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JME 4110 PheNode Camera Arm Design Project

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Joint Engineering Program

University of Missouri–St. Louis ▪ Washington University in St. Louis

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The goal of this design project was to create an extendable camera arm capable of attaching to the shell of the PheNode in-field apparatus created by researchers at the Donald Danforth Plant Science Center. The camera arm extends 36 inches in length, can rotate 180 degrees, and successfully holds a camera for plant imaging with minimal vibrations. We have designed an affordable camera arm that is stable and meets the design parameters given. Our design process is documented in the following report.

JME 4110
Mechanical Engineering Design Project

PheNode Camera Arm

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Kelsey Wortmann

TABLE OF CONTENTS

List of Figures 3
List of Tables 4
1 Introduction 5
1.1 Value proposition / project suggestion 5
1.2 List of team members 5
2 Background Information Study 5
2.1 Desgin Brief 5
2.2 Background summary 5
3 Concept Design and Specification 7
3.1 User Needs and Metrics 7
3.1.1 Record of the user needs interview 7
3.1.2 List of identified metrics 9
3.1.3 Table/list of quantified needs equations 10
3.2 concept drawings 11
3.3 A concept selection process. 14
3.3.1 Concept scoring (not screening) 14
3.3.2 Preliminary analysis of each concept’s physical feasibility 115
3.3.3 Final summary statement 16
3.4 Proposed performance measures for the design 16
3.5 Revision of specifications after concept selection 17
4 Embodiment and fabrication plan 19
4.1 Embodiment/Assembly drawing 19
4.2 Parts List 20
4.3 Draft detail drawings for each manufactured part 21
4.4 Description of the design rationale 21
5 Engineering analysis 22
5.1 Engineering analysis proposal 22
5.1.1 Signed engineering analysis contract 22
5.2 Engineering analysis results 22
5.2.1 Motivation 22
5.2.2 Summary statement of analysis done 23
5.2.3 Methodology 23
5.2.4 Results 28

    - 5.2.5 Significance ... 28
- 6 Risk Assessment ... 29
  - 6.1 Risk Identification ... 29
  - 6.2 Risk Analysis ... 30
  - 6.3 Risk Prioritization ... 31
- 7 Codes and Standards ... 32
  - 7.1 Identification ... 32
  - 7.2 Justification ... 32
  - 7.3 Design Constraints ... 32
    - 7.3.1 Manufacturing ... 32
    - 7.3.2 Economic ... 32
  - 7.4 Significance ... 32
- 8 Working prototype ... 33
  - 8.1 prototype Photos ... 33
  - 8.2 Working Prototype Video ... 33
  - 8.3 Prototype components ... 34
- 9 Design documentation ... 36
  - 9.1 Final Drawings and Documentation ... 36
    - 9.1.1 Engineering Drawings ... 36
    - 9.1.2 Sourcing instructions ... 40
  - 9.2 Final Presentation ... 40
- 10 Teardown ... 40
- 11 Appendix A - Parts List ... 41
- 12 Appendix B - Bill of Materials ... 42
- 13 Appendix C – Complete List of Engineering Drawings ... 44
- 14 Annotated Bibliography ... 47

LIST OF FIGURES

Figure 3.1: Concept Drawing 1: Ball Socket Design. 11
Figure 3.2: Concept Drawing 2: Gravity Oriented Camera 12
Figure 3.3: Concet Drawing 3: T-slot Design 13
Figure 3.4: Concet Drawing 4: Pin Mount Design 13
Figure 3.5: Concept scoring for Concept 1 14
Figure 3.6: Concept scoring for Concept 1 14
Figure 3.7: Concet scoring for Concept 1 15
Figure 3.8: Concet scoring for Concept 1 15
Figure 4.1: Embodiment drawing. 19
Figure 5.1: Free Body Diagram of theoretical prototype of the camera arm 24
Figure 5.2: Free Body Diagram of camera arm member sections 25
Figure 5.3: Free Body Diagram of the ball joint 25
Figure 5.4: Representative SolidWorks prototype model 26
Figure 5.5: Vibrational analysis on the prototype model 27
Figure 5.6: Further results of vibrational analys on prototype model 27
Figure 6.1: Fundamental steps of risk management 29
Figure 8.1: Photograph showing the overall view of our prototype 33
Figure 8.2: Close-up view of the adjustment set screws 34
Figure 8.3: Close-up view of the wire assembly 34
Figure 8.4: Close-up view of the internal camera arm structure 35
Figure 9.1: Final assembly drawing for the camera arm 36
Figure 9.2: Final parts list and assembly drawing for the camera arm 37
Figure 9.3: Modifications made to the ball joint while building the camera arm 38
Figure 9.4: Modifications made to the connecting rod wile building the camera arm 39
Figure 4.3.1: Zinc-plated steel inline ball joint linkage 44
Figure 4.3.2: High-strength alumninum right-hand female-threaded connecting rod 45
Figure 4.3.3: Metal-bonded sealing washer 45
Figure 4.3.4: High-strength alumninum easy-adjust turnbuckle-style threaded connecting rod 46
Figure 4.3.5: Stainless steel button-head socket cap screw 46

LIST OF TABLES

Table 3.1.1: Record of the user needs interview 7
Table 3.1.2: List of identified metrics 9
Table 3.1.3: Table of quantified needs equations 10
Table 3.5.1: Identified metrics for Concept 3 17
Table 3.5.2: Associated needs revised for Concept 3 18
Table 5.1: SolidWorks vibrational analysis data 28
Table 6.3.1: Table of risk prioritization for our project 31
Table 12.1: Final list of parts used in our project 42
Table 12.2: Part explanations for the parts listed in Table 12.1 43

1 INTRODUCTION

1.1 VALUE PROPOSITION / PROJECT SUGGESTION

For this project, we will be designing an affordable camera arm that has swiveling sockets, can mount to the shell of a PheNode system, maintain the ability to fold, and extend to at least 36 inches. We will focus on creating an arm with the ability to maintain its position and hold a camera steady.

1.2 LIST OF TEAM MEMBERS

- Paul Masnica
- Matthias Sommer
- Kelsey Wortmann

2 BACKGROUND INFORMATION STUDY

2.1 DESGIN BRIEF

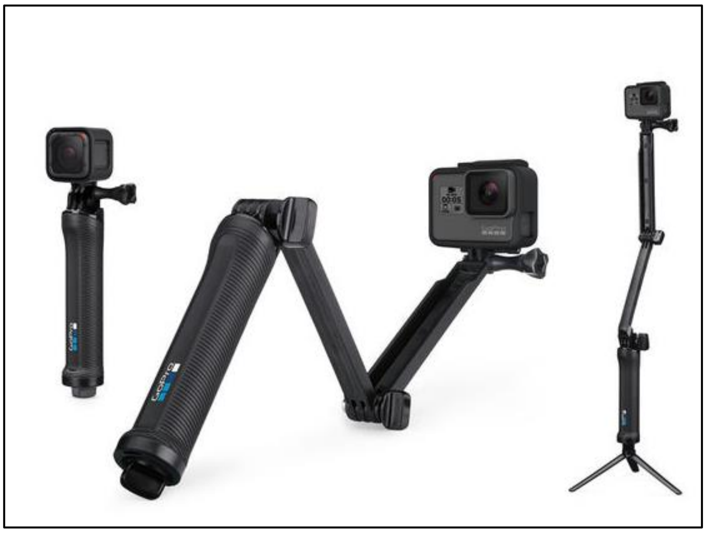
It is our goal to design an affordable camera arm that can mount to the shell of a PheNode system and maintains the following properties:

- The arm will extend to at least 36 inches.
- The arm is mounted on a swiveling socket of some kind.
- The arm folds.

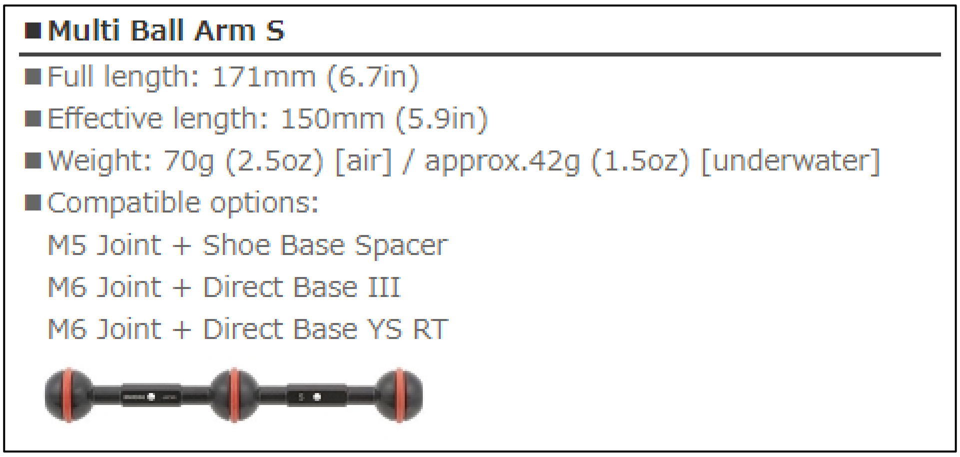
2.2 BACKGROUND SUMMARY

To begin our design process, we conducted a background information study to analyze existing designs relevant to our project.

- Relevant Design #1: The 3-Way GoPro camera arm
  This camera arm provides ideas on how to successfully design our camera arm to extend 36 inches, as well as fold down. This GoPro camera arm extends 20 inches and is a folding arm with a camera mounted at its end. This design shows us the benefits of allowing the arm to bend at multiple joints, and provides ideas on how to look the arm in an extended position. (From: https://shop.gopro.com/mounts/3-way/AFAEM-001.html)



- Relevant Design #2: Multi Ball Arm S from INON
  This arm, although not specifically a camera arm, provides us with an idea of how to use swiveling joints in our design, per request. The ball joints pictured connect the pieces of arm, which may be an idea in how we can get our arm, which will most likely be split into multiple pieces, connected in a way that allows the entire arm to move, bend, fold, and extend. (From: http://www.inon.jp/products/armsystem/arm.html)



■Multi Ball Arm S

■Full length: 171mm (6.7in)

■Effective length: 150mm (5.9in)

■Weight: 70g (2.5oz) [air] / approx.42g (1.5oz) [underwater]

■Compatible options:
M5 Joint + Shoe Base Spacer
M6 Joint + Direct Base III
M6 Joint + Direct Base YS RT

3 CONCEPT DESIGN AND SPECIFICATION

3.1 USER NEEDS AND METRICS

3.1.1 Record of the user needs interview

Project/Product Name: PheNode Camera Arm

Interviewers: Paul Masnica, Matthias Sommer, Kelsey Wortmann

Customer: Nadia Shakoor & Darren O'brien

Address: Donald Danforth Plant Science Center
975 N. Warson Rd, St. Louis, MO 63132

Type of user: Farmers

Currently uses: Walks through fields to examine crops visually

Question	Customer Statement	Interpreted Need	Importance
What is the minimum extension length of the camera arm? What is the maximum?	We would like a 36" arm.	The minimum and maximum length the camera arm will extend is 36".	5
Does the arm need to be able to rotate 360 degrees around the PheNode?	It does not need to rotate 360 degrees, but should be able to rotate nearly 180 degrees. We thought maybe some kind of ball end.	The arm will be able to rotate nearly 180 degrees.	5
How much should the design cost?	Like most things, as little as possible, but less than $100 would be helpful.	The camera arm will cost $100. The arm will be made of cost-conscious materials.	4 5
Is there a minimum or maximum number of folds the arm should have?	No, there is no specific number of folds, I would think one is best, but more is acceptable, as long as it is sturdy and able to maintain position.	The camera arm is sturdy and able to maintain position.	5
Can the arm be screwed onto the PheNode, or is an easier way of adding it desired?	Yes, in some fashion it will be screwed in, this may be a bit tricky.	The arm will be easy to mount.	5
What is the approximate weight of the camera the arm will be holding?	The camera itself weighs very little, maybe a couple ounces, but the mount holds the camera to	The arm will not droop or drift too easily.	5

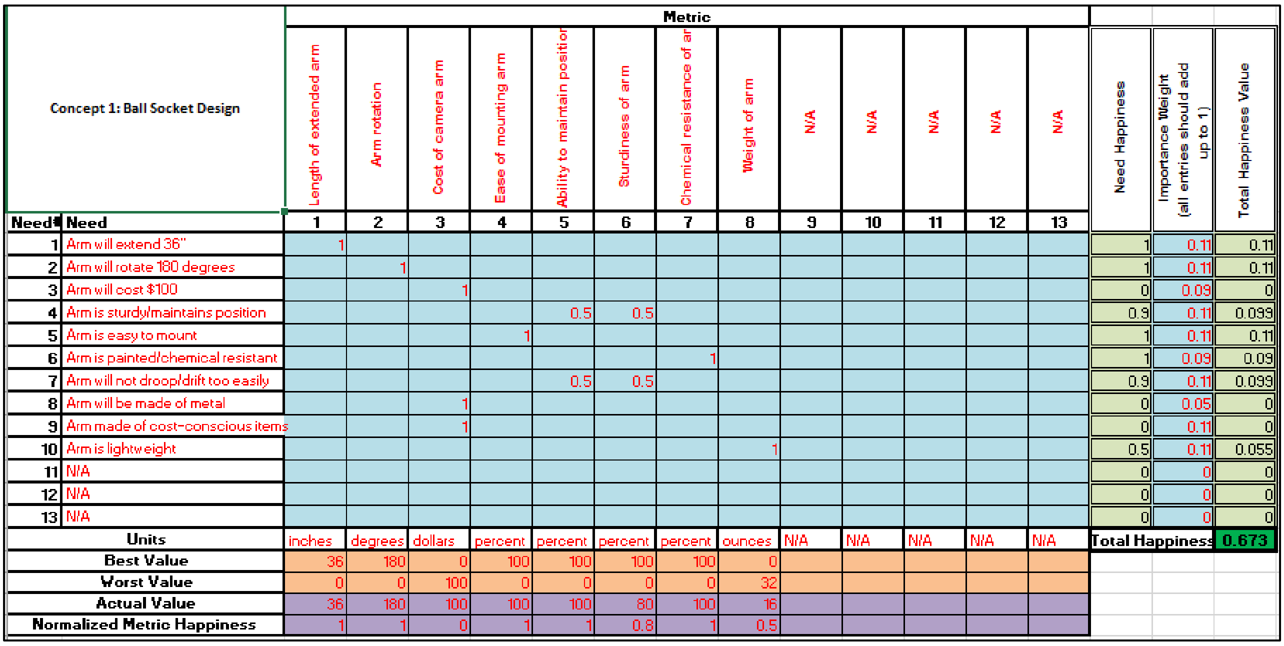
	the arm will weigh more. There are actually two cameras, one RGB, one IR, and the IR camera has two LEDs, but they don't weigh much either.		
Does the arm need to be adjustable along the height of the PheNode?	No, it will fix up near the top so that it can look down on the canopy of the crop.		
Will the camera be screed to the arm, or should we design a holder for it?	We will most likely 3D a camera mount ourselves.		
What chemicals will the arm need to be resistant to?	The same as anything else, it ought to be painted which will give some protection.	The arm will be painted and chemical resistant.	4
Should the arm be able to move on its own and fold in on its own, or is it expected that the farmer will adjust it?	No, it doesn't need to be autonomous, but it needs to be able to maintain the position that it is put in, so it can't droop or drift easily.	The arm will not droop or drift too easily.	5
What material would you prefer the arm be made of?	We don't have a preference, but I anticipate it will be metal.	The arm will be made of metal.	3
Are there any restrictions on what we can use to build the arm?	No, just keeping in mind total weight, ease of mounting, and the need to maintain position.	The arm will not weight more than the PheNode can support.	5

3.1.2 List of identified metrics

Metric Number	Associated Needs	Metric	Units	Minimum Value	Maximum Value
1	1	Length of extended arm	Inches	36	36
2	2	Arm rotation	degrees	0	180
3	3, 4, 9	Cost of camera arm	Dollars	0	100
4	6	Ease of mounting the camera arm	Percent	0	100
5	5,7	Ability of arm to maintain position	Percent	0	100
6	5,7	Sturdiness of arm	Percent	0	100
7	8	Chemical resistance of arm	Percent	0	100
8	10	Weight of arm	Ounces	0	32

3.1.3 Table of quantified needs equations

Below is the table of quantified needs equations used to select a winning concept design. Pictured is the table for Concept 1.



Concept 1: Ball Socket Design		Metric															
		Length of extended arm	Arm rotation	Cost of camera arm	Ease of mounting arm	Ability to maintain positio	Sturdiness of arm	Chemical resistance of ar	Weight of arm	N/A	N/A	N/A	N/A	N/A	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Arm will extend 36"	1													1	0.11	0.11
2	Arm will rotate 180 degrees		1												1	0.11	0.11
3	Arm will cost $100			1											0	0.09	0
4	Arm is sturdy/maintains position					0.5	0.5								0.9	0.11	0.099
5	Arm is easy to mount				1										1	0.11	0.11
6	Arm is painted/chemical resistant							1							1	0.09	0.09
7	Arm will not droop/drift too easily					0.5	0.5								0.9	0.11	0.099
8	Arm will be made of metal			1											0	0.05	0
9	Arm made of cost-conscious items			1											0	0.11	0
10	Arm is lightweight								1						0.5	0.11	0.055
11	N/A														0	0	0
12	N/A														0	0	0
13	N/A														0	0	0
Units		inches	degrees	dollars	percent	percent	percent	percent	ounces	N/A	N/A	N/A	N/A	N/A	Total Happiness		0.673
Best Value		36	180	0	100	100	100	100	0								
Worst Value		0	0	100	0	0	0	0	32								
Actual Value		36	180	100	100	100	80	100	16								
Normalized Metric Happiness		1	1	0	1	1	0.8	1	0.5								

3.2 CONCEPT DRAWINGS

- Concept 1: Ball Socket Design

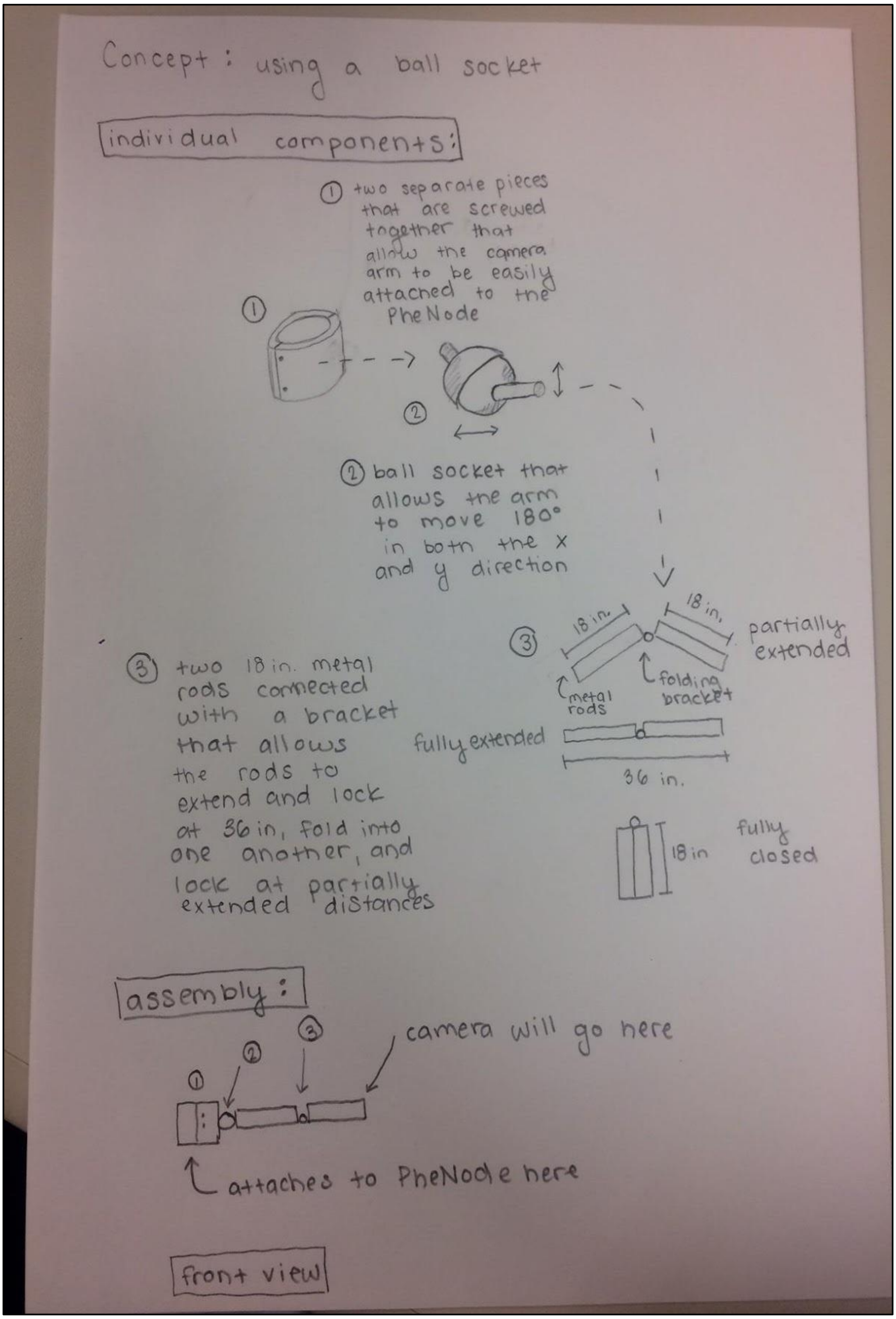
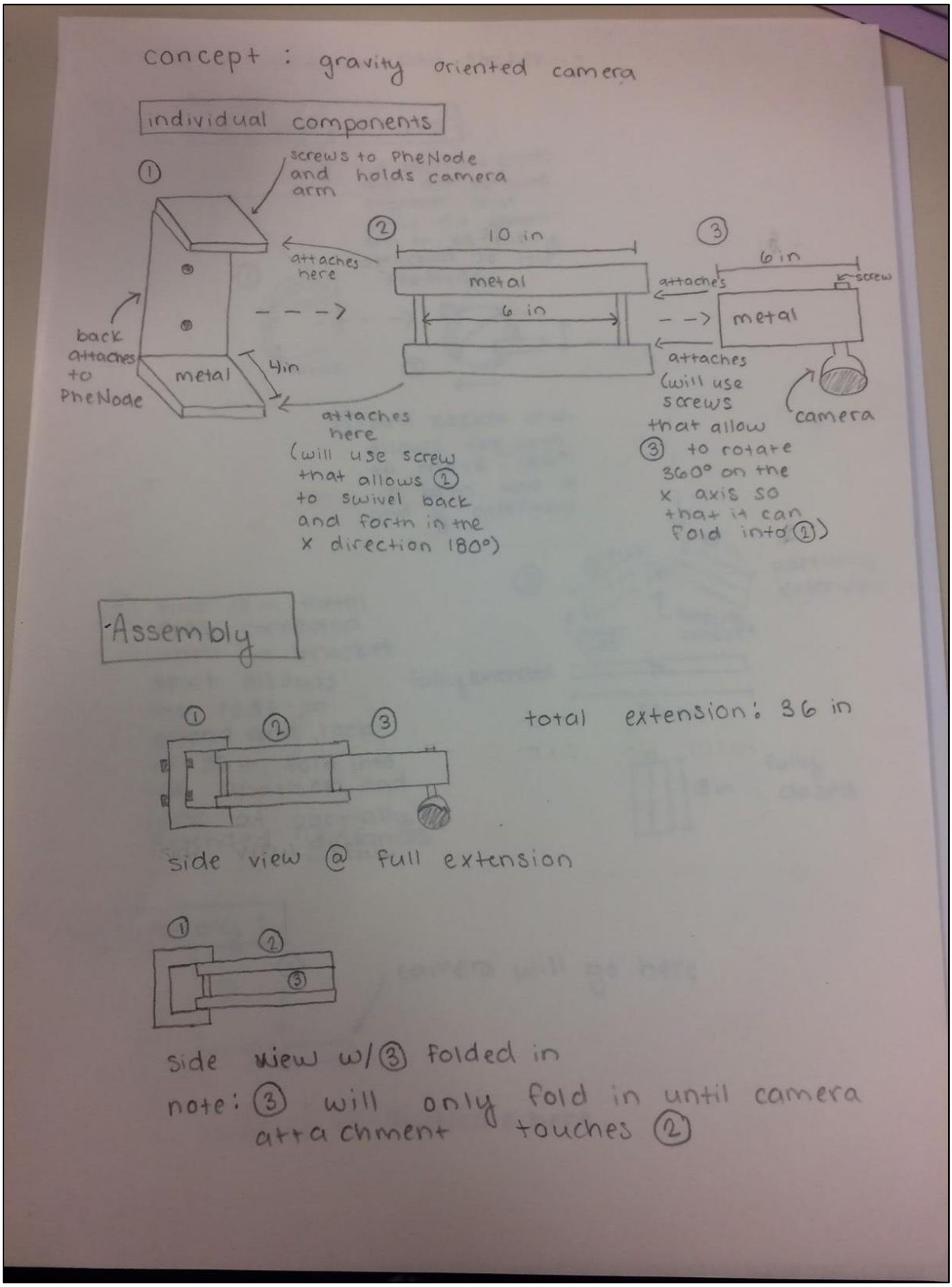


Fig. 3.1. Concept Drawing 1: Ball Socket Design.

- Concept 2: Gravity Oriented Camera



concept : gravity oriented camera

individual components

screws to PheNode and holds camera arm

attaches here (will use screw that allows ② to swivel back and forth in the x direction 180°)

attaches (will use screws that allow ③ to rotate 360° on the x axis so that it can fold into ①)

Assembly

total extension: 36 in

side view @ full extension

side view w/③ folded in

note: ③ will only fold in until camera attachment touches ②

Fig. 3.2. Concept Drawing 2: Gravity Oriented Camera.

- Concept 3: T-slot Design

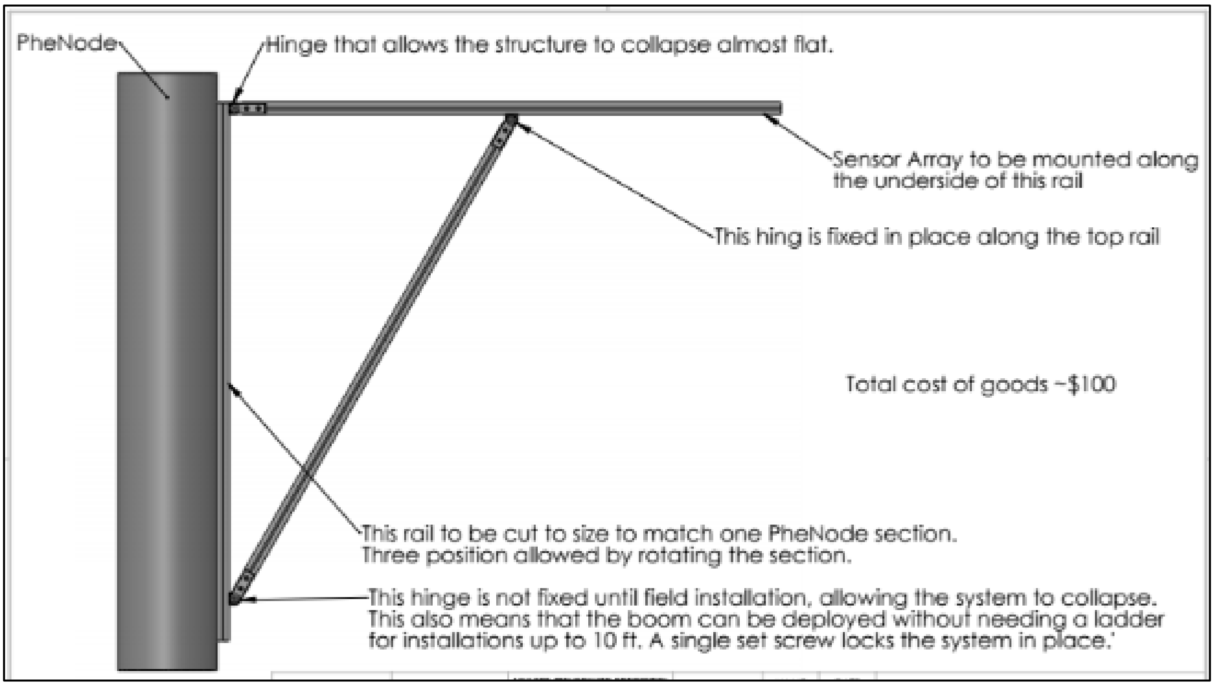


Fig. 3.3. Concept Drawing 3: T-slot Design.

- Concept 4: Pin Mount Design

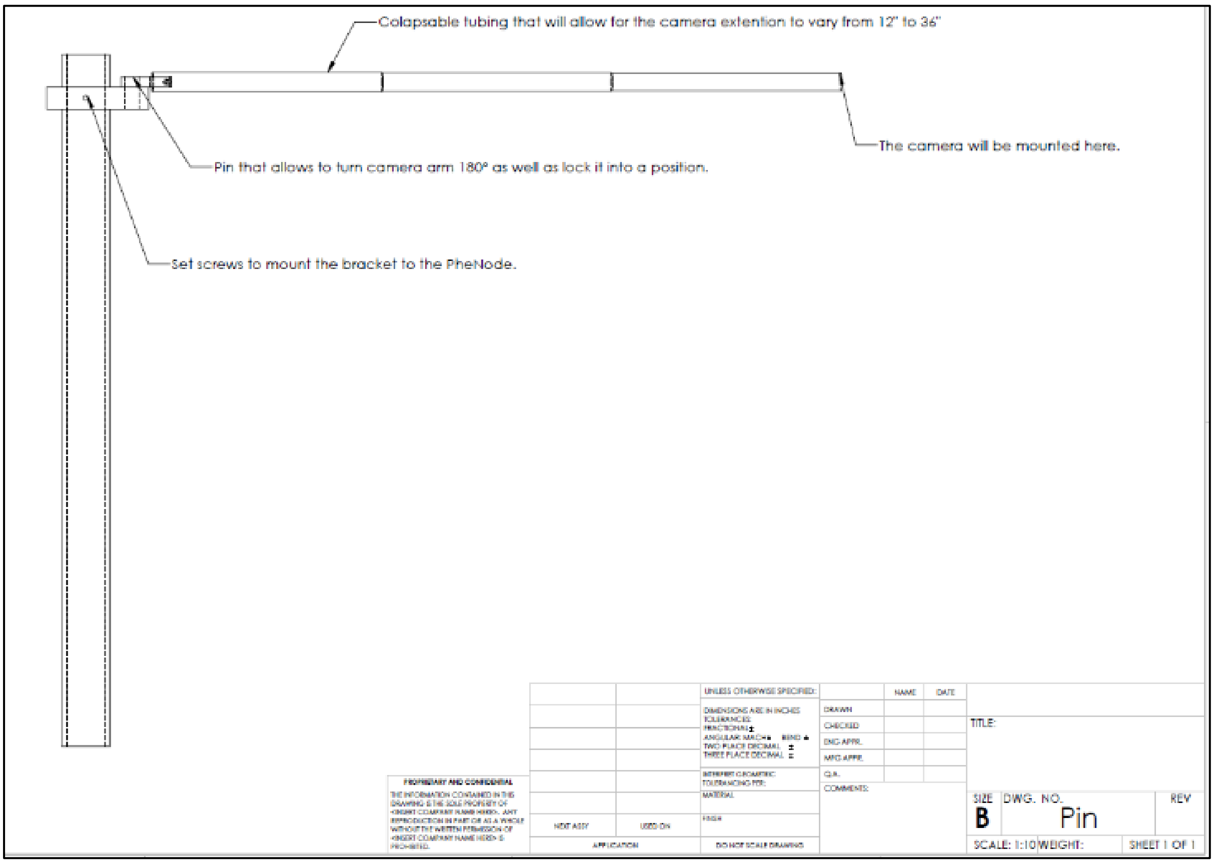
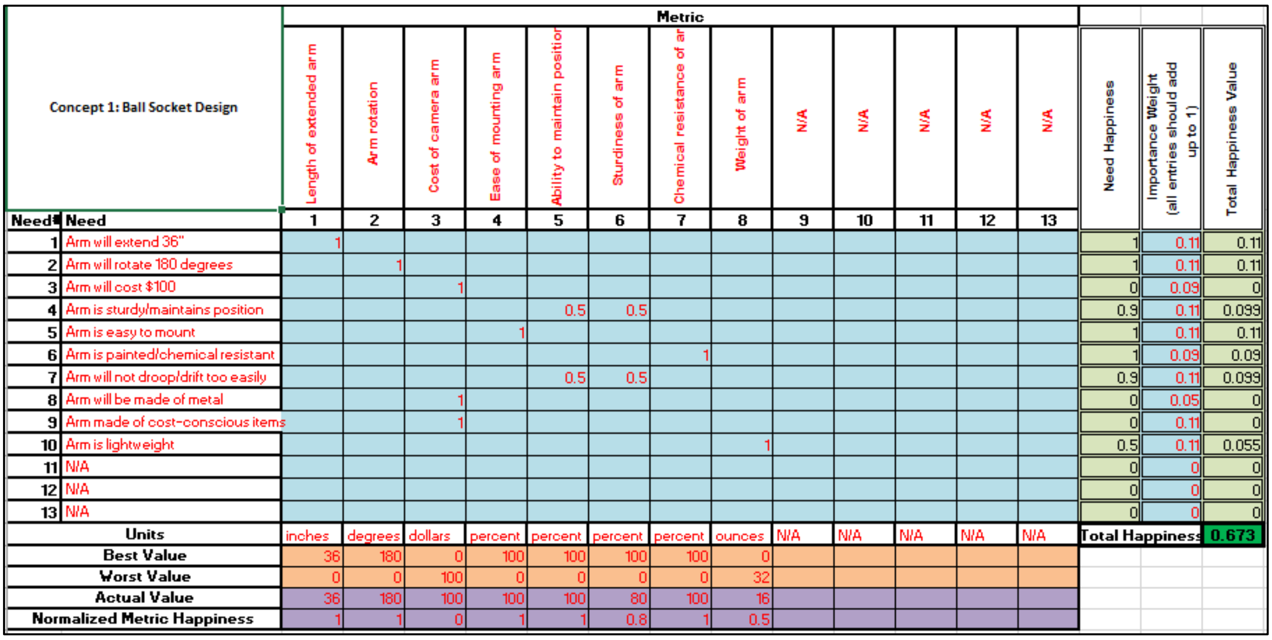


Fig. 3.4. Concept Drawing 4: Pin Mount Design.

3.3 A CONCEPT SELECTION PROCESS.

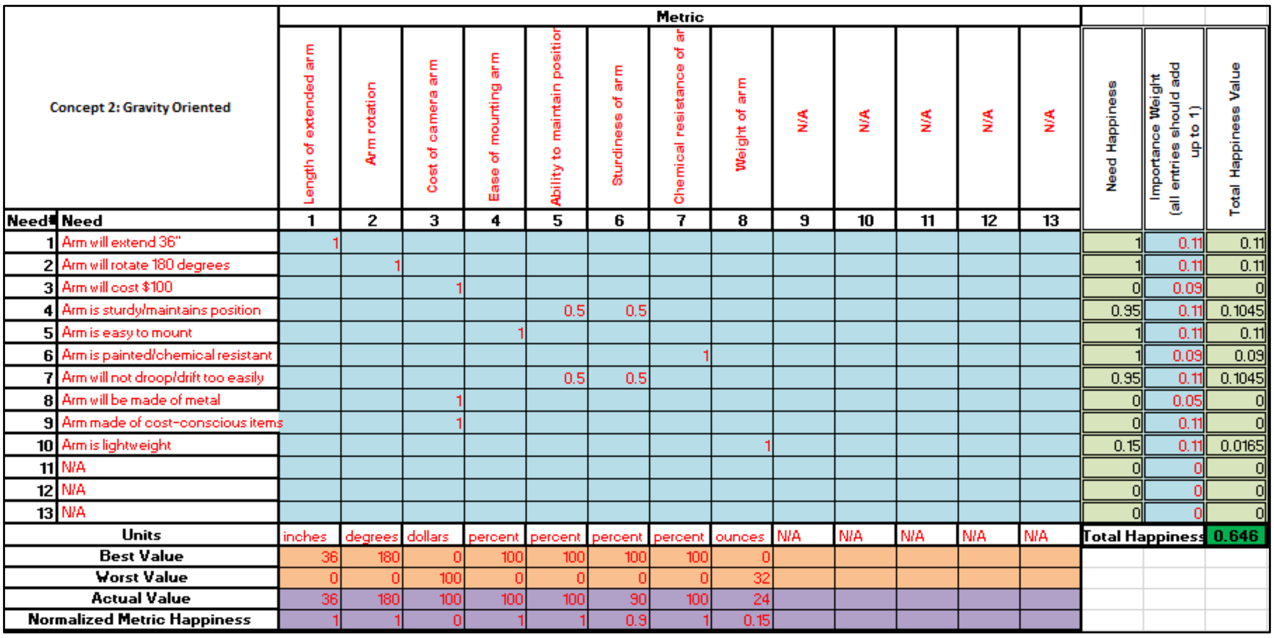
3.3.1 Concept scoring (not screening)

Below are our scorings for each concept using the quantified needs equations.



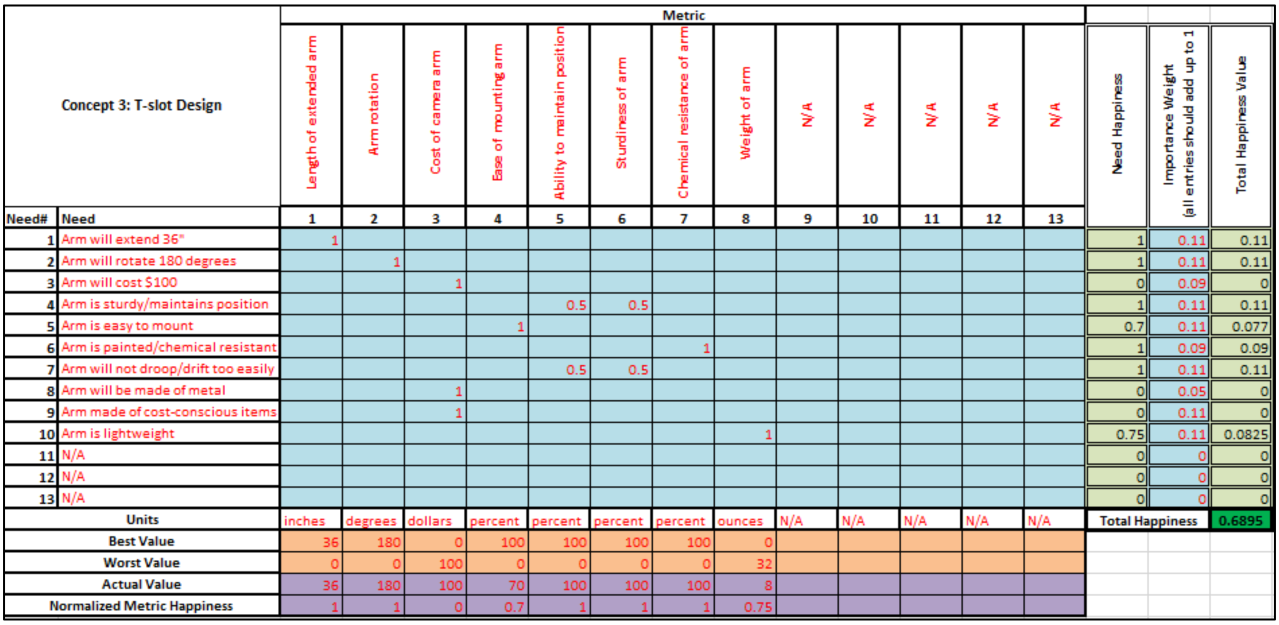
Concept 1: Ball Socket Design		Metric															
		Length of extended arm	Arm rotation	Cost of camera arm	Ease of mounting arm	Ability to maintain positio	Sturdiness of arm	Chemical resistance of ar	Weight of arm	N/A	N/A	N/A	N/A	N/A	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Arm will extend 36"	1													1	0.11	0.11
2	Arm will rotate 180 degrees		1												1	0.11	0.11
3	Arm will cost $100			1											0	0.09	0
4	Arm is sturdy/maintains position					0.5	0.5								0.9	0.11	0.099
5	Arm is easy to mount				1										1	0.11	0.11
6	Arm is painted/chemical resistant							1							1	0.09	0.09
7	Arm will not droop/drift too easily					0.5	0.5								0.9	0.11	0.099
8	Arm will be made of metal			1											0	0.05	0
9	Arm made of cost-conscious items			1											0	0.11	0
10	Arm is lightweight								1						0.5	0.11	0.055
11	N/A														0	0	0
12	N/A														0	0	0
13	N/A														0	0	0
Units		inches	degrees	dollars	percent	percent	percent	percent	ounces	N/A	N/A	N/A	N/A	N/A	Total Happiness		0.673
Best Value		36	180	0	100	100	100	100	0								
Worst Value		0	0	100	0	0	0	0	32								
Actual Value		36	180	100	100	100	80	100	16								
Normalized Metric Happiness		1	1	0	1	1	0.8	1	0.5								

Fig. 3.5. Concept scoring for Concept 1.



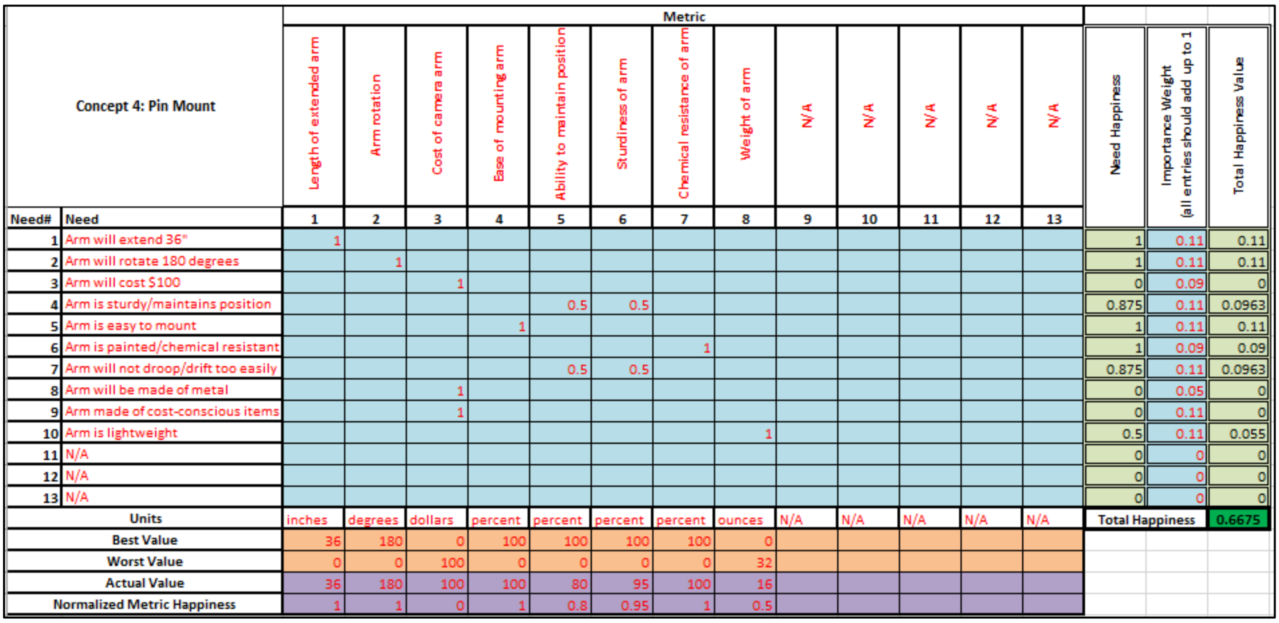
Concept 2: Gravity Oriented		Metric															
		Length of extended arm	Arm rotation	Cost of camera arm	Ease of mounting arm	Ability to maintain positio	Sturdiness of arm	Chemical resistance of ar	Weight of arm	N/A	N/A	N/A	N/A	N/A	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Arm will extend 36"	1													1	0.11	0.11
2	Arm will rotate 180 degrees		1												1	0.11	0.11
3	Arm will cost $100			1											0	0.09	0
4	Arm is sturdy/maintains position					0.5	0.5								0.95	0.11	0.1045
5	Arm is easy to mount				1										1	0.11	0.11
6	Arm is painted/chemical resistant							1							1	0.09	0.09
7	Arm will not droop/drift too easily					0.5	0.5								0.95	0.11	0.1045
8	Arm will be made of metal			1											0	0.05	0
9	Arm made of cost-conscious items			1											0	0.11	0
10	Arm is lightweight								1						0.15	0.11	0.0165
11	N/A														0	0	0
12	N/A														0	0	0
13	N/A														0	0	0
Units		inches	degrees	dollars	percent	percent	percent	percent	ounces	N/A	N/A	N/A	N/A	N/A	Total Happiness		0.646
Best Value		36	180	0	100	100	100	100	0								
Worst Value		0	0	100	0	0	0	0	32								
Actual Value		36	180	100	100	100	90	100	24								
Normalized Metric Happiness		1	1	0	1	1	0.9	1	0.15								

Fig. 3.6. Concept scoring for Concept 2.



Concept 3: T-slot Design		Metric															
		Length of extended arm	Arm rotation	Cost of camera arm	Ease of mounting arm	Ability to maintain position	Sturdiness of arm	Chemical resistance of arm	Weight of arm	N/A	N/A	N/A	N/A	N/A	Need Happiness	Importance Weight (all entries should add up to 1	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Arm will extend 36"	1													1	0.11	0.11
2	Arm will rotate 180 degrees		1												1	0.11	0.11
3	Arm will cost $100			1											0	0.09	0
4	Arm is sturdy/maintains position					0.5	0.5								1	0.11	0.11
5	Arm is easy to mount				1										0.7	0.11	0.077
6	Arm is painted/chemical resistant							1							1	0.09	0.09
7	Arm will not droop/drift too easily					0.5	0.5								1	0.11	0.11
8	Arm will be made of metal			1											0	0.05	0
9	Arm made of cost-conscious items			1											0	0.11	0
10	Arm is lightweight								1						0.75	0.11	0.0825
11	N/A														0	0	0
12	N/A														0	0	0
13	N/A														0	0	0
Units		inches	degrees	dollars	percent	percent	percent	percent	ounces	N/A	N/A	N/A	N/A	N/A	Total Happiness		0.6895
Best Value		36	180	0	100	100	100	100	0								
Worst Value		0	0	100	0	0	0	0	32								
Actual Value		36	180	100	70	100	100	100	8								
Normalized Metric Happiness		1	1	0	0.7	1	1	1	0.75								

Fig. 3.7. Concept scoring for Concept 3.



Concept 4: Pin Mount		Metric															
		Length of extended arm	Arm rotation	Cost of camera arm	Ease of mounting arm	Ability to maintain position	Sturdiness of arm	Chemical resistance of arm	Weight of arm	N/A	N/A	N/A	N/A	N/A	Need Happiness	Importance Weight (all entries should add up to 1	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Arm will extend 36"	1													1	0.11	0.11
2	Arm will rotate 180 degrees		1												1	0.11	0.11
3	Arm will cost $100			1											0	0.09	0
4	Arm is sturdy/maintains position					0.5	0.5								0.875	0.11	0.0963
5	Arm is easy to mount				1										1	0.11	0.11
6	Arm is painted/chemical resistant							1							1	0.09	0.09
7	Arm will not droop/drift too easily					0.5	0.5								0.875	0.11	0.0963
8	Arm will be made of metal			1											0	0.05	0
9	Arm made of cost-conscious items			1											0	0.11	0
10	Arm is lightweight								1						0.5	0.11	0.055
11	N/A														0	0	0
12	N/A														0	0	0
13	N/A														0	0	0
Units		inches	degrees	dollars	percent	percent	percent	percent	ounces	N/A	N/A	N/A	N/A	N/A	Total Happiness		0.6675
Best Value		36	180	0	100	100	100	100	0								
Worst Value		0	0	100	0	0	0	0	32								
Actual Value		36	180	100	100	80	95	100	16								
Normalized Metric Happiness		1	1	0	1	0.8	0.95	1	0.5								

Fig. 3.8. Concept scoring for Concept 4.

3.3.2 Preliminary analysis of each concept's physical feasibility

- Concept 1: The main issue with physical feasibility and this concept will be getting the bracket in the center of the two rods to lock out. By putting a device on the bracket to aid in locking it out, this may affect the arm's ability to completely collapse. Perhaps a really stiff bracket will be needed here so that human force is required to lock the separate arm pieces into place.

- Concept 2: Issues with physical feasibility will arise with this design's ability to collapse in towards the PheNode. The bracket attaching the arm to the PheNode will not allow the arm to collapse up or down, but instead, only sideways, leaving the folded arm jutting out on the side. There will also be issues with folding in the part of the arm which houses the camera into the other section of arm, since the camera will hit the innermost section of arm. Another issue arises with the arm design only functioning along the x-axis.
- Concept 3: The issues with physical feasibility that arise with this design are only related to how the design will attach to the PheNode and rotate 180 degrees. Unlike the other designs which use sockets and pins that allow the design to swivel, this design will have to be physically removed from the PheNode to adjust the angle at which the camera is moved. One solution to avoiding this issue may be putting a rotating holder on the end of the arm that allows for the camera to rotate without rotating the arm.
- Concept 4: This design will be very physically feasible as far as building the arm goes. However, issues arise with the collapsible tubing and its ability to maintain position while extend. If we simply allow the tubing to collapse by inserting each piece of tubing into the tubing before it, this allows for the risk that something could hit it and too easily adjust the position of the camera. We could solve this by allowing the piping to collapse by folding downward using brackets. These brackets will allow the various arm pieces to stay locked in place and make the design sturdier.

3.3.3 Final summary statement

The winner selected from the concept drawings is drawing #3, the T-slot design. Although this design makes it more inconvenient to rotate the arm 180 degrees, it actually helps ensure the arm will remain in place, no matter what angle it is placed in, since after being rotated, the arm structure will once again be fastened to the PheNode, unable to swivel. This arm design also allows the camera arm to easily fold in and out, while the T-slot design allows for a sturdier camera arm. Unlike the other arm designs where the extended arm has no support, this arm will be supported from beneath, adding extra stabilization for the arm and camera. This design is also made keeping in mind the ease of use for taller PheNodes, such as those that reach high above tree canopies. This design aims to eliminate the need for using a ladder when adjusting the camera.

Note: Although the T-slot design, Concept 3, won the scorings, after further discussion with our clients, Concept 1 was selected, using a ball joint in the design where the folding bracket would be.

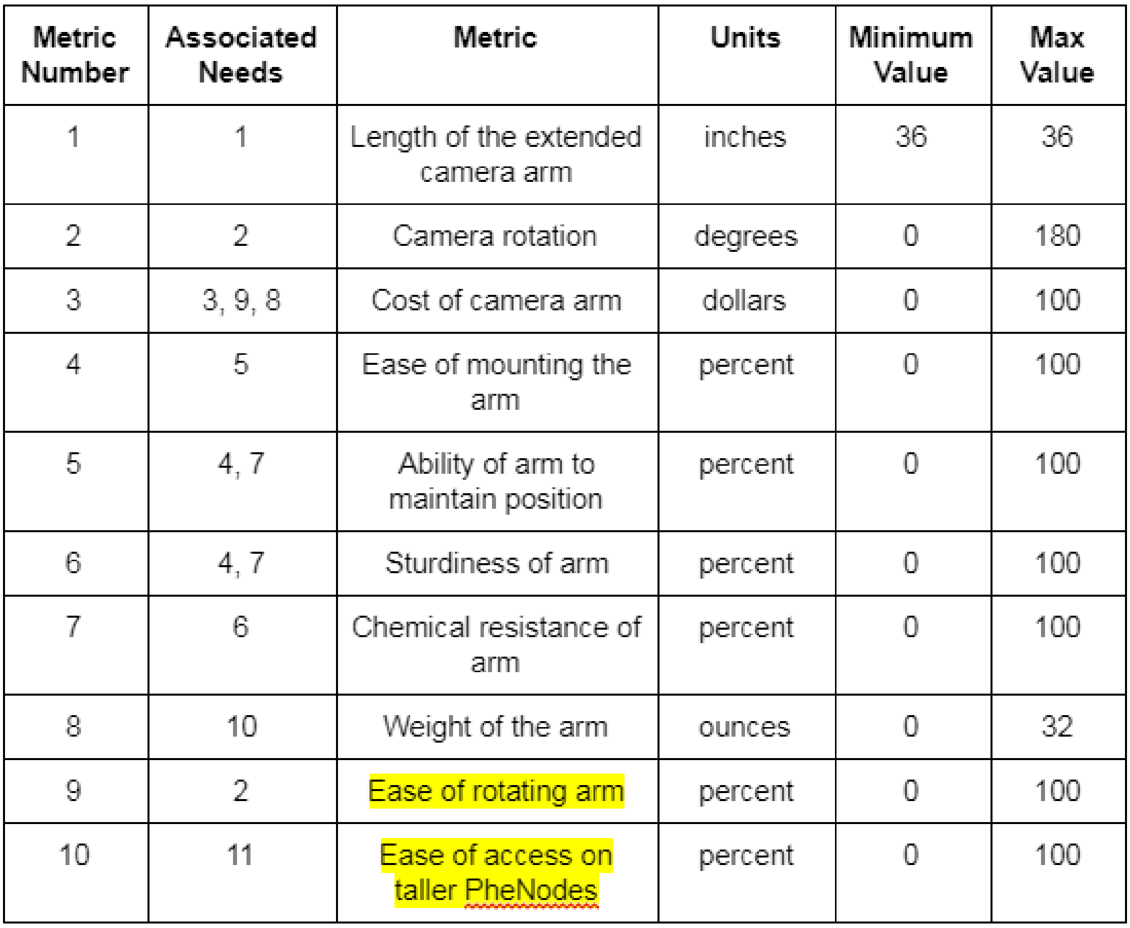
3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

The issues with physical feasibility with concept 3 arise with the ability to rotate the arm 180 degrees. In order to rotate the arm, the farmer would have to completely remove the arm, change its angle of attachment on the PheNode, and reattach the arm. One solution to this would be allowing the camera itself, not the arm, to rotate 180 degrees, via a rotating holder on the end of the arm. Because of this solution, need #2 of the original needs has been altered from "the arm will be able to rotate 190 degrees" to "the camera will be able to rotate 180 degrees. Because the T-slot design allows easier adjustment of the camera arm without using a ladder on taller PheNodes, this has also become a new quantified need. The T-slot design also focuses on the most on keeping the camera stable. Because of this, the importance of that the material of the design is metal has been raised from and 3 to a 5 since metal will be the most sturdy

3.5 REVISION OF SPECIFICATIONS AFTER CONCEPT SELECTION

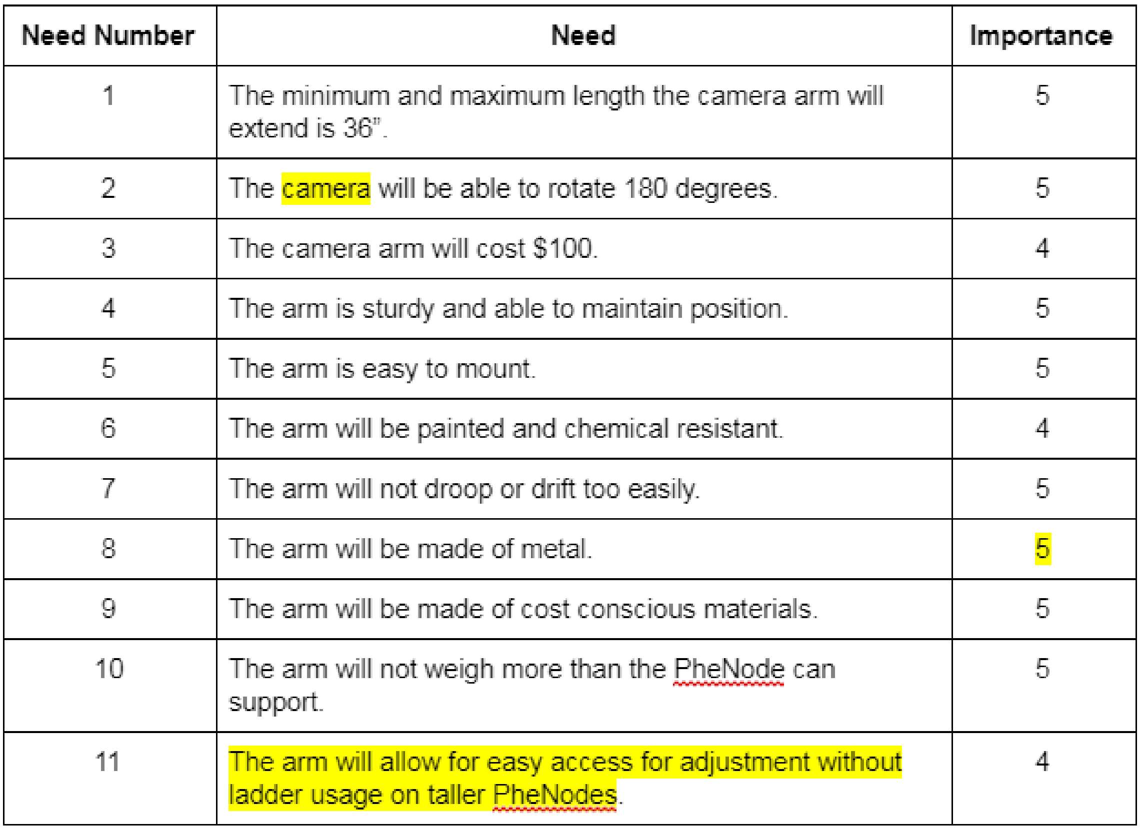
Below is a list of identified metrics that shows the metrics, units, maximum and minimum values, and a list of the associated needs revised for Concept 3, as we as a revised table of quantified needs equations.

Table 3.5.1. Identified metrics for Concept 3.



Metric Number	Associated Needs	Metric	Units	Minimum Value	Max Value
1	1	Length of the extended camera arm	inches	36	36
2	2	Camera rotation	degrees	0	180
3	3, 9, 8	Cost of camera arm	dollars	0	100
4	5	Ease of mounting the arm	percent	0	100
5	4, 7	Ability of arm to maintain position	percent	0	100
6	4, 7	Sturdiness of arm	percent	0	100
7	6	Chemical resistance of arm	percent	0	100
8	10	Weight of the arm	ounces	0	32
9	2	Ease of rotating arm	percent	0	100
10	11	Ease of access on taller PheNodes	percent	0	100

Table 3.5.2. Associated needs revised for Concept 3.



Need Number	Need	Importance
1	The minimum and maximum length the camera arm will extend is 36”.	5
2	The camera will be able to rotate 180 degrees.	5
3	The camera arm will cost $100.	4
4	The arm is sturdy and able to maintain position.	5
5	The arm is easy to mount.	5
6	The arm will be painted and chemical resistant.	4
7	The arm will not droop or drift too easily.	5
8	The arm will be made of metal.	5
9	The arm will be made of cost conscious materials.	5
10	The arm will not weigh more than the PheNode can support.	5
11	The arm will allow for easy access for adjustment without ladder usage on taller PheNodes.	4

4 EMBODIMENT AND FABRICATION PLAN

4.1 EMBODIMENT/ASSEMBLY DRAWING

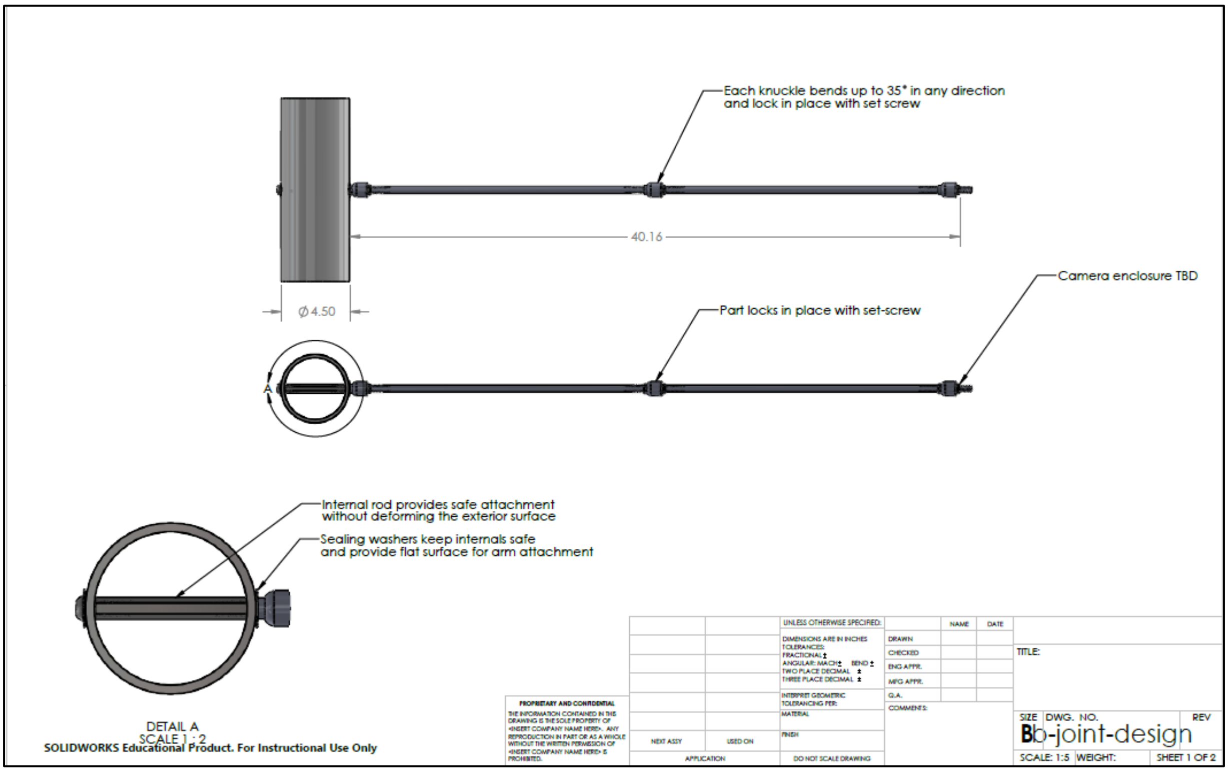
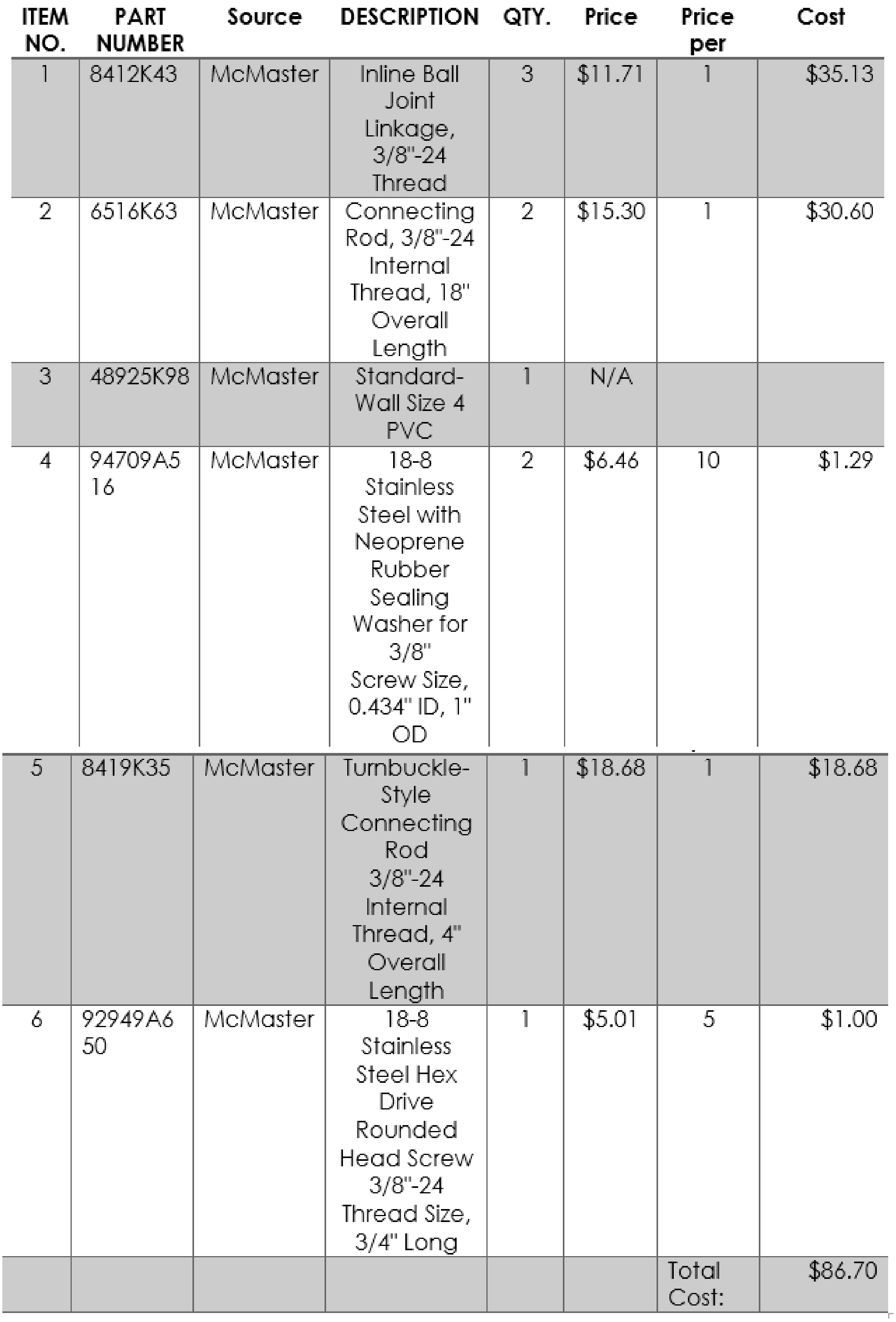


Fig. 4.1 Embodiment drawing.

4.2 PARTS LIST



ITEM NO.	PART NUMBER	Source	DESCRIPTION	QTY.	Price	Price per	Cost
1	8412K43	McMaster	Inline Ball Joint Linkage, 3/8"-24 Thread	3	$11.71	1	$35.13
2	6516K63	McMaster	Connecting Rod, 3/8"-24 Internal Thread, 18" Overall Length	2	$15.30	1	$30.60
3	48925K98	McMaster	Standard-Wall Size 4 PVC	1	N/A		
4	94709A516	McMaster	18-8 Stainless Steel with Neoprene Rubber Sealing Washer for 3/8" Screw Size, 0.434" ID, 1" OD	2	$6.46	10	$1.29
5	8419K35	McMaster	Turnbuckle-Style Connecting Rod 3/8"-24 Internal Thread, 4" Overall Length	1	$18.68	1	$18.68
6	92949A650	McMaster	18-8 Stainless Steel Hex Drive Rounded Head Screw 3/8"-24 Thread Size, 3/4" Long	1	$5.01	5	$1.00
						Total Cost:	$86.70

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART

Please see Appendix C for the drawings for each manufactured part. The provided CAD images, labeled Fig. 4.3.1 – 4.3.5, display the detailed drawings for parts 1, 2, 4, 5, and 6 on the parts list, as provided by McMaster-Carr for each part.

4.4 DESCRIPTION OF THE DESIGN RATIONALE

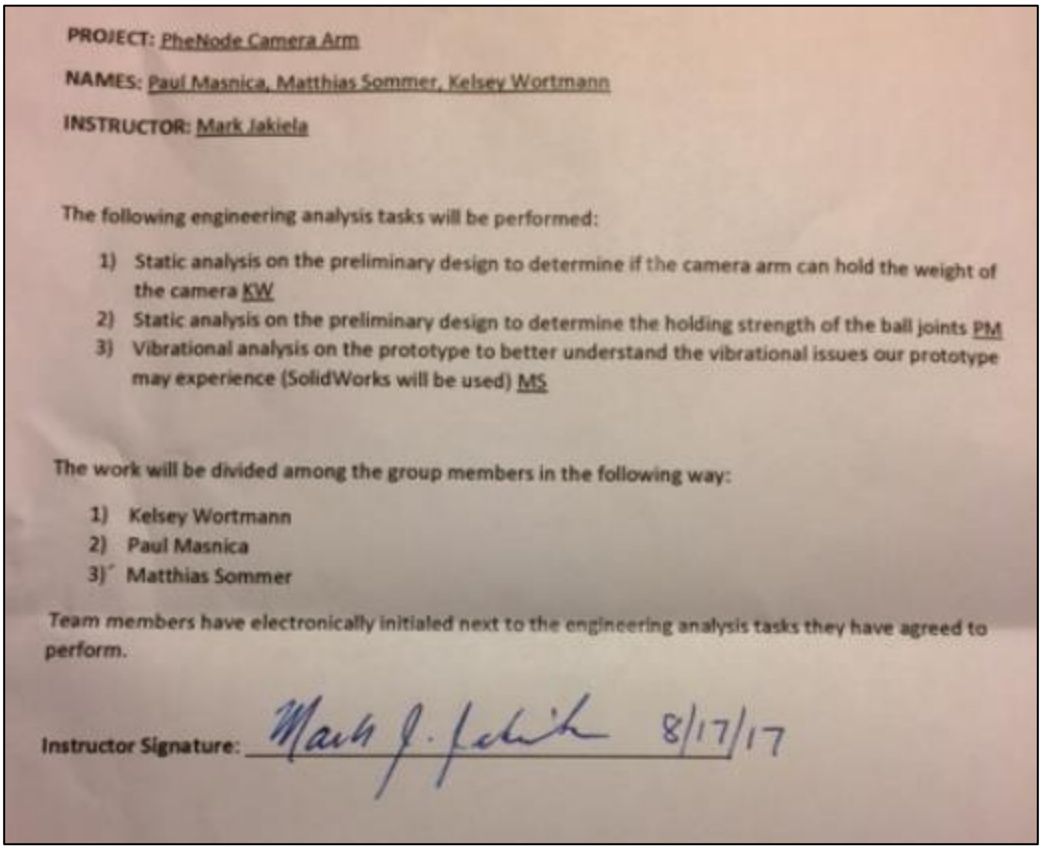
Design Rationale by Item Number:

1. Inline Ball Joint Linkage, 3/8”-24 Thread - The ball joint allows for fastening of the connecting rods as well as 35° motion at each joint. These joints will allow for multiple linkages, and more importantly meet the design criteria of the arm extending 36” as well as having the ability to rotate position, in our case 105°.
2. Connecting Rod, 3/8”-24 Internal Thread, 18” Overall Length – The connecting rods are designed to meet criteria length as well as complimentary pieces for the ball joints. The rods have corresponding diameters and thread to the joints to ensure a good fit. The rods are also not hollow to ensure durability, and rigidity in the field.
3. Standard-Wall Size 4 PVC – This aspect of the design is a representation for a PheNode. It has the same inner and outer diameters as the body of a PheNode, and will allow for accurate prototyping and any required design modifications.
4. 18-8 Stainless Steel with Neoprene Rubber Sealing Washer for 3/8” Screw Size, 0.434” ID, 1” OD – This sealing washer will allow for the set screw on the opposite side of the arm to be securely fastened to the PheNode. This washer will also create a tight seal that will not allow for water or debris to enter the PheNode at this location.
5. Fabricated Connecting Rod 3/8”-24 Internal Thread, 4” Overall Length – This rod securely attaches the PheNode and the arm assembly. It will run internally in the PheNode removing the need for bulky clamps to attach the camera arm. It also adds interior support so that the PheNode won’t deform when the camera arm is attached.
6. 18-8 Stainless Steel Hex Drive Rounded Head Screw 3/8”-24 Thread Size, 3/4” Long – This screw attaches opposite the camera arm to fasten the internal connecting rod as well as the camera arm to the PheNode.

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

5.1.1 Signed engineering analysis contract



PROJECT: PheNode Camera Arm

NAMES: Paul Masnica, Matthias Sommer, Kelsey Wortmann

INSTRUCTOR: Mark Jakiela

The following engineering analysis tasks will be performed:

1) Static analysis on the preliminary design to determine if the camera arm can hold the weight of the camera KW
2) Static analysis on the preliminary design to determine the holding strength of the ball joints PM
3) Vibrational analysis on the prototype to better understand the vibrational issues our prototype may experience (SolidWorks will be used) MS

The work will be divided among the group members in the following way:

1) Kelsey Wortmann
2) Paul Masnica
3) Matthias Sommer

Team members have electronically initialed next to the engineering analysis tasks they have agreed to perform.

Instructor Signature: Mark J. Jakiela 8/17/17

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 Motivation

The first type of analysis that we conducted before we begin building the prototype was with regard to the camera arm's ability to hold the camera's weight. This was the most important thing to analyze since the ability to hold the camera weight will also affect the camera arm's ability to remain stable once set in place. Stability is one of the top design requirements for the camera arm. If the camera arm cannot support the weight of the camera when we analyze it, we must redesign the arm so that it is more stable before we can begin the building phase.

The second type of analysis that was conducted on the preliminary design was finding the holding strength of the joints in the arm. Since we assumed that the separate parts of the arm will act as one piece in our first step of analysis, we would like to ensure that the joints are strong enough to allow for this assumption. If our joints fail to have enough holding strength for the arm and camera, we will once again have to redesign our arm before the building phase.

After building our prototype, we found that the arm tended to vibrate under certain loads and movements. Some vibration was expected since the arm acts as a cantilever beam when mounted to the PheNode, but we wanted to put a scope on the vibrations so they could be understood as part of the design.

5.2.2 Summary statement of analysis done

To analyze whether the arm could hold the camera's weight and the holding strength of the joints, basis static analysis was conducted on the preliminary design of the camera arm. Static analysis was chosen to be conducted because we do not want the arm to move once it has been set into place.

The vibrational analysis that was conducted after the prototype was solved utilizing SolidWorks simulation software since it could be conducted on our model of the prototype, rather than applying the analysis to our actual prototype. Strong wind motion was the cause of the vibrational forces on our model, since wind forces are going to be the most common cause of vibrations for the camera arm once placed in a field.

5.2.3 Methodology

Figure 5.1 below shows the free body diagrams of our arm design. Here we've assumed the combined weight of the two bars is double that of the weight of the camera. The locked ball sockets cause the structure to act as a cantilevered beam and allow us to treat the connected bars as one bar. The top free body diagram shows the force of the weight of the arms as it is originally distributed across the entire structure. The bottom free body diagram shows this as a converted force acting on the center of the structure.

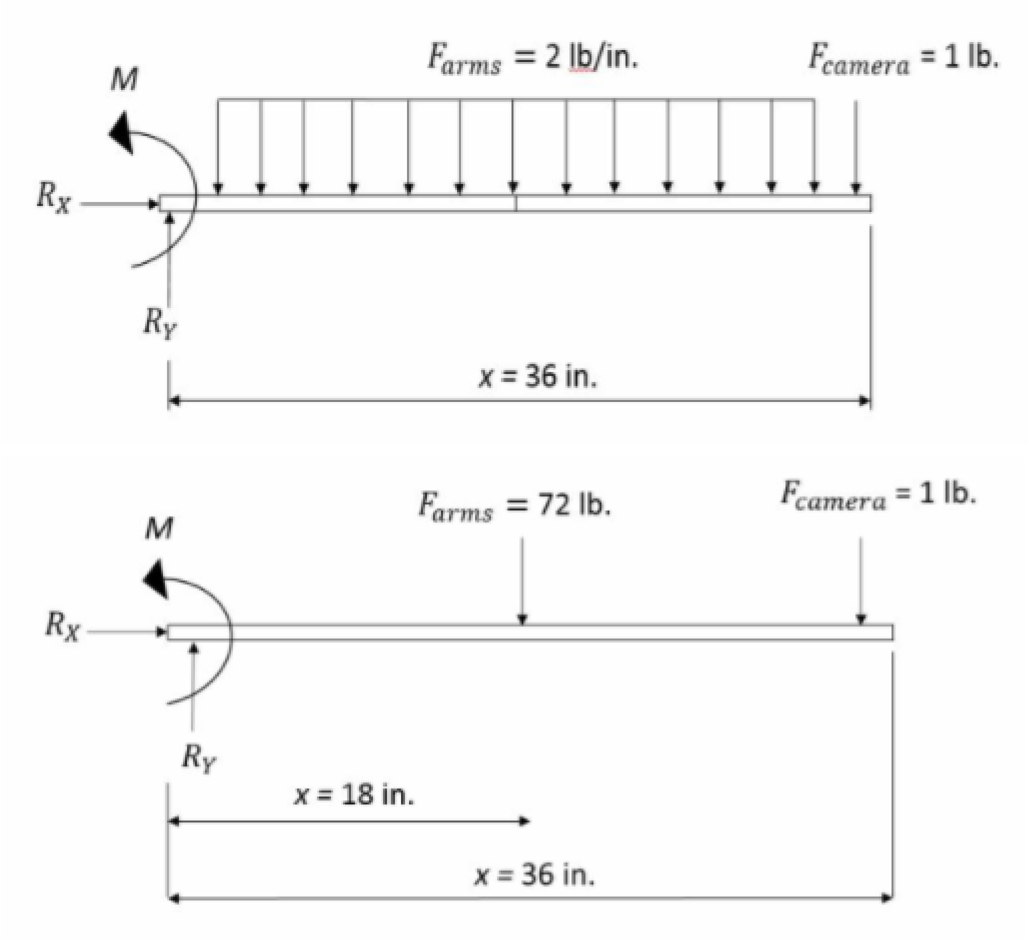


Fig. 5.1. **Free body diagram of the theoretical prototype of the camera arm.**

In Fig. 5.1, *x* represents the total length of the arm structure [inches], R_Y and R_X represent the reactive forces [lbs], *M* represents the moment about the left end of the arm [in.-lbs], and F_{arms} and F_{camera} represent the force of the weight of the arms and camera [lbs], respectively. The moment, *M*, was found using Eq. 5.1, where counterclockwise is the positive direction of the moment. This result will allow us to assess whether or not the camera arm can withstand the weight of the camera.

$$M = 0 = -\,(72\ lbs)\ (18\ in.) - (1\ lb)(36\ in.) \qquad (5.1)$$

$$M = 1332\ in.\text{-}lb$$

To analyze the holding strength of the joints in the arm, we assigned theoretical mass properties to the system. We assumed the mass of all the components, or m_1, to be 3 lbs, and the mass for each additional 18” segment, or m_2, to be 1 lb. Therefore, since there will be two 18” segments, we assumed the maximum load for each joint to be m_3 = 160 lbs. From these assumptions we find the summation of all three masses to be 164 lbs, or our m_{total}. Figure 5.2 shows the free body diagram of our member sections on the arm.

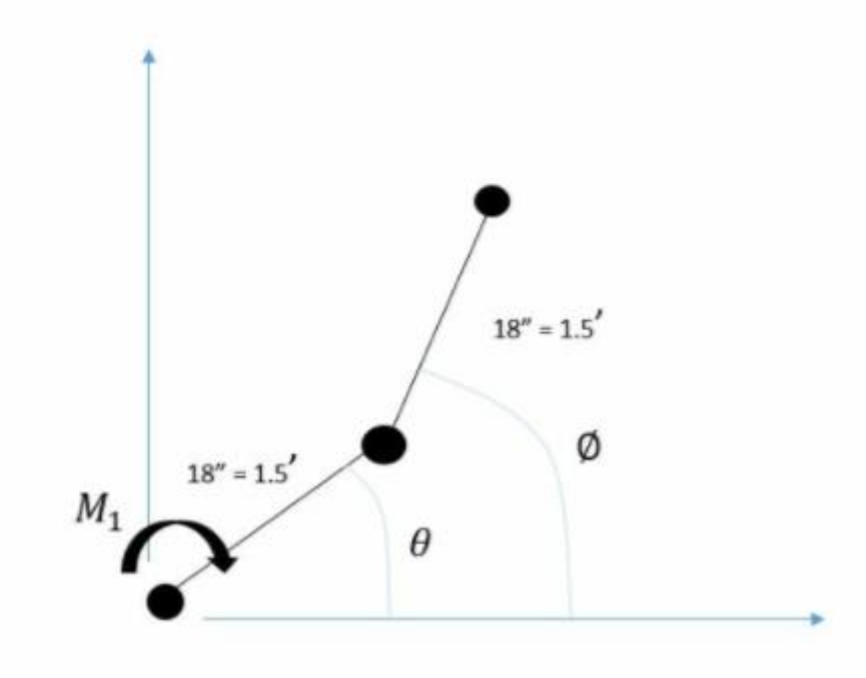


Fig. 5.2. Free body diagram of camera arm member sections.

In Figure 5.2, we are assuming the worst case of loading on our camera arm. We are also assuming θ = 35 degrees and Ø = 70 degrees. In order to find the moment about the arm, M_1, we first had to find the length of the arm, L, using Eq. 5.2:

$$L = 1.5cos\theta + 1.5cos\emptyset = 1.5\cos(35) + 1.5cost(70) = 1.812\ ft. \qquad (5.2)$$

In Eq. 5.2, the value "1.5" represents the 18 in. sections of arms converted to measurements in feet. After solving for L, M_1 was found using Eq. 5.3:

$$M_1 = (L)(m_{total}) = (1.812\ ft.)(164\ lbs) = 297.168\ ft - lbs \qquad (5.3)$$

After solving for M_1, Fig. 5.3, the free body diagram of the ball joint, was used to create a relationship between M_1 and M_2, which then allows for us to sovle for F, the holding force of the joint.

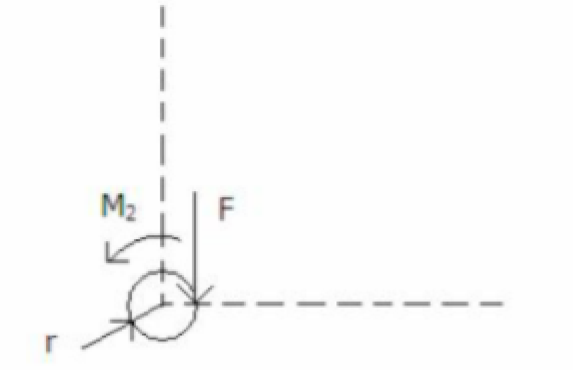


Fig. 5.3. Free body diagram of the ball joint from: edge.rlt.edu/ Edge/P10007/public/Mech%20Calc.doc

In the figure, r represents the radius of the ball joint, which in our case is assumed to be 0.315 in. = 0.02625 feet. Equation 5.4 can be derived from Fig. 5.3 to create a relationship between r, M_2, and F.

$$M_2 = (r)(F) \tag{5.4}$$

In order for our system to be balanced and self-supporting, it can be assumed that $M_2 = M_1$. Therefore, the relationship shown in Eq. 5.5 can be used to solve for the holding force of the joint. This holding force can then be assessed to prove whether or not our ball joints are strong enough for the design.

$$M_1 = (r)(F) \tag{5.5}$$

$$F = \frac{297.168\, ft - lbs}{0.02625\, ft} = 11320.686\, lbs$$

The vibrational analysis on our prototype was conducted using the representative model in Fig. 5.4. The model allowed us to accurately simulate conditions in the field to analyze the effects on the assembly. The lower left potion of the model is the "fixed" side, and the upper right portion is the side that will hold the camera. Using this model we were able to test the deflection and vibration of the arm.

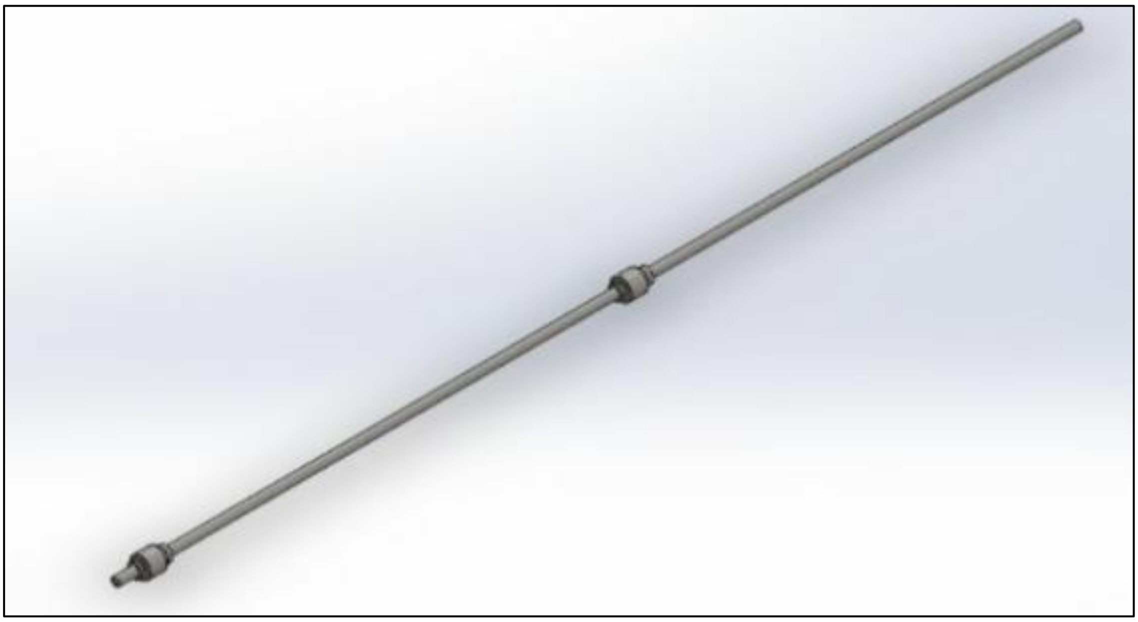


Fig. 5.4. Representative SolidWorks prototype model.

Figure 5.5 shows the simulation of the model using SolidWorks software. It shows how the assembly will react during wind loading. The lower left, blue, portion is the fixed side, and the upper right, red, portion is the end with the camera. A large 20lbf point load had been added to the end of the arm, which was acting as a static beam, in order to view displacement. This simulation allowed us to represent a dynamic simulation on our arm and see the effect of vibration of the assembly.

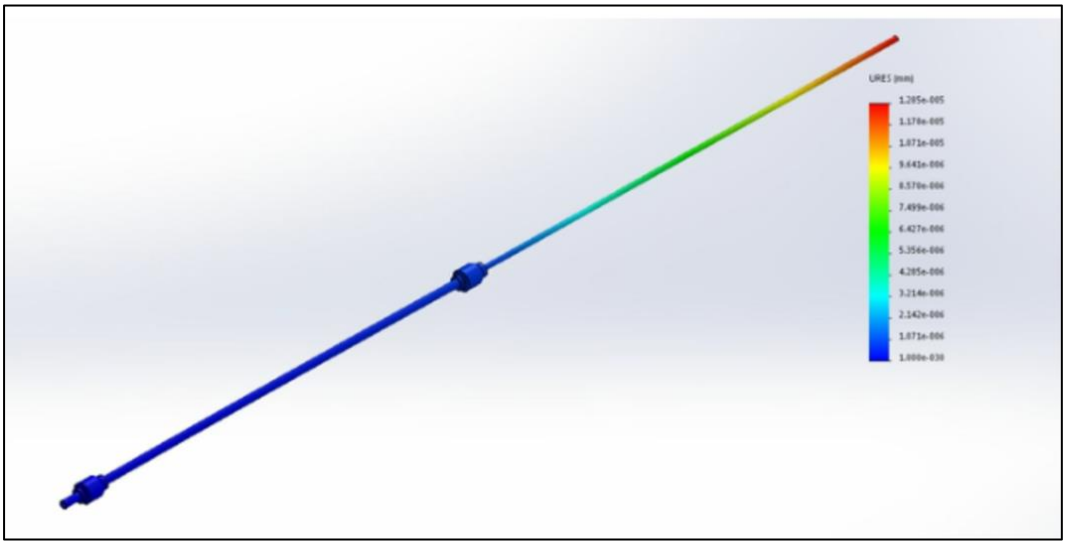


Figure 5.5. Vibrational analysis on prototype model.

Figure 5.6 shows the result of the vibration simulation. The image shows the point of largest deformation, which would be the point at natural frequency.

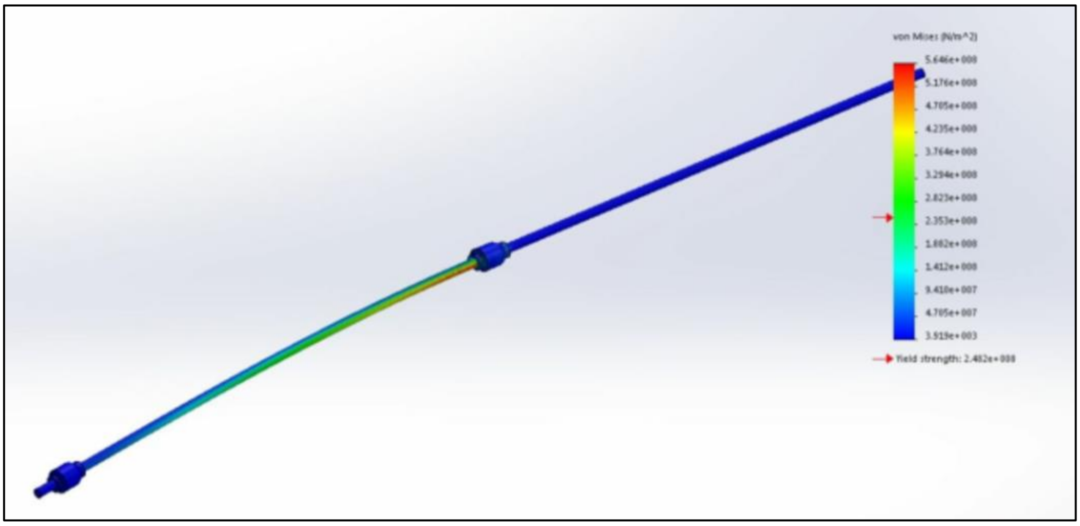


Figure 5.6. Further results of vibrational analysis on prototype model.

Table 5.1 shows the data collected form the SolidWorks analysis. The data allows us to further understand the frequency mentioned previously.

Table 5.1 SolidWorks vibrational analysis data.

Mode Number	Frequency(Hertz)	X direction(in)	Y direction(in)	Z direction(in)
1	7.1778	0.16067	0.39732	6.9183e-013
2	7.189	0.39732	0.16069	2.0593e-010
3	7.389	5.3194e-007	4.0632e-007	5.9167e-019
4	53.246	0.044753	0.12538	9.4892e-011
5	53.333	0.12541	0.044744	2.6535e-010
6	216.87	0.010042	0.041066	3.7185e-011
7	217.21	0.041055	0.010047	5.0833e-010
8	528.94	0.0047606	0.020693	4.1942e-009
9	529.67	0.020681	0.0047673	1.122e-008
10	893.29	3.575e-009	1.8753e-008	9.362e-010
11	987.99	0.0030389	0.01454	5.6891e-009
12	989.26	0.014518	0.0030486	7.1452e-008
13	1206.5	4.0584e-009	3.4214e-011	0.74422
14	1578.6	0.0023301	0.013864	3.3572e-009
15	1580.6	0.013824	0.0023427	6.029e-008
		Sum X = 0.8384	Sum Y = 0.8385	Sum Z = 0.74422

5.2.4 Results

Because the moment found about the left end of the arm is positive, this means the structure will be able to withstand the weight of the camera, so long as the theoretical design holds the weight ratio between the arms and camera when we build it as a prototype. One issue that may arise is adding a holder for the actual camera, which may create too much weight on the end of the arm. This will have to be analyzed after a prototype has been built.

The holding force for the ball joint was found to be 11320.686 lbs. Because we only plan to have a camera weighing a few ounces acting on the end of the camera arm, theoretically our arm design should be able to support the camera arm weight and maintain stability.

The vibrational analysis conducted on our prototype allowed us to conclude that the assembly will be able to perform in the field. However, it is important to note that vibration causing displacement of up to an inch in all three directions will occur during strong winds. This problem will require further analysis beyond the scope of this project to fix, leaving room for future improvements for this design.

5.2.5 Significance

The preliminary analysis allowed for us to ensure our design would work before building our prototype. After concluding that the preliminary analysis did not call for a redesign of our camera arm, we were able to begin the building phase of our project. After building the prototype, further analysis on the model allowed for us to see any real-life design flaws.

Although vibrations were found to cause displacement, our analysis concluded that our prototype design is field-ready, however, there is room for future improvements in the design.

6 RISK ASSESSMENT

Figure 6.1 below shows the fundamental steps of risk management that were used in the risk assessment portion of this project.

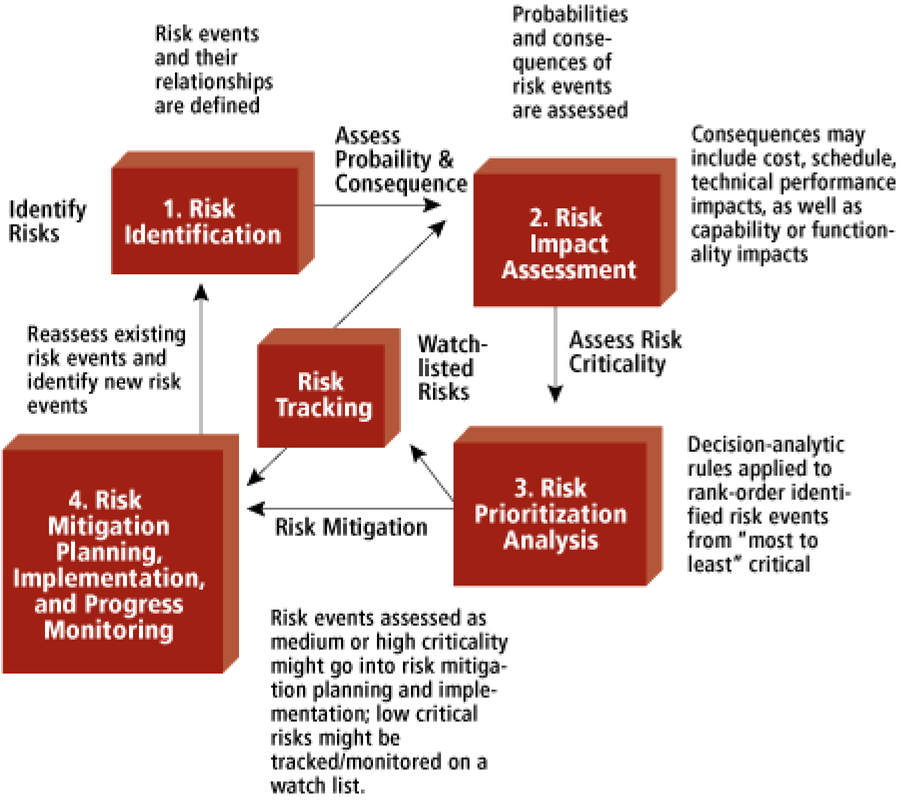


Fig. 6.1. **Fundamental steps of risk management as presented in http://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/risk-management.**

6.1 RISK IDENTIFICATION

Below is a list of the risks we have identified for our project:

1. Operational Risk: If vibrations occur with our arm during strong winds, then users may experience issues with the camera arm on windy days.
2. Time risk: If we found major issues with vibrations or the ability of the arm to maintain stability and position, then the redesign of the prototype will affect an already small time frame for project completion.
3. Money risk: If the pesticide-resistant materials cost too much, then we will go over budget for our project.
4. Manufacturing risk: If our theoretical design becomes physically infeasible, then we will not be able to build an actual prototype.

6.2 RISK ANALYSIS

1. To combat the operational risk, we are ensuring that we have presented adequate vibrational analysis for the design, so users can understand the risk of using the camera arm on windy days. It should also be explained to purchasers that there is still this risk even on the final prototype.

2. To combat the time risk associated with finding too many issues with our prototype, we performed vibrational analysis and simulations on a model of the prototype in SolidWorks before building our actual prototype. This allowed us a free and quick assessment of whether or not our camera arm prototype would need major, time-consuming alterations BEFORE taking the time to build it.

3. To combat the risk associated with money and the cost of pesticide-resistant materials we searched multiple material distributors to ensure we were receiving the best prices. Happiness equations were also used to access the importance of keeping the cost low for our customer.

4. To combat the manufacturing risk, static analysis was performed on the design drawings to ensure the arm design was physically feasible. Had the analysis failed we would have redesigned the concept over and over again until the analysis proved feasibility and we could begin building the prototype.

6.3 RISK PRIORITIZATION

Table 6.3.1 below displays how we prioritized the risks in our project. We have once again identified each risk and then assessed the impact of each individual risk on our project plan. We have also included an assessment of each individual risk with regards to the probability that the risk will occur, as well as the preventative measures being taken to combat these risks, which were mentioned previously.

Table 6.3.1 Table of risk prioritization for our project.

Risk	Impact on Project	Probability the Risk Will Occur	Preventative Measures to Combat the Risk
If vibrations occur with our arm during strong winds, then users may experience issues with the camera arm on windy days.	Minor	High	We are ensuring that we have presented adequate vibrational analysis for the design, so users can understand the risk of using the camera arm on windy days. It should also be explained to purchasers that there is still this risk even on the final prototype.
If we found major issues with vibrations or the ability of the arm to maintain stability and position, then the redesign of the prototype will affect an already small time frame for project completion.	Major	Medium	We performed vibrational analysis and simulations on a model of the prototype in SolidWorks before building our actual prototype. This allowed us a free and quick assessment of whether or not our camera arm prototype would need major, time-consuming alterations BEFORE taking the time to build it.
If the pesticide-resistant materials cost too much, then we will go over budget for our project.	Moderate	Medium	We searched multiple material distributors to ensure we were receiving the best prices. Happiness equations were also used to access the importance of keeping the cost low for our customer.
If our theoretical design becomes physically infeasible, then we will not be able to build an actual prototype.	Major	Low	Static analysis was performed on the design drawings to ensure the arm design was physically feasible. Had the analysis failed we would have redesigned the concept over and over again until the analysis proved feasibility and we could begin building the prototype.

7 CODES AND STANDARDS

7.1 IDENTIFICATION

With the camera arm design, the main codes and standards needed to be recognized are those related to materials that can be used to store/contain pesticides [1].

7.2 JUSTIFICATION

The codes and standards for the materials that can be used to store/contain pesticides were selected for us to determine materials for our design that would allow it to be as resistant as possible to frequent pesticide spraying. We selected standards that were based on storing materials, because we are assuming if the materials can withstand constant contact while holding the pesticides, they can withstand being sprayed by those same pesticides.

7.3 DESIGN CONSTRAINTS

7.3.1 Manufacturing

The codes and standards mentioned above place constraints on our design manufacturing. Because we can only select certain materials, specifically hard materials like metals, this will place a constraint on how we will have to machine the material, as well as protect the materials used.

7.3.2 Economic

The codes and standards mentioned above for the types of materials we can use in conjunction with pesticides places an economic constraint on the design of the project. While we aimed to create a design that is less than $100, cheaper materials, such as plastic, are out of the question for using on our camera arm that will be exposed to pesticides.

7.4 SIGNIFICANCE

The constraints on materials that can be used to resist pesticides has influenced the material selection process for our design, which has in turn created both economical and manufacturing constraints for our design. The material choices that will be affected for our design will be the framings, the fasteners, washers, screws, and ideally every component on the surface of the arm. All the materials used will be selected from the following metals that abide by the mentioned codes and standards: stainless steel, brass, anodized silver, anodized aluminum, and anodized zinc.

8 WORKING PROTOTYPE

8.1 PROTOTYPE PHOTOS

Below is a photograph showing our prototype. The ball joint adjustment points have been labeled.

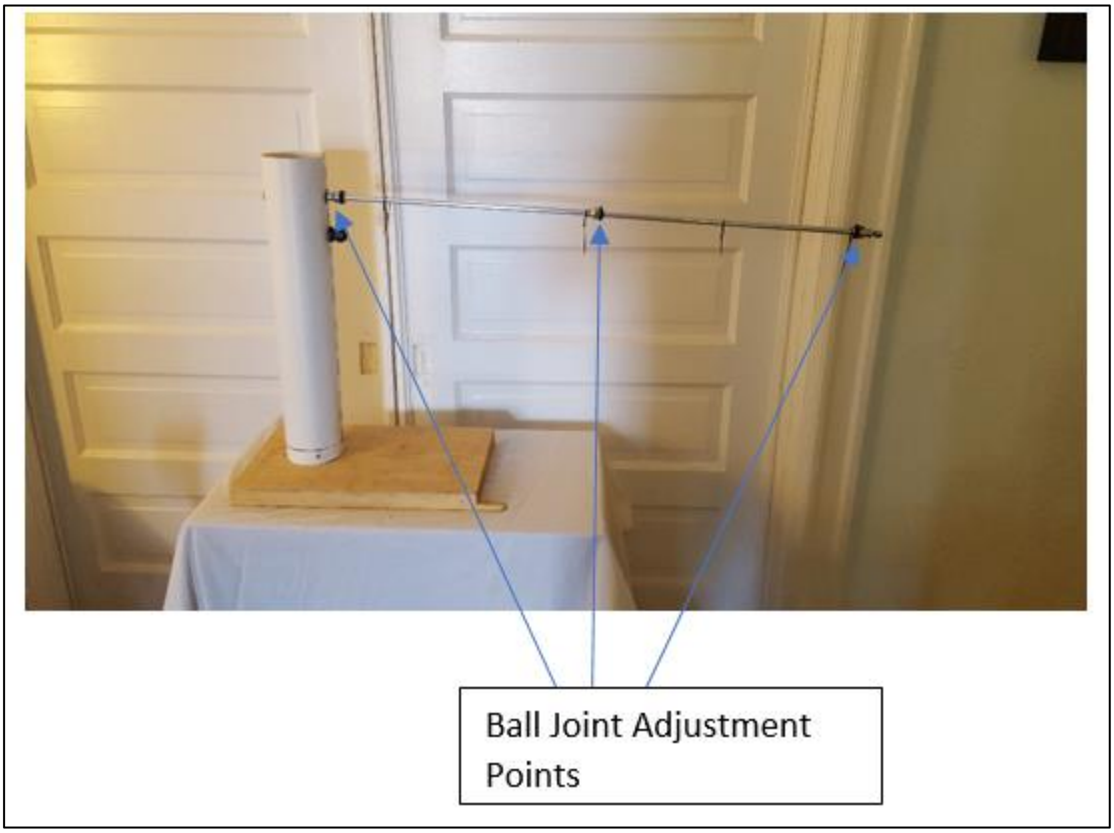


Fig. 8.1 Photograph showing the overall view of our prototype.

8.2 WORKING PROTOTYPE VIDEO

The following video clip shows the final prototype performing under a wind test: https://youtu.be/FcNli7L93e4

8.3 PROTOTYPE COMPONENTS

The following photographs show additional components on our prototype. Figure 8.2 shows a close-up view of the adjustment set screws on each ball joint. These screws allow for the arm to be locked into place once it has been rotated and extended to the desired position.

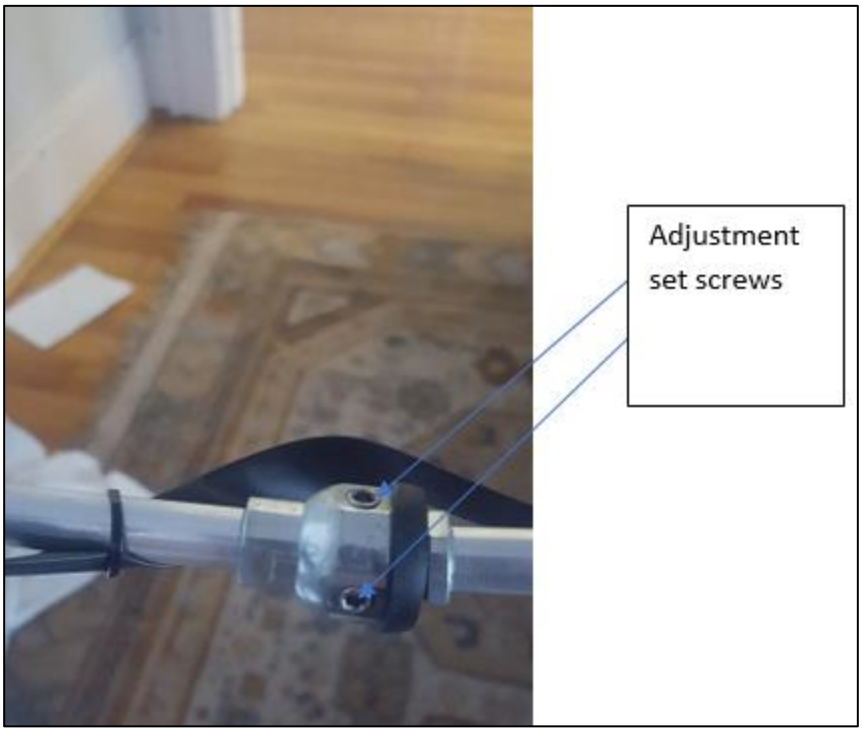


Fig. 8.2 **Close-up view of the adjustment set screws used to lock the ball joints into position.**

Figure 8.3 below shows the wire assembly used to connect the camera wires to the inside of the PheNode via the camera arm. The protective sheath was essential sense the wire would be along the outside of the camera arm and otherwise vulnerable to pesticide sprays.

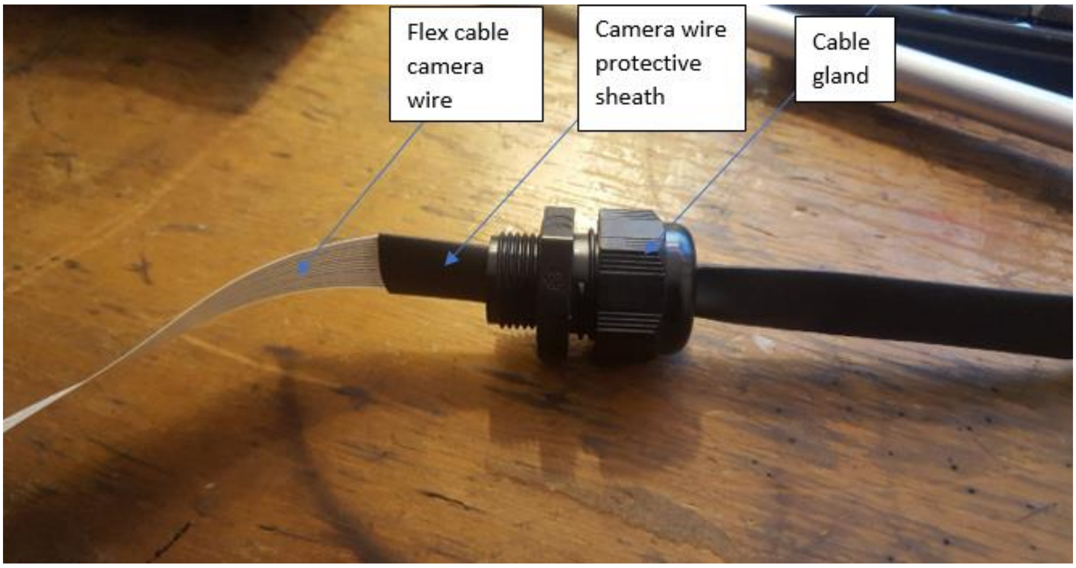


Fig. 8.3 **Close-up view of the wire assembly.**

Figure 8.4 shows the internal structure of the camera arm. This section, as mimicked on a PVC pipe, will go through the center of the PheNode. This is essential to how our PheNode will attach and detach from the PheNode.

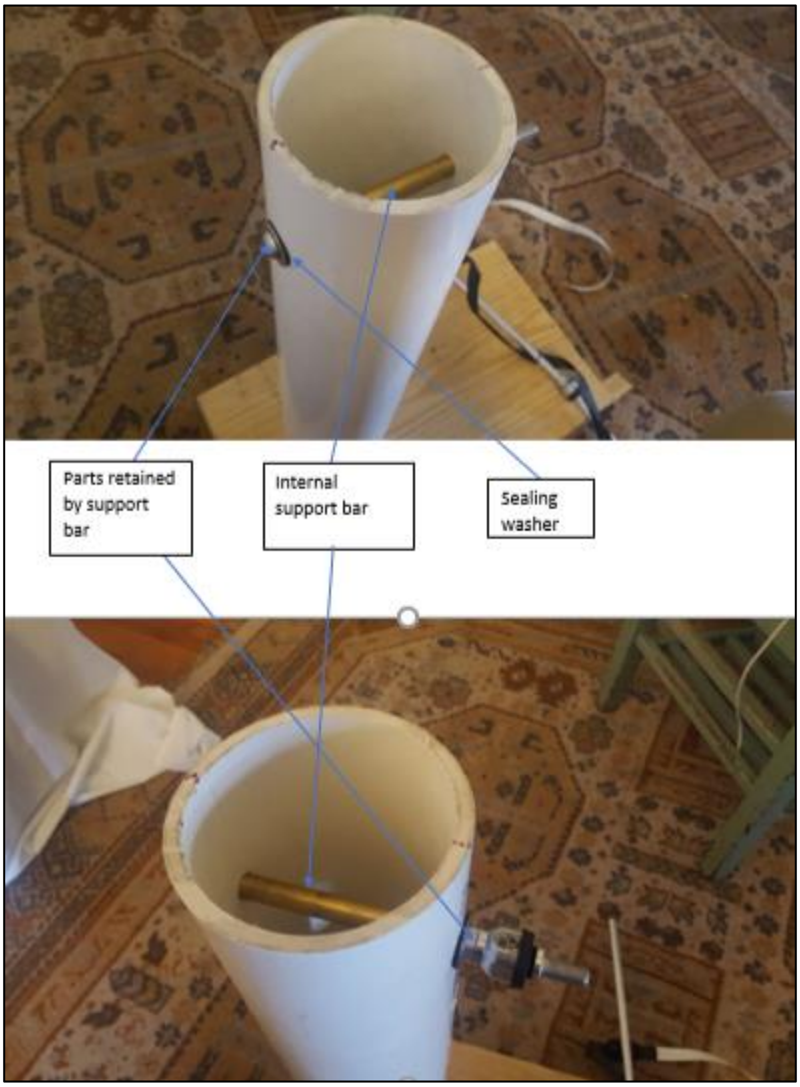


Fig. 8.4 **Close-up view of the internal camera arm structure.**

9 DESIGN DOCUMENTATION

9.1 FINAL DRAWINGS AND DOCUMENTATION

9.1.1 Engineering Drawings

See Appendix C for the individual CAD models. Below is a set of the final engineering drawings for our prototype, including modifications made to purchased parts.

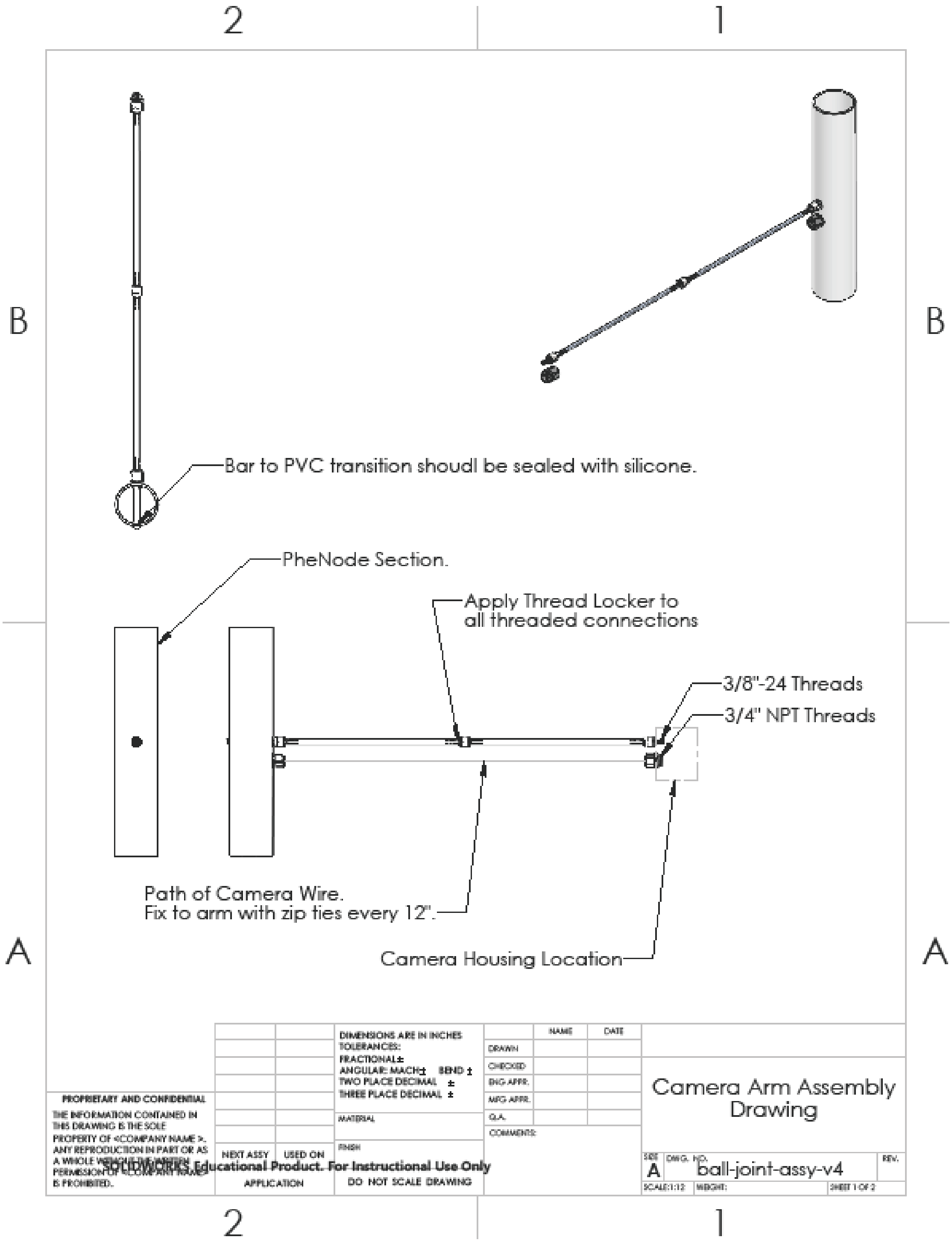
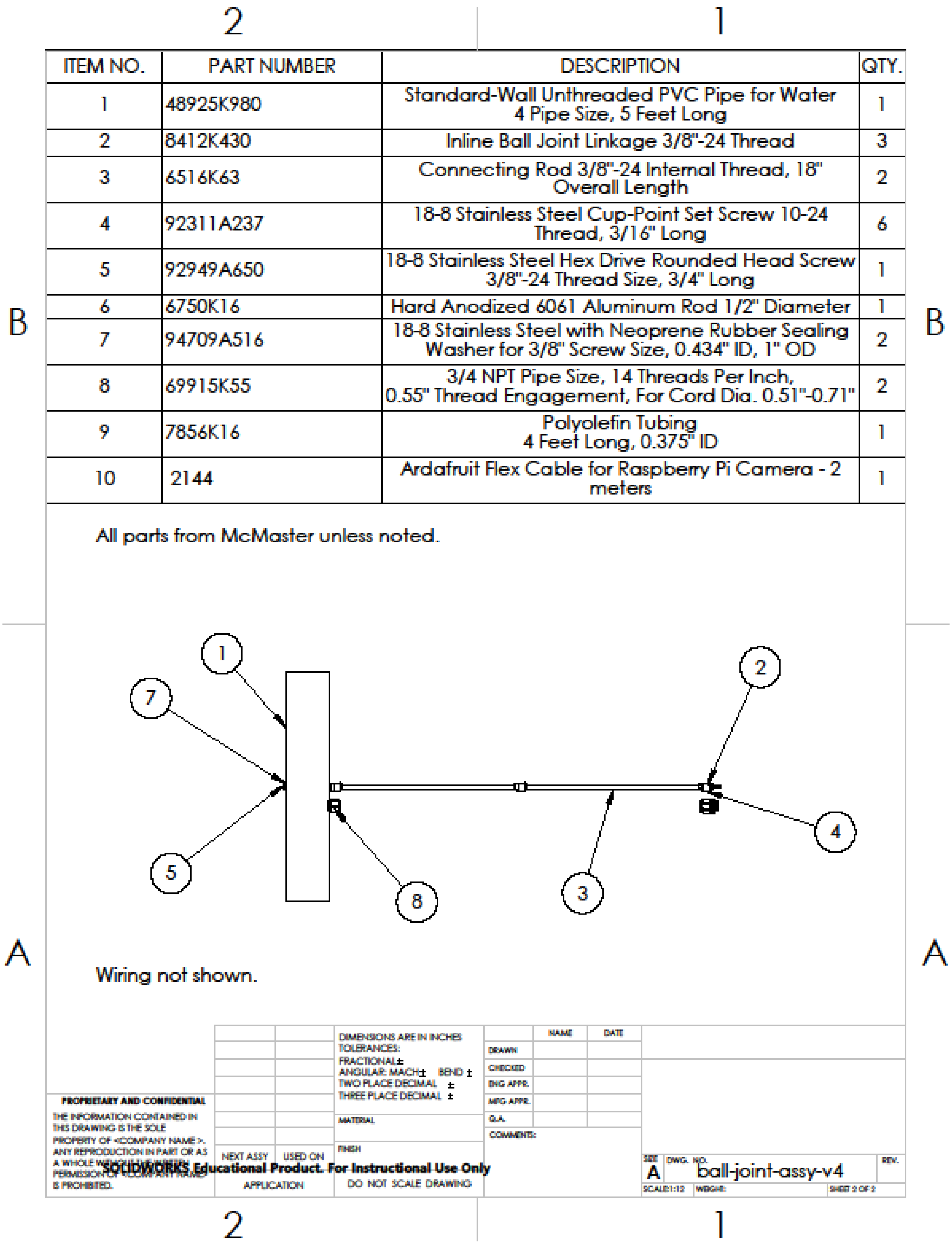


Fig. 9.1 Final assembly drawing for the camera arm.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	48925K980	Standard-Wall Unthreaded PVC Pipe for Water 4 Pipe Size, 5 Feet Long	1
2	8412K430	Inline Ball Joint Linkage 3/8"-24 Thread	3
3	6516K63	Connecting Rod 3/8"-24 Internal Thread, 18" Overall Length	2
4	92311A237	18-8 Stainless Steel Cup-Point Set Screw 10-24 Thread, 3/16" Long	6
5	92949A650	18-8 Stainless Steel Hex Drive Rounded Head Screw 3/8"-24 Thread Size, 3/4" Long	1
6	6750K16	Hard Anodized 6061 Aluminum Rod 1/2" Diameter	1
7	94709A516	18-8 Stainless Steel with Neoprene Rubber Sealing Washer for 3/8" Screw Size, 0.434" ID, 1" OD	2
8	69915K55	3/4 NPT Pipe Size, 14 Threads Per Inch, 0.55" Thread Engagement, For Cord Dia. 0.51"-0.71"	2
9	7856K16	Polyolefin Tubing 4 Feet Long, 0.375" ID	1
10	2144	Ardafruit Flex Cable for Raspberry Pi Camera - 2 meters	1

All parts from McMaster unless noted.

Wiring not shown.

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THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.

NEXT ASSY
USED ON
APPLICATION

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL
FINISH
DO NOT SCALE DRAWING

NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:

SIZE A
DWG. NO. ball-joint-assy-v4
REV.
SCALE:1:12
WEIGHT:
SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only

Fig. 9.2 Final parts list and assembly drawing for the camera arm.

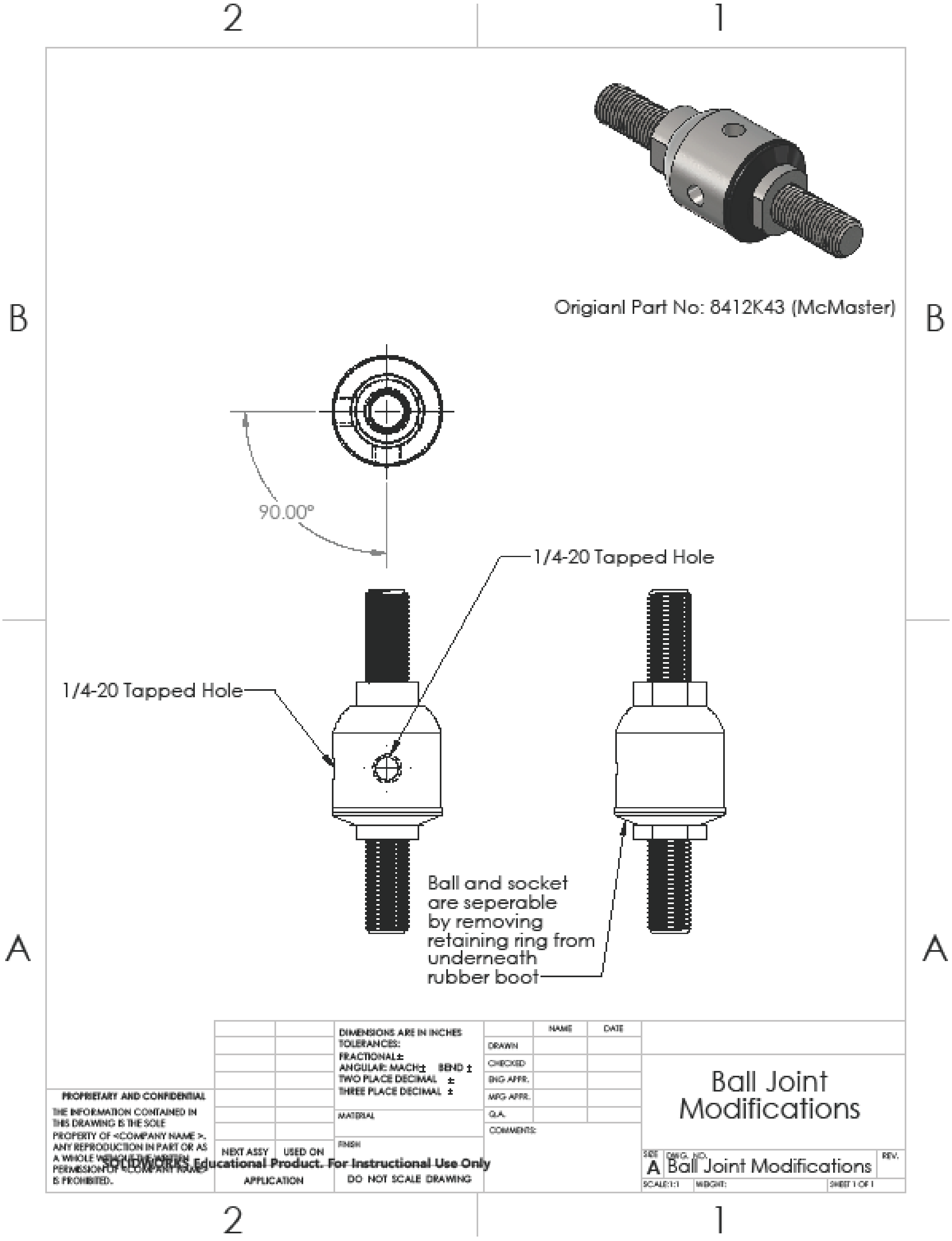


Fig. 9.3 Modifications made to the ball joint while building the camera arm.

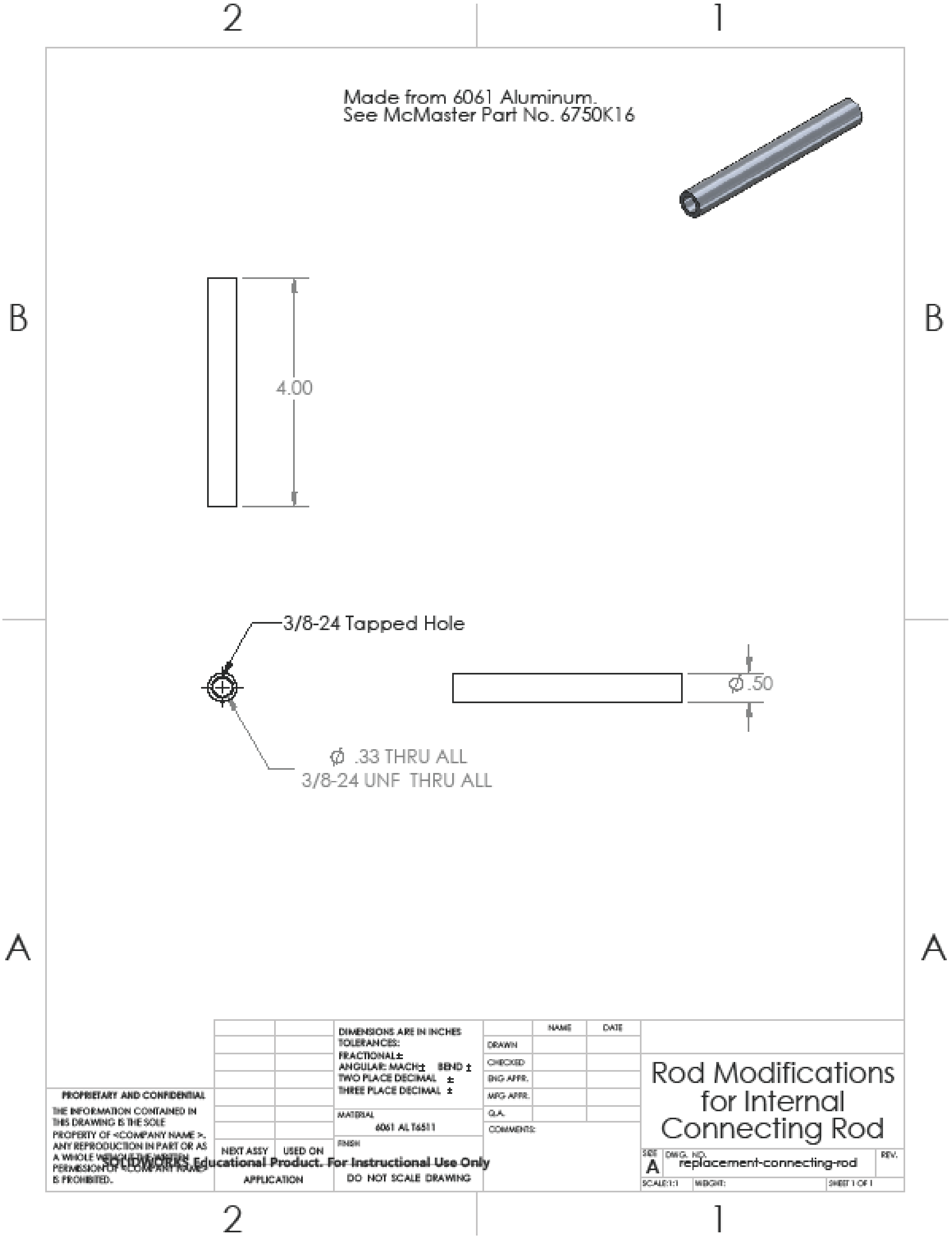


Fig. 9.4 Modifications made to the connecting rod while building the camera arm.

9.1.2 Sourcing instructions

See Table 12.1 in Appendix B for a final list of all materials used in the project. Item numbers 1-9 on the list are sourced from McMaster-Carr. Item number 10

9.2 FINAL PRESENTATION

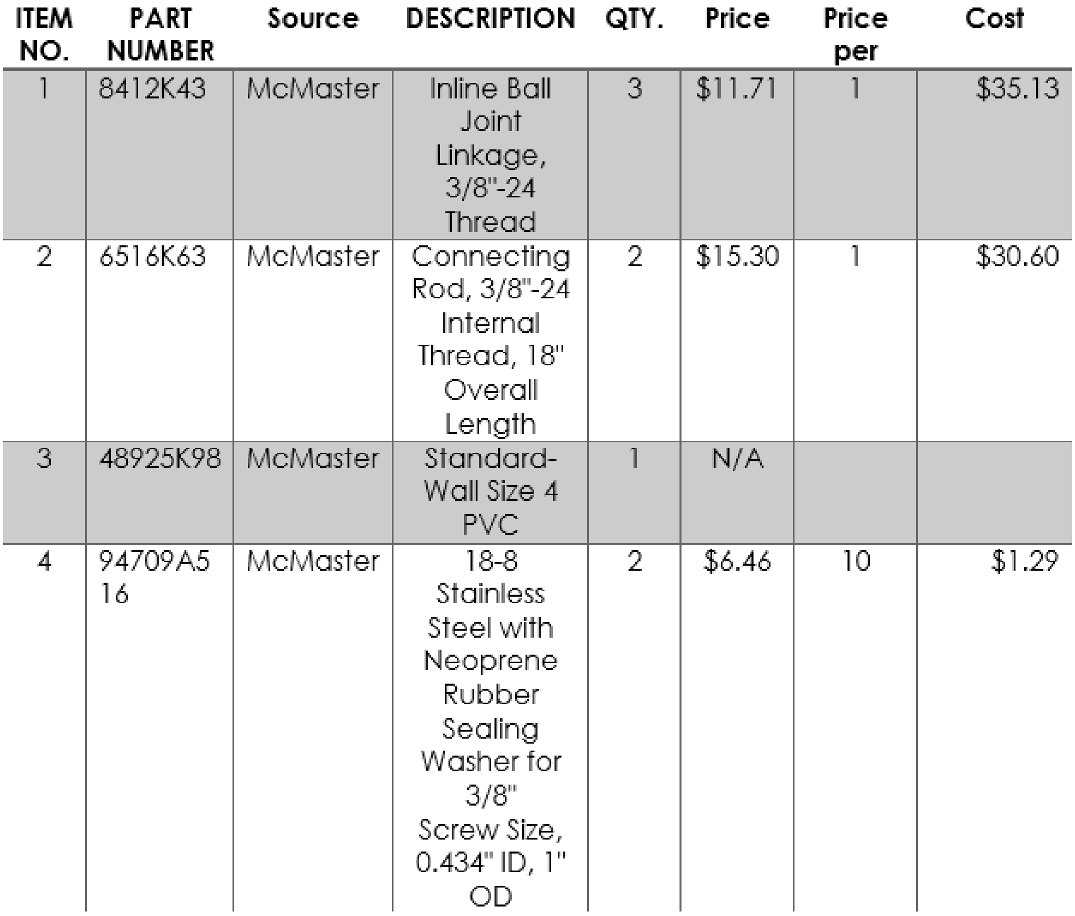
To view the video presentation of our camera arm at the Donald Danforth Plant Science Center, please visit https://youtu.be/EM5TCcb8A0.

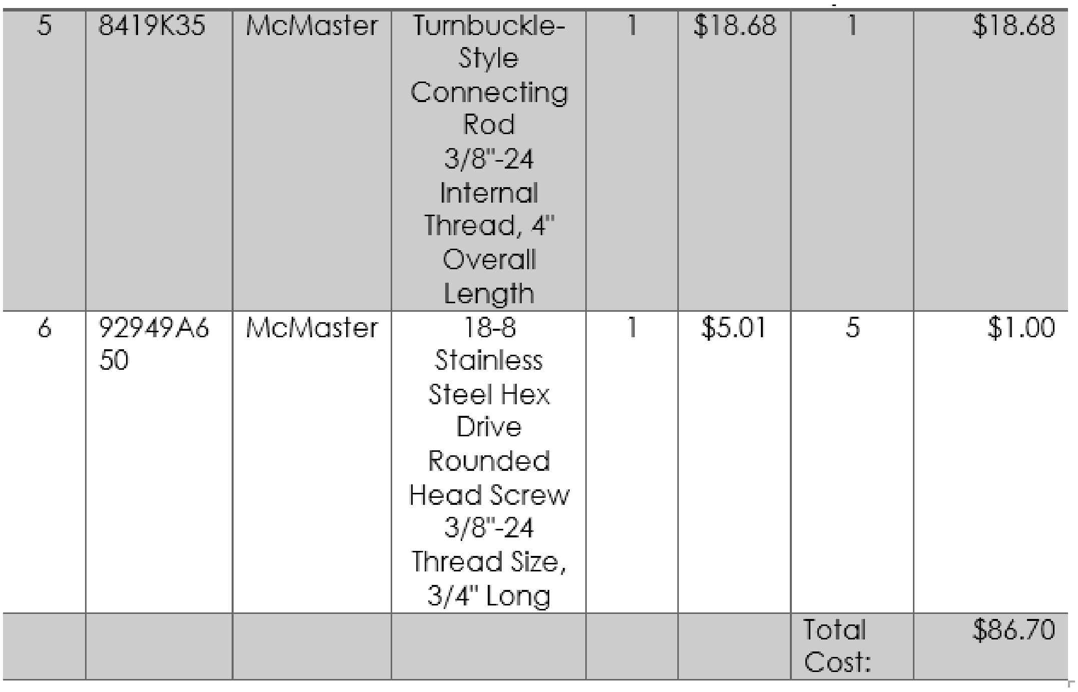
10 TEARDOWN

Teardown for our project will consist of delivering our finished prototype to Nadia Shakoor for the use of the Donald Danforth Plant Science Center.

11 APPENDIX A - PARTS LIST

This is an initial list of parts.





ITEM NO.	PART NUMBER	Source	DESCRIPTION	QTY.	Price	Price per	Cost
1	8412K43	McMaster	Inline Ball Joint Linkage, 3/8"-24 Thread	3	$11.71	1	$35.13
2	6516K63	McMaster	Connecting Rod, 3/8"-24 Internal Thread, 18" Overall Length	2	$15.30	1	$30.60
3	48925K98	McMaster	Standard-Wall Size 4 PVC	1	N/A		
4	94709A516	McMaster	18-8 Stainless Steel with Neoprene Rubber Sealing Washer for 3/8" Screw Size, 0.434" ID, 1" OD	2	$6.46	10	$1.29
5	8419K35	McMaster	Turnbuckle-Style Connecting Rod 3/8"-24 Internal Thread, 4" Overall Length	1	$18.68	1	$18.68
6	92949A650	McMaster	18-8 Stainless Steel Hex Drive Rounded Head Screw 3/8"-24 Thread Size, 3/4" Long	1	$5.01	5	$1.00
						Total Cost:	$86.70

12 APPENDIX B - BILL OF MATERIALS

This is the final list of our parts. Included after is a list of part explanations to give further detail for each item.

Table 12.1 Final list of parts used in our project.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	48925K980	Standard-Wall Unthreaded PVC Pipe for Water 4 Pipe Size, 5 Feet Long, $NA	1
2	8412K430	Inline Ball Joint Linkage 3/8"-24 Thread, $11.71	3
3	6516K63	Connecting Rod 3/8"-24 Internal Thread, 18" Overall Length, $15.30	2
4	92311A237	18-8 Stainless Steel Cup-Point Set Screw 10-24 Thread, 3/16" Long, $0.10	6
5	92949A650	18-8 Stainless Steel Hex Drive Rounded Head Screw 3/8"-24 Thread Size, 3/4" Long, $1.01	1
6	6750K16	Hard Anodized 6061 Aluminum Rod 1/2" Diameter, $3.14	1
7	94709A516	18-8 Stainless Steel with Neoprene Rubber Sealing Washer for 3/8" Screw Size, 0.434" ID, 1" OD, $0.65	2
8	69915K55	3/4 NPT Pipe Size, 14 Threads Per Inch, 0.55" Thread Engagement, For Cord Dia. 0.51"-0.71", $4.43	2
9	7856K16	Polyolefin Tubing 4 Feet Long, 0.375" ID, $3.27	1
10*	2144	Ardafruit Flex Cable for Raspberry Pi Camera - 2 meters, $5.95	1

*Note: All parts sourced from McMaster-Carr except part 10. Part 10 can be purchased at https://www.adafruit.com/product/2144.

Table 12.2. Part explanations for the parts listed in Table 12.1.

ITEM NO.	DESCRIPTION
1	This part is a paceholder for the PheNode. The Phenode is constructed from No. 4 PVC, which is what this part is. This allows the PheNode dimensions to be accurately represented without having the PheNode itself.
2	The ball joints allow the camera arm to move 35 degrees in any direction. This is the only moving part and allows the camera to be focused on anything in reach of the arm.
3	These parts form the long sections of the camera arm. In future this part could be produced at mill rather than purchased as the part is simple and likely very inexpensive in bulk.
4	These set screws lock the ball joints in position (two per joint).
5	This screw attaches the internal anodized rod support on one end. One of the ball joints secures the other end.
6	This is the internal support that the arm attaches to. This part is now made at mill rather than purchased as the original part was expensive, and had left-handed threads on one side. It was difficult to find matching left-handed bolts.
7	These washers seal the outside of the housing where the arm intersects.
8	These cable glands allow the camera wire to pass through the instrument exterior without letting moisture or debris in.
9	This tubing coats the exterior of the camera wire, which is fragile. It also seals against the cable glands.
10	This is the camera cable that is sold for the Raspberry Pi camera used by the PheNode.

13 APPENDIX C – COMPLETE LIST OF ENGINEERING DRAWINGS

13.1 Engineering drawings for Section 4.3

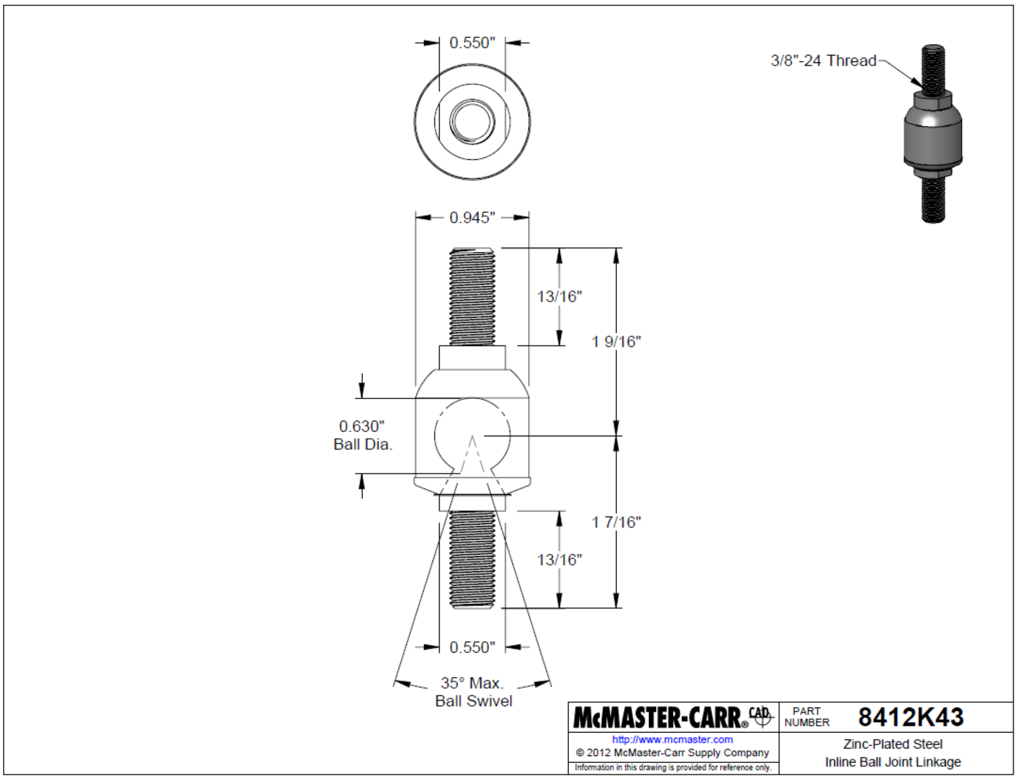


Fig. 4.3.1. **Zinc-Plated Steel Inline Ball Joint Linkage. Part #1 on the Parts List.**

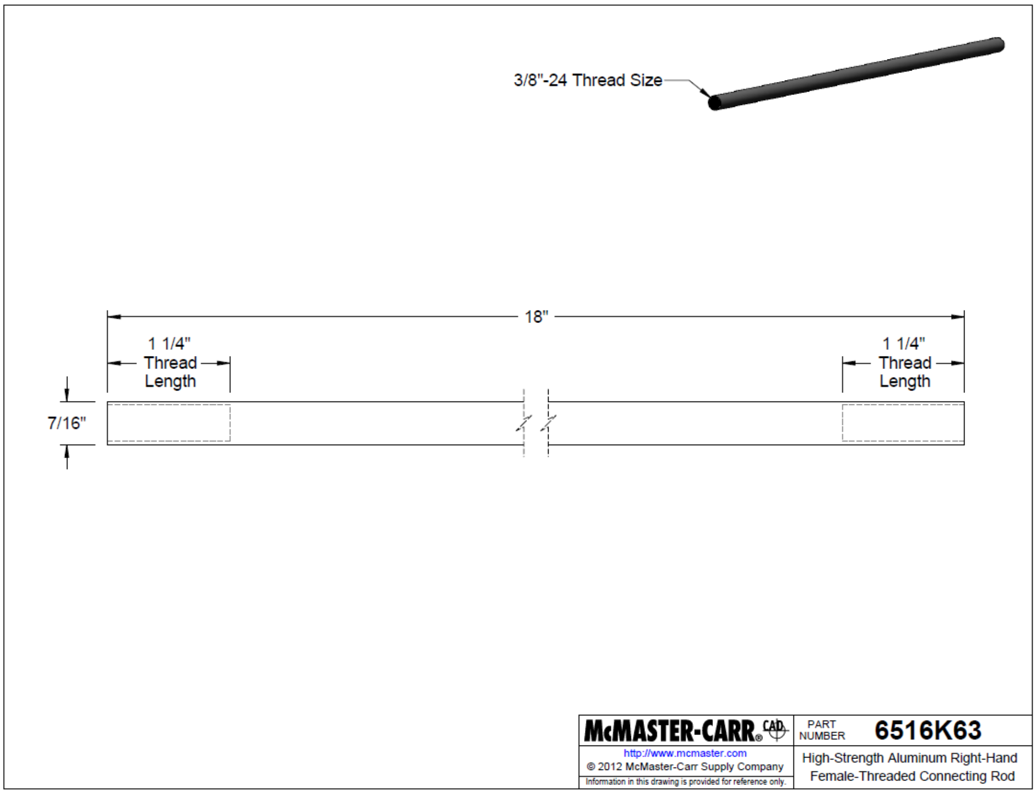


Fig. 4.3.2. **High-Strength Aluminum Right-Hand Female-Threaded Connecting Rod. Part #2 on the Parts List.**

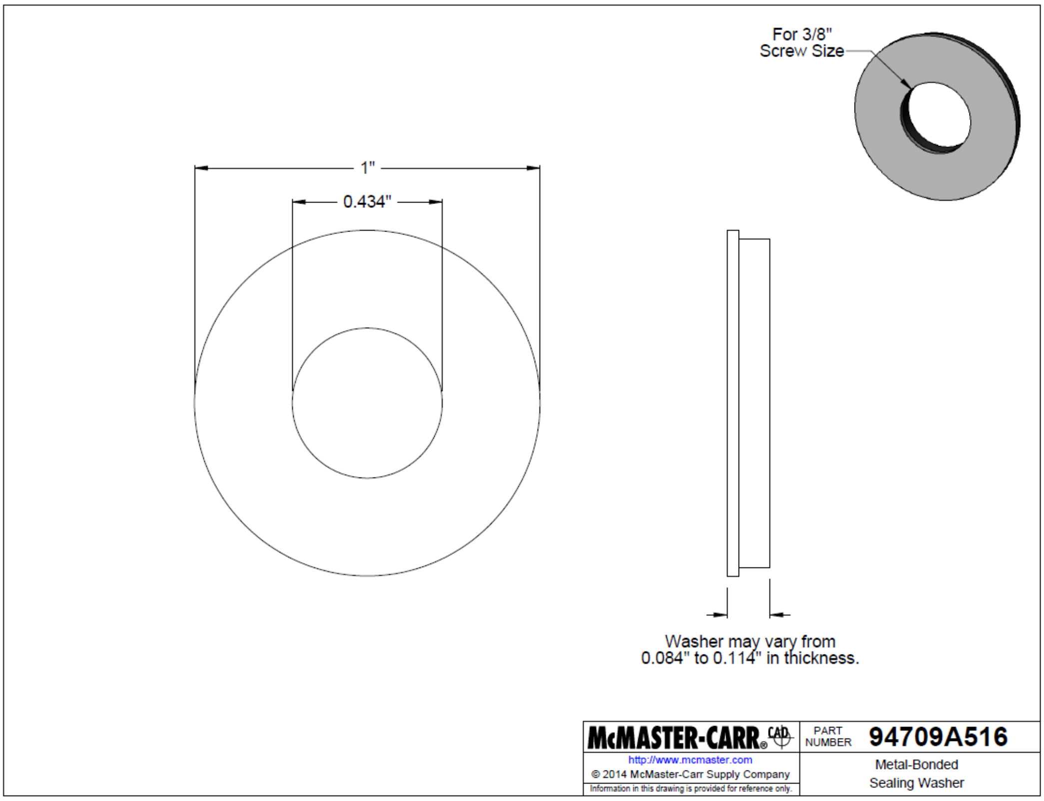


Fig. 4.3.3. **Metal-Bonded Sealing Washer. Part #4 on the Parts List.**

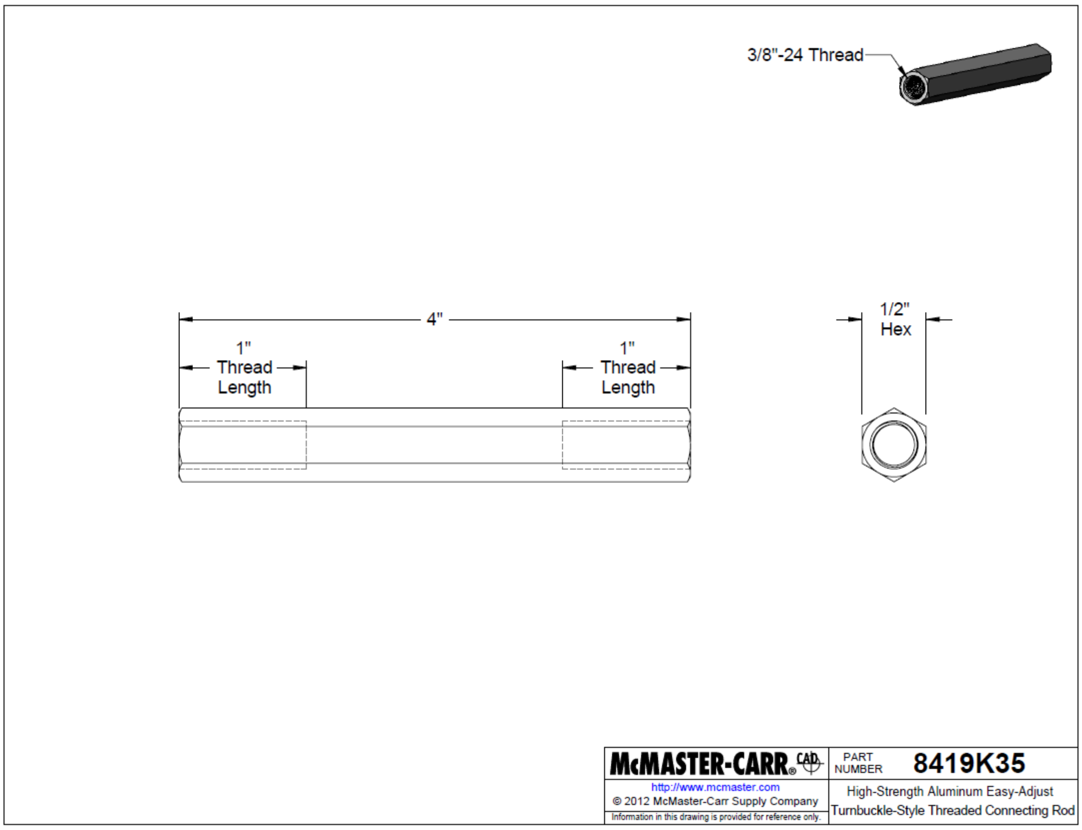


Fig. 4.3.4. High-Strength Aluminum Easy-Adjust Turnbuckle-Style Threaded Connecting Rod. Part #5 on the Parts List.

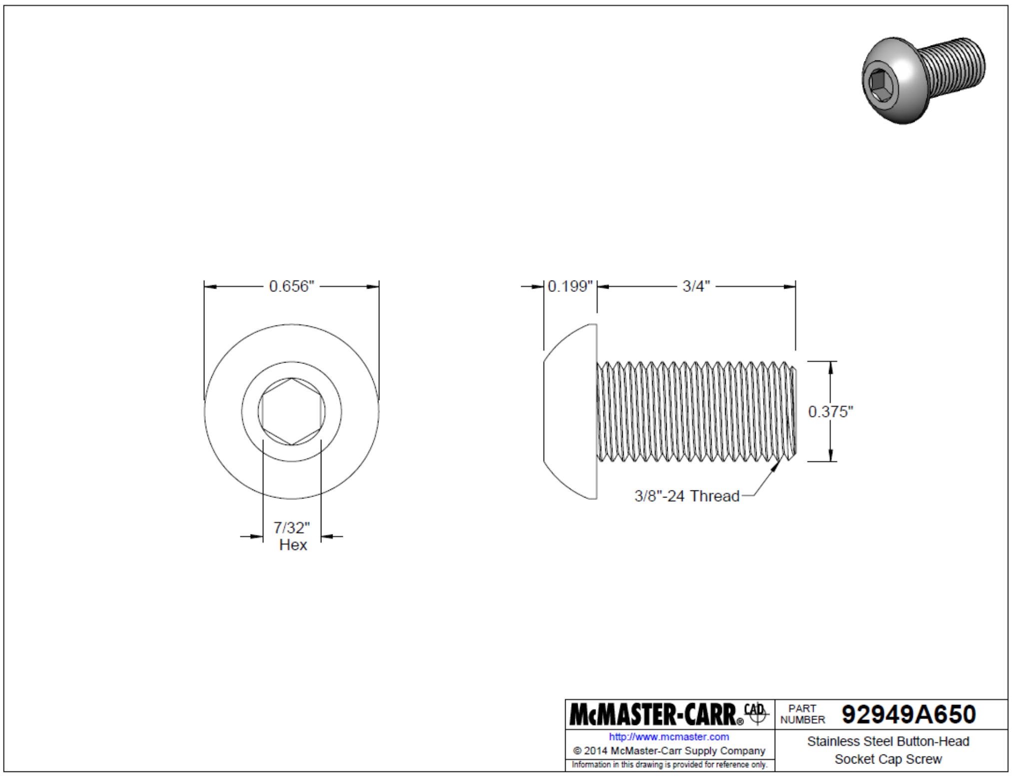


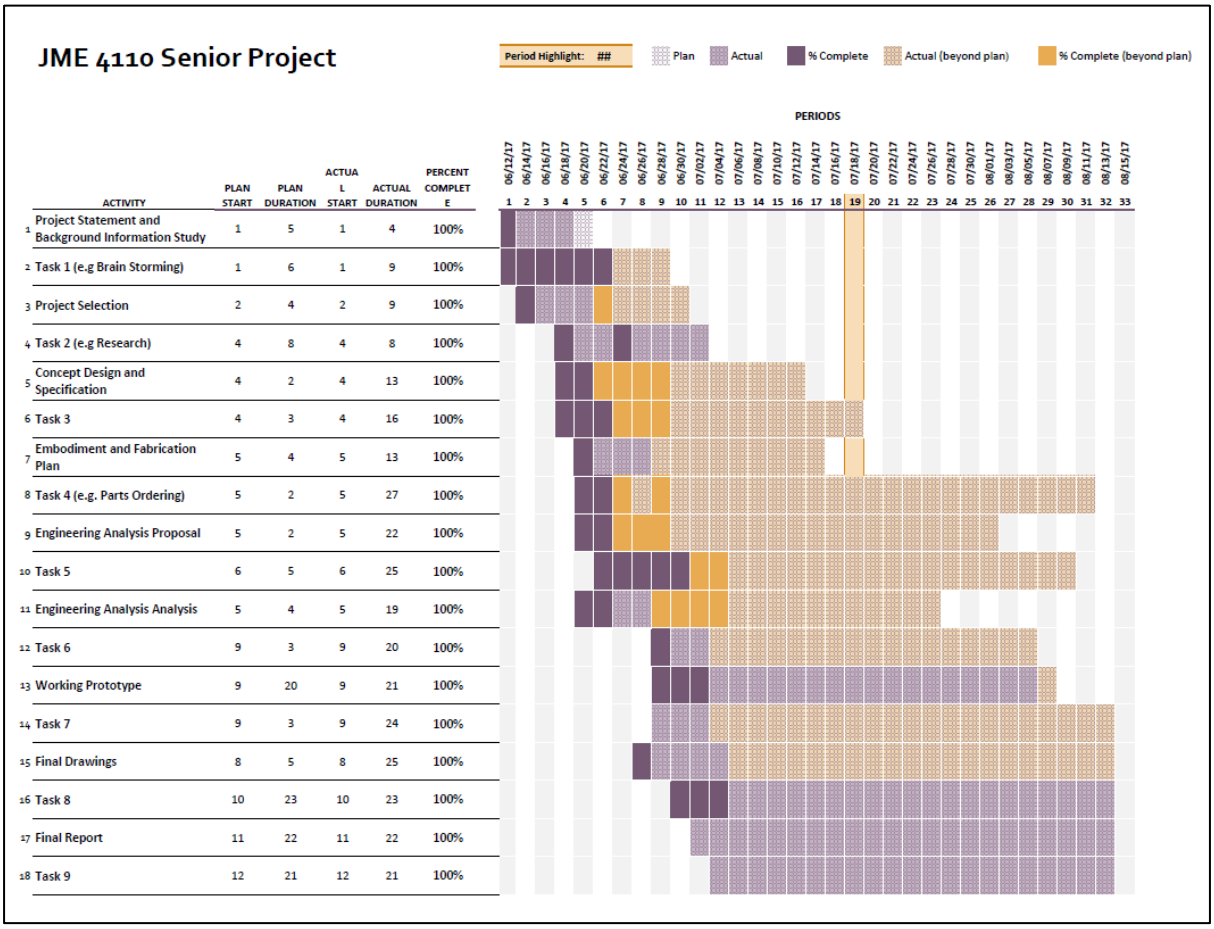
Fig. 4.3.5. Stainless Steel Button-Head Socket Cap Screw. Part #6 on the Parts List.

13.2 Engineering Drawings for Section 9.1.1

The files embedded below are a pack and go zip of all our CAD drawings, including the McMaster-Carr files shown above in 13.1. They are SolidWorks 2017 formatted files.

ball-joint-assy-v4.zip

14 APPENDIX D – GANTT CHART FOR OUR PROJECT



JME 4110 Senior Project

	ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
1	Project Statement and Background Information Study	1	5	1	4	100%
2	Task 1 (e.g Brain Storming)	1	6	1	9	100%
3	Project Selection	2	4	2	9	100%
4	Task 2 (e.g Research)	4	8	4	8	100%
5	Concept Design and Specification	4	2	4	13	100%
6	Task 3	4	3	4	16	100%
7	Embodiment and Fabrication Plan	5	4	5	13	100%
8	Task 4 (e.g. Parts Ordering)	5	2	5	27	100%
9	Engineering Analysis Proposal	5	2	5	22	100%
10	Task 5	6	5	6	25	100%
11	Engineering Analysis Analysis	5	4	5	19	100%
12	Task 6	9	3	9	20	100%
13	Working Prototype	9	20	9	21	100%
14	Task 7	9	3	9	24	100%
15	Final Drawings	8	5	8	25	100%
16	Task 8	10	23	10	23	100%
17	Final Report	11	22	11	22	100%
18	Task 9	12	21	12	21	100%

15 ANNOTATED BIBLIOGRAPHY

[1] US Environmental Protection Agency Office of Pesticides Programs. "Table 7: Standards for Containment Structures (40 CFR Part 165 Subpart E)." Environmental Protection Agency, October 2008. From: https://www.epa.gov/ sites /production/files/2015-05/documents/regulations-glance-table-7.pdf