Autonomous Ground Photographer

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Executive Summary

This project aimed to create an autonomous ground photographer for Dr. Penczykowski, whose lab researches the effects of powdery mildew on three plant species. Data is currently collected in the field by manually counting the number of infected plants, with the assistance of a simple PVC rig to create a grid pattern. Though many options exist for crop imaging and phenotyping, these systems are designed for larger scale applications and a smaller portable device was needed for Dr. Penczykowski's purposes. After careful analysis of the design task, three performance goals the device would need to accomplish were identified: (i) the ability to capture consistent photographs with repeated use, (ii) sufficient battery life for a minimum of three complete device cycles, and (iii) a cycle time of 20 minutes or less. Additional factors that were considered while designing the device were to ensure portability and ease of use. The final device consists of a camera housing that moves along a bar to capture images at discrete steps. The bar then moves on a frame in a planar motion to cover a 1.5 x 1.5 m plot of the desired plants. Important design decisions were decided by using various engineering models, including beam deflection and motor torque. The device was found to adequately perform the aforementioned goals that were set. The following report details the design process of this product.

MEMS 411: MECHANICAL ENGINEERING DESIGN PROJECT
FALL 2018

Ground Photographer

Elise Ashley

Kate Padilla

Nick Smith

Sylvia Tan

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1 INTRODUCTION

Dr. Penczykowski, an assistant professor of Biology at WUSTL, researches infectious disease ecology, where one area of focus is understanding how the variation in climate affects infectious disease dynamics and pathogen stream diversity. To do so, she is studying three plants (Plantago lanceolata, Plantago major, and Plantago rugelii) that are infected with powdery mildews along the Mississippi River. To the naked eye, the powdery mildew is seen as a “white powder” and can be easily noted by the researcher.

To collect data, researchers in Dr. Penczykowski’s lab use a simple PVC rig of 50 x 50 cm, shown in Fig. 1, to create a grid on the ground. With the grid pattern, the researcher manually counts the number of infected plants. Although the current method used in their field work allows them to collect the required data, it is both time and labor intensive. Therefore, this project aims to automate this process and reduce the time required to be out in the field.

Currently, there are many available options for crop imaging that included a multitude of sensors and camera to monitor the physiology and phenotyping data of the crops. However, these systems are designed for large-scale greenhouse or field work and include capabilities that are not required for Dr. Penczykowski’s purposes. Therefore, this project seeks to develop a portable imaging device to be used in a smaller-scale setting.

Figure 1. Current 50 x 50 cm PVC rig used to count infected plants by hand.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

2.1.1 Current Designs

In this section, three existing products will be explored. These are products that address problems similar to the ones we are working to address, but diverge from the scope of this project to some capacity.

Design 1 - Rover FluorCam

Figure 2. Rover FluorCam
(Source: Photon Systems Instruments)

Link: http://psi.cz/products/customized-fluorcams/rover-fc-900-r

Description: The Rover FluorCam is a customizable fluorescence imaging system for physiological screening in greenhouses and large-scale fields. It is an automated system utilizing wheels that provide stability and maneuverability among the plants. Additionally, it is able to move along rough terrains. It has a total scan area of 35 x 35 cm and its height can be adjusted between 20 cm to 150 cm to allow it to capture taller crops without disturbing or destroying them. A cabinet may also be attached to it to enclose the camera and light panels for control of dark adaptation and actinic light. As well, other camera types can be attached to it for different forms of analysis.

Design 2 – Transect FluorCam

(Source: LemnaTec)
Figure 3. Transect FluorCam (Left) Internal imaging system in a weather-proof cabinet (Right)

Link: https://www.lemnatec.com/products/field-phenotyping/field-scanalyzer/

Description: The Field Scanalyzer is a fully-automated system that captures crops and plants growing in a large-scale field. The cameras, sensors and illumination system are enclosed within a weather-proof cabinet that is attached to a motorized gantry, moving in both the X and Y direction. Additionally, the gantry is able to withstand a total payload of 500 kg, thus allowing other forms of sensors and camera to be attached if required. In all, the sensors and cameras are used to monitor the growth and physiology of the plant continuously. Lastly, the system can scan a wide range of crops areas, such as a 10 x 110 m area or a 20 x 200 m area.

Design 3 – Spidercam

Figure 4. Spidercam in use over crops
(Source: UNL Institute of Agriculture and Natural Resources)

Link: https://ard.unl.edu/phenotyping/field-phenotyping-facility

Description: The Spidercam is a remotely-controlled, stabilized camera suspended by eight tensioned cables that can be extended or shortened to position the camera anywhere within a given 3D space. The cable lengths are adjusted using a system of four computerized winches. Originally used to record aerial footage of field sports, it has also seen applications in field phenotyping and monitoring. The Spidercam can be positioned to an accuracy of 1 cm, and has an imaging height range of ground-level to 9 m. Its 30-kg payload includes a variety of cameras and sensors, including two spectrometers, a thermal infrared camera, lidar, visible RBG, and near infrared.

2.1.2 Patents

In this section, two patents will be described. Patents that relate to the scope of our project were explored, in particular. This was done to gain a better understanding of existing technology and how it might impact the way we design our project.

Position data-powered control system for camera and stage equipment for automated alignment to defined mobile objects
DE202010013678U1

(no image available)

This patent combines the use of known components in the Spidercam with a data processing program to automatically align, position, and move camera and lighting units versus manually. The unit is fitted with a device that allows for position data determination, which is sent to a digital interface for processing. The same device allows for coordinates to be sent to the carrier unit to orient the camera to the desired position. Though the system as a whole can be oriented autonomously with remote-control, this may be enabled or disabled as desired.

As Spidercams are used in some cases for phenotype imaging, this patent is helpful in understanding how the software of the device affects the camera's motion.

Positive retracting mechanical expansible shaft
US4492346A

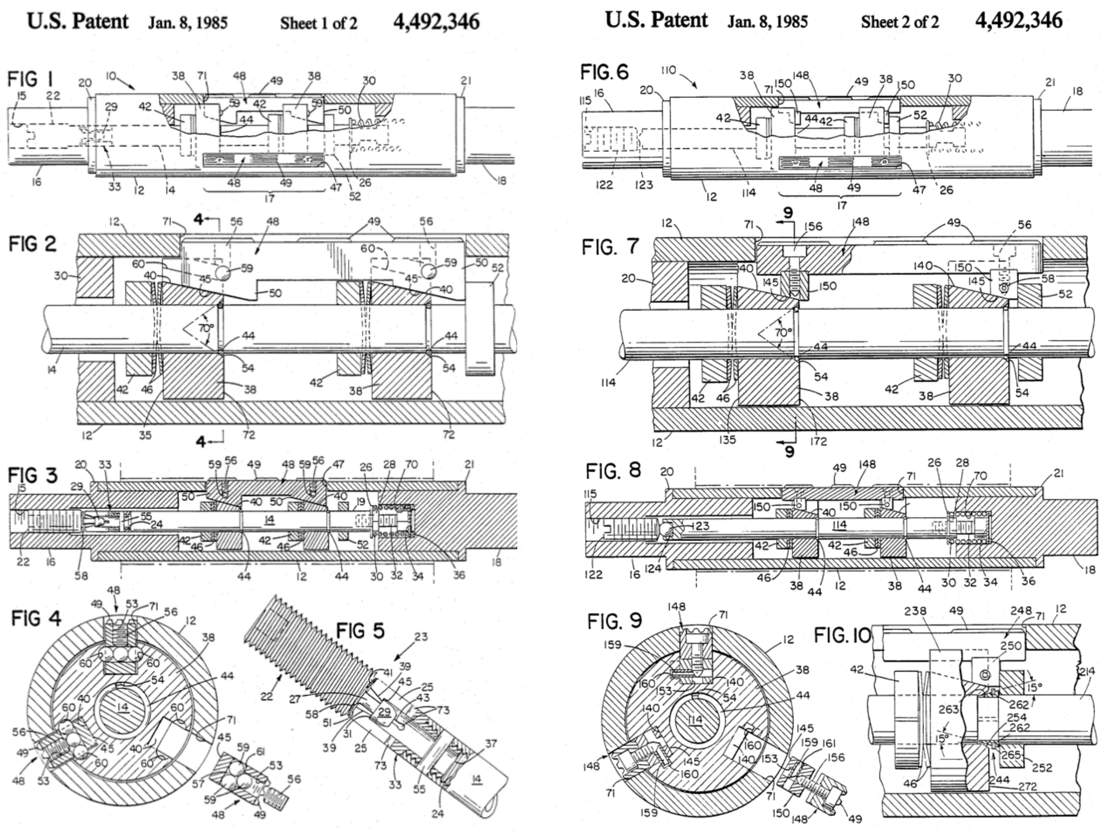


Figure 5. Patent Images for expansible shaft

This patent describes the mechanism used to actually move a Spidercam. An axially-extending housing encloses an operating rod mounted coaxially to the aforementioned housing and positioned for axial movement relative to the housing. Within the expansible shaft of the set up are screws which are rotationally and axially moveable with respective to the housing. Additionally, they are rotatably connected to the rod in such a way that a clockwise screw rotation moves the rod axially in one direction while a counterclockwise rotation will move the rod axially in the opposite direction.

2.1.3 Codes and Standards

Codes and standards that may pertain to the scope of this project are detailed below. These were looked at to gain an understanding of possible constraints to our project and the aspects that need to be considered if we want to meet specific standards.

Photography – Tripod connections
ISO 1222

This International Standard sets specifications for the screw connections used to attach a camera to a tripod or similar camera accessory. Specifically, the standard requires a 1/4-20 UNC or 3/8-16 UNC thread to be used. When designing the ground photography system, it will be important that the mounting system implemented is compatible with the camera.

Identification and communication interoperability method for external power supplies used with portable computing devices
IEC 63002: 2016

This standard defines the interoperability guidelines for an external power supply used by a portable computer system that also implements the IEC 62680-1-2 (*Universal Serial Bus Power Delivery Specification*) with the IEC 62680-1-3 (*Universal Serial Bus Interfaces for data and power-Common Components- Type-CTM Type-C Cable and Connector Specification*). It is applicable to external power supplies under 100 watts, particularly for multimedia devices such as notebook computers, tablets, smart phones.

2.2 USER NEEDS

An interview with Dr. Rachel Penczykowski was conducted to gain an understanding of the scope of this project and the requirements that need to be met in order for it to be a success. Based on this interview, a list of interpreted needs was compiled. Each need was ranked on a scale of 1 to 5, with 1 being least important and 5 being highly important. The results of this process are presented in Table 1.

Table 1. Customer Needs Interview

Product: Ground photographer

Customer: Dr. Rachel Penczykowski

Notes: Dr. Penczykowski gave a brief explanation of her work, ranging from the intent of her research to the process she uses now to capture images. This was followed by a question session in which we discussed desired features. The whole interview took about 50 minutes.

Address: 407 McDonnell Hall, Washington University Danforth Campus

Date: September 7, 2018

Question	Customer Statement	Interpreted Need	Imp.
Portability	Able to be carried by one person up to 50 m 30 minutes for set up, imaging, and breakdown Fits in car or SUV	Ground photographer is lightweight and collapsible.	5 3
Camera Size & Resolution	Has a point-and-shoot Nikon COOLPIX S6200 to take a few photographs, do not want to use a phone or tablet Able to capture a disease area of 1 cm diameter	Ground photographer is able to effectively image diseased plants.	5
Camera Height	Plants can grow up to 40 cm tall, camera should be about 50 cm off the ground	Ground photographer captures close-up images.	3
Weather/ Terrain	Will not be used in rain, but should be able to handle high humidity and mud Low light or dappling may cause bad image quality Mostly flat terrain everywhere, should be able to handle small changes in terrain	Ground photographer can withstand wet/muddy environment. Ground photographer can capture images in different light conditions.	5 5
Power Supply	Can be used at least 3 times between charging	Ground photographer has sufficient power for several uses.	5

Based on the desires and requirements generated from the interview with Dr. Penczykowski, the identified customer needs were then isolated into discrete needs and ranked. These interpreted customer needs are displayed in Table 2.

Table 2. Interpreted Customer Needs

Need Number	Need	Importance
1	Ground photographer is lightweight.	5
2	Ground photographer is collapsible.	3
3	Ground photographer is able to effectively image diseased plants.	5
4	Ground photographer captures close-up images.	3
5	Ground photographer withstands wet/muddy environment.	5
6	Ground photographer can capture images in different light conditions.	5
7	Ground photographer has sufficient power for several uses.	5

2.3 DESIGN METRICS

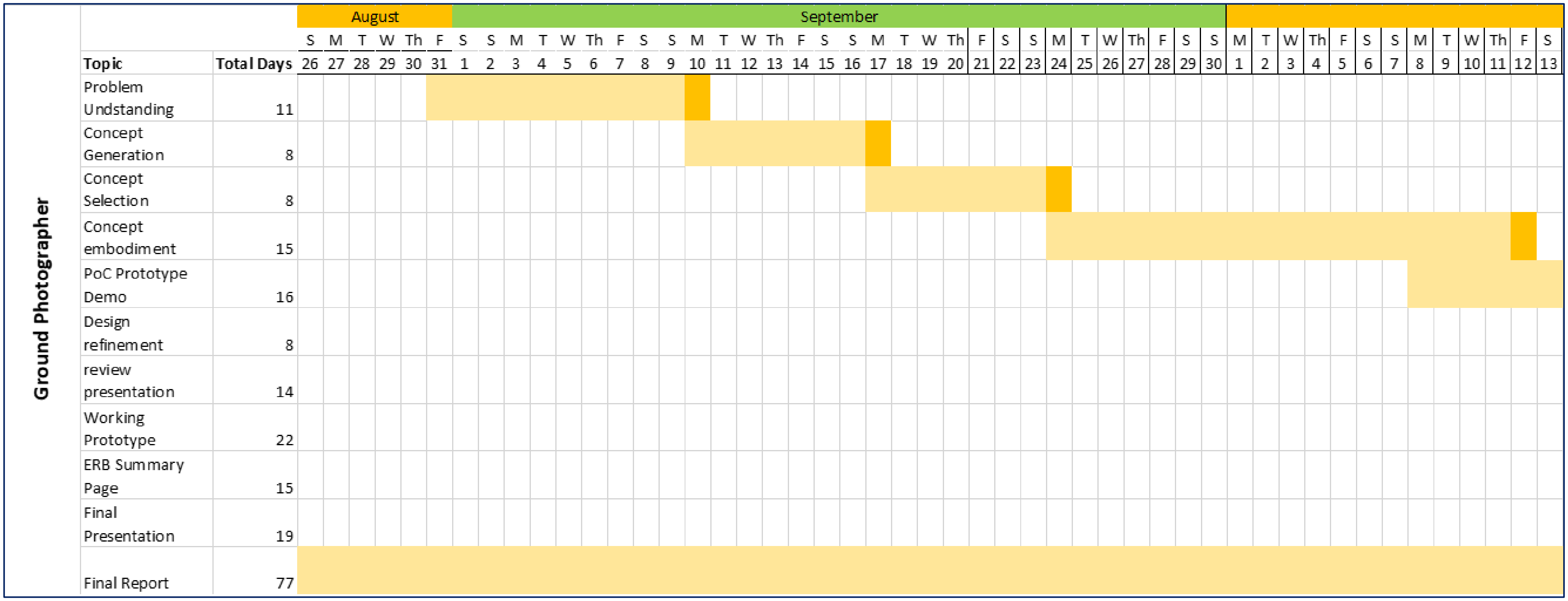
Specific project metrics were created in order to address each of the interpreted customer needs identified. Ideal specifications for the end-product of the project were determined, as well as acceptable specifications that should be met at the minimum. Target specifications are shown in Table 3.

Table 3. Target Specifications

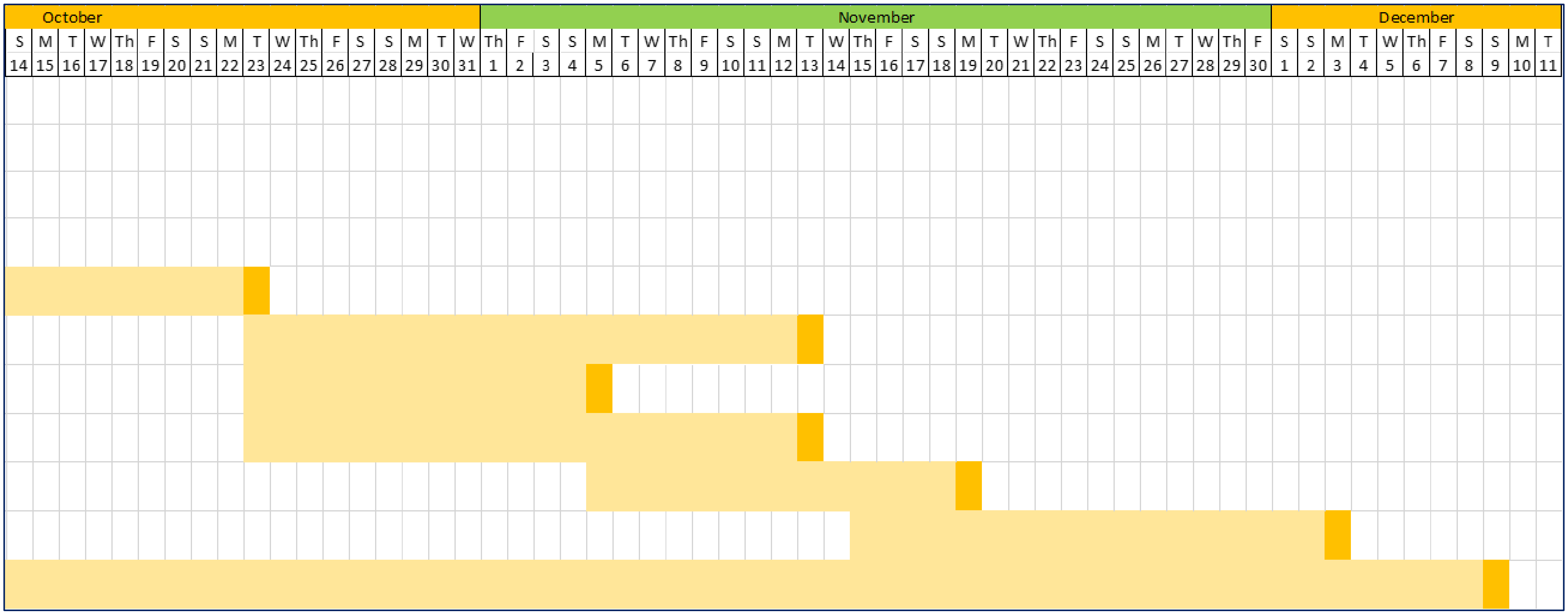
Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total Weight	kg	< 22.5	< 12
2	2	Dimensions (Broken-Down)	m^3	< 0.75 x 2 x 0.75	< 0.5 x 1.5 x 0.5
3	2	Set-up/Breakdown Time	min	< 10	< 5
4	3	Imaging Time	min	< 10	< 5
5	4	Camera-ground distance	m	< 1	< 0.5
6	7	Battery life	min	> 120	> 180
7	2	Compliant with *ISO 1222* Tripod Connections Standard	Binary	Pass	Pass
8	3	Compliant with *IEC 63002: 2016* External Power Supply for Portable Computing Devices Standard	Binary	Pass	Pass

2.4 PROJECT MANAGEMENT

The following Gantt chart was used to manage project progress and deadlines.



Gantt Cont.


October
November
December
S M T W Th F S S M T W Th F S S M T W Th F S S M T W Th F S S M T W Th F S S M T W Th F S S M T W Th F S S M T
14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 1 2 3 4 5 6 7 8 9 10 11

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

The mockup prototype focused on the mechanism for a unidirectional motion of the camera within a support bar. To represent a possible design for the bar, a housing was constructed out of a foam board. A slit was cut along the length of the bottom of the housing (fig. 5a) to allow for the camera to be attached to the internal components. A pulley/belt system was constructed inside of the housing which consisted of two foam board pulleys, each attached to a wooden dowel as the axel (fig. 5b). A cotton string represented the belt and it was wounded around the pulleys. Lastly, a wooden block with two holes cut through them substituted as the camera and case. The strings trended through the wooden block were also adhered with superglue to the belt. Movement of the camera along the housing can be seen in figure 7.

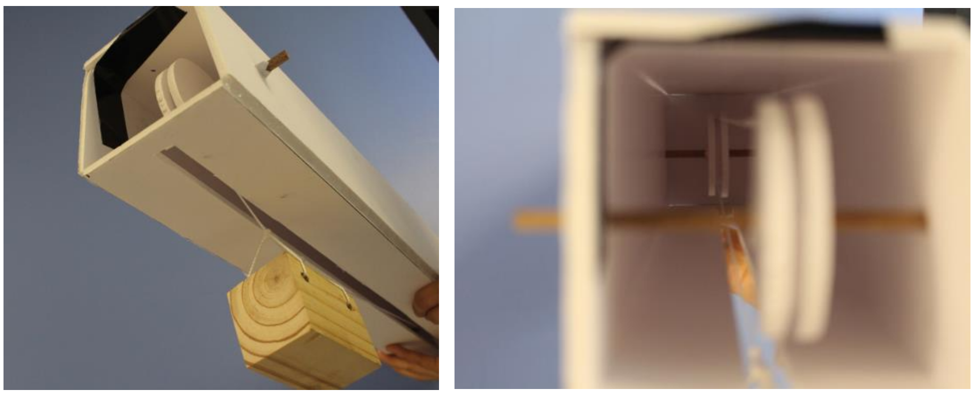


Figure 6. Mockup prototype. (a) Bottom view showing the slit cut through. (b) Internal pulley to allow lateral movement

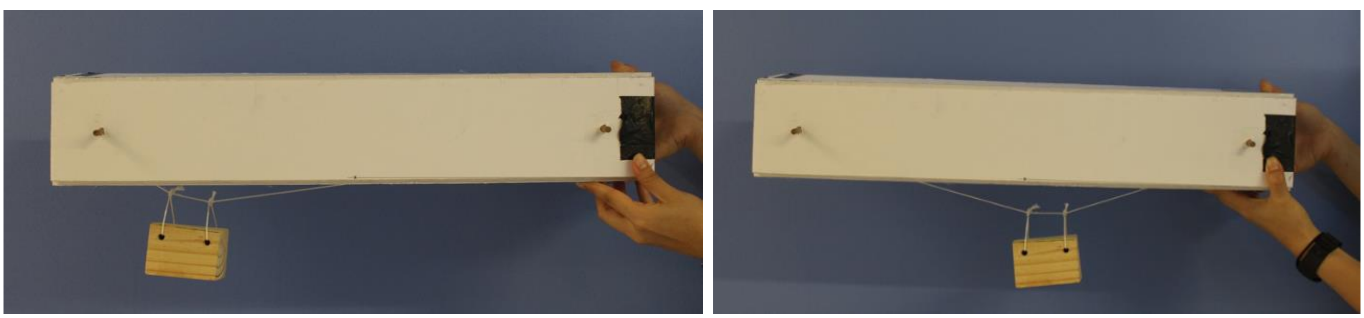


Figure 7. Movement of the camera in the mockup prototype

The mockup proved that this mechanism for laterally movement is a possible solution. Incorporation of a Geneva Wheel may aid in ensuring that the camera takes pictures at several discrete locations along the length of the support bar. Although the movement of the camera was achieved, the mockup lacked the ability to press the shutter on the camera, Additionally, mockup lacked the ability to move forward as it only consisted of one component of a hypothetical design. As these required functions were ignored, consideration of how the photo would be taken automatically at a specific interval of time, and a second mechanism for moving the entire apparatus in forward needs to be taken.

3.2 FUNCTIONAL DECOMPOSITION

3.2.1 Function Tree

A hierarchy was created to plan out an overview of the basic-level functions that will be required of our project. These functions were determined based on the interpreted customer needs and design metrics identified previously.

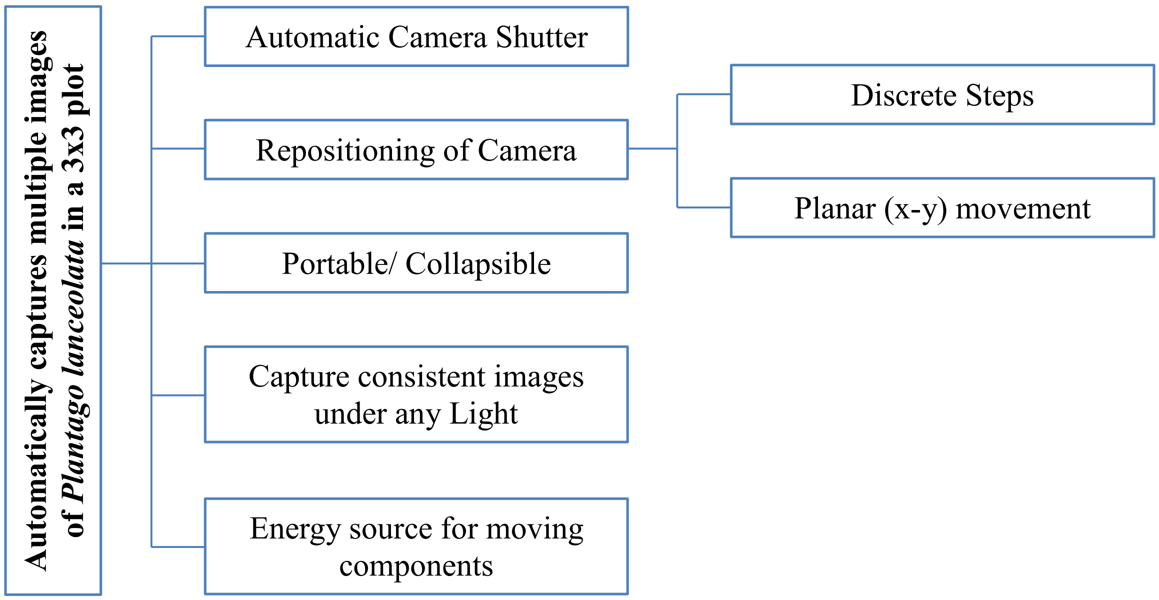
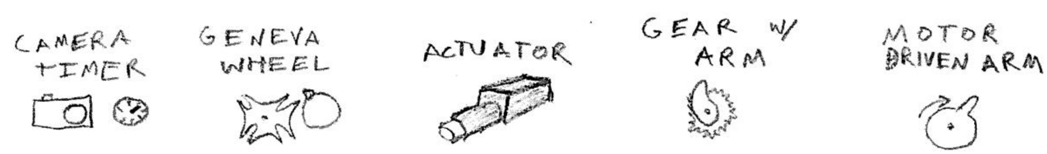
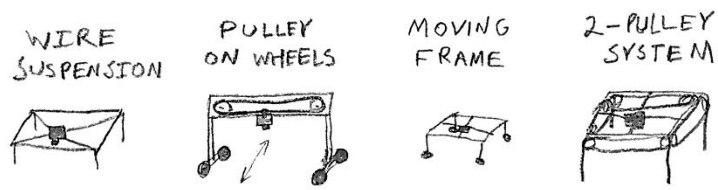
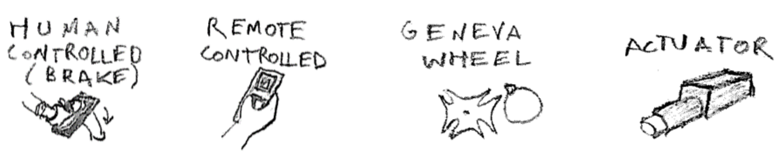
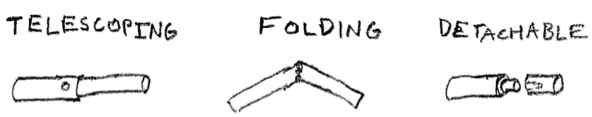


Figure 8. Function Tree of Ground Photographer

3.2.2 Morphological Chart

For each of the identified functions required of our project, potential solutions were brainstormed. All of these solutions are presented in Table 4.

Table 4. Morphological Chart for Ground Photographer

Sub-functions	Solutions
1. **Automatic Camera Shutter**	
2. **Planar (x-y) Movement**	
3. **Moving in discrete steps**	
4. **Portable/ Collapsible**	
5. **Capturing consistent images under any light**	
6. **Energy Source for moving components**	

3.3 ALTERNATIVE DESIGN CONCEPTS

Each group member then sketched a potential end-result for the project, combining different solutions to the functions that were created as a group in the morphological chart.

3.3.1 Alternative Design 1

Concept Name: Multi-Pulley Camera Rig
Group Member: Elise Ashley

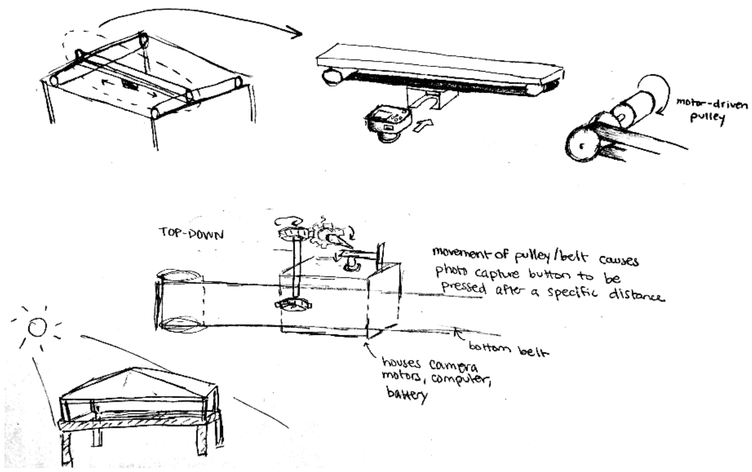


Figure 9: Preliminary sketches of multi-pulley camera rig

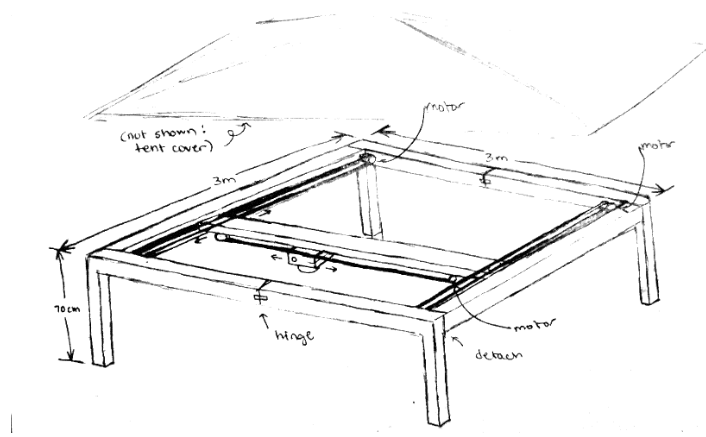


Figure 10: Final sketch of multi-pulley camera rig

Description:
A camera rig is set in a 3m x 3m frame. Given an XY-coordinate system parallel to the ground, one belt-pulley system is run by a motor to move the camera in the x-direction along a beam. A second belt-pulley system is run by two motors to move beam and camera in the y-direction, allowing the camera to access everywhere in the 3x3 plot. A canopy covers the entire frame to provide even lighting across the entire plot.

Solutions:
1. Gear with Arm
2. 2-Pulley System
3. Geneva Wheel
4. Folding

5. Tent
6. Battery

3.3.2 Alternative Design 2

Concept Name: Cable Suspension Camera
Group Member: Kate Padilla

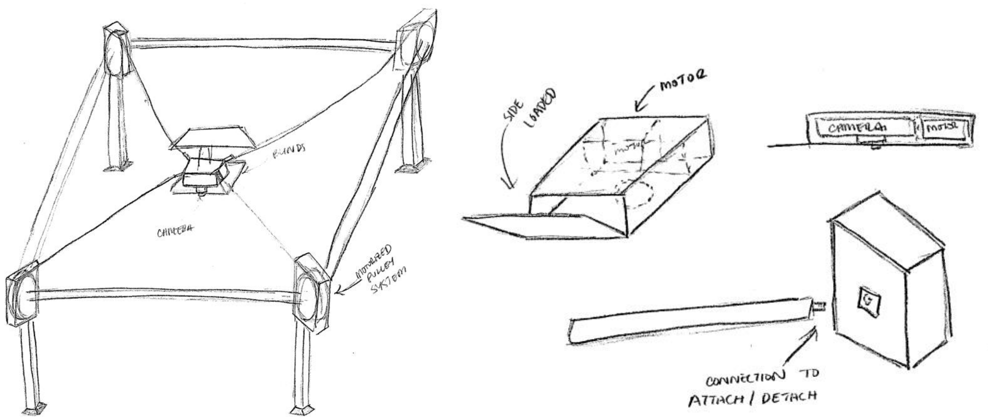


Figure 11. Preliminary sketches of cable suspension camera

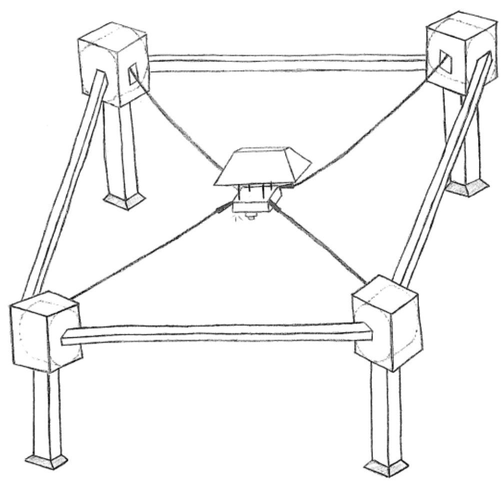


Figure 12. Final sketches of cable suspension camera

Description:
A collapsible 3 x 3 frame is set up, where motorized pulleys are placed at each corner. Cables held relatively taught run from each pulley and are connected to a central housing unit. Within this housing in the camera and a motorized system to automate the shutter of the camera. Additionally, the unit is covered by a small canopy to provide even lighting. The pulleys are programed to move the camera along discrete steps in the xy-plane to captures images of the desired spaces.

Solutions:
1. Timed Motor driven arm
2. Wire suspension
3. Actuator
4. Detachable
5. Blinds/Tent

6. Battery

3.3.3 Alternative Design 3

Concept Name: Pulley on Wheels
Group Member: Nick Smith

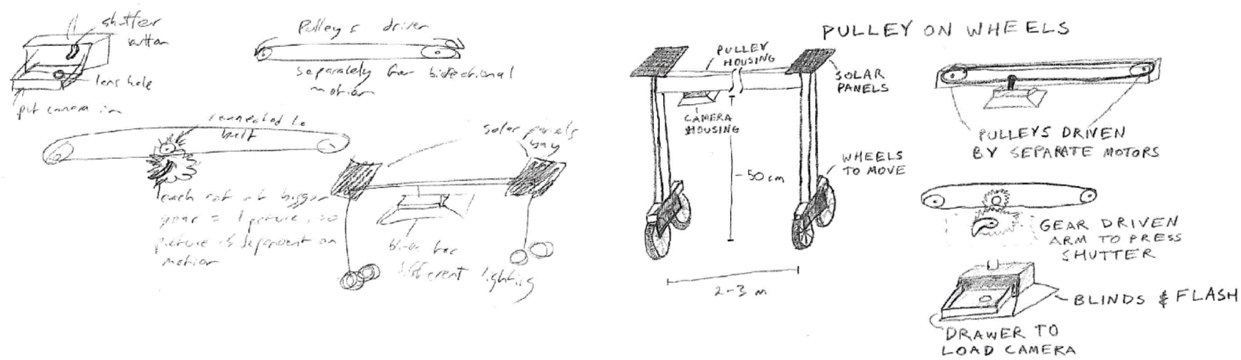


Figure 13. Preliminary sketches of pulley on wheels

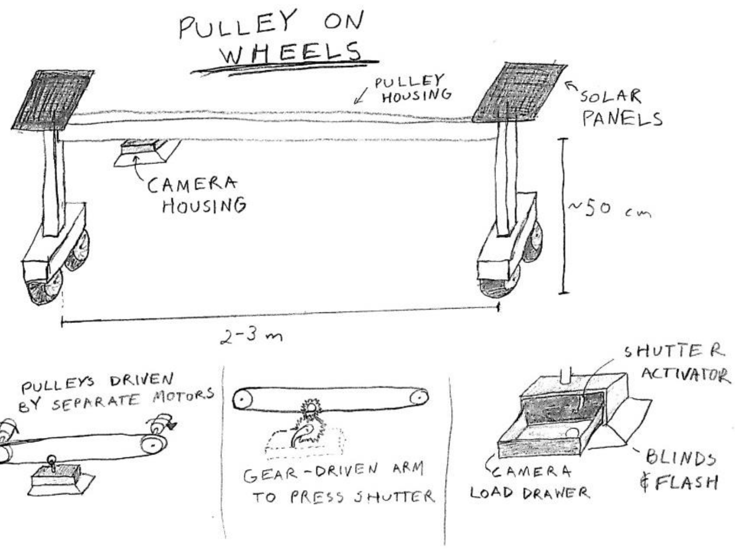


Figure 14. Final sketches of pulley on wheels

Description:
A crossbeam contains two motor-driven pulleys controlled by a single microcontroller. The camera is driven by a belt between the two pulleys that allows the camera to travel horizontally along the underside of the beam. A larger gear with an attached arm allows for a mechanism to press the camera shutter for a set distance that the camera travels along the length of the beam. The camera is housed in a case which can be accessed from a drawer that allows for the user to have easy access to the camera. The whole beam is then moved by wheels at the base of its support, which are controlled by motors and the same microcontroller as the pulleys. The whole design is powered by solar energy with backup batteries as the device is intended for use in good weather.

Solutions:
1. Gear with arm
2. Pulley on wheels
3. Computer controlled
4. Detachable pieces
5. Blinds and flash
6. Solar and batteries

3.3.4 Alternative Design 4

Concept Name: Rover Camera
Group Member: Sylvia Tan

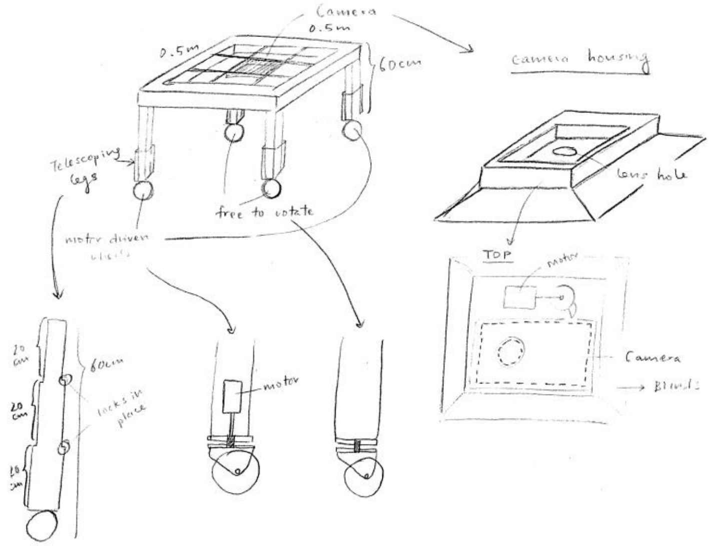


Figure 15: Preliminary sketches of Rover Camera

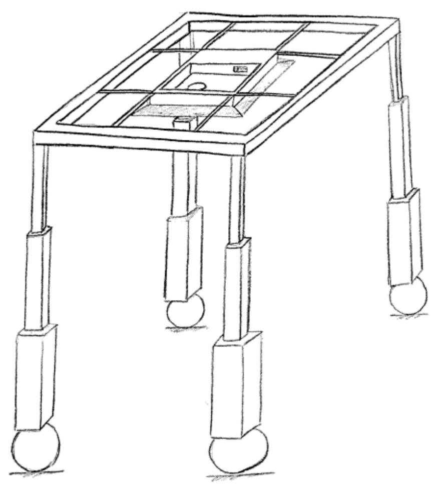


Figure 16: Final sketches of Rover Camera

Description:
A microcontroller moves two servo motors: one to rotate and move 2 wheels to allow the entire apparatus to move in either in the x or y direction, and another to press the shutter button on the camera after the apparatus is set in position. The legs are telescoping to allow it to be adjusted to the required height and the housing of the camera includes blinds to shade it from any harsh sunlight.

Solutions:
1. Motor Driven Arm
2. Moving Frame
3. Actuator
4. Telescoping
5. Blind
6. Battery

4 CONCEPT SELECTION

4.1 SELECTION CRITERIA

Before selecting a concept to base our design off of, a hierarchy was created to weigh the importance of various aspects of the design. Six project criteria were identified. Each was ranked against every other criterion, with a score of 1/9 meaning the criterion was much less important than the other and a score of 9 meaning it was much more important than the other. A score of 1.00 indicated the two criteria in comparison were of equal importance. All scores were totaled, and a weight was ultimately given to each criterion. This process and the results are presented in Table 5.

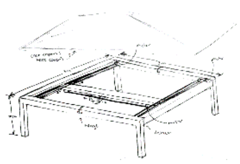
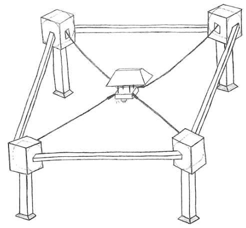
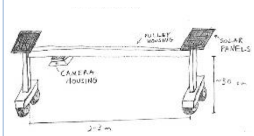
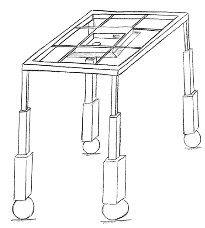
Table 5. Analytic Hierarchy Process (AHP) for weighted scoring matric

	Ease of Field Setup	Weight	Cost of Manufacturing	Ease of Manufacturing/ Collapsibility	Height Adjustability	Consistent Imaging	Row Total	Weight Value	Weight (%)
Ease of Field Setup	**1.00**	2.00	5.00	0.50	7.00	0.25	15.75	0.18	**18.36**
Weight	0.50	**1.00**	7.00	0.33	7.00	0.20	16.03	0.19	**18.69**
Cost of Manufacturing	0.20	0.14	**1.00**	0.25	5.00	0.17	6.76	0.08	**7.88**
Ease of Manufacturing/ Collapsibility	2.00	3.00	4.00	**1.00**	8.00	0.50	18.50	0.22	**21.57**
Height Adjustability	0.14	0.14	0.20	0.13	**1.00**	0.11	1.72	0.02	**2.01**
Consistent Imaging	4.00	5.00	6.00	2.00	9.00	**1.00**	27.00	0.31	**31.48**
						Column Total:	**85.76**	**1.00**	**100**

4.2 CONCEPT EVALUATION

Each of the design concepts detailed in Section 3.3 were rated based on the six selection criteria. The weights determined in Section 4.1 were then applied to the criteria ratings. Based on this, a score for each concept was calculated, and a concept was ranked as the most likely to be successful.

Table 6. Weight Scoring Matrix for alternative designs.

		Alternative Design Concepts							
		 **Multi-Pulley**		 **Cable Suspension**		 **Pulley on Wheels**		 **Rover**	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Ease of Field Setup	18.36	2	0.37	3	0.55	4	0.73	5	0.92
Weight	18.69	3	0.56	3	0.56	3	0.56	4	0.75
Cost of Manufacturing	7.88	4	0.32	3	0.24	2	0.16	2	0.16
Ease of Manufacturing/ Collapsibility	21.57	2	0.43	4	0.86	3	0.65	4	0.86
Height Adjustability	2.01	4	0.08	4	0.08	4	0.08	4	0.08
Consistent Imaging	31.48	5	1.57	3	0.94	2	0.63	1	0.31
	Total score	**3.329**		**3.236**		**2.810**		**3.081**	
	Rank	**1**		**2**		**4**		**3**	

4.3 EVALUATION RESULTS

Based on the results of the concept evaluation, the Multi-Pulley concept ranked highest. Looking at each criterion, this design was rated a 2 in 'Ease of Field Setup'. This is because after expanding the frame and locking the legs into place, the center bar also needs to be installed while ensuring that all the pulley belts are taut and in alignment. It was rated a 3 for 'Weight', as its frame could be made of a lightweight material, such as aluminum or PVC piping. However, at least three motors are also required and would thus add more weight to the system. The concept was rated a 4 for 'Cost of Manufacturing'—the frame could be made of common materials, such as PVC piping, and it would not require the same robustness of motors as the wheel-driven designs, further reducing costs relative to other possibilities.

For 'Ease of Manufacturing/Collapsibility', we explored how feasible it would be to make this design collapsible so it could fit in a vehicle to be transported. For this, the Multi-Pulley concept was rated a 2. Collapsing the design is challenging as it could possibly require removing and folding the center beam, which has a pulley, power supply, and camera housing attached. Additionally, being able to re-expand the beams such that the pulleys are consistently taught and aligned is critical for the success of the design. All concepts were rated a 4 in 'Height Adjustability', as they could all make use of telescoping legs in the same manner, similarly to how an adjustable tripod works. However, compared to the other designs, the Multi-Pulley concept ranked the highest in 'Consistent Imaging' with a 5. This is primarily due to having all the camera movements along a smooth track, thus eliminating the risk of uneven or unforeseen terrain causing variability in the images.

This exercise was valuable in helping us understand the importance of various design criteria. It also allowed for reflection and for new ideas to be explored as a group. Through the process, it was determined that all our initial designs had unique strengths and differences. Additionally, it became clear that none of these designs should become realized as-is, and that a combination of the best features of multiple designs would prove to be the most successful. Although the Multi-Pulley system was ranked the best option, it will be difficult to make a working collapsible design, which is absolutely necessary to make transport possible. The setup of the rig also needs to be quick and easy for the end-user. The Multi-Pulley system requires an installation of the center beam and attachment of the beam to two end-pulleys, which could take a long time. Thinking about this issue, it was argued that replacing the pulleys with wheels would eliminate the complications of needing a consistently taught belt. Therefore, a new design (Fig. 16) was created, combining the wheels of two of our designs with the elevated track of the Multi-Pulley design. By replacing the pulleys with wheels, but having the wheels drive the camera rig along an elevated track, the issue of wheels having to withstand mud or terrain obstacles is further eliminated.

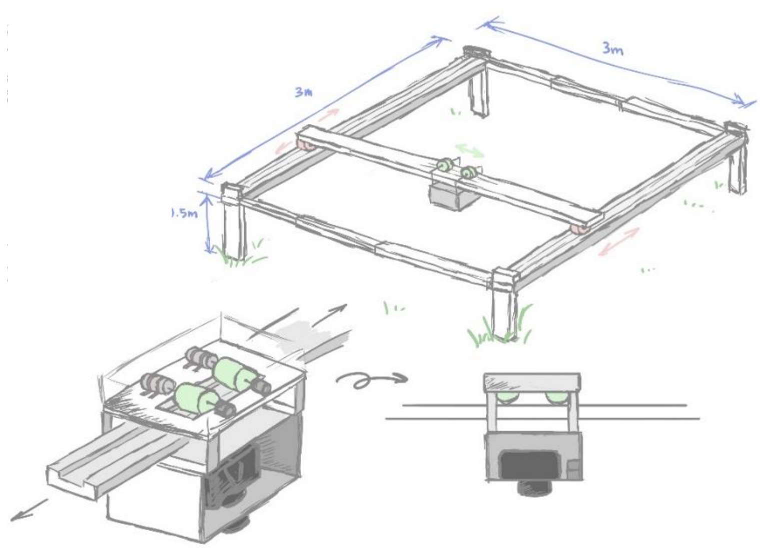


Figure 17. New Design Concept

4.4 ENGINEERING MODELS/RELATIONSHIPS

4.4.1 Engineering Model 1 – Image Resolution and Height Selection

The height at which to set the camera for the ground photographer device is dependent on the desired object size in the captured image and the resolution of the camera being used. The relation between resolution, or more specifically horizontal or vertical pixel count, and the size of the object is as follows,

$$Object\ width\ in\ pixels = Horizontal\ pixel\ count * \frac{Object\ size\ in\ image}{Width\ of\ image\ area}$$

$$Object\ height\ in\ pixels = Vertical\ pixel\ count * \frac{Object\ size\ in\ image}{Height\ of\ image\ area}$$

The customer can specify the size in pixels with which they would want the smallest feature in the image to by detectable by and the area of the image in order to find the object size in the image. The pixel count used would depend on the specifications of the camera used. Most often, the standard size a pixel should correspond to for an actual "in real life" dimension is 1 pixel to 1 mm. However, this can be lowered or increased depending on the clarity the user wants in their images. Once the size the object will appear in the image is known, the following relation can be used to find the distance the object must be from the camera lens.

$$Object\ size\ in\ image = Actual\ object\ size * \frac{Focal\ length}{Object\ distance\ from\ camera}$$

Again, the focal length in this calculation would depend on the camera and lens being used. For most point and shoot cameras, the focal length in use in any certain mode is difficult to determine, making it more desirable to use a DSLR camera so that these specifications can be certain.

4.4.2 Engineering Model 2 – Beam Deflection and Material Selection

As the camera moves across the beam to capture sequential images, the weight of the camera and its connected components exert a downward force on the beam at various locations as seen in figure 17.

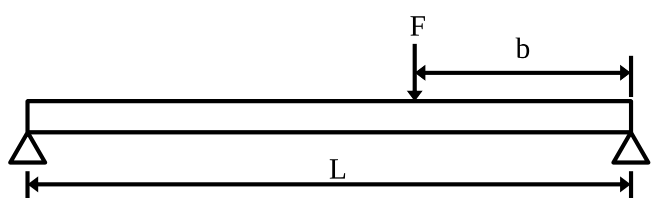


Figure 18. Schematic of beam deflection

This force results in a downwards deflection in the beam. Although the deflection changes as the camera moves along the beam, only the maximum deflection is of concern as it is the lowest point the camera will be at. This can be calculated by the following equation,

$$\delta_{max} = \frac{Fb(L^2 - b^2)^{3/2}}{9\sqrt{3}LEI}, \qquad at\ x = \sqrt{\frac{L^2 - b^2}{3}} \quad [1]$$

where, δ_{max} is the maximum deflection in the beam [m], F is weight of the camera, wheel and resulting housing, L is the overall length of the beam [m], E is the Young's Modulus of material the beam is made up of [Pa], and I is the moment of inertia of the beam [kg m^2], which depends on the cross-section geometry of the beam

Using this equation, the type of material the beam supporting the camera should be made up of can be determined as,

$$E = \frac{Fb(L^2 - b^2)^{3/2}}{\delta_{max} 9\sqrt{3} LI}$$

where the maximum deflection is dependent on how the change in height will affect the resolution of the image as determined by the first engineering model

4.4.3 Engineering Model 3 – Required Torque and Motor Selection

The motor torque required will change throughout the range of motion of the moving components. The torque can be analyzed through dynamic analysis of the components that the motor will drive, which are the wheel and the weight supported by the wheel. A free body diagram of the components in motion is shown in Figure 18.

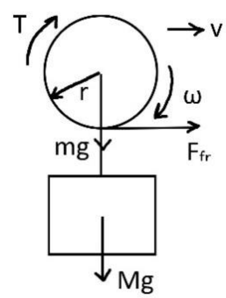


Figure 19. Free body diagram of motor torque.

T represents the torque supplied by the motor [Nm], v represents the linear velocity of the wheel [m/s], ω represents its angular velocity [rad/s], r represents the radius of the wheel [m], F_{fr} represents the force due to friction [N], m represents the mass of the wheel and connecting motor [kg] , M represents the mass of the camera and housing [kg], and g is the acceleration due to gravity [m/s^2].

To begin motion, the motor torque would need to overcome static friction. The motor torque required to begin moving can be given as:

$$T_{start} = r\mu_s(m + M)g$$

where μ_s is the coefficient of static friction. Once the wheel has begun moving, torque is then required to accelerate the wheel to a desired angular velocity. The torque required to achieve a desired angular acceleration can be found as:

$$T = I\alpha + r\mu_k(m + M)g$$

where I is the moment of inertia of the wheel [kg m^2], α is the angular acceleration of the wheel [rad/s^2], and μ_k is the coefficient of kinetic friction. When the wheel reaches a desired angular velocity, the only torque required is the that required to overcome kinetic friction. This torque can be found as:

$$T = r\mu_k(m + M)g$$

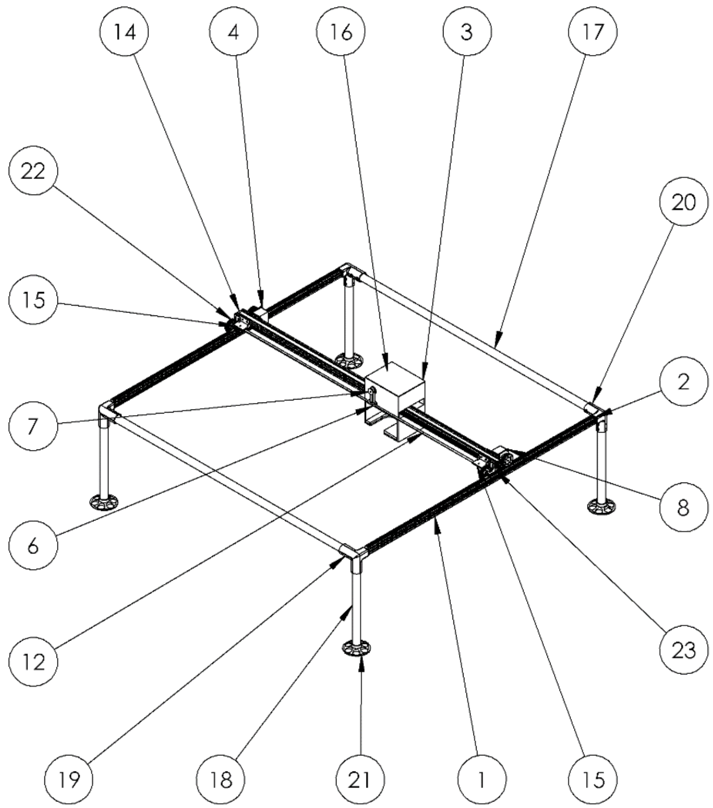
Of all of the torques described above, it is most likely that either the torque required to start motion or the torque required to accelerate will be the maximum torque required from the motor. As this value is dependent on μ_s, the torque is dependent on the material of the wheel and track the wheel is in contact with.

Determining the maximum torque required for each motor in our device would help us to know how powerful of a motor we will need in different parts of the device. It will also help us with determining the battery life of our device, as power can easily be calculated from the torque and angular velocity.

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

5.1.1 Assembly View and BOM



ITEM #	ITEM NAME	QTY.
1	25x25 T-Slotted Beam	2
2	M1 Gear Rack	2
3	Camera Housing	1
4	NEMA 23 Stepper Motor	3
5	150mm Bearing Pad	2
6	Idler Wheel	2
7	Pulley	1
8	Motor L-Bracket	3
9	Breadboard	1
10	Arduino	1
11	M1 Gear	2
12	Belt	1
13	Belt Clamp	2
14	25x50 T-slotted Beam	1
15	Belt clamp bracket	2
16	Battery	1
17	PVC pipe -frame	2
18	PVC pipe - Legs	4
19	Right corner bracket	2
20	Left corner bracket	2
21	foot	4
22	Idler Gear	2
23	Idler Gear Bracket	2
24	Camera Foam Board	1
25	M4 Hex nut	12
26	M4x10 Socket Head Cap Screw	4
27	M4 Roll-in T-Nut with Ball Spring	4
28	M4x16 Socket Head Cap Screw	8
29	M4 Split Lock Washer	10
30	M6 Slide-in T-Nut	12
31	M6x12 Flanged Button Head Socket Cap Screw	16
32	#1-1/4 Screw	2
33	1/4-20 1.5 Hex Head Screw	2
34	1/4-20 Hex Nut	2

SIZE A | **Ground Photographer**

SCALE: 1:20 | SHEET 1 OF 2

Figure 20. Assembly View of the Ground Photographer with the corresponding Bill of Materials

5.1.2 Exploded View

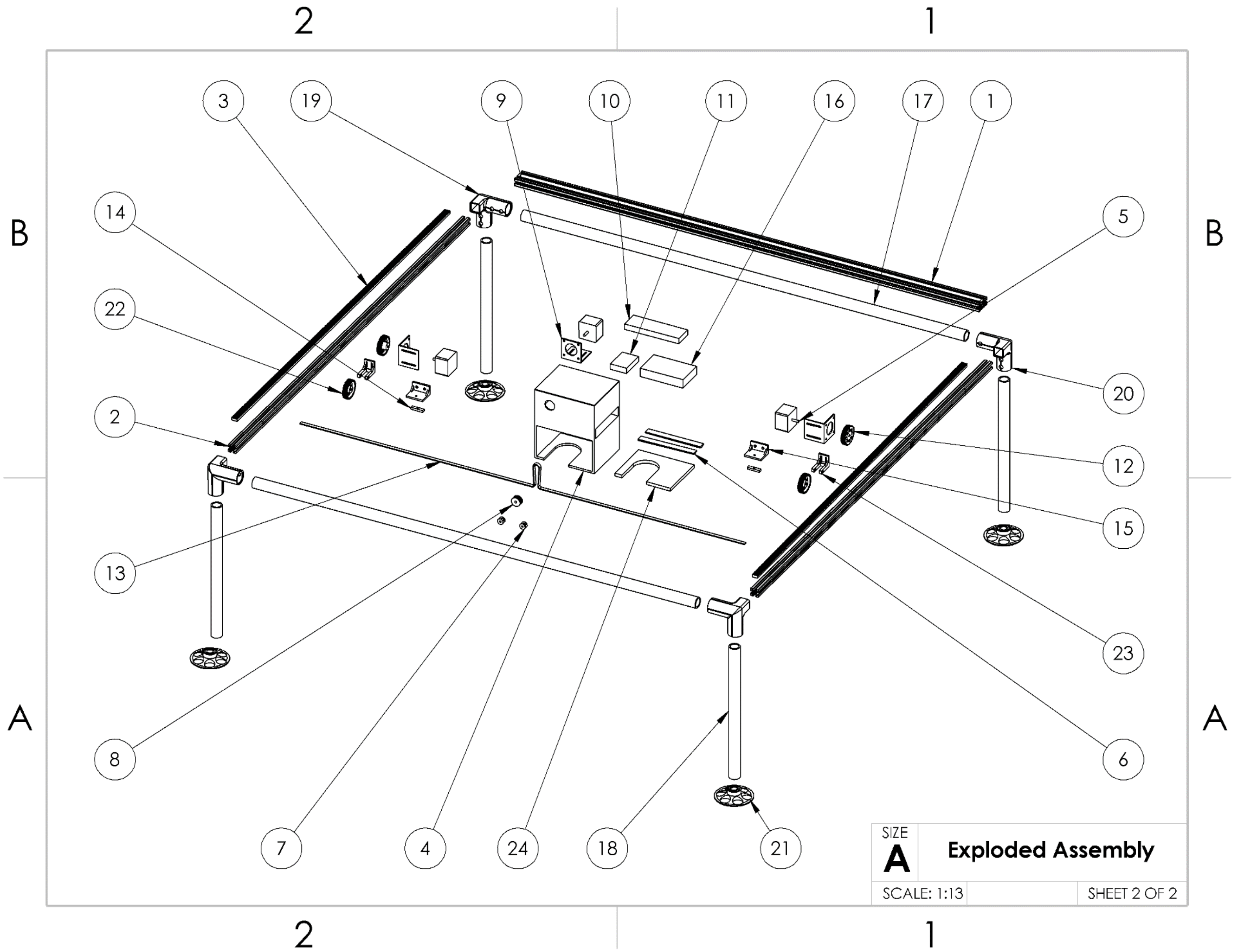


Figure 21. Exploded view of the Ground Photographer

5.1.3 Top, Right, and Side View Drawings

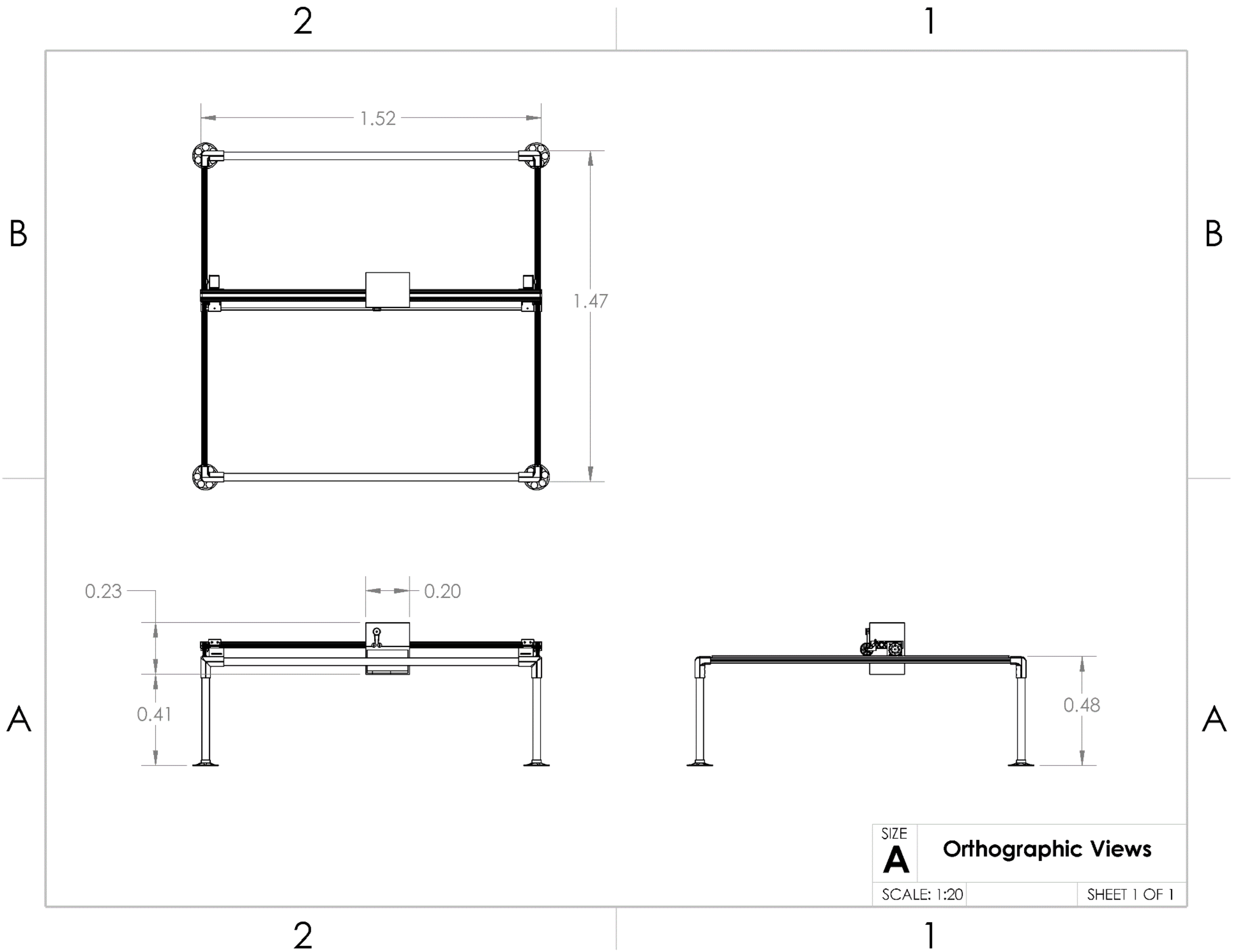


Figure 22. Front, Top and Right view with basic overall dimensions of the ground photographer

5.1.4 Initial Parts List

Below is the purchased parts list for the initial proof of concept prototype. The list does not account for parts that did not require payment, such as common materials available for our use, and parts that were 3D-printed on-site.

Table 7. Parts list

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Four Open T-Slots Bar	80/20 Inc.	25-2525	6105-T5 Aluminum, 25 x 25 mm profile, 1450 mm	$13.94	2	$27.88
2	Square Tube Profile Bar	80/20 Inc.	9000	6105-T5 Aluminum, 1" x 1", 1450 mm	$9.02	2	$18.04
3	Square Tube Profile Bar	80/20 Inc.	9000	6105-T5 Aluminum, 1" x 1", 440 mm	$3.85	4	$15.40
4	Six Open T-Slots Bar	80/20 Inc.	25-2550	6105-T5 Aluminum, 25 x 50 mm profile, 1520 mm	$19.30	1	$19.30
5	Bearing Pad	80/20 Inc.	25-6700	25 Series, single keyed, 950mm	$21.77	1	$21.77
	(80/20 shipping)	-	-	-	-	-	$27.81
6	Stepper Motor	Pololu	1476	Unipolar/Bipolar, 200 Steps/Rec, 5.7V, 1A	$24.95	3	$74.85
7	L-Bracket	Pololu	2258	Steel, for NEMA 23 Stepper Motor (Screws included)	$4.95	3	$14.85
8	Universal Mouting Hub	Pololu	1993	Aluminum, 1/4" hub, 4-40 Holes, 2-Pack	$7.95	1	$7.95
9	Stepper Motor Driver	Pololu	1182	A4988 Driver, Header Pins not Soldered	$5.95	3	$17.85
10	Breadboard	Pololu	351	400-Point Breadboard	$3.75	1	$3.75
11	Wire	Pololu	2060	Pre-Crimpted 60" wire, pack of 2	$3.95	1	$3.95
-	(Pololu shipping)	-	-	-	-	-	$20.95
12	Timing Pulley	Amazon	B079BNZDRZ	GT2, 6.35mm bore, 10mm width, pack of 4	$9.90	1	$9.90
13	Timing Belt	Amazon	43237-2	GT2, 10mm width, 5m long	$11.98	1	$11.98
14	Idler Wheel	Amazon	TRTAV2072	GT2, 5mm bore, 10mm width, pack of 5	$8.59	1	$8.59
15	Clamp Mount	Amazon	20160459	GT2, Aluminum, pack of 5	$7.99	1	$7.99
16	Arudino	Amazon	EL-CB-001	Elegoo EL-CB-001 UNO R3 Board	$10.86	1	$10.86
Total							$323.67

5.2 PROOF-OF-CONCEPT

5.2.1 Prototype Performance Goals

Three performance goals were identified, as a means of quantifying the success of the project. The Ground Photographer will be considered successful in accomplishing what it was designed to do if it meets these three goals.

1. It will take consistent photographs with overlap throughout each cycle, with respect to
   a. motion blur,
   b. focus,
   c. exposure, and
   d. lighting consistency.
2. It will complete three 3m x 3m cycles without charging batteries.
3. It will complete one 3m x 3m cycle in no more than 20 minutes.

5.2.2 Design Rationale for PoC Components

Based on the engineering models in Section 4.4, field test and further research, specific components of the Ground Photographer were selected and their respective rationales are outlines below.

5.2.2.1 Image Resolution and Height Selection

Initially, the height at which the camera was to be set at was determined as a function of the area that needed to be captured and the resolution of the camera. Additionally, due to the height at which the plants grew, the camera needed to be set above 30cm to ensure fully grown Plantago plants could be captured.

However, instead of using the engineering model, experimental data was obtained to determine the height at which the camera would be set. Field test was done with Dr. Penczykowski at Forest Park in St. Louis, MO, an area that is currently used for the research. Dr. Penczykowski first used a camera with a macro lens to take a photo with the size and resolution that she would require to view the powdery mildew (Fig. 23).

Figure 23. A 20 by 30cm plot of land taken by Dr. Penczykowski with a Nikon D3400 and macro lens

Although only a 20 cm by 30 cm area was needed, to ensure that there would be enough overlap to stitch the photos together after, a slightly larger area was needed to be captured. Due to the use of a macro lens, to obtain the picture above, the camera had to be at a height of 89 cm above ground. However, a camera at this height had challenges in ensuring stability and would require longer and heavier equipment.

Therefore, further test photos were taken with a zoom lens at lower heights (30, 40, 50, and 60 cm) as seen in Fig. 24.

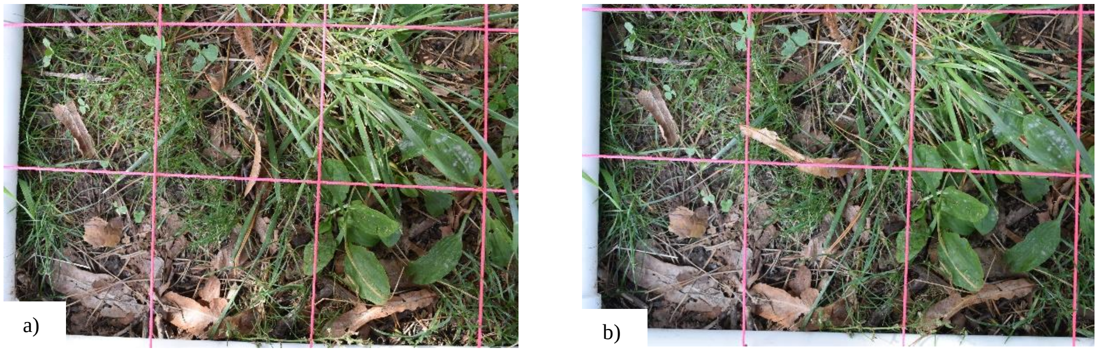


Figure 24. Pictures taken with a macro lens. a) Taken at 30cm above ground. b) Taken at 50cm above ground.

The picture taken at the lowest height of 30 cm was sent to Dr. Penczykowski to determine if had a resolution that provided would clear enough data to view the powdery mildew on the plants' surface. Based on her comments, it was then decided to set the camera at a height of 35 cm would be appropriate. This minimizes the necessary leg length for the ground photographer, thus making the design more compact and portable.

5.2.2.2 Beam Deflection and Material Selection

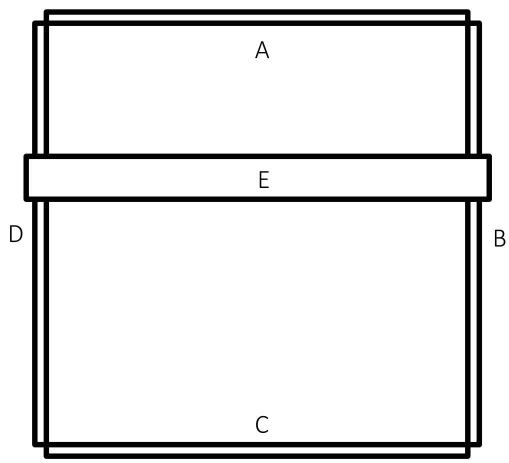


Figure 25. Top View of the Ground Photographer with each beam labeled

<u>*Deflection in bars B and D:*</u>

The camera with a zoom lens weighs approximately 920 g. Additionally, bar E weighs 2.83 kg. However, since bar E and the camera are supported by both bars D and B, only half the weight will be loaded on either bar. Therefore, an overall mass of 2.25 kg was used as an approximation for the amount of weight acting on either B or D individually. Additionally, this was an overestimate as the housing for the camera, motor and electronics are also attached to the bar but their specific weights are unknown.

Bars B and D are identical with an overall length of 1450 mm where the maximum deflection would occur directly in the middle assuming a point load. The bar is made up of 6105-T5 Aluminum with a Young's Modulus of 70,326.5 N/mm^2, and the profile used (fig. 23) has a moment of inertia of 1.9688 cm [2]

Figure 26. T-slotted profile of bar B and D

Therefore, based on the second engineering model, the maximum deflection is

$$\delta_{max} = \frac{Fb(L^2 - b^2)^{3/2}}{9\sqrt{3}LEI}$$

$$= \frac{2.25kg(9.81m/s^2)(725mm)((1450mm)^2 - (725mm)^2)^{3/2}}{9\sqrt{3}(1450mm)(70{,}326.5N/mm^2)(1.9688cm^4)}$$

$$= 1.0125\,mm$$

However, the official 80/20 website also has a deflection calculator for each given bar they sell [3]. Using their calculator, a maximum deflection of 2.67 mm for the same parameters.

<u>*Deflection in bar E:*</u>

Similarly, the deflection in bar E was calculated. As the camera and its housing are the only objects acting on the bar, a mass of 1.5kg was assumed. Using the profile as seen in Figure 24, the moment of inertia was 4.592114 cm [4]. The bar is made of the same material was bar D and B having the same Young's Modulus of 70326.5N/mm^2.

Figure 27. T-slotted profile for bar E

Therefore, based on the second engineering model, the maximum deflection is

$$\delta_{max} = \frac{Fb(L^2 - b^2)^{3/2}}{9\sqrt{3}LEI}$$

$$= \frac{1.5kg(9.81m/s^2)(760mm)((1520mm)^2 - (760mm)^2)^{3/2}}{9\sqrt{3}(1520mm)(70{,}326.5N/mm^2)(4.592114cm^4)}$$

$$= 0.3334\,mm$$

However, based on the 8020 online calculator, a deflection of 0.59436 mm is expected for the given parameters. In all, the maximum deflection of the entire apparatus would be 3.26 mm.

5.2.2.3 Required Torque and Motor Selection

Due to the change of the Ground Photographer's design, where a pinion and rack is used instead of a wheel, engineering model 4.43 was no longer directly applicable.

To select the size of the motor, research was done on motors for 3D printers and CNC machines. NEMA 17 motors are commonly used for these applications, however, for CNC machines that cut stronger materials, NEMA 23 motors are suggested as it requires more torque. Although a NEMA 23 motor is not necessarily stronger than NEMA 17 motor, NEMA 23 motors do typically provide more torque and therefore, a NEMA 23 motors was purchased instead.

5.2.2.4 Battery Selection

In order to determine the necessary battery capacity to power the design, the required charge, *C*, required to run the motors must be calculated. This is a function of the current required for each motor multiplied by the time in hours that it will be used [5]. Since it is preferable to have each cycle last no longer than 20 minutes, with the goal to have the ground photographer run at least 3 cycles on one battery charge, and motors that require 1 A each, the following calculation can be made:

$$C = I * t = (1\ A) * (1\ hr) = 1\ Ah$$

Where *I* is the current specification of each motor [A] and *t* is the total run time for one charge of the battery [hr]. It can be found that 1 Ah (amp-hours) is the necessary capacity required for each motor to fulfill the desired device specifications.

To protect the overall battery life, the battery should not be run down to zero during each charge cycle. For a lead acid battery, 20% of the battery should always be left after all cycles are completed [5]. Doing so help extends the overall number of cycles you get and slows down the rate at which the battery starts to degrade. The same principle could be applied to lithium polymer batteries. Keeping this in mind, the actual capacity with the necessary safety factor can be recalculated as

$$C' = C/0.8 = 1\ Ah/0.8 = 1.25\ Ah \qquad [5]$$

From the above calculation, it is determined that a minimum of 1.25 Ah is needed to run each motor in the device safely with lead acid batteries. This means a total capacity of 3.75 Ah is required for all three motors. For lithium polymer batteries, minimizing discharge can help to extend the battery life. In the case that lithium polymer batteries are used, it would be wise to choose a battery with capacity well above 3.75 Ah [6].

For a lithium polymer battery, it is also important to consider the maximum discharge rating of the battery. A discharge rating is generally specified for lithium polymer batteries in the form of a number followed by C, for example 20C. A 5 Ah battery with a max discharge rating of 50C could safely provide 5*50=250 A, however, the battery will only last 1.2 minutes if the system is pulling 250 A [6]. As our system will not likely require a high current, most discharge rates should be acceptable.

The motors chosen for the device have a voltage rating of 5.7 V. In order to power the Arduino selected for our device, a voltage between 7 and 12 V is required. This means a battery must be selected with a minimum voltage of 7 V, which will need to be stepped down for the motors.

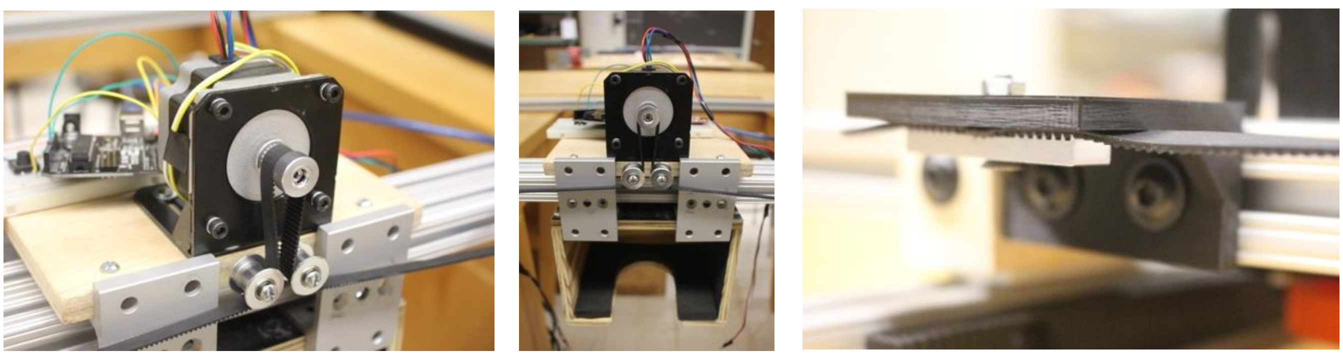
5.2.3 Proof of Concept Prototype Images

A proof of concept that was scaled down by approximately 36% was made as seen in Figures 28 a and b. The entire frame had an overall dimension of 0.96 x 0.91 m

a. b.

Figure 28. Photos of the full set-up of the proof of concept a. Top view. b. Front view

To move the camera across the length of the bar, a single motor with a timing belt was used as seen in Figure 29 a and b. To ensure the belt remained in tension, it was clamped down at the ends of the bar (Fig. 29 c.)



a. b. c.

Figure 29. Photos of the proof of concepts. a. motor and timing pulley. b. full housing of the camera and motor. c. clamp and mount for the timing belt

To move the center bar along the entire frame, two motors were connected at the ends using an L-bracket, and the gears and gear rack were 3D printed (Fig. 30)

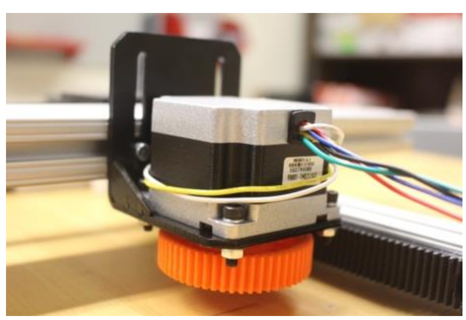


Figure 30. Motors at the end of the center bar with a 3D printed gear connected to it

6 WORKING PROTOTYPE

6.1 OVERVIEW

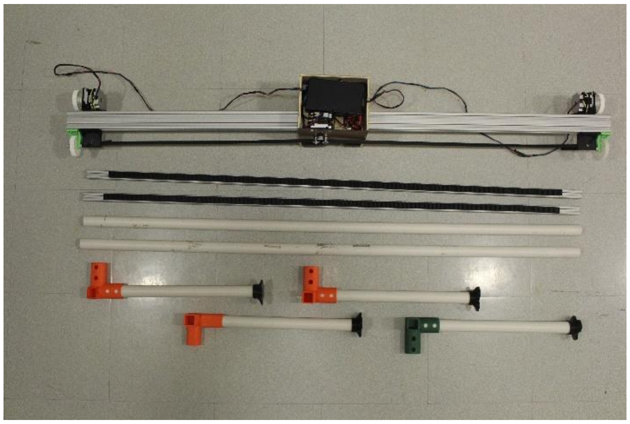
After the proof of concept demo, one major change was made to the design, along with some minor changes. At the time of the final prototype demo, the central bar was unable to move consistently across the frame when the rack and pinion was aligned parallel to the ground on either end of the bar. This is strongly believed to be because this mechanism required the frame to be perfectly square. With an improperly-squared frame, the level of contact between the racks and pinions varied from end to end of the frame. Additionally, even if the frame was squared, the pressure the pinions exerted on the racks was occasionally enough to push the racks, and thus the beams they were connected to, outwards and re-misaligning the frame.

From these difficulties, a new approach was taken to moving the bar across the frame. The motors driving the pinions were rotated 90-degrees, such that they were perpendicular to the ground, and the beams containing the racks were rotated such that the racks faced upwards. This method used gravity to keep the pinions in constant contact with the racks, resulting in a lesser degree of precision in squaring the frame being required. New brackets and additional idler wheels were also added to the design to offset the weight of the beam and camera. Pictures of this new design are shown in Section 6.2.

Aside from this major design change, two additional minor changes were made after the demo. The frequency at which the code ran to trigger the camera shutter was adjusted in fine increments until the camera recognized the code more consistently and would not skip any photos during a run. A button was also added and the device would only run once through after the button was pressed.

6.2 DEMONSTRATION DOCUMENTATION

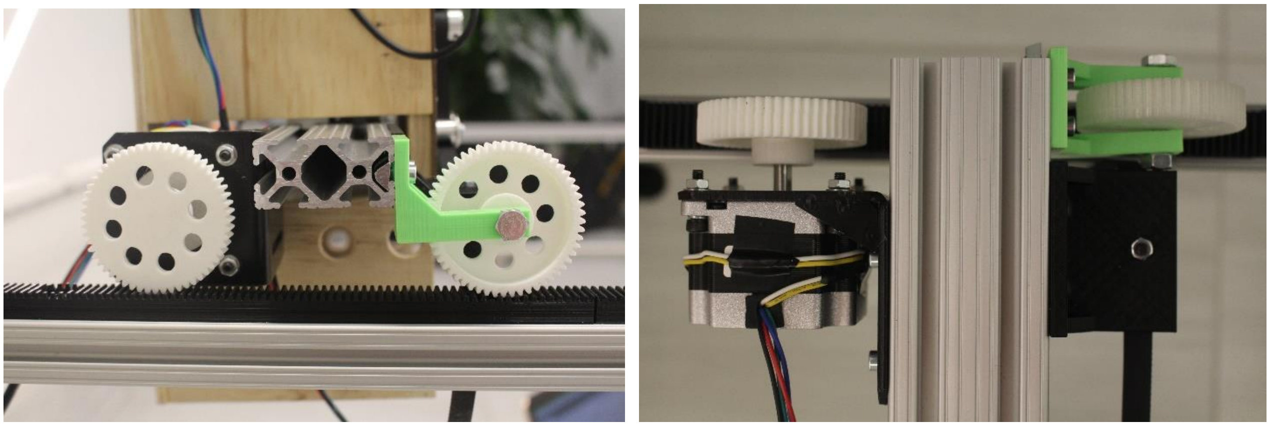
Our final working prototype is detailed below. The prototype measured 1.5 m x 1.5 m x 0.47 m and all wiring and motors were fixed to the central bar of the project. This allowed for the central beam to be easily lifted off the frame during disassembly (Fig. 31 a).



a.

Figure 31. a. Collapsed final prototype.

As described in Section 6.1, the racks and pinions at either side of the prototype were modified so that the pinions pressed downward onto the racks (Fig. 32 a). The orientation of the motors for the pinions was changed, and new brackets (green) were designed and 3D-printed such that idler gears could be added to support the weight of the beam (Fig. 32 b).



a. b.

Figure 32. a. side view of pinion and idler gear on top of rack. b. top view of pinion and idler gear mounted to central beam.

Figure 33 shows the full final assembly of the working prototype. A demo of the project was conducted outside under windy conditions, to model a potential actual use scenario.

Figure 33. Full assembly of final working prototype.

6.3 EXPERIMENTAL RESULTS

After running our final working prototype through testing, we evaluated how well it was able to reach its three performance goals. An analysis of the results of our final demo is detailed below.

6.3.1 Performance Goal 1 Results

The first performance goal was that the prototype could take consistent photographs of the right size and position. The term "consistency" referred to motion blur, focus, exposure, and lighting. The photographs taken by the prototype were sharp—meaning it was deemed features 0.5 mm in diameter could be identified in them—and of the correct size, with each photo covering about 20 cm x 30 cm of ground. With respect to lighting, shadows produced by the legs of the frame were sometimes apparent in the photos. While a shading device was initially desired for this project, it was not of the highest priority, and was not added at the time of the demo. Proper shading over the field plot would greatly enhance lighting consistency in the future.

6.3.2 Performance Goal 2 Results

The second performance goal stated that the prototype could compete three full 3 m x 3 m cycles on a single battery charge. Four cycles covering 1.5 m x 1.5 m were assumed to be equivalent to one 3 m x 3 m plot. After running 25 1.5 m x 1.5 m cycles, or the approximate 8 equivalent full cycles, the battery in use was indicated to have lost less than 20% of its charge. From this, we determine that our prototype far-exceeded expectations for this goal.

6.3.3 Performance Goal 3 Results

The third performance goal for this project was that it could complete one full 3 m x 3 m cycle in 20 minutes or less. This goal was determined based on the desire that an entire use-case including setup, use, and take-down of the prototype take less than 30 minutes. It was first determined that a single user could set up our final working prototype comfortably in under 2.5 minutes. The prototype was able to complete one 1.5 m x 1.5 m imaging cycle in 3 minutes and 35 seconds. Scaling this up to 3 m x 3 m, a full cycle could thus be completed in under 15 minutes, far-exceeding our performance goal.

7 DESIGN REFINEMENT

With the CAD model, computational analyzes were performed to ensure it meet the require design conditions. Additionally, five different safety factors were determined, its design for manufacturing for one of the part in the proof of concept, and its design for usability were also considered.

7.1 FEM STRESS/DEFLECTION ANALYSIS

An FEM analysis on the deflection of the center bar, made of 6105-T5 aluminum, was done in SolidWorks. For the boundary conditions, each end of the bar was restrained to be fixed and a load of 9.81 N was placed at the bottom of the box to represent the weight of the camera, and a load of 9.81 N was placed on the top of the box to represent the weight of the motors and required electronics (Fig. 31).

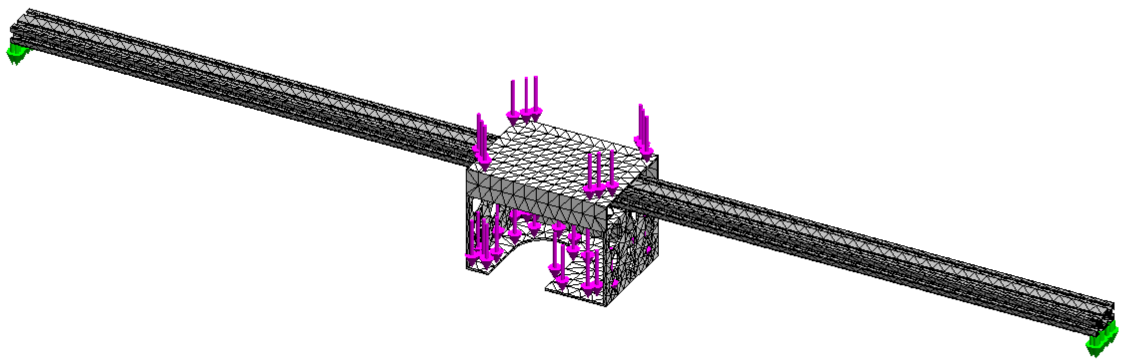


Figure 34. Mesh, loads, and boundary conditions for a FEM deflection analysis of the center bar

According to the analysis, the maximum deflection has a magnitude of 0.1888mm. However, the type of boundary conditions does not accurately represent the real-world machine's expected condition. In the computational analysis, a fixed boundary conditions prevent any form of movement about that selected face. However, in the real model, the bar is only constrained in one dimension as there nothing preventing it from moving up and down.

For the loads, uniform loads were approximate to act on the top and bottom of the box. However, at the top of the box, the loads are due to multiple objects, each of different masses where the motor weighs significantly heavier than the electronics. Therefore, this might cause inaccurate results of the displacement field.

Lastly, as the bar analyzed has a uniform cross-section with no notches inside, the mesh size used is adequate analysis ran.

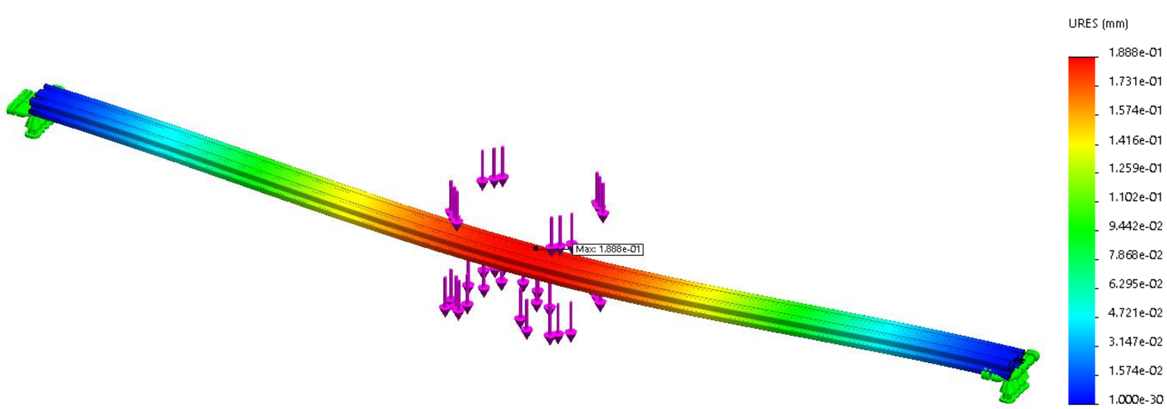


Figure 35. Displacement analysis of the center bar

7.2 DESIGN FOR SAFETY

Five risks associated with our ground photographer have been identified. Each risk will be explained in detail.

7.2.1 Risk 1

Risk Name: Transporting bars

Description: The user could sustain cuts from the corners and sharp gear teeth when moving the bars to the field, setting it up, and breaking it down after.

Impact: Mild (2)

Injuries sustained from the device would be shallow cuts or minor scrapes. While uncomfortable, these damages would not be very severe.

Likelihood: Medium High (4)

Since the device is made to be portable, transporting the bars will occur often. As there is nothing to protect the user from the corners or teeth of the gears, accidental cuts and grazes against these sharp edges may occur frequently if the user is not careful.

7.2.2 Risk 2

Risk Name: Finger injuries

Description: The current design of the device has many exposed gears and teeth that are moving at different rates. As these are exposed and do not have a safety stop, if the user places their finger or any object in the way of the gears, they risk hurting themselves.

Impact: Mild (2)

The rate at which the gears rotate is relatively low and would not provide a large force against the user, should their finger get caught. This would result in any injuries the user may sustain being rather minor.

Likelihood: Low (1)

The device is designed so that the user does not need to have any contact with the gears after it has been started. For the reason, the user most likely will not be close to the gears as they operate.

7.2.3 Risk 3

Risk Name: Gear Fusion

Description: Both the gear and rack are made through 3D printing of PLA. Therefore, if the gear and rack are moving too fast relative to each other, the friction between the tooth could generate a heat too high that causes the gear and rack to melt and fuse together. If so, the motor turning the gear would be jammed and the device would not work as intended.

Impact: Significant (4)

Fusion between the gear and rack would severely hinder the performance of the device as the central bar would then be unable to navigate around the frame. The device would be inoperable until the gear and rack could be replaced.

Likelihood: Low (1)

The rate at which is the gears are rotating is relatively low, resulting in a basically negligible amount of heat. Not enough heat would be produced to fuse the gear and rack.

7.2.4 Risk 4

Risk Name: Repetitive Stress

Description: To assemble and break down the device, the user must bend down multiple times as the device is only set to a height of approximately 40cm. This put repetitive stress of the user's back and joints.

Impact: Moderate (3)

The stress produced on the user's back and joints and a result of this risk would be highly uncomfortable and can worsen over time, resulting in serious and prolongs health issues.

Likelihood: High (5)

To set up, start, and disassemble the device, the user will have to bend often and for certain cases for extended periods of time. Since the device is at a height of about 0.5 m, there is almost no way to avoid the need for bending.

7.2.5 Risk 5

Risk Name: Battery Explosion

Description: A high voltage and current battery is used in this device to ensure it is able to run the life cycle as needed. However, blunt impact to the battery, or improper use of it, can cause certain types of batteries to catch fire or explode.

Impact: Significant (4)

As the battery is the supply of power for the device, a broken battery would make the device inoperable until it could be replaced. Additionally, the chemicals within the battery can be harmful to the user if they were to be exposed through an explosion.

Likelihood: Low-medium (2)

A strong protective material encloses the internal components of the battery and protects it from short falls. The battery is also contained within the camera housing during operations of the devices, negating any need to handle the battery and risk dropping it. As well, the battery is at a height of about 0.5 m from the ground when the device is assembled. Such a short fall should not greatly impact the battery or the contents within.

7.2.6 Heat Map of Risks

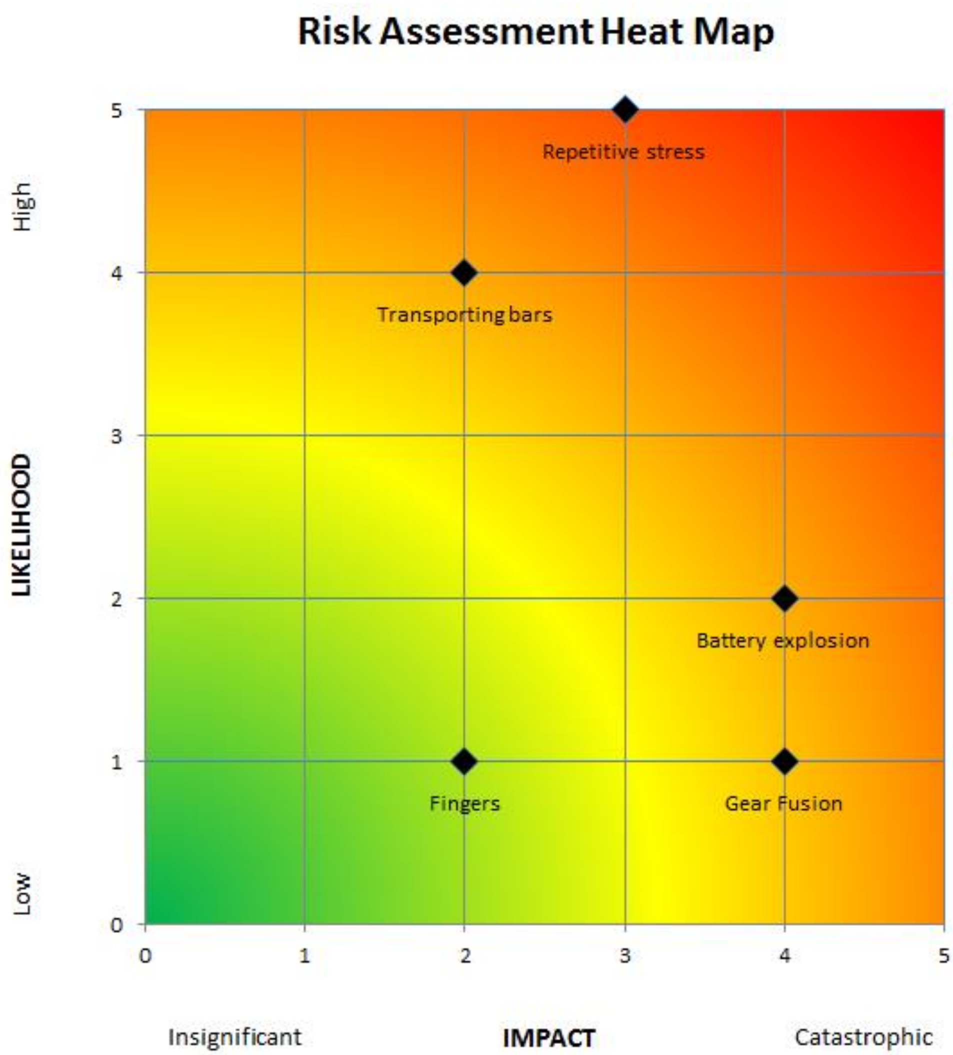


Figure 36. Risk Assessment Heat Map

7.2.7 Risk Prioritization

As indicated by the heat map in Figure 33, repetitive stress from multiple uses of the device is the highest risk associated with the device. For this reason, it is the highest priority to avoid. While some of this risk is inevitable due to the requirements of the device, the risk can be mitigated by designing easy to assemble components. The second highest priority risk is the transportation of the bars that could lead to cutting oneself on sharp edges. Limiting the number of sharp edges by filling and adding rounded corner and providing a bag for transportation would help to reduce this risk.

The next priority is the battery explosion. This can be tackled by designing the circuits to ensure there is no overcharging or discharging, choosing a battery that is less likely to explode, or by providing a fireproof protective case surrounding the battery. Gear fusion is the next highest priority. Melting or fusion of the gears can be prevented by limiting the speed that the gears move and the amount of time that the device is running. The last priority is getting one's fingers caught in the moving components. The likelihood of this occurring is low as the device is designed with the intention that the user would not have to manipulate it once it starts running. However, if the user does come into contact with it while the gears are moving, this risk can be limited by providing protective casing around moving components.

7.3 DESIGN FOR MANUFACTURING

7.3.1 Draft Analysis

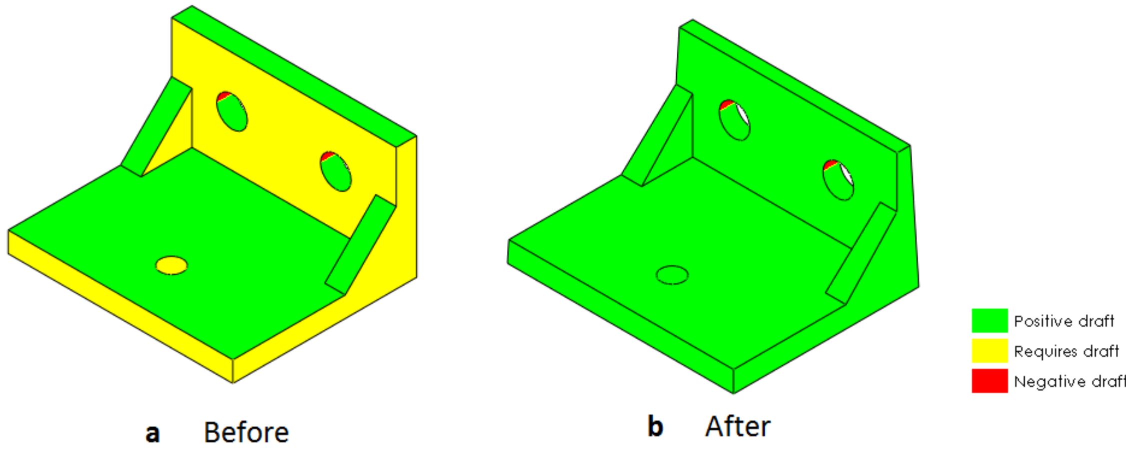


Figure 37. Images of the clamp mount used for draft analysis in SolidWorks. a. draft analysis of original clamp mount. b. draft analysis after adding 2 degrees to the required faces.

A draft analysis was performed on the bracket onto which the belt is clamped due to the simple geometry of the part. Images of the draft analysis before and after drafting the bracket are shown in Figures 34 a and b. A draft angle of 2 degrees was applied to the walls that the initial analysis deemed in need of a draft. The face of the part with one hole was chosen as the pull direction to reduce wall thinning on stress holding areas. The face with the single hole kept a consistent wall thickness, which is important as this holds the belt tension. Additionally, it is longer than the face with two holes and thus, would have thinned more if the latter face was chosen as the pull direction. After adding the draft, the face with two holes thinned; however, the final thickness is appropriate for mounting it to the center bar.

The two holes in the face would also need to be created with pins in the mold, therefore, the draft analysis on the interior of the holes is ignored. Overall, the final analysis indicates the drafting would be successful. However, this part is currently made though FDM 3D printing, which is sufficiently strong and does not require modification of the dimensions or thinning of walls.

7.3.2 Turn with Mill/Drill

Using a manufacturing process of turning with a mill or drill, there are 12 rules that needed to be followed. For the gear used, only 1 rule failed as seen in Figure 35. For a mill, internal sharp corners are hard to achieve and thus should be avoided, or the use of a more expensive process such as EDM is needed. For this gear, the bore profile was designed to match that of the motor's shaft profile. However, if a mill was to be used, this would need to be changed and a different method of attaching the gear to the motor shaft would be required.

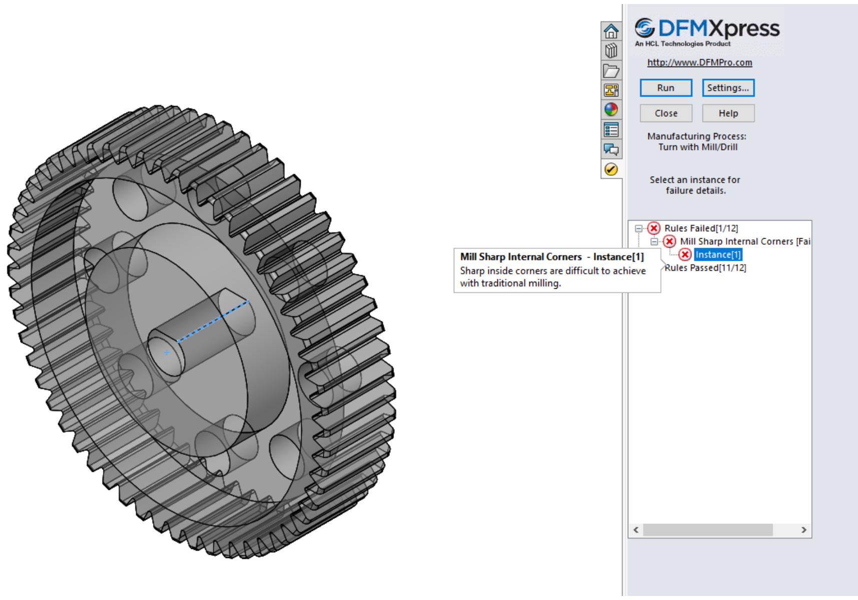


Figure 38. DFM analysis in SolidWorks for a Mill/Drill only process for the gear attached to the motor

7.3.3 Injection Molding

Using an injection molding process, two rules need to be followed: the part is not too thin to ensure there are no filling problems that causes high stress and structural failures, and that the part is not too thick to prevent cooling problems and defects. However, for this gear, both rules fail as seen in Figure 36. The distance between the tooth were too close with a distance of only 0.0553in, but the program suggested a thickness of at least 0.0787. In contrast, all the other parts of the model were too thick. For example, the face of the gear has a thickness of 0.2in; however, a thickness of less than 0.01181 is recommended.

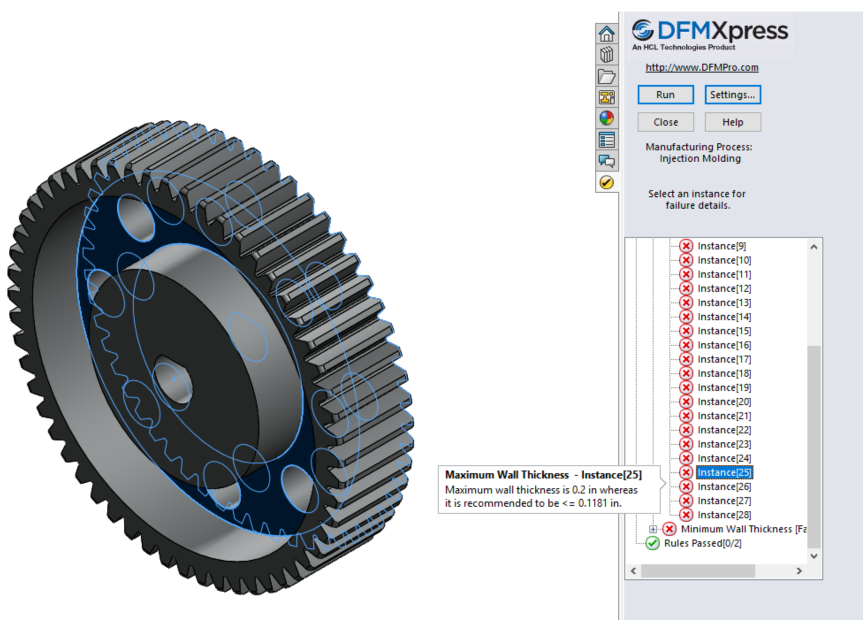


Figure 39. DFM analysis in SolidWorks for an Injection Modeling process for the gear attached to the motor

7.4 DESIGN FOR USABILITY

7.4.1 Vision Impairment

Vision impairment creates several problems for users of our device. A lack of good sight would make it difficult for a user to ensure that the camera is correctly aligned within the box in our device. To avoid this, alignments within the camera box can be added to ensure it is inserted in the same position each time. Additionally, a vision impairment could make it difficult to see the button to start the motion and ensure that the device is running properly. To mitigate this, the button size can be enlarged to make it more accessibly for the user. Lastly, it would be difficult for a user with impaired vision to ensure the components are perfectly aligned when assembling the device. Similar to creating alignments for the camera, the bar connectors can be made to be more robust in ensuring that that bars will always be perfectly squared and aligned properly.

7.4.2 Hearing Impairment

Hearing impairment would not cause major errors for a user of our device as no part of the device relies on auditory signals for the user. However, if a failure were to occur with the motors, sound is a signal for this and a hearing-impaired user would not be able to identify this. When the motors are running properly, a hum or whir coming from the motors that are usually quiet.

The only issues that might arise for a user with hearing impairment would be an ability to hear the motors running, especially in the case that an issue arises with the device and the user is unable to determine whether or not the motors are receiving a signal, as this can manifest in a

7.4.3 Physical Impairment

Physical impairment would be an issue for users of our device. While a primary goal of the device is automation, the device requires transportation, assembly and break down in the field. Users with arthritis or a limb immobilization might have difficulty carrying the device, as it consists of a metal frame that is heavy. Additionally, each of the bars of the frame are approximately 1.5 meters in length, which would be difficult to carry with only available arm. To assist users with this issue, they can place the device on a transport system such as a dolly to help them carry it.

7.4.4 Language Impairment

Language impairment would have no influence on the usability of our device. All controls for the device are free of words and the camera that is used can be set to the language of the user’s choice. Additionally, assembly of the device is self-explanatory and requires no knowledge of the English language to complete.

7.4.5 Control Impairment

Control impairment would have little to no influence on the user’s ability to use our device. Since the machine is design to be automated, once assembled and started, the camera will move, take pictures, and stop on its own with no necessary input from the user. Assembly is made to be simple and easy to minimize the time necessary to set up the device, so impairments such as distraction or fatigue should have almost no effect.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

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

Overall, our project aligned with the initial project description. We were able to take clear photos with sufficient resolution within the time frame that Dr. Penczykowski specified. The battery selected provided sufficient charge for several runs, and the device was easy to assemble and use. The only factors that fall outside the desired specifications were that the device was only 1.5 m x 1.5 m, instead of the desired 3 m x 3 m, the motion of the bar along the frame was not always consistent, and the addition of a sun shade was overlooked. The sun shade is a simple technical fix that can be achieved by adding a shade to the frame. However, achieving a consistent motion of the bar across the frame is a larger challenge where the frame has to be perfectly squared. Additionally, the size of the frame is a challenge as it currently requires user input to be able to capture the full 3 m x 3 m plot.

8.1.2 Was the project more or less difficult than expected?

Going in to this project, we expected the most difficult part of the project to be fabricating a designed that was both collapsible and easy for an individual to carry. This did prove to be a challenge, and it was one of the primary reasons for us reducing the scope of the device to encompass only 1.5 m x 1.5 m, instead of the initially requested 3 m x 3 m.

One aspect of the project that was more difficult than expected was triggering of the DSLR camera to capture photos. While many cameras have means of being connected to a circuit and controlled by an Arduino, the Nikon D3400 the project was designed for did not have the capability. Therefore, the camera had to be controlled using an IR LED instead, where a specific sequence of light emitted by the LED was required for the camera to recognize the command. Although the final device has the camera working as needed, the process to reach such a point was more difficult and time-consuming than anticipated.

Finally, the last challenge we faced was designing a method to move the central bar across the frame. A rack and pinion was determined to be the best method given the goal of keeping all moving component only on the central bar. Initially, the rack and pinion were position horizontally such that they were parallel to the ground. With this design, the frame had to be perfectly squared to ensure a constant and consistent pressure between the racks and pinions. However, developing a simple and quick method of squaring the frame was the biggest final challenge in this project. As such, the method of motion was modified instead to have it be less dependent on the precision of the frame.

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

Overall, time was properly managed throughout the design process. However, more time was spent on concept generation and selection, which instead should have been allocated to the fabrication process. It is only when the physical components of the design are assembled together do problems arise. Additionally, the process of concept selection could have been sped up to provide more time for construction and design. To speed up the concept selection process, it would have also been helpful to be given time to consult with engineers who have mechanical design experience so as to obtain a better understanding of the type of solutions that may or may not work.

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

A component that was unexpectedly harder to make was the method of which the camera was to take photos. Initially, we assumed that we would be able to connect the camera to an Arduino to directly communicate with the camera when to take the pictures. However, it was discovered that the camera our client used does not have this ability, thus, we had to look into alternate methods. Using an infrared signal that required a simple circuit with an IR LED was the next best option. With this method, we encountered challenges with finding a compatible code with the camera we were testing. As a specific pattern of pulse was needed for the camera to read it as a signal to trigger a photo, achieving this pattern proved to be harder than expected. Different methods were being considered at the same time; however, the correct was found and all was left were small changes to suit our requirements.

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

While there were flaws with our design and improvements can be made to better reach the user's needs, the overall concept of the design was appropriate, and it was able to meet its performance goals. However, another design, the Spidercam®, could potentially be more lightweight and collapsible solution. If more time was given to the project to learn the coding algorithms needed, a much more successful design could have been achieved.

For the design that we chose, there could be a better solution to move the central bar across the frame that would be simpler and lighter, thus resulting in a more successful design.

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 focused on researching camera-mounting devices and codes relating to collapsible mechanical parts. We also looked into codes relating to external batteries, as we knew a battery would be required to allow our project to run through multiple cycles out in the field. In the end, these codes did not influence our design concepts greatly, as our design ultimately went in another direction. One of the standards we found related to retractable shafts, as we knew our design needed to collapse to fit into a car, and we were contemplating having telescoping tubes expand out. However, we ultimately reduced the scope of our project, negating the need for this standard to apply to our project.

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

While generating and evaluating design concepts at the beginning of the process, it was not initially apparent that there was no method of hardwiring the DSLR camera we were designing for to trigger a photo. This information was left out as micro-USB connections are almost universal for DSLR cameras. Therefore, additional planning and designing were required upon discovering that the Nikon D3400 is one such camera that does not have this ability. To compensate for this, an IR LED emitting a specific sequence of burst of light had to be used instead.

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

Although the motor was selected based on its supplied torque and voltage, where we ensured it was above the required torque of the design, it would have helpful to consider the voltage-torque curve for the motors selected. When selecting the motors and battery, we still did not have a full understanding of all of the factors that play into torque-requirements for what we were trying to accomplish. Additionally, other deflection analysis could have been done on components such as the camera and electronic housing. This would have guided us in choosing a material that might have been lighter and would make our design easier to transport. Instead, the thickness and type of wood used for the camera housing were chosen based on available parts.

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

If we were to redo the course, it would be beneficial for us to spend more time in the initial proof of concept phase. When producing our first prototype, there were still many details of the design that were not fully defined. As such, there were many challenges that arose after due to the lack of preparation of how the different components of the design could be assembled. If time had been spent instead on making simple proof of concepts and iterating through them to decide how the different mechanism would work individually before assembling them together, we might have been able to produce a different and better final solution.

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

There are several small upgrades that could be made to improve the device. Firstly, when running for extended periods of time, the motors driving the gears across the frame would stutter occasionally. This is likely due to the fact that the two motors are running through one driver, causing the driver heat up considerably. Therefore, it would be beneficial to include heat sinks to help dissipate the heat generated and prevent the drivers from burning out as well. Secondly, a wider rack with guard rails could be added to the frame to ensure gear and pinion are always in contact with each other. Although they currently do have a small tolerance that allows for the gears to move and still be in contact with the rack, if the gears do slip off, the entire beam will fall.

Thirdly, the rack being used is 3D printed and thus contains holes where bolts are inserted for it to be mounted to the aluminum bar. As these holes are of a significant size, it could cause one of the gears to be temporarily stuck and cause the motor to skip steps. This will result in the bar to either become misaligned or derailed. It would also be helpful to cut more precise PVC pipes machine new corners. To obtain a perfectly square frame, the length of the PVC pipes is essential as any difference will inversely affect the frame. Similarly, the corner pieces connecting the pipes and bars affect how well a square frame can be made. With the design and parts used, the corners had to be a custom design and thus, were 3D printed. A Fused Deposition Modeling (FDM) printer was used which results in anisotropic properties in the parts, importantly the strength of the corners. As a snug tolerance was needed, this led to some of the corners splitting along the layer lines as they were weaker and prone to failure along the direction of the layers. To change this, stronger corners can be made through machining or injection molding. This would correspondingly help stabilize the frame.

Moreover, in our working prototype, the wires connecting the Arduino to the two motors driving the bar across the frame are freely hanging. When the camera is at each end of the beam, the wires are occasionally caught in the line of the camera and obstruct certain features in the photo. Additionally, when transporting the beam, the wires can be caught onto objects. Therefore, a method of containing and raising the wires above the level of the camera is necessary. Lastly, a sun shade would also help to increase the consistency of pictures.

8.3 TEAM ORGANIZATION

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

Our team included a wide range of skills that complemented each other. Some members of the team had extensive experience with CAD modeling and 3D printing. These members were able to focus on designing customized parts to be printed and making iterations when needed. This also allowed us to print several parts, such as the rack and pinions, that would have been more costly to purchase. Similarly, members with coding experience programmed the Arduino to run the stepper drivers and IR LED, and worked on troubleshooting functionality issues. Overall, all members of the team worked together in discussing engineering solutions and researching options for how to meet the project's performance goals.

While the project ran smoothly, some additional skills would have allowed us to work more effectively. At the start of this project, no member of the group had sufficient experience working with Arduinos, and had not had recent experience with circuitry. However, these skills were gained quickly and did not prove to be a significant issue. Another additional knowledge that would have been beneficial is understanding the methods of selecting a motor size. We found it difficult to identify engineering models to encompass all of the factors included in the torque requirements in tandem with the motor and battery selections. Therefore, with additional knowledge, a more appropriate motor selection might have been done.

8.3.2 1.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

Through this design process, every group member gained a lot of experience and confidence in circuitry and coding, opening up a world of possibilities for other projects. The overall structure of our project resembled that of a 3D-printer in many ways, with the camera housing representing the head of a printer. Similarly, the housing is driven back and forth along a beam, and the beam is driven back and forth along a frame. Having a better understanding as to various ways to make these movements happen, it inspired some of our group members to attempt creating a 3D-printer that extrudes materials other than plastics.

Lastly, going through the process of design thinking in a collaborative setting inspired group member to continue working on other similar projects as independent studies, and further in graduate school.

Appendix A – Cost Accounting Worksheet

Table 8. Table of parts bought in creating the ground photographer

#	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Four Open T-Slots	80/20 Inc.	1010	6105-T5 Aluminum, 25x25 mm profile, 1450 mm length	$11.82	2	$23.63
4	Six Open T-Slots	80/20 Inc.	1020	6105-T5 Aluminum, 25x50 mm profile, 1520 mm length	$21.00	1	$21.00
5	Stepper Motor	Pololu	1476	Unipolar/Bipolar, 200 Steps/Rec, 5.7V, 1A	$24.95	3	$74.85
6	L-Bracket	Pololu	2258	Steel, for NEMA 23 Stepper Motor (Screws included)	$4.95	3	$14.85
7	Universal Mouting Hub	Pololu	1993	Aluminium, 1/4" hub, 4-40 Holes, 2-Pack	$7.95	1	$7.95
8	Stepper Motor Driver	Pololu	1182	A4988 Driver, Header Pins not Soldered	$5.95	3	$17.85
9	Breadboard	Pololu	351	400-Point Breadboard	$3.75	1	$3.75
10	Pulley	Amazon	B079BNZDRZ	GT2, 6.35mm bore, 10mm width, pack of 4	$9.90	1	$9.90
11	Pulley belt	Amazon	43237-2	GT2, 10mm width, 5m long	$11.98	1	$11.98
12	Idler Wheel	Amazon	TRTAV2072	GT2, 5mm bore, 10mm width, pack of 5	$8.59	1	$8.59
13	Clamp Mount	Amazon	20160459	GT2, Aluminum, pack of 5	$7.99	1	$7.99
14	Wire	Pololu	2060	Pre-Crimpted 60" wire, pack of 2	$3.95	1	$3.95
16	Arudino	Amazon	EL-CB-001	Elegoo EL-CB-001 UNO R3 Board	$10.86	1	$10.86
17	Battery	Amazon	YB1206000	12 V Rechargeable 6000mAh Li-Ion Battery Pack	$29.99	1	$29.99
20	IR Remote	Amazon	B07C98VCLS	ML-L3 replacement for Nikon DSLR, CR-2025 3v battery	$7.99	1	$7.99
21	Motor Driver	Amazon			$14.99	1	$14.99
22	8-32 lock nuts	Home Depot	800151	Coarse Stainless Steel Nylon	$1.18	1	$1.18
23	M4 - 0.7 nuts	Home Depot	803668	Zinc-Plated Nylon	$0.47	1	$0.47

24	Female D-sub Crimps	Micro Center	DHA-2102-10	Pack of 10	$1.99	2	$3.98
25	Female DC connector	Micro Center	69-A17	5.75 inch leads, 5.5mm x 2.1mm	$2.99	1	$2.99
26	1/4 2'x2' Plywood	Home Depot	1502002	Sanded	$4.85	1	$4.85
27	1/8 2' x 4' Hardboard	Home Depot	7005015	Tempered	$4.27	1	$4.27
28	IR LED	Adafruit	ID:387	Super-bright 5mm IR LED	$0.75	5	$3.75
29	Buttons	Adafruit	ID:1009	Colorful round tactile button switch assortment - 15 pack	$5.95	1	$5.95
Total:							**$297.56**

Appendix B – Final Design Documentation

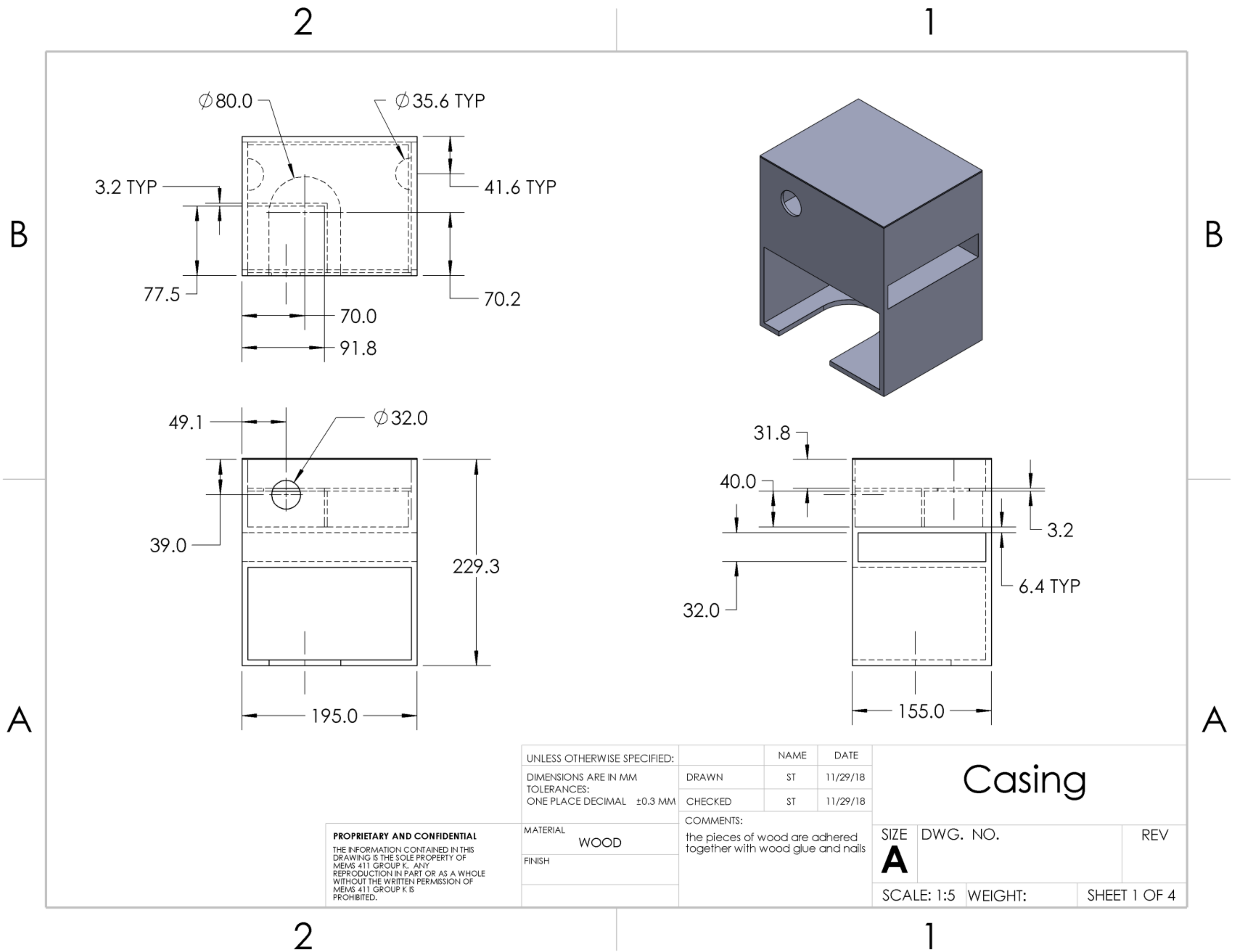


Figure 40. Drawing of the camera housing in SolidWorks

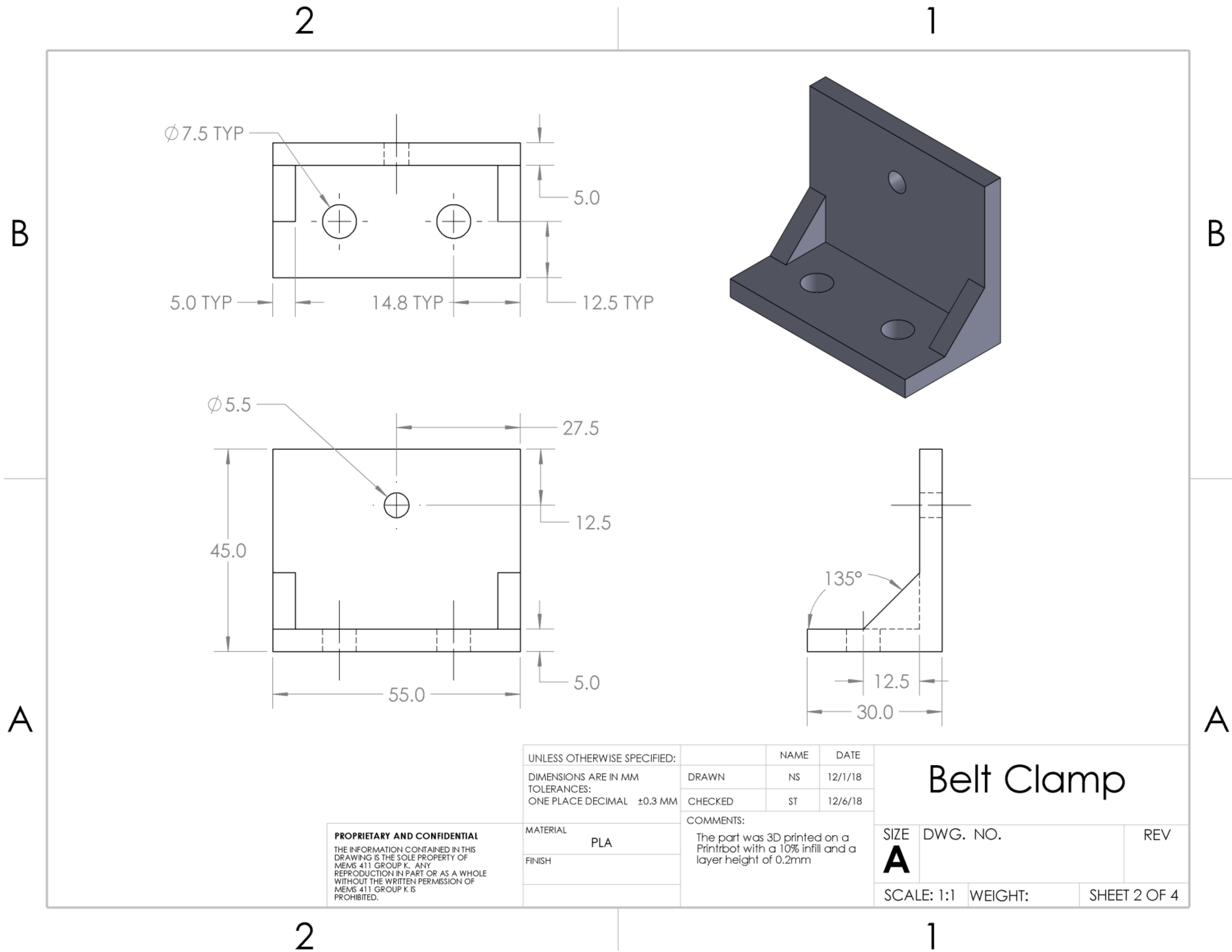


Figure 41. Drawing of the belt camp in SolidWorks

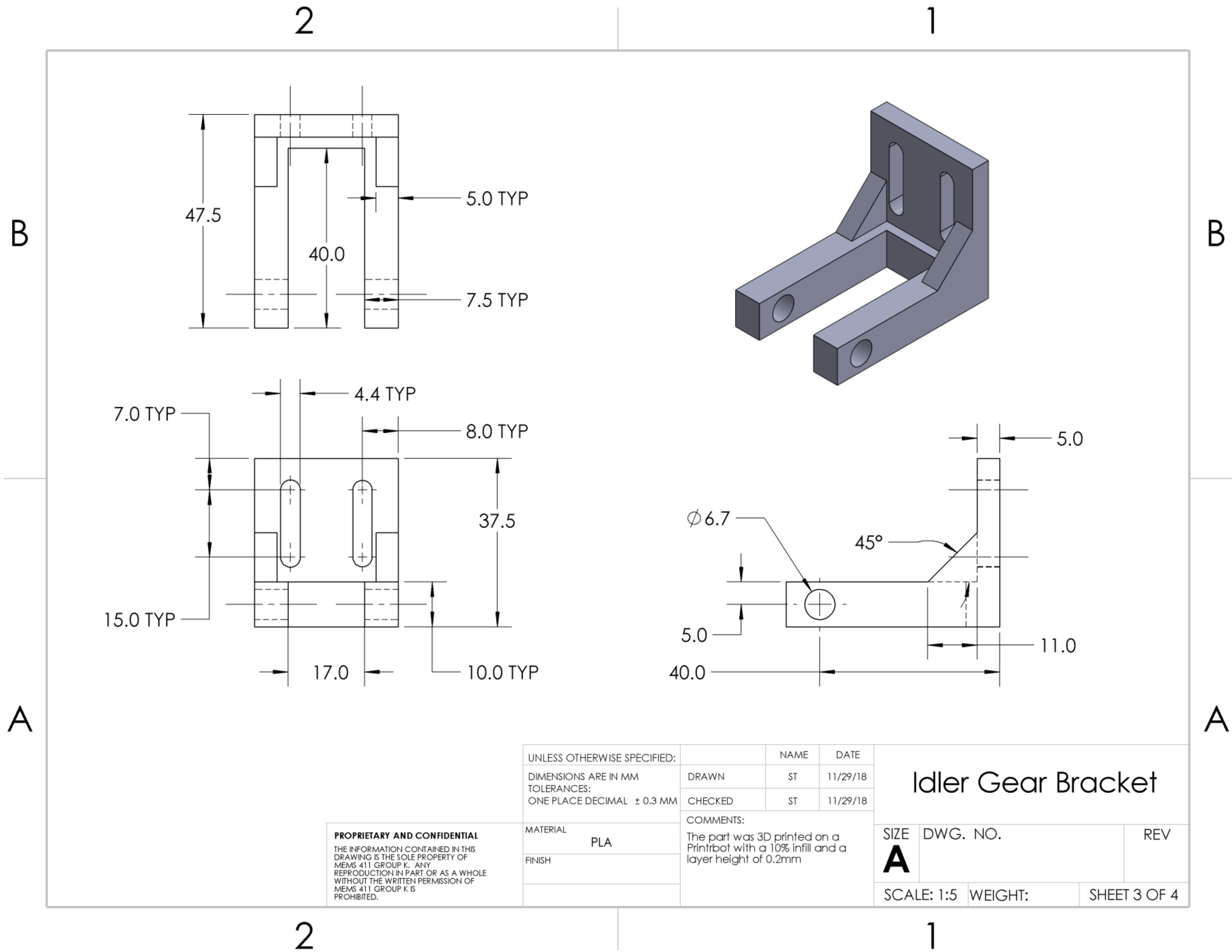


Figure 42. Drawing of the Idler Gear Bracket in SolidWorks

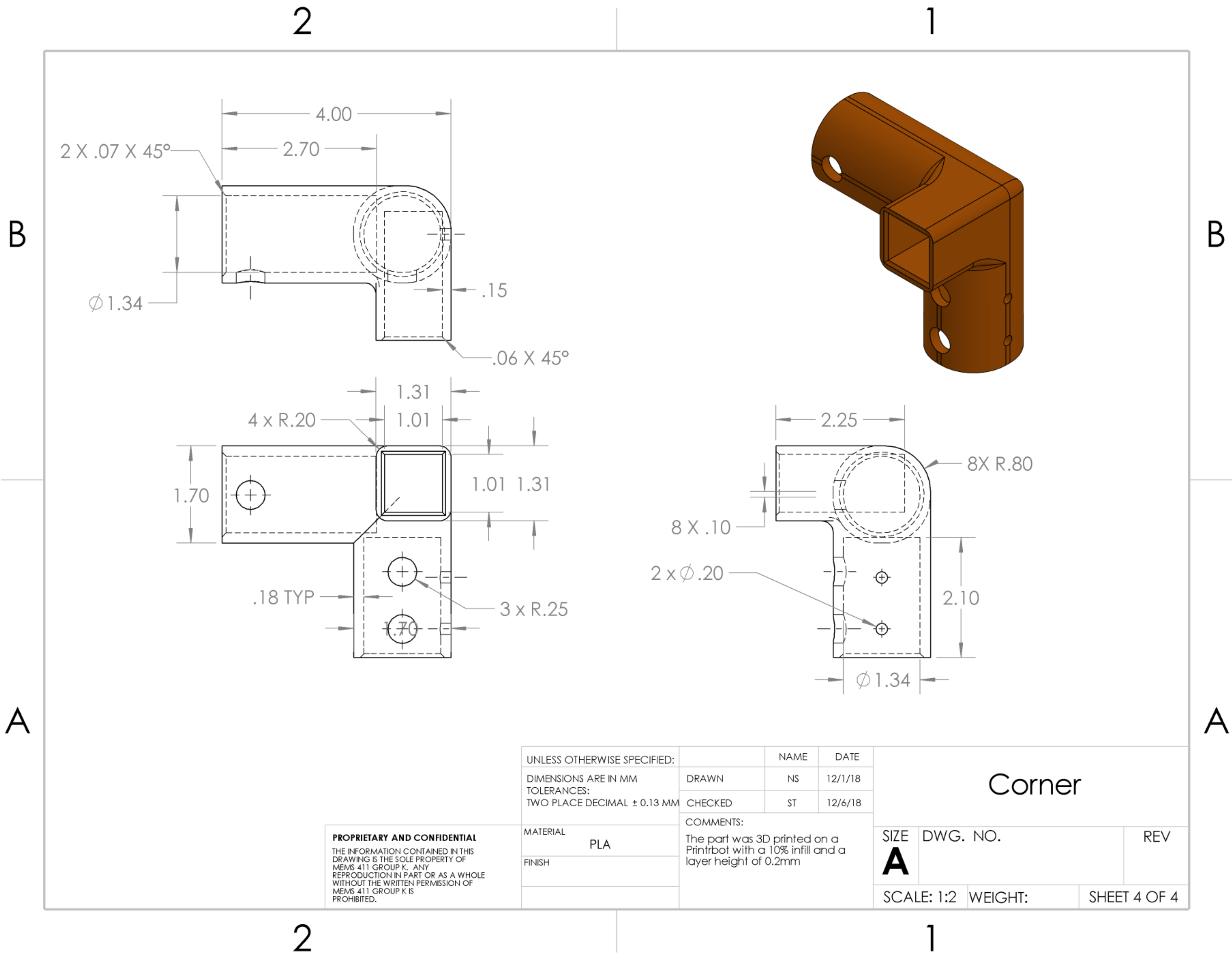


Figure 43. Drawing of the corner in SolidWorks

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