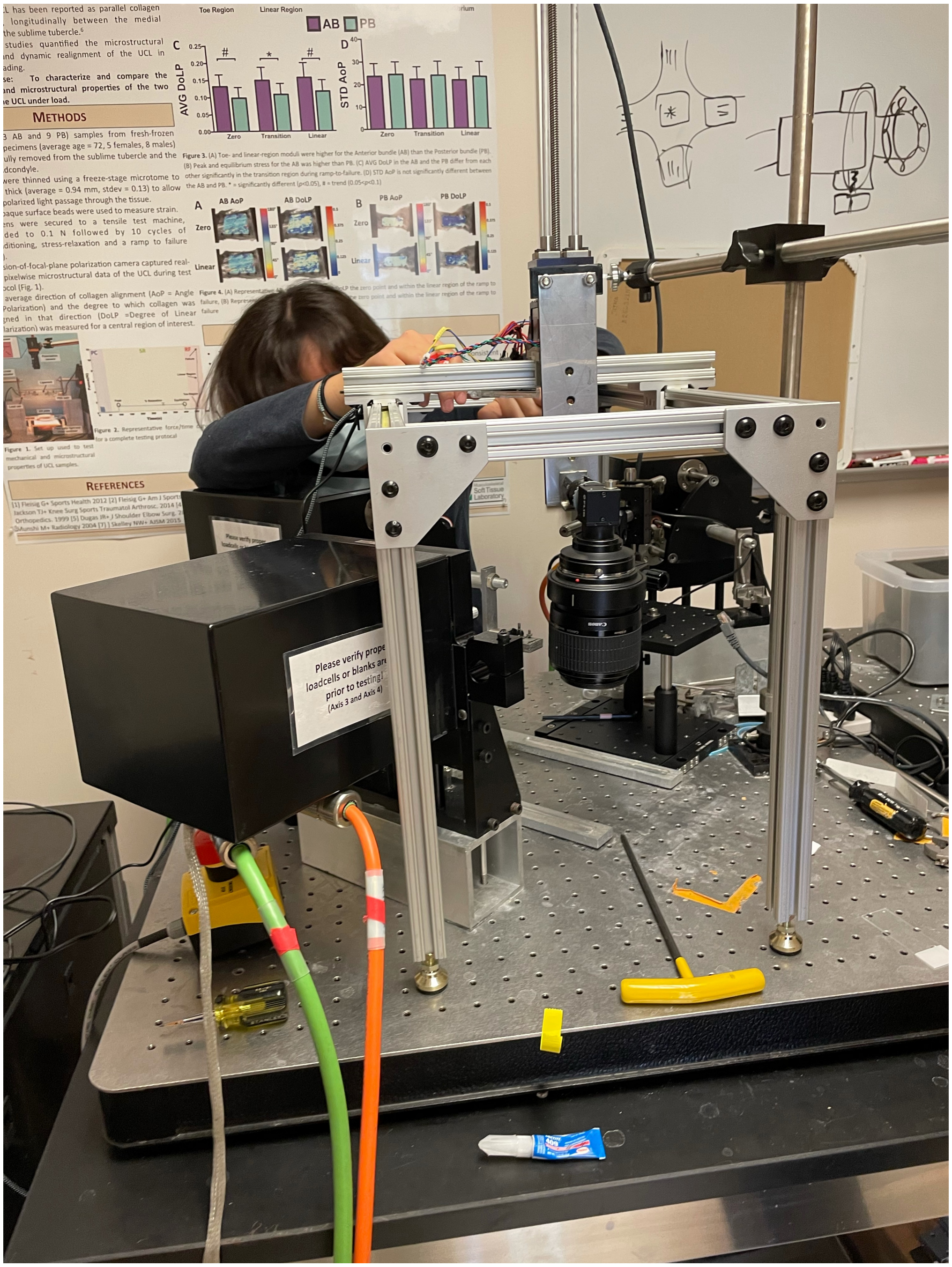


Figure 32: Final Design

The device fits with all three testing setups used in the lab. The primary use of this device is for the planar biaxial testing machine. The final prototype is shown in this setup below.

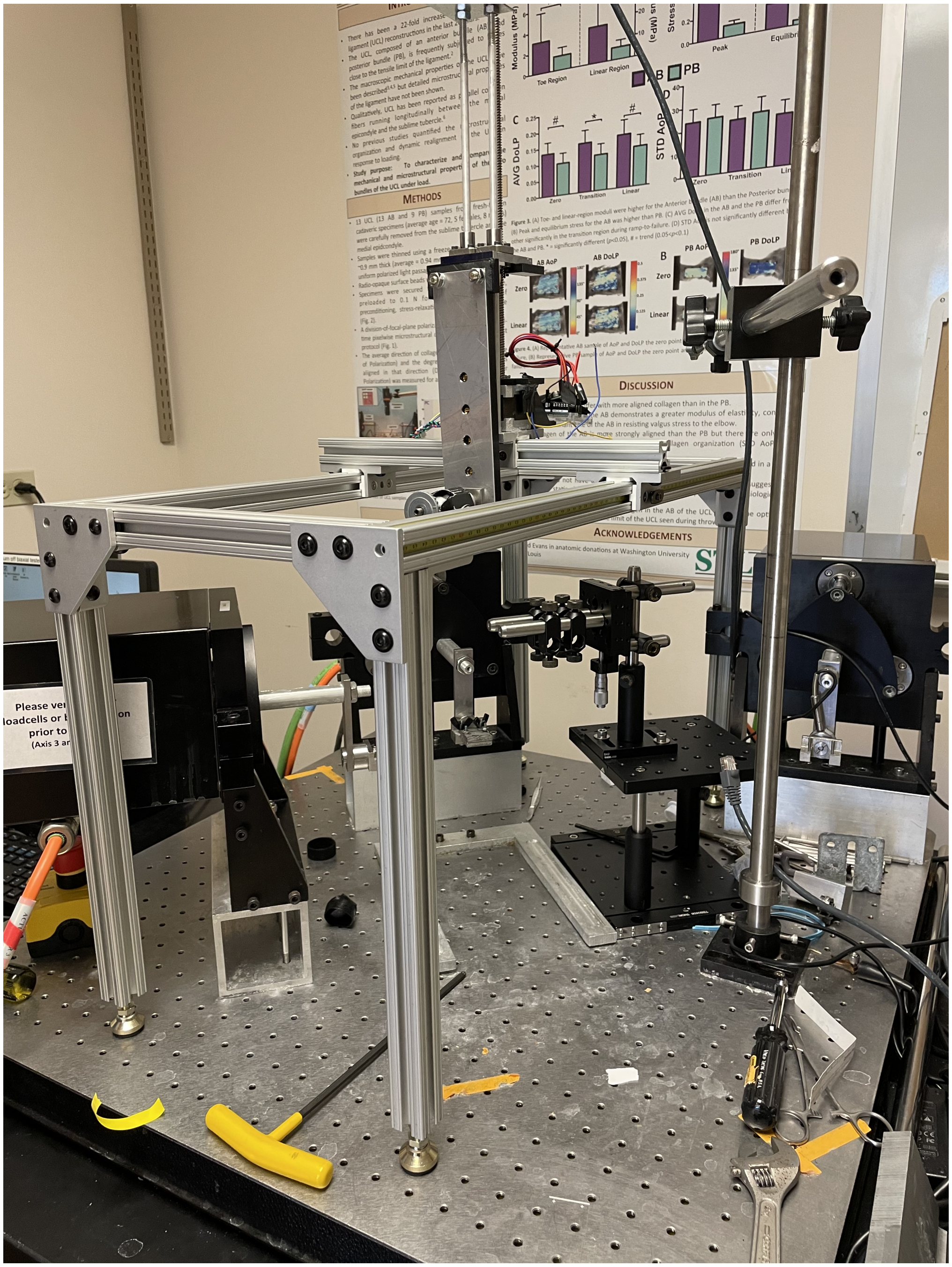


Figure 33: Device in Use

The user can identify the x and y coordinates of the camera using the tape measure placed within the horizontal rails. The x and y position of the camera is set manually, and the user can record these locations to replicate the camera position if necessary.

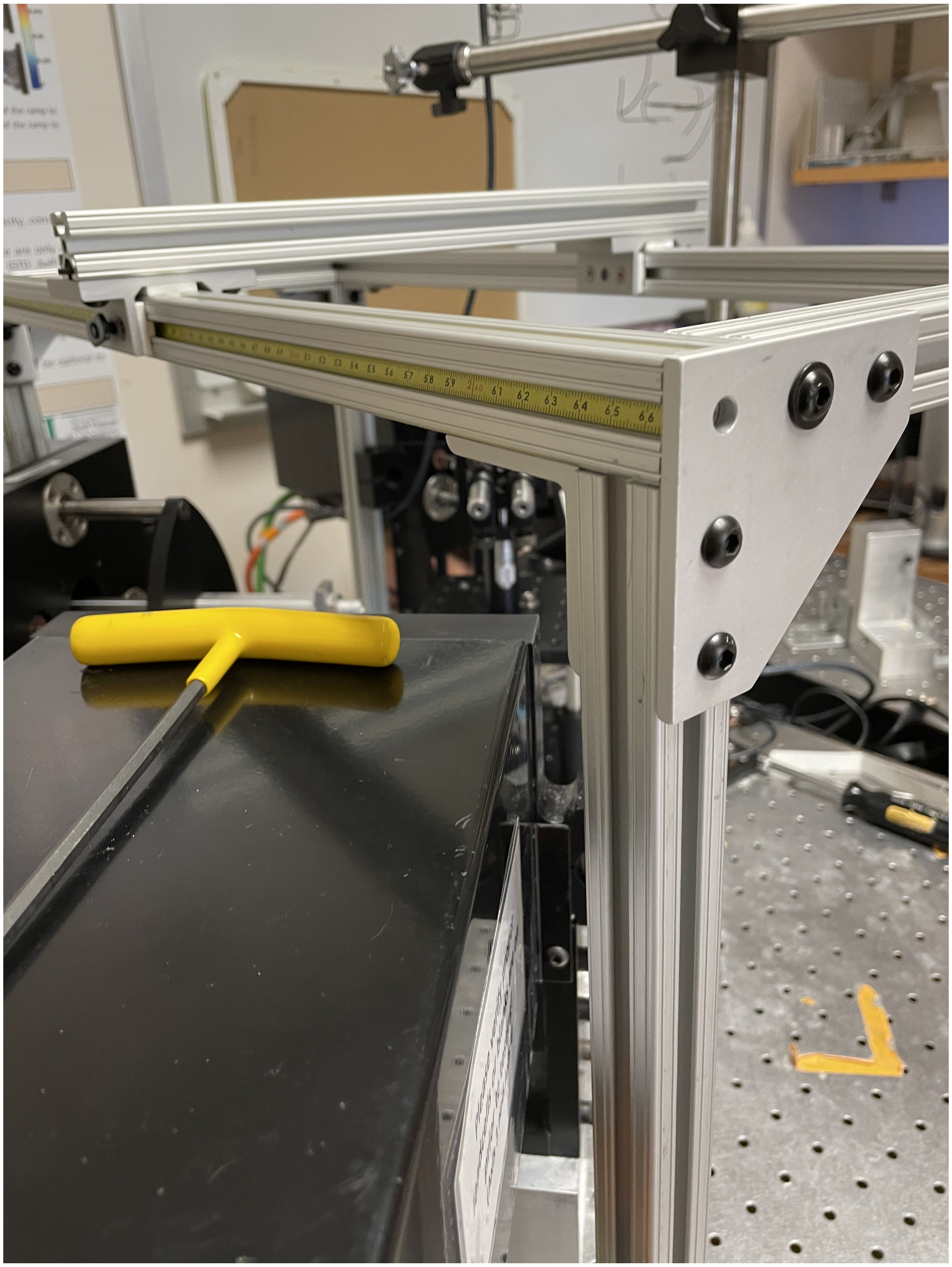
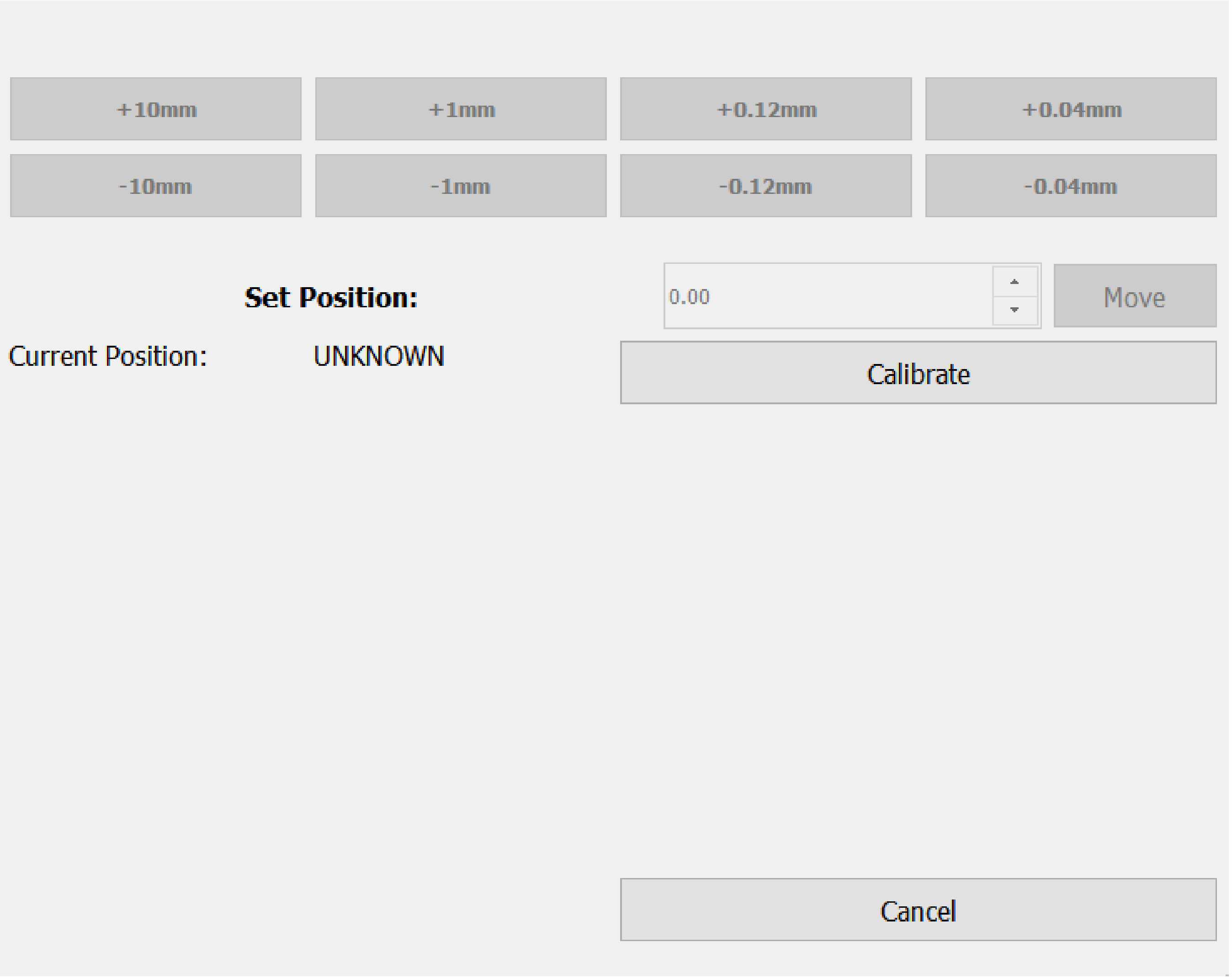


Figure 34: X and Y Coordinates

The user interface was designed to allow custom movement and also set movement. The UI will tell the user the current position and prevents the user from clicking buttons until the stepper motor has finished moving. It will also prevent the user from moving to an invalid position. The calibrate button will run a calibration routine so that the stepper motor knows its location.



Set Position: 0.00

Current Position: UNKNOWN

Figure 35: User Interface

8 Discussion

8.1 Project Development and Evolution

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

- The results align with our project description. We created a camera system that could move in 3 axes. The only customer need we did not complete was a light stand. This was a very low priority item and could be made by the lab after we left.

Was the project more or less difficult than expected?

- The project was more difficult that expected. If the item attached to the lead screw was not a camera it would have been easier. However, with the camera the field of view and direction are important as well as moving the camera. Initially, we thought it would be easy to attach the camera to the lead screw, but the final design was very involved.

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

- We should have spent less time on testing if the frame was going to fit. In the end we had a lot of leeway and used 2 weeks to build the prototype out of wood. We should have spent more time designing the camera mount as the machine shop required a lot of time and we should have been more prepared for it.

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

- The camera mount was much harder to make that expected. Since we could not obstruct the field of view creating a working design was much harder than anticipated. Creating the x-y motion was very easy and we just had to purchase sliders and rulers from McMaster Carr. Installation was easy and didn't require us designing any custom components.

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

- I think the chosen concept was the best concept to chosen. Our other concepts used different coordinate systems which would have increased the difficult of creating motion in 3-axes. The Cartesian robot was a good choice.

8.2 Design Resources

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

- The team chose the codes and standards which were important for choosing elements of our product. For example, the lead screw torque was necessary to calculate before purchasing a motor. We also knew that the camera field of view could not be blocked. This meant that hte camera would likely be extended on a beam so knowing that deflection was important. These models allowed us to pick parts and know that they would be successful before complete testing.

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

- We were not missing any critical information. The only big issues that arose from our chosen concept was the time that was needed to machine parts. This time was underestimated and cost us many weeks worth of build time.

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

- Electrical analyses and stepper motor testing would have been useful. The stepper motor driver used had built-in stall detection; however, it required testing to determine properties of the motor. These tests would have required extra time and equipment that we did not have but would reduce the number of wires and code.

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

- We would buy the painted 8020 so that we could engrave the measurement system instead of using adhesive backed rulers. Also, we would have made the x and y motion smoother. The x motion tends to bind since it is on two sliders. Maybe these could be put on lead screws and manually moved instead of relying on a low friction slider.

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

- Given more time we would have designed a new solution for the camera mount. The current solution deflects the moment off of the lead screw, but does not prevent bending in the camera mounting plate itself. For a large camera and lens this causes the plate to bend in which could obstruct the z-axis motion. To fix this we would likely need a thicker steel plate and have the treads in the plate instead of using heat set inserts which have some play.

8.3 Team Organization

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

– The team member skills complimented each other well. One team member was good at coding, another was good in the machine shop and the other teammates were good at CAD and building. In the end, this worked well as our design required skill in all of these areas. One skill that would have helped was electrical engineering. Some of the circuitry wasted more time than it should have and if we had someone good at circuits we would have saved a lot of time.

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

– This design project didn't inspire any specific project, but it showed our team the power of an Arduino. By using an Arduino we unlocked the potential to do so many other projects. With this skill set the number of projects possible increased greatly.

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