Sun-Detecting Umbrella System

Final Design Report

Prepared for the Faculty of Engineering, University of Manitoba

Sponsored by: Atom-Jet Industries

Required for MECH 4860: Engineering Design

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Submitted on December 4, 2019

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Executive Summary

This project, as put forward by Atom Jet Industries, was to first develop a fully functional small-scale prototype of a self-adjusting sun-tracking umbrella. This prototype would serve as a proof-of-concept to be expanded upon by developing a full-scale commercial version of the umbrella design complete with a detailed description, drawings and a bill of materials. The critical design requirements were that the umbrella must be easy to set up and take down requiring no more than two people, is simple and safe to operate, can be adjusted to stand on different surfaces and be portable. The most important design requirement is that the system should be able to locate the sun and track its movements to provide constant shade in any location or time of year. Our team was successful in developing a working prototype of the system that is controlled by a SparkFun RedBoard microcontroller, actuated via servo motors and detects the sun using photoresistors. The commercial version of the design was developed with the system being lightweight, only requiring a single button to operate, features an adjustable base and includes safety measures to protect the user. In addition to the commercial design, part drawings and a full detailed bill of materials was created.

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1. Introduction

The introduction of the report contains the background information of the project. Section 1.1 of the introduction explains the client's background information. Section 1.2 defines the project's objectives, deliverables and briefly defines the scope. Section 1.3 outlines the design requirements for the project based on the client's needs. Section 1.4 lists the team's overall expectations for the project.

1.1 Client Background

Atom-Jet Industries is an international company consisting of an Agriculture, Custom Brazing and a Machining and Advanced Manufacturing divisions that provide products and services to agricultural and industrial markets [1]. Atom-Jet also has their own Research and Development department that works on innovating current product designs to meet customer' needs and specifications. Recently, a new branch has been created in Atom-Jet's Research and Development department with a focus on producing new products and services to expand into new markets. This department is tasked with investigating design ideas created by upper management to evaluate their potential to be developed into new projects, products and services. Creative freedom is highly valued at Atom-Jet, so the Research and Development division is granted the liberty to investigate design ideas and report their findings to upper management who decide on a project's viability.

Currently, there are a few projects in development in this division; one of which was submitted to the capstone course to be worked on by a student team. The submitted project has not been worked on by Atom-Jet, thus allowing the student team to have complete control over the design and methods used to complete the project. The student team is essentially working as a part of Atom-Jet's new Research and Development division to determine the feasibility of the submitted project. Furthermore, Atom-Jet wants to see the level of quality that a student team can produce within the time frame set by the capstone course and with limited resources. The student team will then submit their final designs and recommendations to Atom-Jet for consideration in Atom-Jet's new business endeavors. The following section of the report states the project's definition including its objectives and deliverables.

1.2 Project Definition

Atom-Jet Industries desires a design for a sun-detecting and self-adjusting umbrella system. This system should detect the position of the sun and change its orientation to provide the optimal amount of shade. The umbrella system should be autonomous, and able to work anywhere in the world regardless of location or time of year. This system should have an easy setup and take down procedure requiring no more than two people to assemble and carry. Also, the umbrella system should be adaptable to stand on any kind of surface whether it be flat or uneven.

The main deliverables for this project are a small-scale prototype of the umbrella system, a full-scale design of the umbrella system with two-dimensional drawings and CAD models for each part of the umbrella system. The prototype is to be manufactured by the student team and it will be used for a proof-of-concept and demonstration purposes. The full-scale design is intended to serve as a foundation for Atom-Jet to build upon with their design experience to develop into a product that expands their business into new markets. The two-dimensional drawings will be used for manufacturing and assembling both the prototype and the full-scale designs of the umbrella system. The prototype and commercial designs for the umbrella system should include a detailed analysis and supporting calculations to justify the specific design choices made by the team. The next section of the report describes the design requirements for the project based on the client's needs. The scope of the umbrella system is for use as a patio umbrella in either a commercial setting such as a restaurant patio or in a personal setting such as on a deck. The specific approach taken to determine the scope of the project is discussed in the methodology section of the report.

1.3 Design Requirements

To determine the design requirements for the project, the team met with their Atom-Jet which resulted in a list of client needs. Due to the open-ended nature of the project, the team also determined additional needs which represent attributes and features that were deemed to be conducive in creating a better design that meet the needs of the client. From this list of needs, the team established the design requirements for the project; the main design requirements are shown in TABLE I. The remaining additional design requirements are in a separate table in Appendix [A].

TABLE I: DESIGN REQUIREMENTS

Design Requirement	**Description of Requirement**
Autonomous	▪ The umbrella system performs self-adjustments to follow the sun's movement across the sky ensuring optimal shade for all users.
Provides Shade	▪ The design needs to operate as a functioning umbrella by providing optimal shade for all users through proper canopy material selection as well as through its sun-tracking ability.
Simple Setup and Take Down	▪ Minimal physical effort requiring no more than two people. ▪ The setup process includes placing the umbrella system, opening it for use, and initial activation. ▪ The take down process includes a stop command then closing the canopy; also includes removing the umbrella system and minimal disassembly if being put into storage.
Safe to Operate	▪ The design should be incapable of injuring any users or damaging any property while in operation or non-operation. ▪ Note: This does not include self-inflicted injuries or damage to property caused by user interaction.
Simple to Operate	▪ Minimal user input required to control the umbrella system. ▪ The design should be able to operate without a complicated interface.
Adjustable Base	▪ The design should be able to adapt to stand on flat or uneven surfaces while in operation or non-operation.
Portable	▪ The umbrella system should be lightweight and not be difficult to transport.

In Section 2 of the report further expands the design requirements to be incorporated into the development of the umbrella's dimensions and features. In Sections 3 and 4, the details of the mechanical, electronic and software components of the design are described and explained as to how each component meets their respective design requirements for both the prototype and commercial designs.

1.4 Project Expectations

The team has established a list of overall expectations for the project. This list of expectations includes:

- Overall team satisfaction with the quality of the design and deliverables.
- Client's satisfaction with the quality of the design and deliverables.
- The total cost to manufacture the commercial design is reasonable.
- The design can be feasibility manufactured, reproduced and sold for a reasonable price in its respective market.
- The design is reliable and safe to use.
- Potential customers are also satisfied with the quality of the design.

Following the introduction section, the report continues with Section 2 which describes the methodology behind the umbrella's design. Section 3 presents the full in-depth analysis of the umbrella's mechanical components. Section 4 provides a detailed explanation of the system's electrical components and software design. Section 5 outline the instructions for a user to operate and assemble the design. Section 6 contains the bill of material (BOM). Section 7 contains the conclusion of the report and Section 8 details recommendations for the project. Following Section 8 is the references section of the report. After the references section, the report finishes with an appendix section which includes an appendix for the additional design requirements, the analytical calculations and results, the technical drawings for each of the components and the software code.

2. Methodology

This section of the report details the development of the methodological processes that were used to establish the baseline concepts of the design. Due to the project's wide scope, the team devoted the nascent stages of the design process to determining the specific setting for the design. From these efforts, the team managed to narrow the scope which allowed for basic design details such as sizing and functionality to be defined. These initial parameters serve as the foundation upon which the detailed design was created. Section 2.1 details the working environment for the umbrella. Section 2.2 summarizes the details of the concept design. Section 2.3 outlines the analytical calculations that provide design guidelines. Section 2.4 introduces the specific features and design approaches developed for the system to meet the project's requirements.

2.1 Working Environment

There are many different styles and sizes of umbrellas that are best suited for specific environments. By determining the working environment of the umbrella, the team could visualize how large it should be and how many users could be seated underneath it and still receive an optimal amount of shade. A backyard/patio setting defines the umbrella as a social center piece which users can gather underneath to enjoy a meal or relax and take refuge from the sun. Backyard/Patio settings also commonly have multiple people seated at a table which dictates the size, functionality and structure of the umbrella. To fit in this setting, the umbrella was designed to be placed through the center of a table and have a large enough canopy to shade multiple users.

The umbrella should be tall enough and have the rotation of its motors limited such that it won't collide with any user seated underneath it or nearby. The umbrella should also be able to alert users when it is adjusting, thus maintaining their safety. These alerts should straddle a balance between being obvious enough to cut through the noise and commotion of a raucous dinner, yet subtle and soothing enough to not annoy someone relaxing. According to several patio umbrella sizing guides [2], [3], [4], a 10x10 [ft^2] umbrella area can accommodate about 4-6 people depending on seating arrangements. This size is common in both a personal backyard as well as in restaurants patio settings.

2.2 Summary of Design Concept

During the concept development phase of the project, potential design concepts were generated and weighed against each other to establish the umbrella's initial design. The culmination of the concept development phase was the concept definition report (CDR), from which the resulting preliminary design concept was generated as displayed in Figure 1.

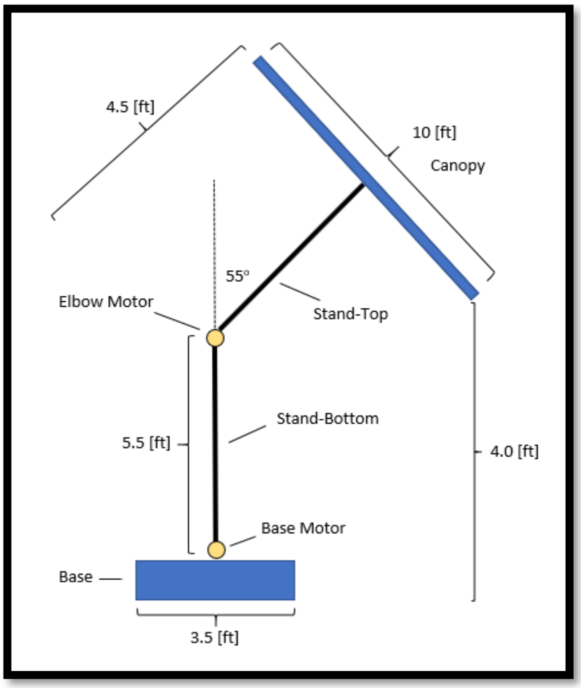


Figure 1: Preliminary Umbrella Design Concept

The preliminary umbrella design features four basic structural components and two motors. The base is the foundation of the umbrella that provides the entire system with its stability. A flat-bottom square design was chosen due to its simplicity and ease of manufacturing. Housed within the base is the base motor which is used to rotate the entire umbrella. Connected to the base motor is the stand-bottom which is a fixed rigid hollow tube. Mounted to the stand-bottom is the elbow motor which allows the umbrella to angle about its midpoint to and follow the movement of the sun. The stand-top is a hollow tube that extends outwards and is connected to the umbrella's canopy which provides shade to the user.

The general dimensions of the umbrella were determined by deciding on a maximum allowed angle of rotation for the elbow motor and the desired distance between the floor and the lowest extending portion of the canopy. An angle of 55° from the positive vertical axis was chosen along with having 4 [ft] of space underneath the umbrella. These measurements dictated the size of the stand-bottom and stand-top to be 5.5 [ft] and 4.5 [ft] respectively. The angle of rotation was decided to be only 55° as increasing this value any further would only add extra usage when the sun is low in the sky such as sunrise and set. However, this slightly extended range at non-essential hours of the day does not outweigh the added stress and moments that extending the canopy out any further would incur on the umbrella. Additionally, in order to always maintain at least 4 [ft] of usable space underneath the umbrella, increasing the elbow motor's angle of rotation any further would also increase the lengths of both stand components making the umbrella too large which negatively impacting its ease of use.

2.3 Analytical Analysis

The analytical analysis section details the methods used to determine the initial dimensions, physical and mechanical properties of each component in the design. Calculations were performed to determine the weight of the base which controls the stability of the design, to determine the thickness of the stand and to determine the deflection of the canopy. Section 2.3.1 details the starting dimensions for analytical analysis. Section 2.3.2 derives the forces and moments imparted on the system as related to the base design. Section 2.3.3 entails the full analysis to determine the required weight of the base. Section 2.3.4 explains the considerations required to determine the dimensions of the stand. Section 2.3.5 provides the analytical framework to determine the deflection of the umbrella's canopy.

2.3.1 Umbrella Dimensions

Starting with the previously determined 10x10 [ft^2] umbrella size and with the umbrella connected to the center stand in a backyard/patio with a table, the team could begin analysis on other important dimensions of the umbrella. Figure 2 shows the reference values for the analysis.

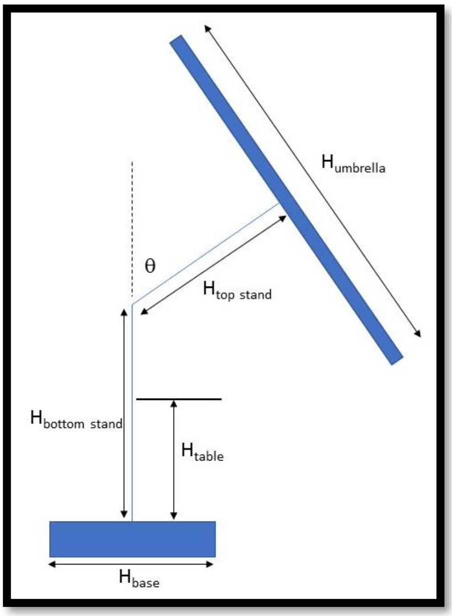


Figure 2: Overall Umbrella Reference Dimensions

TABLE II summarizes the starting dimensional values from Figure 2.

TABLE II: DETERMINED UMBRELLA DIMENSIONS AND VALUES

Umbrella Dimensions	Abbreviation	Size (feet)	Size (m)
Umbrella	$H_{umbrella}$	10.0	3.0
Top Stand	$H_{top\ stand}$	4.5	1.4
Bottom Stand	$H_{bottom\ stand}$	5.5	1.7
Base Width	H_{base}	3.5	1.0
Table Height	H_{table}	2.5	0.8

2.3.2 Force and Moment Analysis

This analysis begins by observing the top portion of the umbrella as a mass at some distance away from the elbow motor joint between the upper and lower stand portions. This mass creates a moment at the joint which counteracts the restoring moment generated by the mass and length of the base called the top moment (M_{top}). Since the mass of the stand-top is a function of angle θ and affects the horizontal vector of the top moment, the mass of the stand-top can be ignored as it will alter the center of gravity only slightly, resulting in much simpler calculations. Figure 3 shows this relationship using a free body diagram.

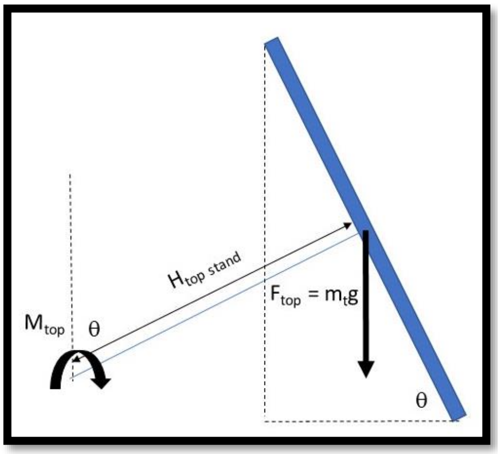


Figure 3: Umbrella Top Portion Reference Geometry

By taking a cut of the joint and analyzing the problem separately, the following formula for the top moment is determined.

Equation 1

$$M_{top} = F_{top}H_{top\ stand}\sin\theta = m_t g H_{top\ stand} * \sin\theta$$

Wind loading on the umbrella is another factor to consider which creates a negative moment about the umbrella. A distributed wind load (M_{wind}) can be approximated as a point load related to the vertical component of the height of the stand-top and angle θ on the umbrella canopy. This creates an additional moment about the stand connection point and contributes to lowering the stability of the umbrella. Figure 4 shows this relationship using a free body diagram.

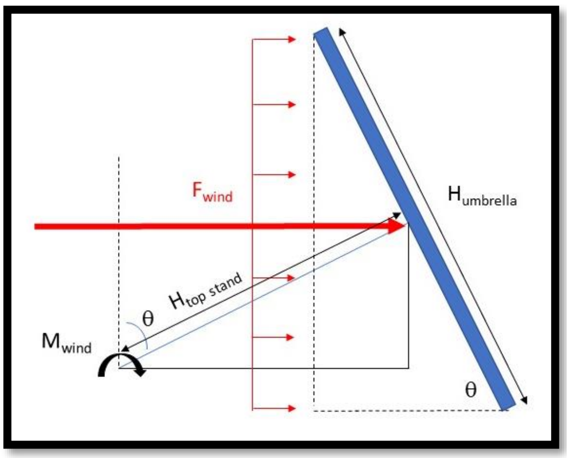


Figure 4: Umbrella Top Reference Geometry with Wind Load

The wetted area at the umbrella tilted angle θ can now be calculated using this geometry.

Equation 2

$$A_{wetted} = H_{umbrella} * sin\theta * H_{umbrella}$$

The force of the wind on this wetted area can be found as follows.

Equation 3

$$F_{wind} = A_{wetted} * \rho_{air} V_{wind,avg}^2$$

The moment created by the wind on the umbrella when open and tilted at some angle θ is calculated as follows.

Equation 4

$$M_{wind} = h * F_{wind} = H_{top\ stand} * cos\theta * F_{wind}$$

The moment generated from the wind load as the umbrella's stand pushes against the table must also be considered. This table force is equal to the force generated from the wind, however, it is located where the stand-bottom makes contact with the table. It is assumed that the table is perfectly rigid and strong enough to withstand the additional force. Since this force is not located at the same location as the wind force, a counter-moment is created as the wind blows against the umbrella. The higher the wind load, the higher the wind force and restoring wind force. The resulting table moment (M_{table}) is calculated as follows.

Equation 5

$$M_{table} = R_{table} H_{table} = F_{wind} H_{table}$$

The restoring moment generated from the base of the umbrella as it resists tipping due to the negative wind and umbrella top (canopy) moments can also be found by using the Figure 5. The restoring moment is calculated as follows.

Equation 6

$$M_{base} = R_{base} \frac{H_{base}}{2} = g m_{base} \frac{H_{base}}{2}$$

With the negative moments generated due to mass of the umbrella top canopy and wind determined, and the positive moment from the restoring wind force also determined, a final analysis of the stand-bottom and base is performed to find the size and mass required of the base to prevent any tipping of the umbrella under specified conditions. Figure 5 shows the reference geometry.

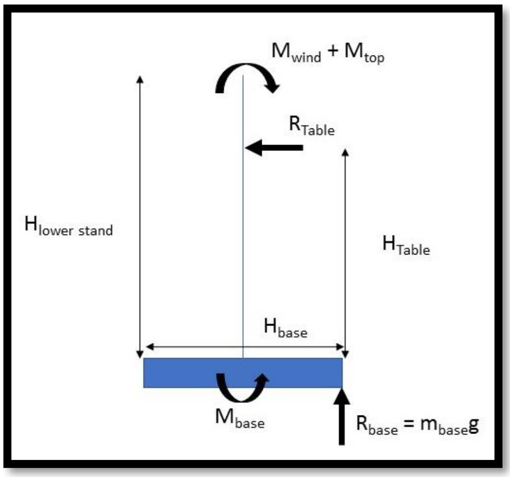


Figure 5: Reference Geometry for Umbrella Base and Lower Stand

Taking the sum of the moments about the lower stand and base, the following equation is derived.

Equation 7

$$\sum M = 0$$

$$M_{top} + M_{wind} = M_{base} + M_{table}$$

Equation 8

$$\left(m_{top} g H_{top\ stand} * \sin\theta\right) + \left(F_{wind} H_{top\ stand} * cos\theta\right) = \left(m_{base} g \frac{H_{base}}{2}\right) + F_{wind} H_{Table}$$

Rearranging the equation equal to the mass of the base, the required mass of the base can be determined after making assumptions on the starting size and mass of the top portion of the umbrella.

Equation 9

$$m_{base} = \frac{2\left[\left(m_{top} g H_{top\ stand} \sin\theta\right) + \left(F_{wind} H_{top\ stand} * cos\theta\right) - F_{wind} H_{table}\right]}{g H_{base}}$$

2.3.3 Full Scale Umbrella Analysis

With equations derived for each of the external forces acting on the umbrella, and general sizes and dimensions determined, the analysis to determine the weight and dimensions of the base can proceed. The main variables are the mass of the top umbrella canopy, mass of the base, and length of the base. According to the previously derived relationship in Equation 6 at a certain mass of the umbrella, the restoring moment of the complete umbrella can be adjusted by varying the base mass and length. Basically, the heavier the base the less length is required or the lighter the base the more length is required to counter act moments created by wind and the mass of the umbrella.

The previously determined Equation 9 is the sum of all the positive and negative moments acting on the umbrella design. As outlined in detail below, these moments are varied as the angle and wind speed act on the umbrella and generally converge to an ideal value for mass and length of the umbrella base.

2.3.3.1 Constant Wind Speed, Variable Angle

Taking the average wind speed for Winnipeg, Manitoba as 17 [km/h] [5], the moment from wind acting on the umbrella canopy can be calculated using Equation 4. As the wetted area increases force due to wind also increases, however, the moment generated increases to a point and then falls as the force acting on the umbrella decreases lower to the ground. This maximum angle is located at 55°, which again serves as the maximum operating angle of the umbrella. As a result of the angle θ increasing, the negative top moment increases at a similar rate as the positive wind moment since the horizontal vector due to the umbrella canopy rotating is related to the vertical vector of the wind force. The negative wind and top moments, and the positive table moment, are shown in Figure 6 with the wind speed kept constant for average Winnipeg wind as the angle θ is increased from the umbrella canopy rotating.

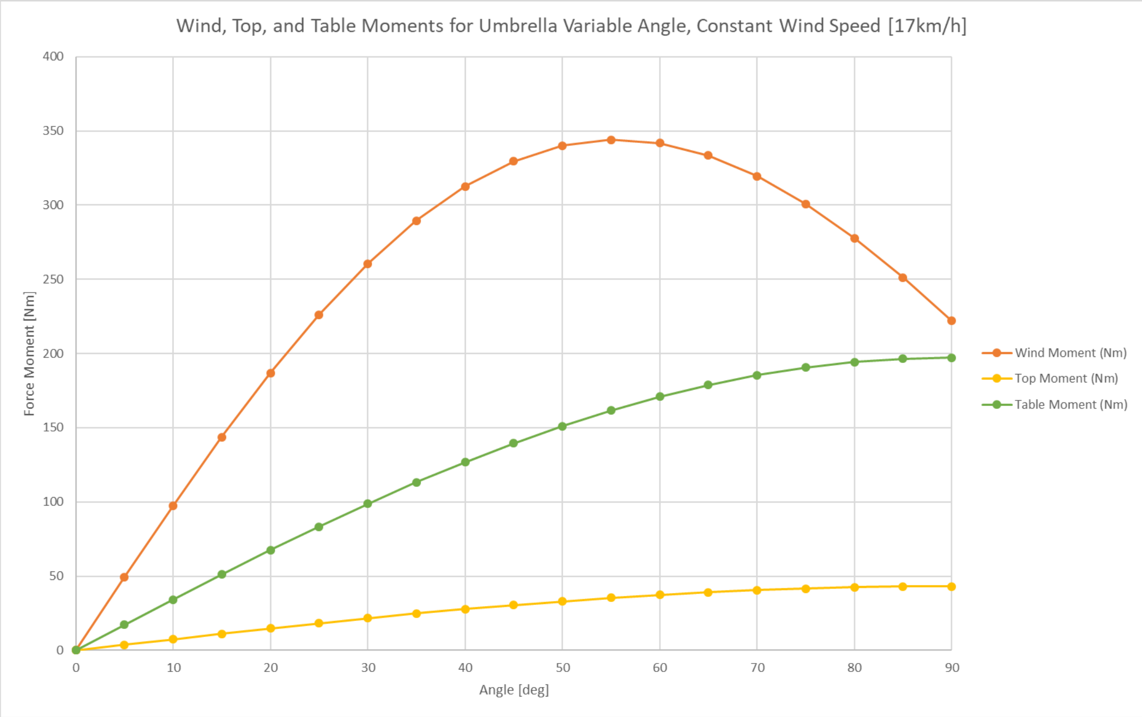


Figure 6: Moments for Umbrella with Variable Angle and Constant Wind Speed

The positive restoring moment from the base of the umbrella is a function of the mass and length. The mass and length are inversely proportional to each other. With the length of the base kept at a constant 1.0 [m] (or 3.5 [ft]), Figure 7 shows the relationship to the base mass as the angle θ is increased.

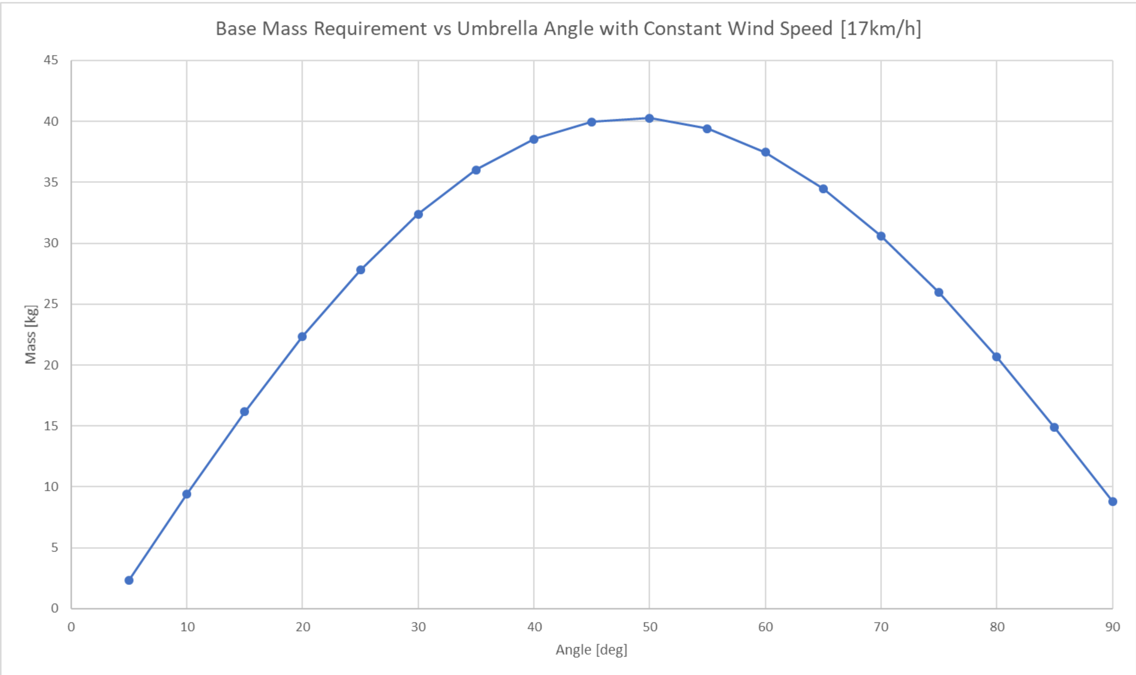


Figure 7: Base Mass Requirement for Constant Wind, Variable Angle

As expected, the base mass increases with a similar trend as the negative wind moment since the positive table moment and negative top moments essentially cancel each other out. The maximum required mass occurs at the same angle 55° as the maximum negative wind moment on the umbrella canopy. Figure 8 shows the base length requirements under similar conditions.

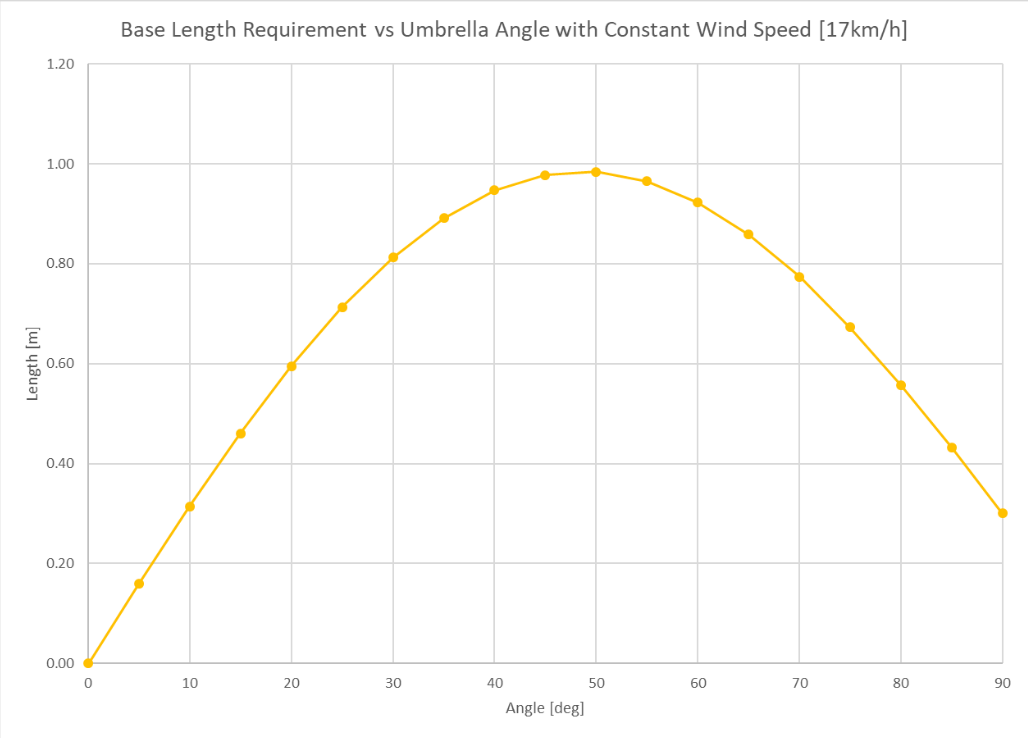


Figure 8: Base Length Requirement for Constant Wind, Variable Angle

With this consistent trend, further calculations are done using a constant angle with a variable wind speed in the next section.

2.3.3.2 Constant Angle, Variable Wind Speed

The second operating values of the umbrella involve the umbrella canopy at a fixed angle while varying the wind speed. An angle of 55° was chosen because it is the angle of maximum negative wind moment generated from the umbrella canopy as it rotates. Values for the negative top and wind moments are shown in Figure 9 along with the table moment

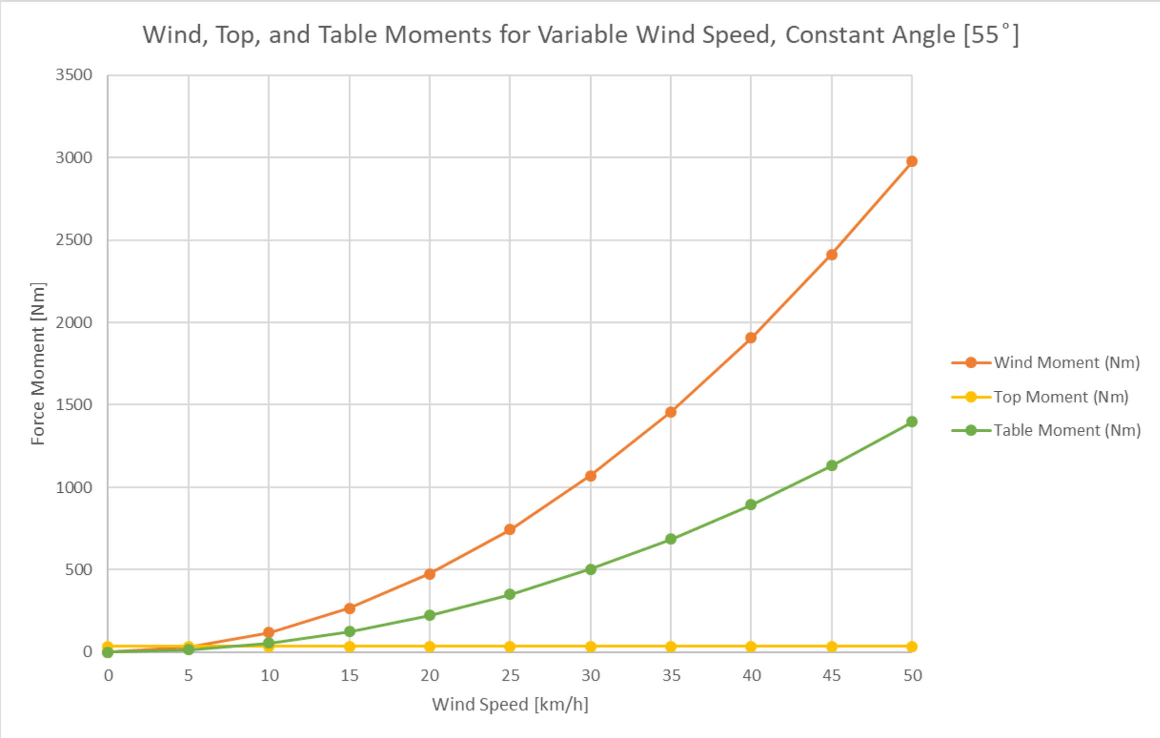


Figure 9: Wind, Top, and Table Moments for Variable Wind Speed, Constant Angle

A similar trend is observed as was seen in Section 2.3.3.1 due to the positive table moment being dependent on the force that the wind creates on the umbrella canopy. The negative top moment is constant since the umbrella canopy is not rotating and is not dependent on the force of the wind. While the length of the base is kept at a constant 1.0 [m] (or 3.5 [ft]), the Figure 10 shows the relationship of the base mass as the wind speed is increased.

Figure 10: Base Mass Requirements for Constant Angle, Variable Wind

The base mass increases with a similar trend as the negative wind moment since the required restoring force is dependent on the wind force. Figure 10 shows the unrealistic mass requirement for the base given a very high wind, such as 50 [km/h] with the umbrella canopy at an angle of 55°. It is for this reason the umbrella is recommended for use in average wind speeds only, and to be stored during intense winds. Figure 11 confirms the same trend when the mass of the base is kept at a constant 39 [kg] and the length requirement of the base is shown against the wind speed of the surrounding air.

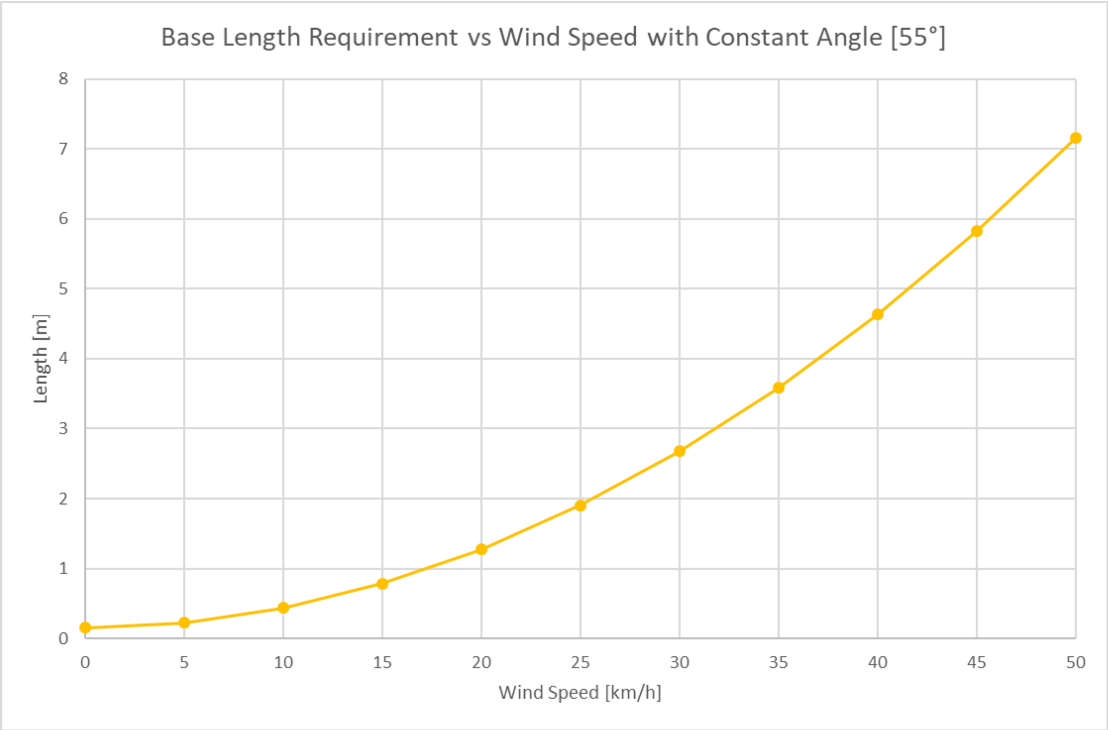


Figure 11: Base Length Requirements for Constant Angle, Variable Wind

2.3.3.3 Calculation of Free-Standing Umbrella (No Table Attached)

A potential feature of the design is the ability for the umbrella to freely stand without the aid of a table. Following the relationship outlined in Equation 9, the table moment is zero when the table is absent which means the mass and the length of the base need to change to counter the negative wind and top moments. Since the base is intended to be a fixed object, only adjustments to the mass will be considered. With the negative moments remaining, the fixed wind speeds, and variable umbrella canopy angle, Figure 12 shows the new mass requirements without the table attached.

Figure 12: Base Mass Requirement for Constant Wind, Variable Angle No Table

The mass requirement for the base jumps to over 70 [kg] when the positive table moment is removed, which is nearly double what the mass requirements are with the table attached. A similar increase in mass is observed for the umbrella under a constant angle of 55° and variable wind speed, as shown in Figure 13.

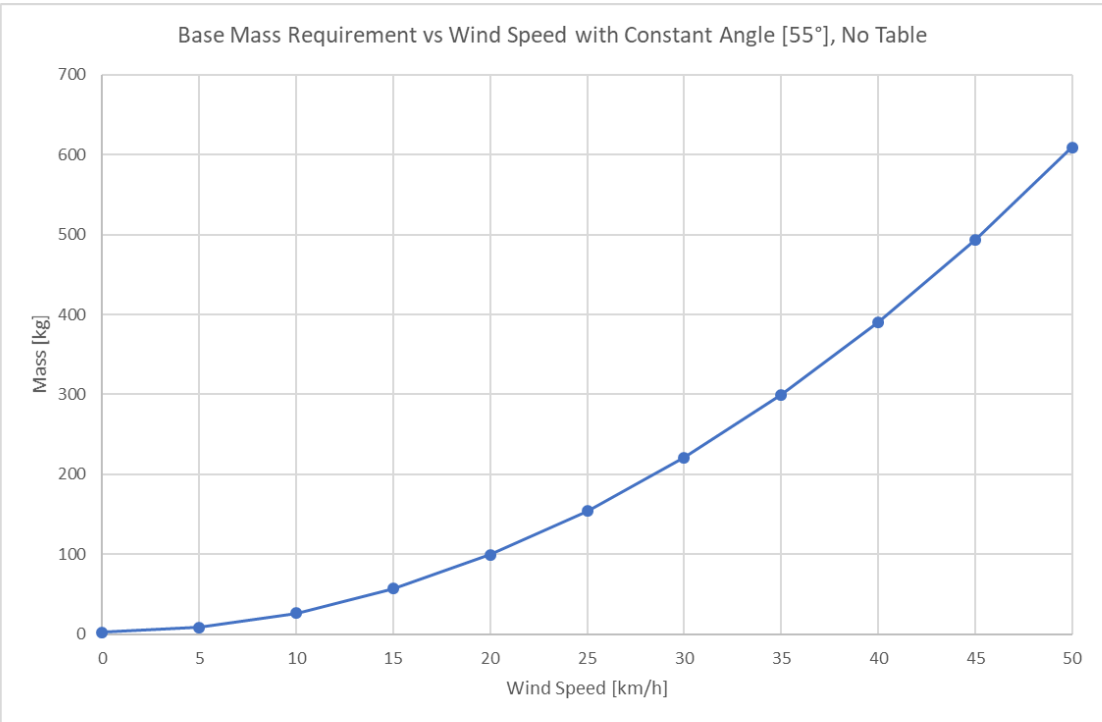


Figure 13: Base Mass Requirement for Constant Angle, Variable Wind

Due to the high mass requirements of the umbrella base without a table, design will only be considered for the umbrella assembly attached to a table. Treating the umbrella as a free-standing object can be accomplished by simply adding mass to the base to create the necessary stability required for average winds. The team recommends purchasing an umbrella base weight, of which many different varieties exist for the consumer and are easily located at common retail stores.

2.3.3.4 Final Base Dimensions

The mass and length of the base were selected both from mathematical analysis, and also by common reasoning. It is not feasible to have a base mass of 300 [kg] just to have the length at only 10 [cm], for example, and the team kept this idea in mind when selecting the parameters. The resulting base mass and length requirements are summarized in TABLE III.

TABLE III: FINAL BASE DESIGN SPECIFICATIONS

Base Condition	Length [m]	Length [feet]	Mass [kg]	Mass [lb]
Table Attached	1.0	3.5	39.0	86.0
No Table Attached	1.0	3.5	70.0	154.0

2.3.4 Stand Dimension Analysis

The dimensional analysis for determining the sizing of the umbrella's stand is performed at the maximum rotational angle of the elbow motor at 55°. The cross-sectional area of the stand is a hollow cylinder. The force analysis of the stand-top can be performed by simplifying the mass of the canopy to a single point load and considering the mass of the stand-top at its center. Figure 14 displays the simplified analytical approach.

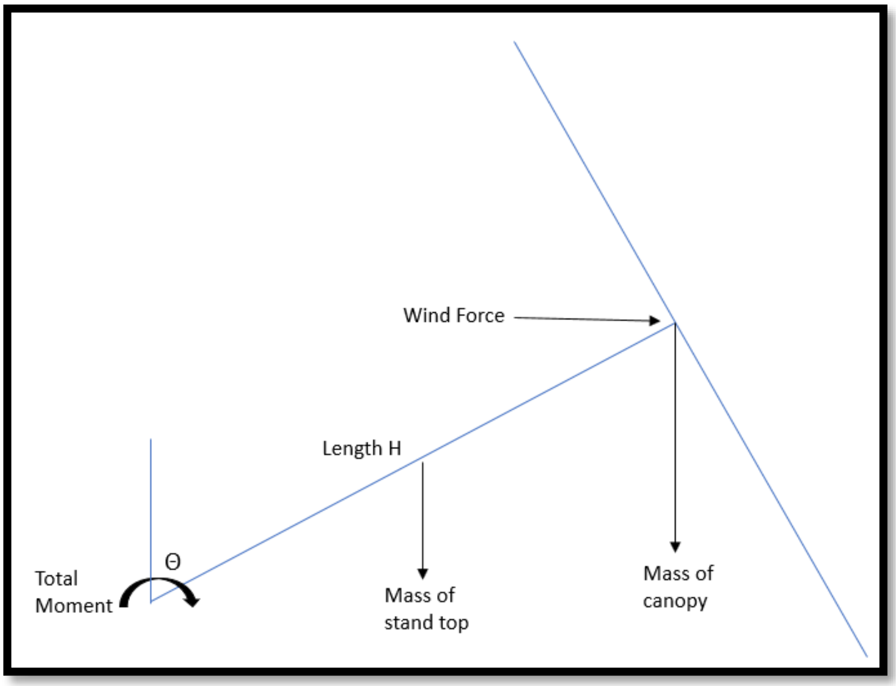


Figure 14. Force and Moment Analysis of Umbrella Stand.

According to the force analysis of the stand-top, the total moment about the elbow joint can be determined using Equation 10.

Equation 10

$$M_{total} = M_{canopy} + M_{stand-top} + M_{wind}$$

$$= \left(m_{canopy} g H * \sin\theta\right) + \left(m_{stand-top} g \frac{H}{2} * \sin\theta\right) + \left(F_{wind} H * cos\theta\right)$$

The moment of inertia of the stand-top is calculated using Equation 11.

Equation 11

$$I = \frac{\pi}{4}\left(R_{outer}^4 - R_{inner}^4\right)$$

After determining the moment of inertia, the tensile stress experienced by the stand-top can be calculated using Equation 12.

Equation 12

$$\sigma_{max} = \frac{M y_{max}}{I}$$

According to Equation 12, the maximum tensile stress acts on the edge of the outer diameter of the stand-top. This maximum value is used for the tensile stress analysis. The safety factor for the stand can be determined using Equation 13.

Equation 13

$$Safety\ factor = \frac{yield\ stress}{stress\ on\ top\ stand}$$

After the maximum tensile stress is calculated, the material of the umbrella's stand can be determined by comparing the yielding tensile strength of different materials. In addition, the dimensions of the stand are determined based on the sizes of hollow pipe readily available on the market. Based on the calculations provided in Appendix B.5, the chosen material and dimensions for the stand are Aluminum 6061 with outer and inner diameters of 2 [in] and 1.75 [in] respectively.

2.3.5 Deflection of the Umbrella Top

The canopy of the umbrella consists of four arms that are each supported by a joint that connects the arms to a sliding collar that moves vertically along the stand-top. The canopy fabric is attached to canopy along each of the four arms. These arms, in conjunction with the support joints, keep the canopy flat when fully deployed. The concern with these extended arms is that they are constantly supporting the weight of the canopy as well as their own weight when fully deployed. The resulting distributed load experienced by each arm causes them to deflect.

If the arms in the canopy were to deflect significantly, the light-detecting sensors may not be able to accurate detect the position of the sun which causes the whole system to fail. Therefore, deflection of the arms should be minimized to keep them relatively flat when fully extended. For the prototype design, the team is not concerned with the extended arms deflecting as the load experienced by canopy is negligible due to the low material density and volume of the parts used in the prototype. To determine the deflection of the extended arms in the commercial design, the team treated each arm as a prismatic beam in bending [6]. The team then derived a second-order linear differential equation that describes the shape of the deflection. Through symmetry, the deflection of each arm would be the same. Applying St. Venant's principle, the equation for the elastic curve of an extended arm is as follows:

Equation 14

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI}$$

The term $M(x)$ is the moment, as a function of distance(x), experienced over the length of the extended arm; measured in [Nm]. The term EI is the flexural rigidity of the beam and it varies along the beam. The term E is the Modulus of Elasticity for the chosen extended arm material; measured in [Pa]. The team has chosen Aluminum 6061 T4 as it is lightweight, has good strength properties, and is a ductile material. The modulus of elasticity of Aluminum 6061 T4 is 6.9 x 10^{10} Pa [7]. The term I is the moment of inertia of the chosen cross-section of the extended arm; measured in [m^4]. To reduce weight, the team chose a cylindrical hollow cross-section for the extended arm.

Multiplying both sides of Equation 14 and taking the integral of both sides of the equation produces the following expression:

Equation 15

$$EI\frac{dy}{dx} = \int_0^x M(x) + C_1$$

This expression can be used to describe the slope of the deflection. Taking the integral of both sides of Equation 15 produces the following expression:

Equation 16

$$EIy = \int_0^x \left(\int_0^x M(x) + C_1 \right) dx + C_2$$

Rearranging Equation 16 to solve for the deflection of the curve (y):

Equation 17

$$y(x) = \frac{1}{EI}\left[\int_0^x \left(\int_0^x M(x) + C_1 \right) dx + C_2 \right]$$

To solve for the constants C_1 and C_2, boundary conditions were chosen at the locations along the arm where the deflection is zero. The free body diagram simulating the extended arm is shown in Figure 15:

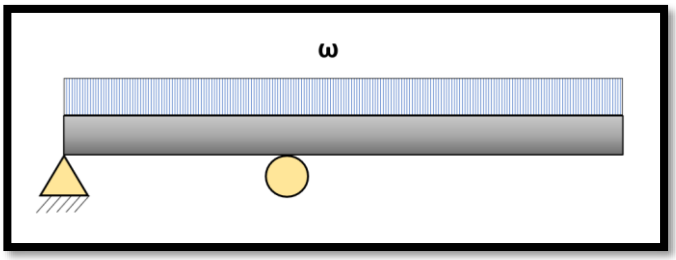


Figure 15: The Free Body Diagram of Umbrella Top.

A pin support simulates the connection between the extended are and the top of the umbrella and a roller support simulates the connection between the extended arm and the support arm. Along the length of the extended arm is a distributed load due to the force of gravity and the weight of the canopy fabric. When fully-deployed, the team assumes that each arm supports roughly a quarter of the total weight of the fabric when neglecting the weight of the fabric supported at the center of the canopy by the stand-top. The arms are placed along the diagonals of the 10x10 [ft^2] canopy area each having a length of half of the total diagonal length.

Using Pythagoras' theorem, the corresponding length of each arm (*c*) is calculated as follows:

Equation 18

$$c = \frac{\sqrt{a^2 + b^2}}{2} = \frac{\sqrt{10\ [ft]^{\ 2} + 10\ [ft]^2}}{2} = 7.071\ [ft] = 2.155\ [m]$$

This length includes the mounting component which is not included in the deflection analysis. After removing this additional length, the total length of each arm is 2.138 [m] which accounts for the distance from the center of the pin support to the end of the extended arm. The derivation of the equation of the deflection curve is shown in Appendix B.6. The resulting equation for the deflection is shown as follows:

Equation 19

$$y(x) = \frac{1}{EI}\left[-\frac{\omega x^4}{24} + \frac{1.8075\omega(x-0.7)^3}{6} - 0.011751\omega x + 0.22606\omega\right]$$

For the prototype umbrella design, the extended arm has a rectangular cross-section and initially the commercial design had a rectangular cross-section with a 0.002 [m] thickness (b) and a width of 0.020 (a) [m]. The corresponding moment of inertia for a rectangular cross-section was calculated as:

Equation 20

$$I = \frac{1}{12}(a)(b)^3$$

$$I = \frac{1}{12}(0.02\ m)(0.002\ m)^3 = 1.3333\ x\ 10^{-11}\ [m^4]$$

The distributed gravity load along the extended arm is a function of its mass and length. This relationship is shown in the following equation:

Equation 21

$$\omega = \frac{mg}{L}$$

Using a CAD model with the chosen material, the mass of the extended arm was determined to be 0.506 [kg]. The total mass in this model includes the housings for both connections along the extended arm. For the commercial design, the chosen canopy fabric material was a 100% polyester taffeta fabric with a density of 56 [g/m^2] [8]. The area of the canopy is 100 [ft^2] or 9 [m^2] which corresponds to a total fabric mass of 0.504 [g]. The distributed load applied to each arm by the fabric when fully deployed is 126 [g]. The total distributed load applied to each arm when fully deployed was then calculated as follows:

$$\omega = \frac{(0.24857\ kg + 0.126\ kg)(9.81\,\frac{m}{s^2})}{(2.138\ m)} = 1.7187\ [N/m]$$

With all missing parameters now known, the corresponding deflection function is plotted, in increments of 0.01 [m], in Figure 16:

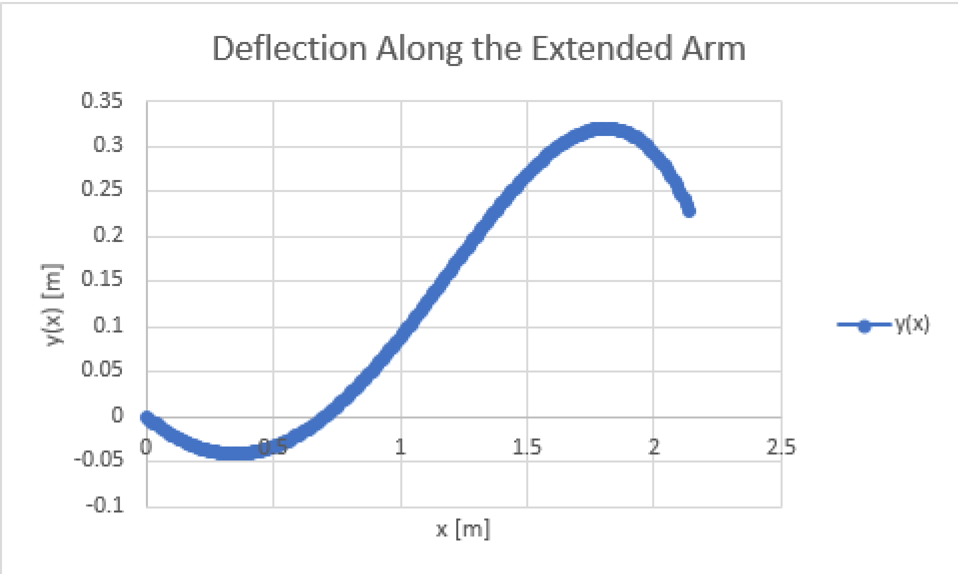


Figure 16: The Deflection along the Extended Arm.

With the rectangular cross-section and chosen dimensions, the deflection is too extreme for the sensors to function properly. Therefore, the team decided to change the cross-section to a hollow cylindrical cross-section and chose appropriate dimensions to minimize the deflection. The new cross-section has an outer diameter of 0.01905 [m] with an inner diameter of 0.015748 [m]. These dimensions were used as they correspond to available hollow aluminum tubes. The corresponding moment of inertia is calculated as follows:

Equation 22

$$I = \frac{\pi}{64}((d_{outer})^4 - (d_{inner})^4)$$

$$I = \frac{\pi}{64}((0.01905\ m)^4 - (0.015748\ m)^4) = 3.44566\ x\ 10^{-9}\ [m^4]$$

The new value of the distributed load is calculated as follows:

$$\omega = \frac{(0.506\ kg + 0.126\ kg)(9.81\frac{m}{s^2})}{(2.138\ m)} = 2.8999\ [N/m]$$

The plot of the new equation for deflection along the arm, in increments of 0.01 [m], is shown in Figure 17:

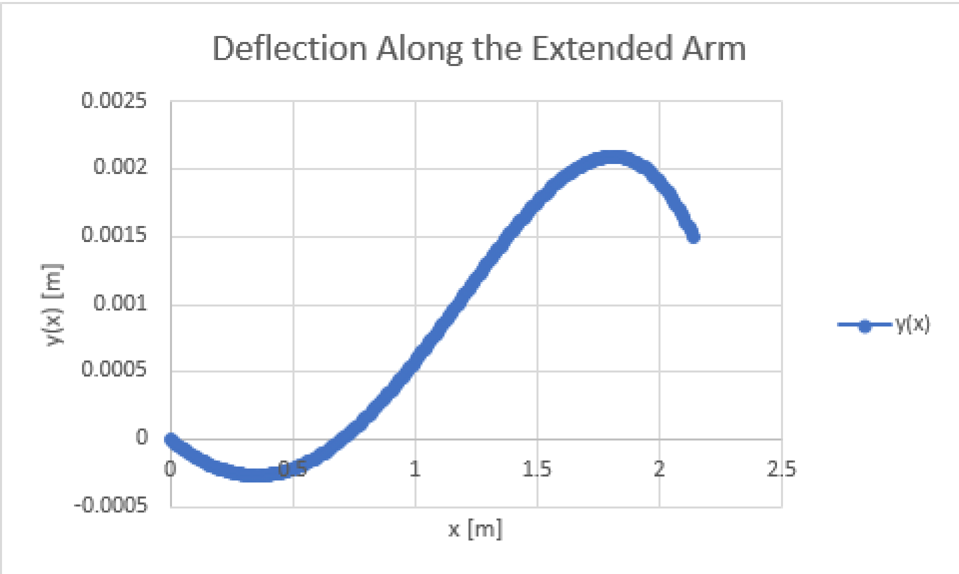


Figure 17: The Deflection along the Extended Arm.

From Figure 17, the maximum deflection is in the extended arm is roughly 0.0021 [m] occurring at approximately 1.8 [m] from the pin support. Using the hollow cylindrical cross-section has reduced the deflection along the extended arm.

2.4 Design Features

In order to satisfy the design requirements listed in Section 1.3, the umbrella's design must incorporate several important features. The design features created to address these requirements were first established during the concept development phase of the project and the methods used to develop these features were documented in the Concept Development Report.

To achieve a simple setup/takedown and overall ease of use, the umbrella was designed to be quick to assemble and requires a minimum amount of user input to operate and control the system. The portability of the umbrella was accomplished by using lightweight materials and designing the umbrella to efficiently collapse with minimal effort required. To accommodate a variety of surfaces the base is designed with adjustable feet. To maintain safety while in use, the umbrella uses a combination of visual and audio cues to alert the user of when it is moving and what it is currently doing. Each of these features are completely described in Section 3 for the mechanical features and Section 4 for the electrical and software features. The descriptions for the features include the information as to how they work, the justifications for the specific design choices and how they specifically meet the design requirements.

3. Mechanical Design

Within this section of the report, the entirety of the umbrella's mechanical design is described. The mechanical design is broken into three main sub-systems, which are base, stand, and canopy. Section 3.1 briefly introduces the complete assemblies of both prototype and commercial versions of the umbrella. Section 3.2 provides full details of the design of the prototype. Section 3.3 expands on the design on the commercial version and highlights key changes from the prototype design.

3.1 Full Assembly

Within this section, the full assemblies for both the prototype and commercial design are shown to provide context to the in-depth component descriptions provided in the following sub-sections. Figure 18 displays the complete assembly of the prototype umbrella in an open position.

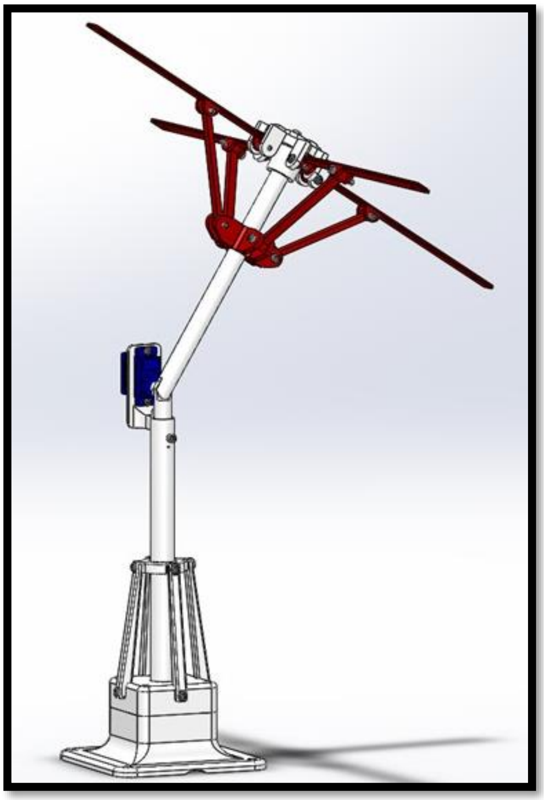


Figure 18:. Prototype Full Assembly Open

Figure 19 shows a model of the complete prototype assembly in a closed position.

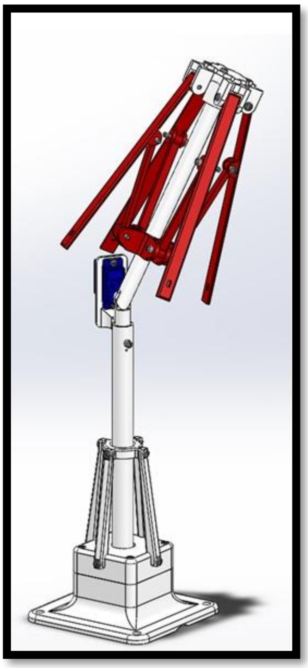


Figure 19: Prototype Full Assembly Closed

Figure 20 displays a render of the full assembly of the final design for the full-scale commercial umbrella from behind.

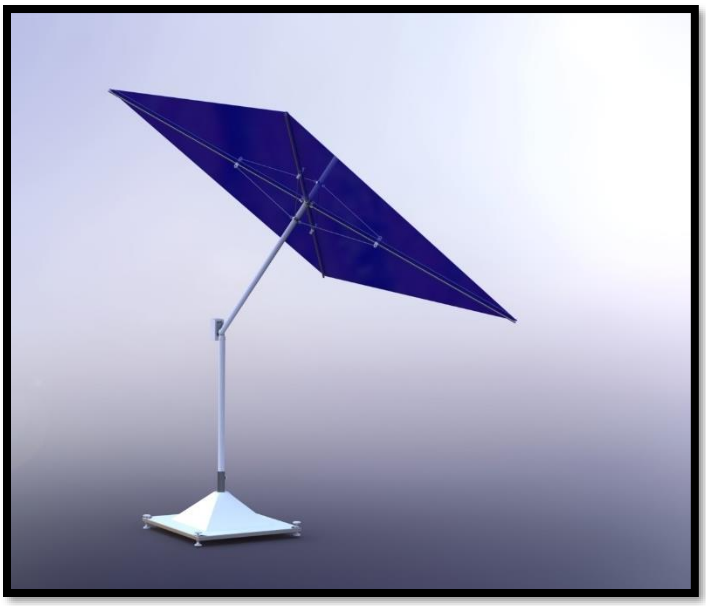


Figure 20: Commercial Umbrella Full Assembly Back View

Figure 21 depicts the full assembly for the final design of the full-scale commercial umbrella from the front.

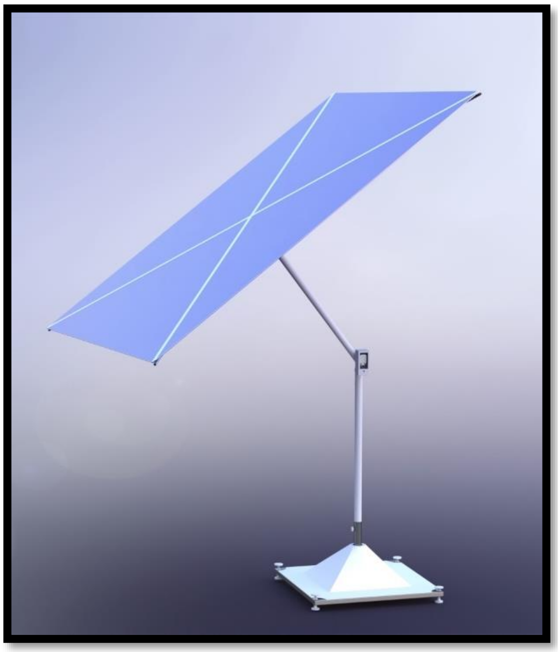


Figure 21: Commercial Umbrella Full Assembly Front View

3.2 Prototype Sub-Assemblies

The prototype umbrella design is separated into three main sub-assemblies; these being the canopy at the top of the umbrella, the stand which is the middle portion of the umbrella, and the base at the bottom of the umbrella. An in-depth analysis of each of the prototype sub-assemblies is provided in Section 3.2.1 for the canopy, Section 3.2.2 for the stand and Section 3.2.3 for the base. Section 3.3 contains the in-depth analysis for the commercial design.

3.2.1 3D Printer Specifications

The Creality Ender 3 is the chosen 3D printer to print the components of the umbrella prototype assembly. It operates with a 1.75 [mm] feed spool, complete with a heated base and a fixed brass extruder [9]. Since the prototype is meant only to serve as a proof of concept, PLA plastic was used as it is a cheap and sufficient material choice. TABLE IV outlines material properties for PLA.

TABLE IV: PLA PLASTIC MATERIAL PROPERTIES [10]

Prototype Material	Density g/cm^3	Cost per 100 [g]
PLA Plastic	1.2	$2.80

Assembly of the printed parts involved the following machine screws, all with similar 11/32” Allen style hex heads, listed in TABLE V.

TABLE V: MACHINE SCREW PROPERTIES

Machine Screw	Thread Type	Material
1/4" Hex Head	4-40	Stainless Steel
9/16" Hex Head	4-40	Stainless Steel
1 1/4" Hex Head	4-40	Stainless Steel

3.2.2 Canopy Sub-Assembly

The canopy sub-assembly contains the components that make up the top portion of the umbrella. The canopy sub-assembly is composed of a central umbrella fixture, a compression plate for securing the canopy fabric to the canopy, four frame arms that hold the canopy fabric and the light-detecting sensors, and four support arms that connect the frame arms to a sliding support fixture. The support fixture slides vertically along the stand-top to open and close the canopy. The prototype canopy was designed with the consideration of 3D printing all components out of PLA. Additionally, the assembly contains twelve socket-head screws and locknuts for securing the sub-assembly. Figure 22 depicts the canopy sub-assembly in the opened position.

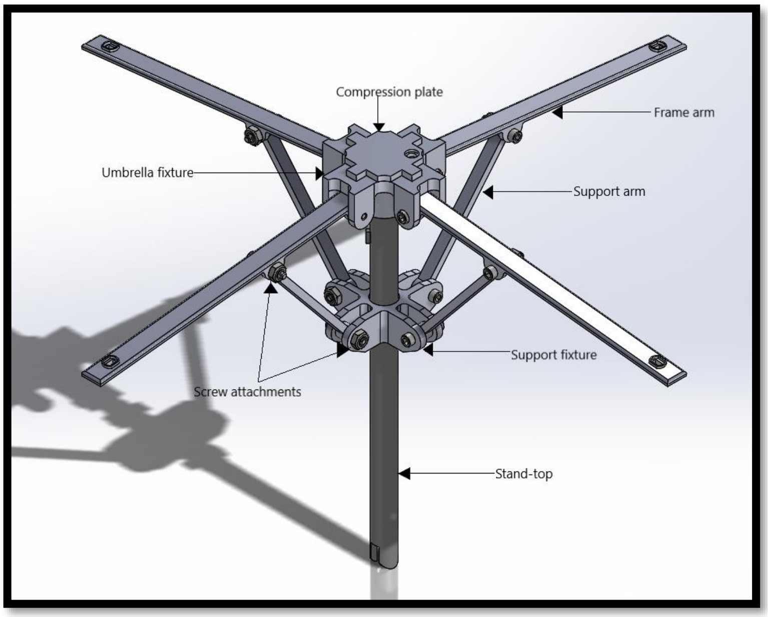


Figure 22: Canopy Sub-Assembly Open Position

Figure 23 depicts the canopy with the support fixture pulled to its bottom most position, closing the umbrella.

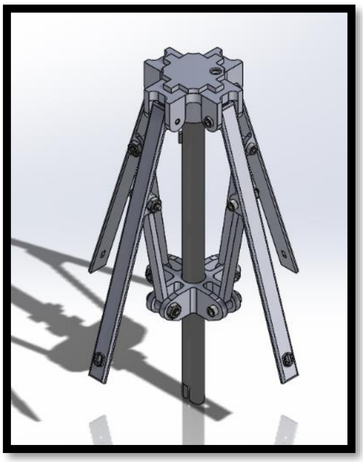


Figure 23: Canopy Sub-Assembly Closed Position

3.2.2.1 Umbrella Fixture

The umbrella fixture is the central core component of the canopy. It is a symmetrical cross-shaped component with four hinge joints at each end of the cross where the frame arms are connected. The edges of the component are filleted to reduce weight. Additionally, four square holes are located on the top face for the insertion of the compression plate as well as a small hole to locate a screw to secure both components. Figure 24 displays a top view of the umbrella fixture.

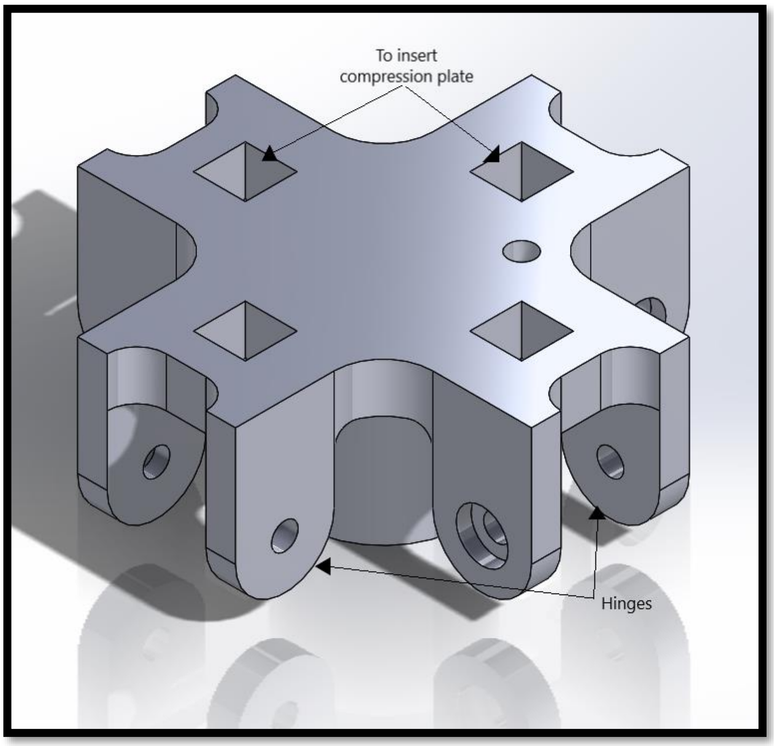


Figure 24: Umbrella Fixture Top View

The underside of the umbrella fixture features a cylindrical extruded section to connect the canopy to the stand-top. A rectangular keyway is cut into the collar to locate and prevent rotation between the canopy and stand-top. The stand-top is press fit into the collar. Figure 25 displays the umbrella fixture from its underside.

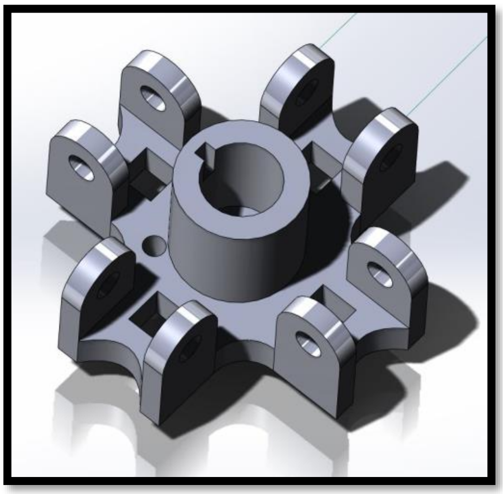


Figure 25: Umbrella Fixture Bottom View

3.2.2.2 Compression Plate

The compression plate is the upper most component of the canopy sub-assembly. It is a cross-shaped component with four protruding legs that press fit into the similarly shaped holes on the umbrella fixture. The canopy's fabric is sandwiched in between both the compression plate and umbrella fixture and is secured in place by tightening a screw through the counterbore hole. Figure 26 shows the compression plate from a top view.

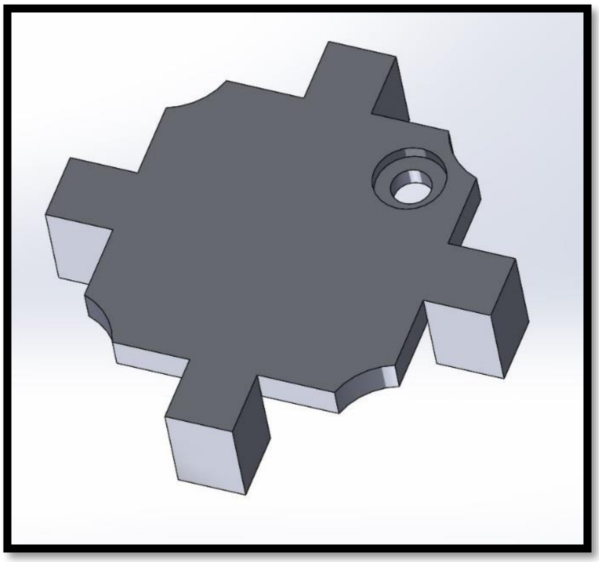


Figure 26: Compression Plate's Top View

Figure 27 shows the underside of the compression plate.

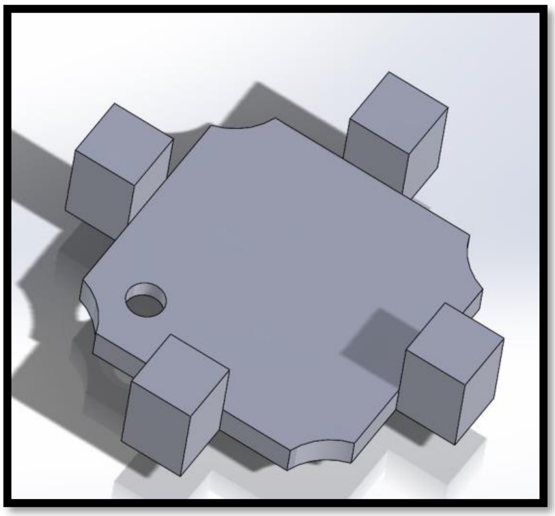


Figure 27: Compression Plate's Bottom View

3.2.2.3 Frame Arm

The frame arms are flat rectangular beams that extend out from the umbrella fixture. The frame arms have two hinge joints, one for connection to the umbrella fixture, and the other located at a third of its length to connect the support arms. At the end of the frame arm is a small extruded feature for the placement of the system's photoresistors. Rectangular holes are cut through the arm beneath the sensors to allow space for the legs of the photoresistors. Figure 28 displays the model of a frame arm.

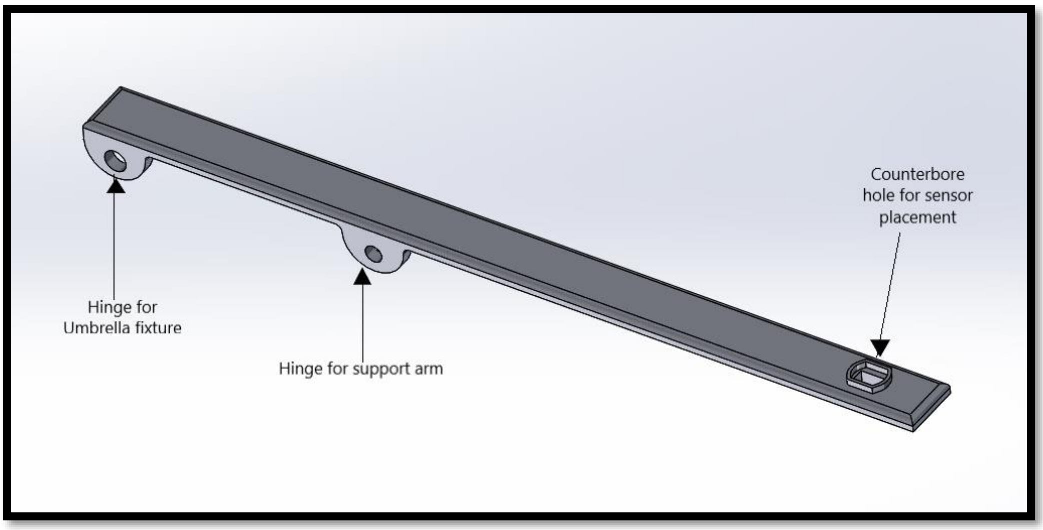


Figure 28: Frame Arm's Top View

3.2.2.4 Support Arm

The support arms are dog bone shaped linkages with holes slightly larger than those of the connecting parts so that the threads of the screws can cut into the outer portions of the connecting hinge joints while allowing the support arms to rotate freely. The support arms are connected to the mid-span hinge joint of the frame arms at one end, and to the support fixture at the other end. Figure 29 displays a render of the support arm.

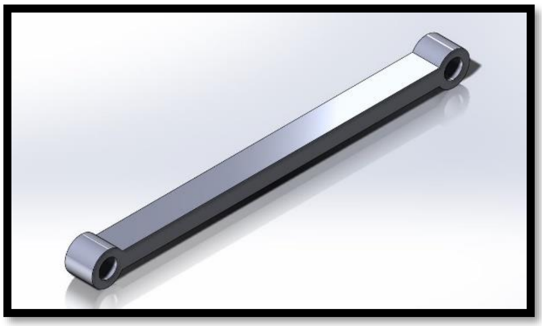


Figure 29: Support Arm

3.2.2.5 Support Fixture

The support fixture is a sliding adjustable collar that controls the opening and closing mechanism of the canopy. The support fixture is manually pulled along the length of the stand-top either extending the umbrella's arms if pull upward or collapsing them if pulled downward. A screw pin is inserted into the support fixture to secure it in place at its top position. Figure 30 displays a render of the support fixture.

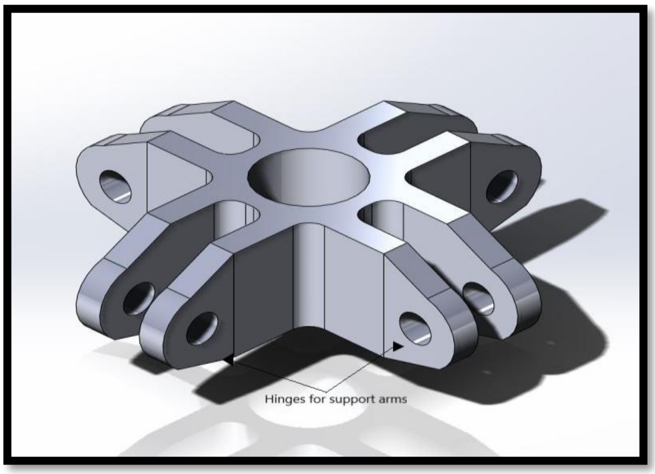


Figure 30: Support Fixture

3.2.3 Stand Sub-Assembly

The stand sub-assembly is the collection of components that make up the middle section of the umbrella. Comprised of two straight hollow tubes and mounting fixtures, the stand connects the umbrella's base and canopy. Four components make up the stand sub-assembly, the stand-bottom, motor-support, stand-middle and stand-top. Figure 31 displays a cross-sectional view of the stand assembly.

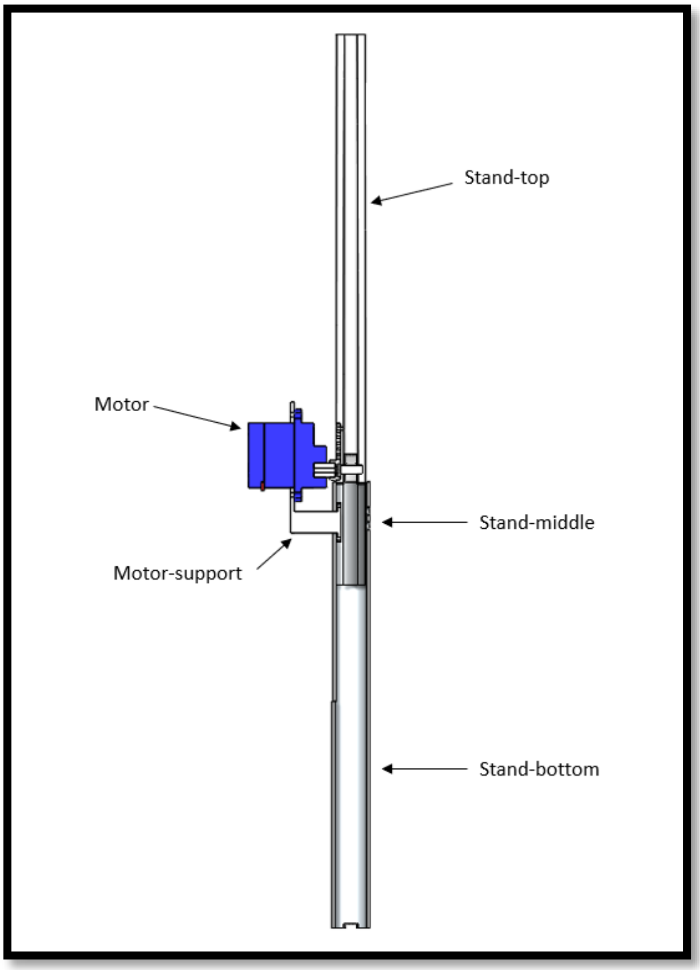


Figure 31: Cross-sectional View of Stand Sub-Assembly.

3.2.3.1 Stand-Top

The stand-top is the uppermost portion of the sub-assembly. It is a hollow extruded tube that at its lower section is attached to and receives rotational torque from the elbow motor. The stand-top is attached to the elbow motor via a flat slot that is cut into the side of the component with the profile of a servo motor horn. Two screws are threaded through the horn into the stand-top; one at the tip of the horn and the other through the center of the horn. The screw through the center of the horn allows the stand-top and stand-middle to act as a hinge joint. The top section of the stand-top features a small extruded key that is used to locate and prevent rotation between the stand-top and canopy sub-assembly. Figure 32 displays a cross-sectional view of the stand-top.

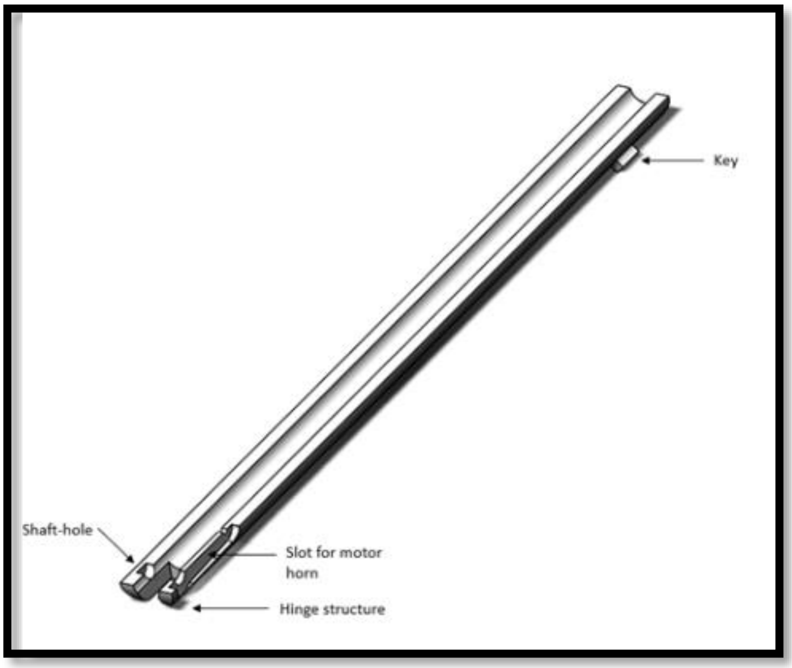


Figure 32: Cross-sectional View of Stand-top.

Figure 33 displays a close up render of the notch at the bottom of the stand-top where the servo horn is attached.

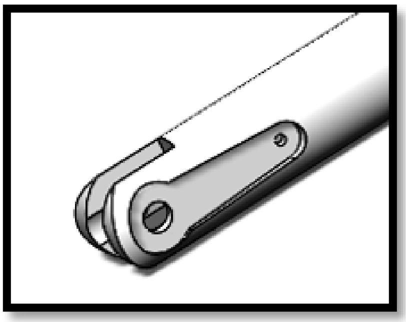


Figure 33: Servo Horn Notch on Stand-top

3.2.3.2 Stand-Middle

The stand middle is the central connecting component to which the other parts of the stand sub-assembly are attached. The top of the stand-middle is the second half of the hinge joint that connects the stand-middle and stand-top. At the midsection of the stand-middle, a flat rectangular slot is cut into the side of the component. This slot is used to locate and secure the motor-fixture to the stand-middle through a combination of gluing and drilling screws through both parts. The bottom portion of the stand-middle slides into the top of the stand-bottom. Figure 34 displays the stand-middle.

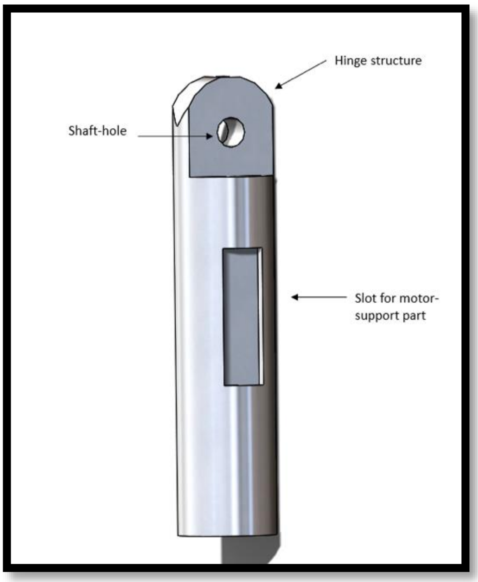


Figure 34: Stand-Middle

3.2.3.3 Motor-support of Stand

The motor-support is a rectangular extrusion in which in elbow motor is housed. The motor-support extends out from the side of the stand-middle and is connected via two screw holes and gluing. The other half of the component consists of the rectangular frame that holds the elbow motor. Two holes are used to mount the motor to the frame by fastening screws through the motors side flanges. Figure 35 shows the motor-support.

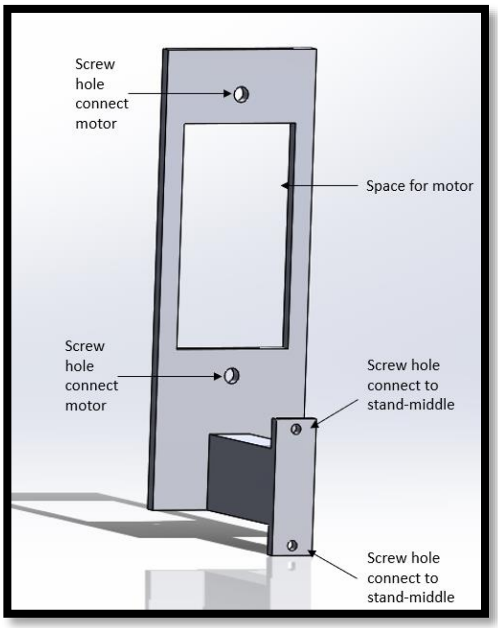


Figure 35: Motor-Support

3.2.3.4 Stand-Bottom

The stand-bottom is the lower most section of the stand sub-assembly. This hollow tube connects to the stand-middle at its top and the base motor at its foot. Along the upper section of the stand-bottom is a large rectangular slit that is used as a track to allow room for the motor-support when sliding the rest of the canopy up and down. Two holes allow screws to be tightened and hold the stand middle and connecting components in place. At the foot of the stand-bottom two supporting arms exist to mount the stand-bottom to the base motor's servo horn. Figure 36 displays a cross-sectional view of the stand-bottom.

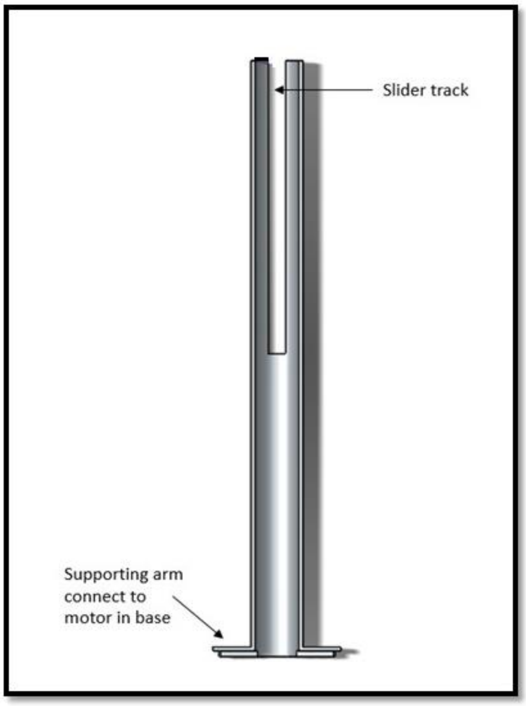


Figure 36: Cross-sectional View of Stand-bottom.

The slit on the stand-bottom allows for the length of the stand to be adjusted; this satisfies the design requirement for portability.

3.2.4 Base Sub-Assembly

Design of the base assembly attempted to stay as true to the commercial design as possible, following the overall dimensions and key mounting points for the servo motor. Due to the scale and size of the components, however, the design is quite different than the commercial product, but nonetheless aims to achieve the same results and display a working example of the umbrella design.

Since the base is intended to be 3D printed using PLA plastic material, the design consisted of shapes and geometry that can be printed. Large fillets and any overhanging components were changed in the design phase to ensure accurate and functional parts. Figure 37 shows the resulting complete assembly.

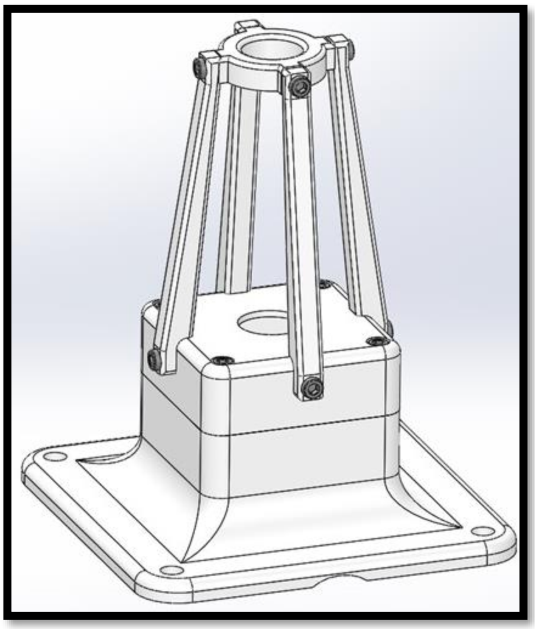


Figure 37: Overall Base Prototype Assembly

The base sub-assembly consists of 3 parts; the lower base, the base cap, and the upper supports. The lower base houses the servo motor and the base cap covers and protects the rotating servo from debris. Long upper supports provide added stability to the stand-bottom to prevent wobbling while in motion. The base cap is mounted onto the lower base by four 9/16" 4-40 threaded machine screws that thread into the lower base holding the sub-assembly together. Figure 38 shows an exploded view of the base sub-assembly.

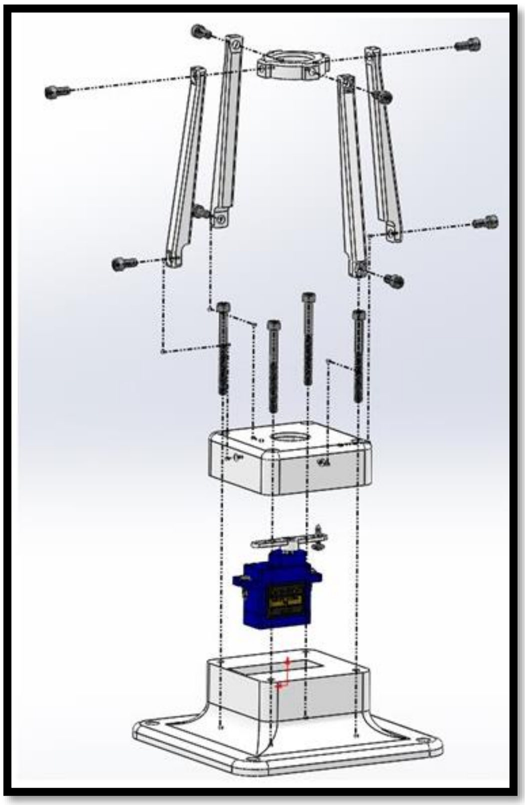


Figure 38: Exploded View of Base Prototype Assembly

The machine screws are loose in the base cap and threaded into the lower base by under sizing the holes during 3D printing. This creates a tight fit around the screw where threads are created simply by tightening the screws into the PLA plastic material. Figure 39 shows a segmented view of this idea.

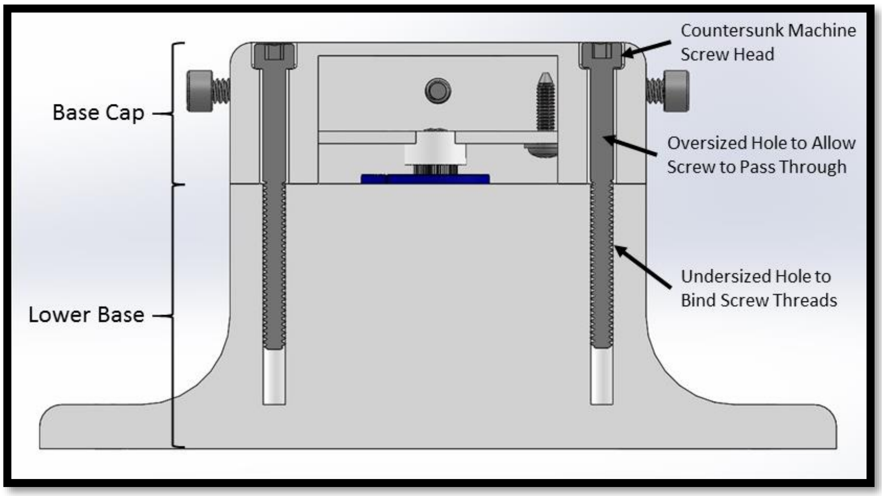


Figure 39: Cut View of Base Prototype for Screw Locations

Lastly, the servo motor is offset within the lower base such that the central rotating portion of the motor lies in the center of the prototype design. This ensures an accurate demonstration of the prototype in motion as any imbalances on the rotational axis could cause the entire assembly to behave differently to the commercial model. Figure 40 shows this offset in another cut view.

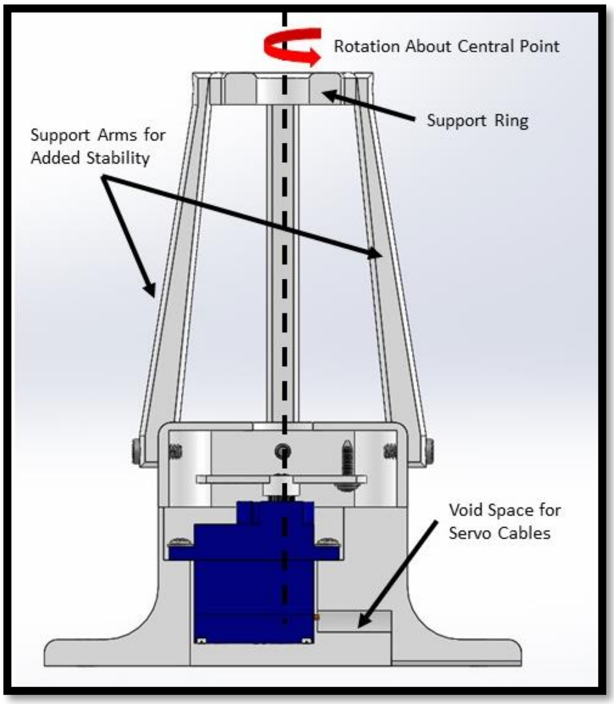


Figure 40: Cut View of Base Prototype for Servo Location

3.3 Commercial Design

The commercial version of the umbrella is similarly divided into the three main sub-assemblies from the prototype: the canopy, stand and base. Within this section the alterations from the prototype, and final component descriptions are provided for each of the major sub-assemblies.

3.3.1 Commercial Canopy Sub-Assembly

Many alterations were required to improve the viability of the canopy design from the prototype. The prototype was designed specifically to be 3D printed and due to its small scale, the necessary strength requirements were lower. The large size of the commercial canopy presents a design challenge in balancing the strength of the system to minimize the deflection of the arms while maintaining a lower overall weight. Lowering the weight of this sub-assembly reduces the load on the motors and increases portability. The alterations for the full-scale commercial components of the canopy will be discussed in this section. A render of the commercial version of the canopy sub-assembly (including the stand-top) in a fully open position is provided in Figure 41.

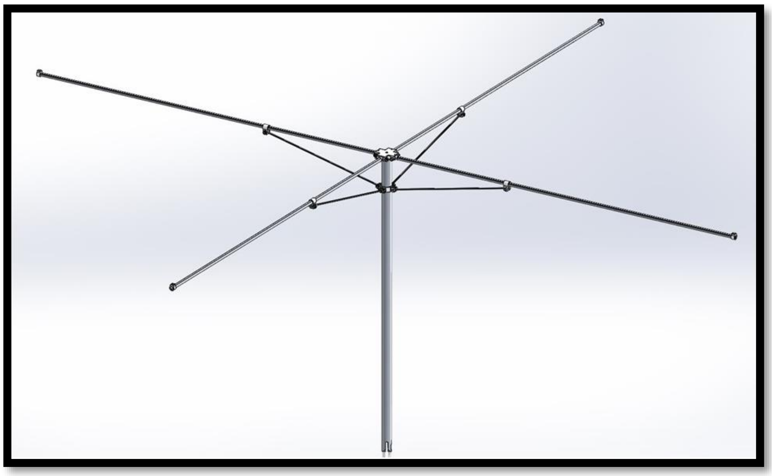


Figure 41: Commercial Canopy Sub-Assembly Open Position

Figure 42 displays the commercial canopy sub-assembly in a closed position

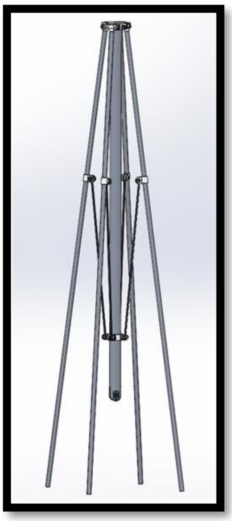


Figure 42: Commercial Canopy Sub-Assembly Closed Position

Figure 43 shows a close-up view of the commercial canopy sub-assembly, highlighting the connections of the components.

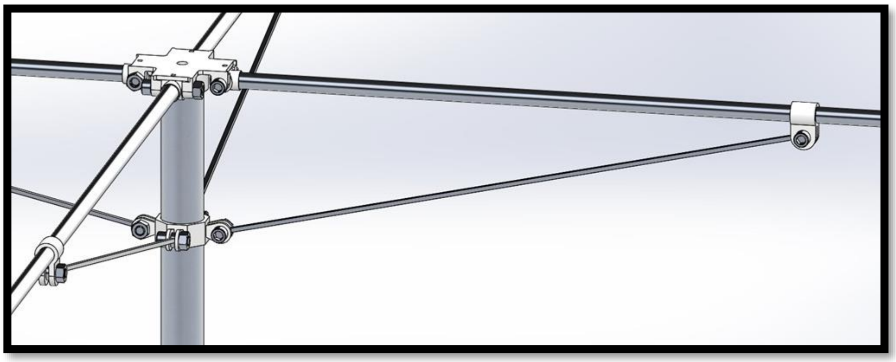


Figure 43: Close-Up View of Canopy Sub-Assembly

3.3.1.1 Commercial Frame Arms

From the analysis performed in Section 2.3.5, it was determined that a full redesign of the frame arms was required to make the components structurally viable at the commercial size. It was decided to replace the original cross-section of the frame arms with a hollow cylinder. Using a hollow profile also assists in managing cables as the sensor wires can run through the arms. Figure 44 displays a render of the commercial support arm.

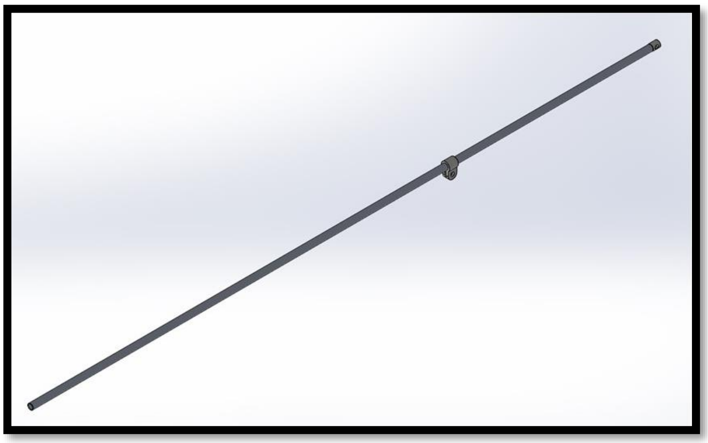


Figure 44: Commercial Frame Arm

In the place of the prototype's hinge joints that were attached directly to the 3D printed parts, three collars made of ABS were designed to be bonded to the commercial frame arms and act as the hinge joint connections. Figure 45 displays the mid-span collar which is used to connect the frame arms and support arms.

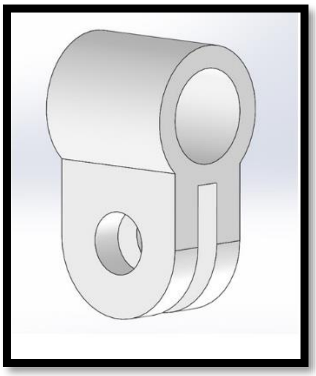


Figure 45: Mid-span Collar

Figure 46 shows the frame collar that connects the end of the frame arm to the umbrella fixture.

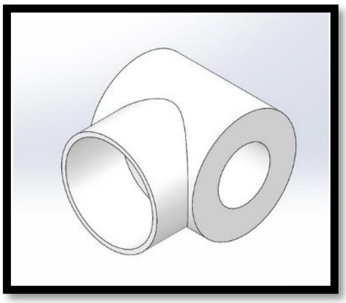


Figure 46: Frame Collar

For sensor placement, a third collar was designed to sit at the end of the frame arms. This collar not only serves as a mounting location for the sensors, but also serves as a mounting point for the canopy fabric of the umbrella. The sensor collar is pictured in Figure 47.

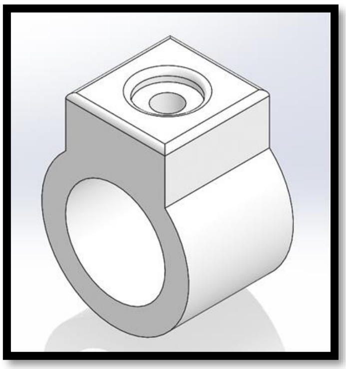


Figure 47: Sensor Collar

The collar has a countersunk hole for settling the sensor with an extruded bottom to connect the wires. By bonding the sensor collars to the end of each frame arm, the canopy fabric remains flat when fully extended. The sensor collar bonds to the end of the frame arm as shown in Figure 48.

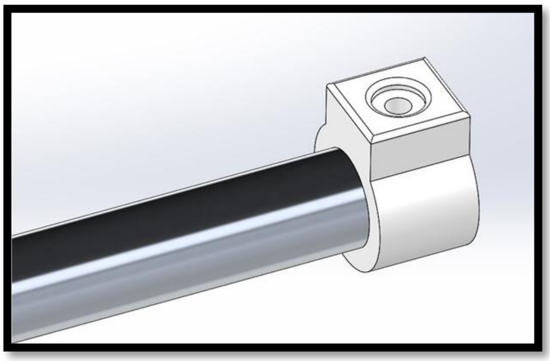


Figure 48: Sensor Collar Connection with the Frame Arm

3.3.1.2 Commercial Umbrella Fixtures

In addition to increasing the size of the umbrella fixture from the prototype design, a hole was placed in its center to allow an aluminum rivet to attach the canopy fabric. Figure 49 displays the top view of the commercial umbrella fixture:

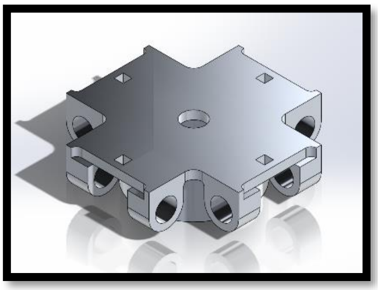


Figure 49: Commercial Umbrella Fixture Top View

Figure 50 displays the bottom of the commercial umbrella fixture.

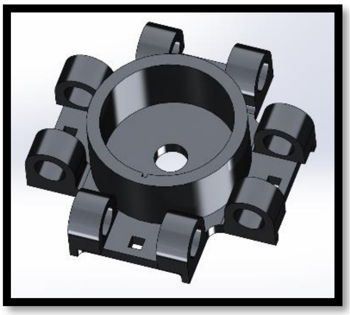


Figure 50: Commercial Umbrella Fixture Bottom View

3.3.2 Commercial Stand Sub-Assembly

Like the prototype, the commercial stand sub-assembly consists of four major components, the stand-top, stand-middle, motor-support and stand-bottom. In addition to the increased dimensions, there are a few minor design alterations to the sub-assembly that are discussed in the following sub-sections. A side view of the commercial stand sub-assembly is shown in Figure 51.

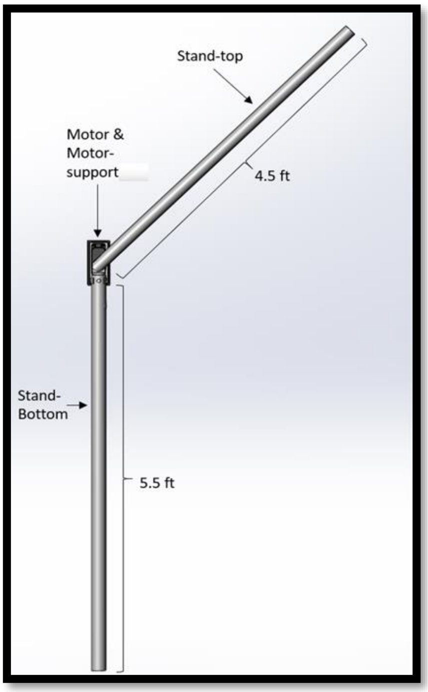


Figure 51: Complete Commercial Stand Sub-Assembly.

3.3.2.1 Motor Cover and Support

The motor-support is updated from the prototype design to accommodate a larger motor and additionally includes ample space for user controls. The commercial umbrella's revised motor-support is separated into two components, the motor-support and the motor-cover. The commercial motor-support has a circular clamp-shaped fixture that wraps around the stand bottom and is attached via screws. The commercial motor-support is depicted in Figure 52.

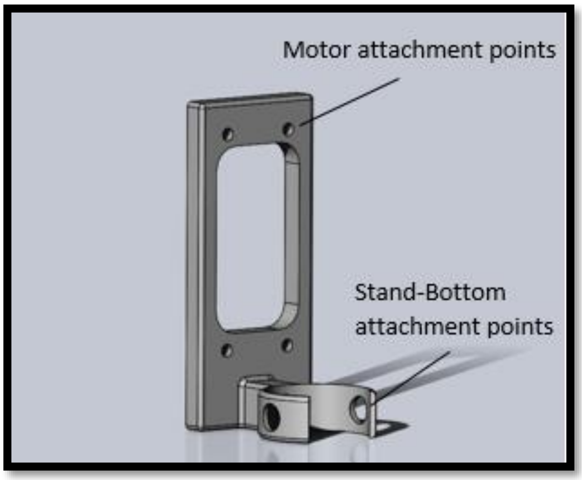


Figure 52: Commercial Motor-Support

Mounted directly to the commercial motor-support is the motor-case. The motor-case is used to contain the motor and acts as a housing for the system’s controls. The design presented is a placeholder model as additional considerations, as outlined in Section 4.3.5.3, are required to customize this component to the specific desires of the client. This placeholder model features ample space to store a digital display as well as a hole for a push button. The commercial motor-cover is shown in Figure 53.

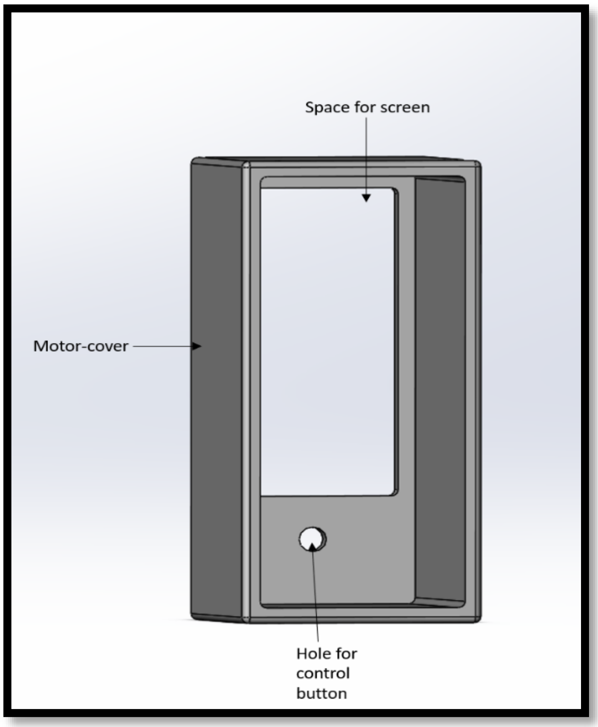


Figure 53: Commercial Motor Cover

3.3.3 Commercial Base Sub-Assembly

The design of the commercial base alters drastically from the prototype. In addition to the scaling of components to full-size several new features were added to improve the versatility and usability of the umbrella.

3.3.3.1 Overall Design

The design process for the commercial base began by performing the analysis detailed in Section 2.3.3. As the required mass and size of the base is heavily dependent on the mass of the umbrella's canopy, the design of the base sub-assembly was completed last. The calculated mass and width of the base are 39 [kg] and 1 [m] respectively. Figure 54 shows a top view of the final design with the plastic covering attached.

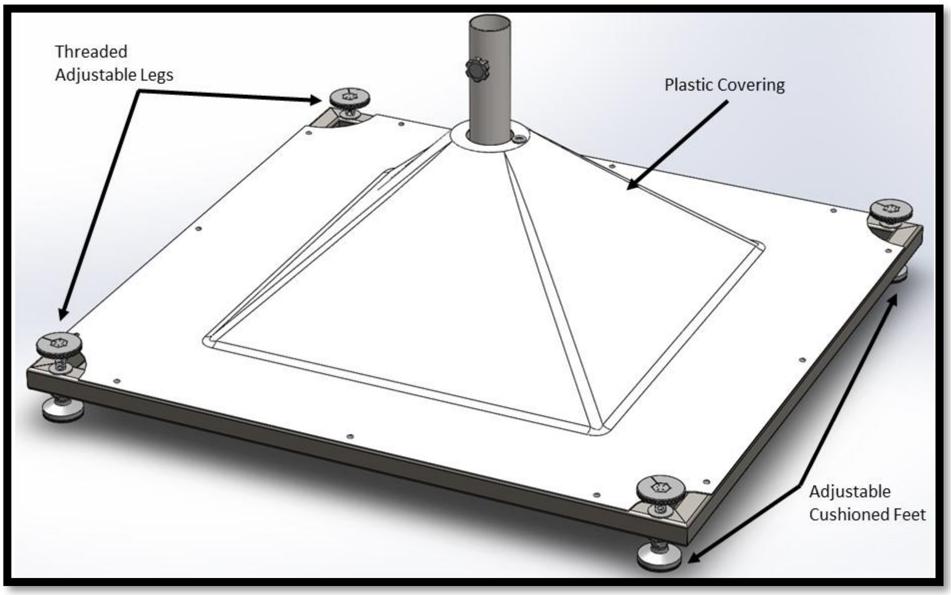


Figure 54: Commercial Base Design with Plastic Covering

Figure 55 shows the underside of the base assembly with the plastic covering attached.

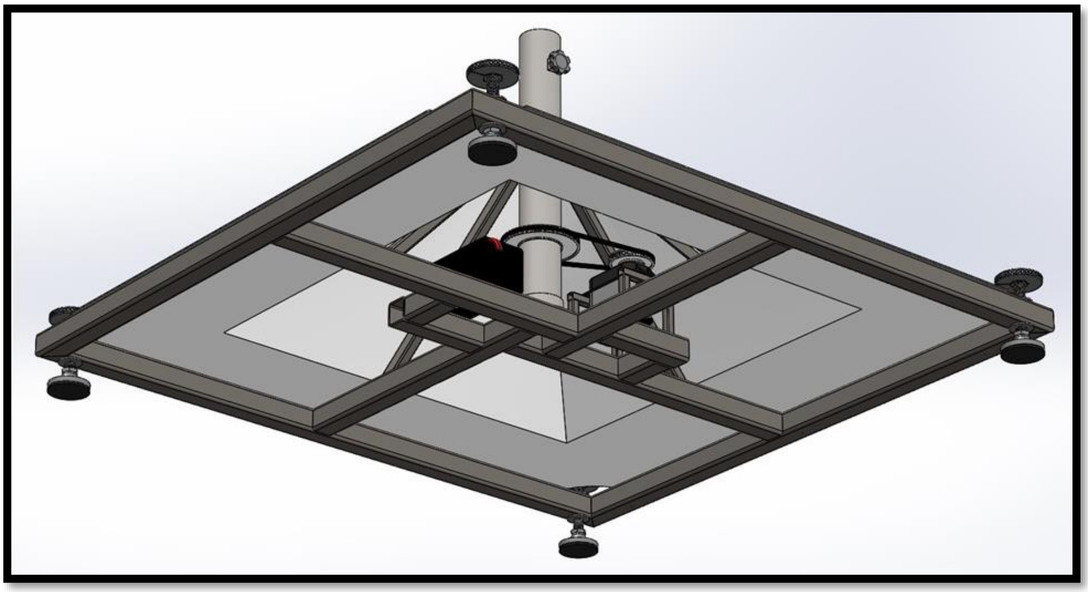


Figure 55: Underside View of Commercial Base Design

The required 1x1 [m^2] width of the base is measured between the centers of its feet. The calculated mass of 39 [kg] is achieved though not only the weight of the base itself, but the combined weight of the motor, battery, and other internal components that is houses as well as the stand and canopy assemblies. The adjustable legs and cushioned swivel feet were included in the commercial base to meet the design requirements specified by Atom-Jet. The adjustable feet allow the umbrella to be stably placed on a variety surfaces such as gravel, grass, wood, stone, or uneven deck boarding. The plastic cover is used to conceal the internal components and increases the aesthetics of the design. Figure 56 displays the commercial base with the plastic cover removed to highlight the arrangement of the systems internal components.

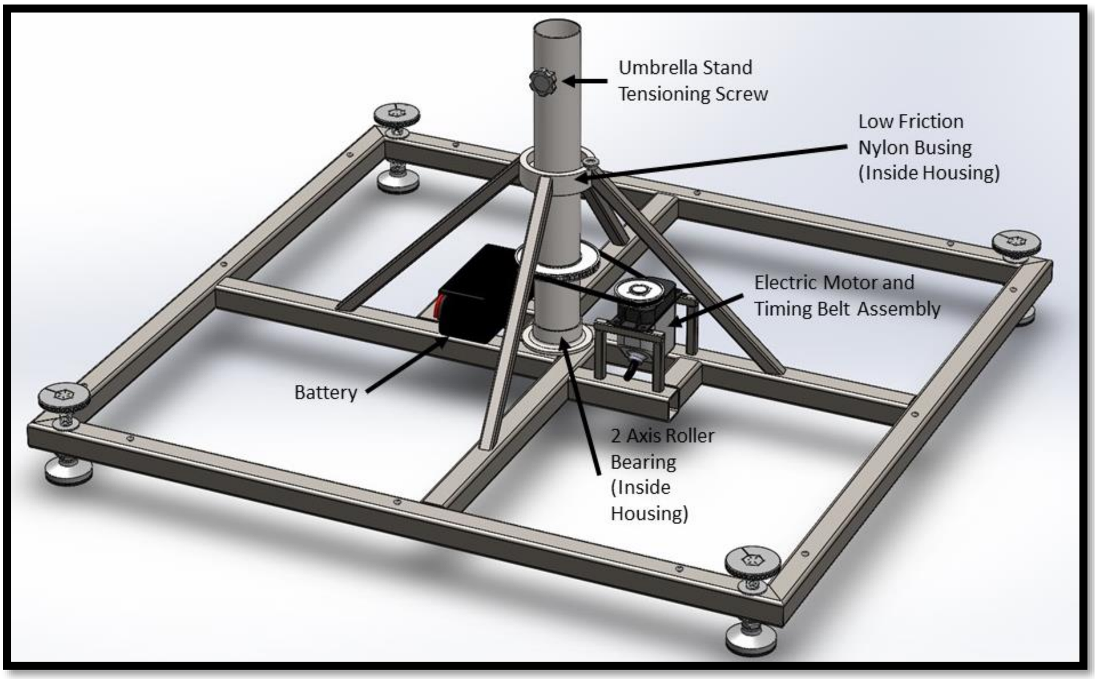


Figure 56: Commercial Base Design without Plastic Covering

3.3.3.2 Frame and Structural Components

The frame of the base is designed from 1 ½" x 1 ½" square tube 12ga steel cut at a 45° angle to achieve the desired square shape of the base footprint. 12ga steel is both strong, durable, and was necessary to achieve the desired overall mass of the base assembly. Additionally, the resistive properties of this material make it an ideal choice for long exposure to the weather. The CAD model for one of the square tube sections is shown in Figure 57 while complete detailed drawings are available in the Appendix C.

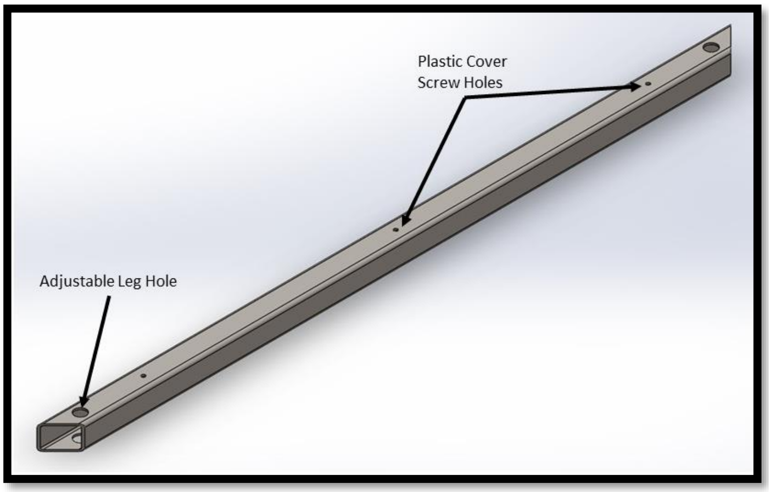


Figure 57: Square Tube Steel Frame Bar

Holes are drilled into the square steel tube for the legs and set screw holes are used to mount the plastic cover. The intention for these holes is to attach two 5/8" threaded weld nuts via welding or brazing to the surface. These weld nuts will provide the threading necessary for the adjustable legs, where twisting of the bolts allows the user to achieve the desired height or leveling to +/- 0.75 [in] on all the legs. A cut image of the complete hex bolt, hand grip, weld nut, and adjustable feet is shown below in Figure 58.

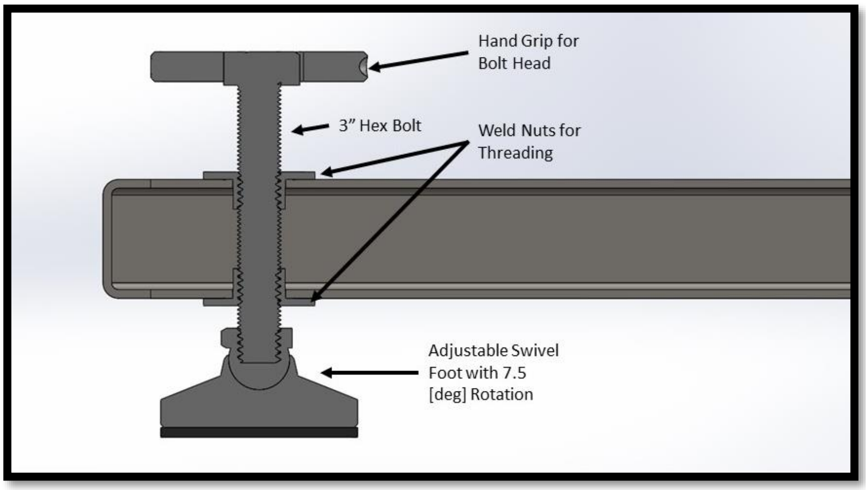


Figure 58: Cut View of Adjustable Legs

To achieve a levelled base using the adjustable feet, an added convenience for the user is the addition of a bubble level located at the central shaft on the plastic covering. A level base will allow an even distribution of forces about the entire umbrella assembly and increase stability. Figure 59 shows the bubble attached to the assembly.

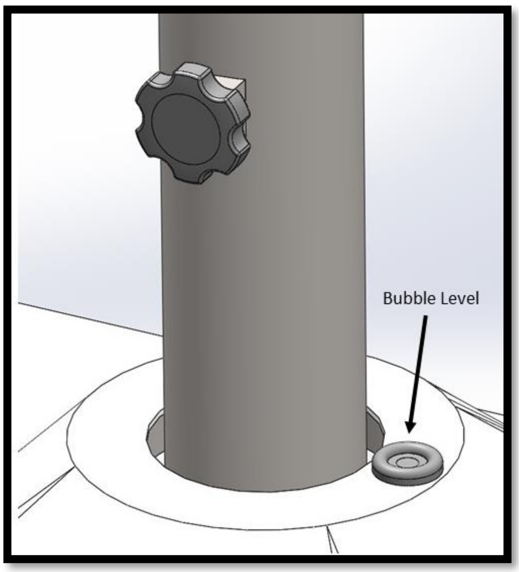


Figure 59: Bubble Level Mounting Location

The hand grip is another feature added for the convenience of the user. The hand grip replaces the need to use a wrench to tighten the base. Additionally, the adjustable swivel feet of the base design feature a cushioned bottom to prevent damage to the surface that the base is placed upon or the umbrella base itself. The swivel feet are able to rotate 7.5° about their vertical axes either side allowing the umbrella to maintain a level setup on uneven surfaces.

3.3.3.3 Rotating Umbrella Stand

To provide smooth rotation between the motor and the stand-bottom, a two-axis roller bearing located at the stand-bottoms mounting point is used in combination with a low friction nylon bushing mounted higher up on the shaft. Figure 60 details the configuration of these components.

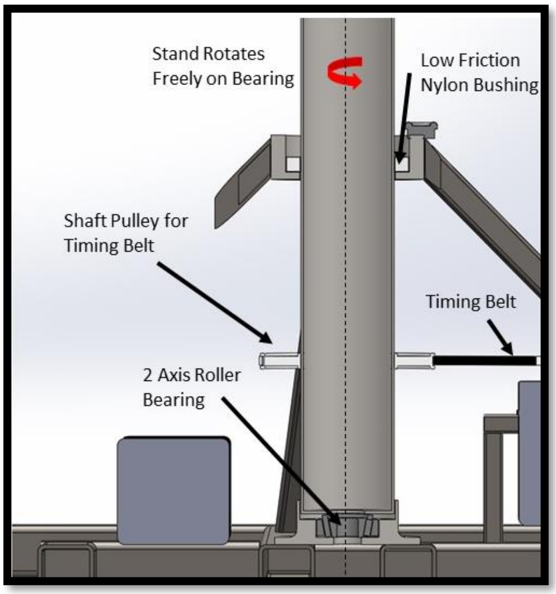


Figure 60: Rotating Shaft Assembly of Commercial Base Design

The two-axis bearing lowers the frictional force that resists the rotation of the umbrella, thus reducing the torque requirements of the motor. The bearing is press-set within a custom designed steel housing featuring an access hole at the bottom, used to remove the bearing if replacement is necessary. The bearing housing is welded onto the welded square tube frame mentioned in Section 3.3.3.2. Figure 61 shows the bearing housing in more detail.

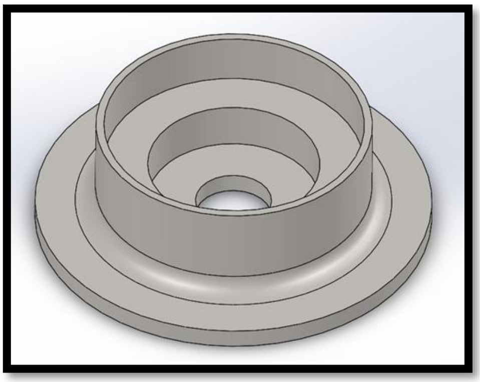


Figure 61: Shaft Bearing Housing

3.3.3.4 Shaft Rotation System

Rotation of the stand-bottom is achieved by the grip and timing-belt that are fixed to the shaft and connected to the motor. Selection of the timing belt assembly was determined based on the requirements of the design and environmental conditions. Since a geared assembly would require a custom build gear box and mounting of a gear onto the shaft, the team determined the assembly would be too complex and require too close of tolerances to achieve a working design. If the shaft gear were to be exposed to dirt or foreign objects a gear assembly could jam easily. A V-belt was also not chosen due to the amount of slip normally encountered on these types of assemblies. Any slip in the belt would affect the performance of the shaft rotation due to the low rpm of the design and would greatly reduce the output generated from the motor. Therefore, a low rpm timing belt assembly was chosen to provide the necessary rotation to the shaft. Values for pitch diameter of the pulleys and the accompanying timing belt selection are based on standard timing belt selection criteria. Figure 62 shows the dimensions based on a standard ¼" XL timing belt with pitch length 0.200 [in] and number of teeth N_a and N_b at 72 and 40 respectively.

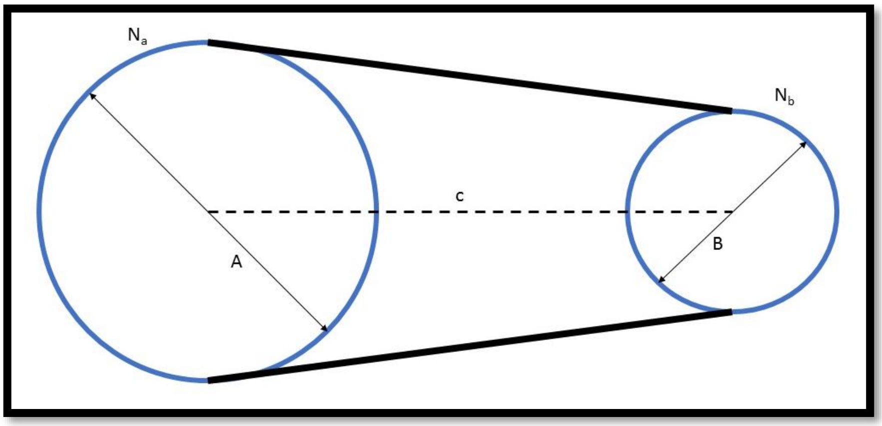


Figure 62: Geometry of Required Timing Belt Assembly

TABLE VI details the resulting calculations from the timing belt specification.

TABLE VI: PULLEY AND BELT REQUIREMENTS BASED ON BELT GEOMETRY

Belt Detail	Symbol	Value [in]	Value [mm]
Available Belt Pitch Length	-	0.200	5.08
Shaft Pulley Pitch Diameter	A	4.58	116.33
Motor Pulley Pitch Diameter	B	2.55	64.77
Center to Center Distance	c	6.00	152.40
Resulting Belt Pitch Length	-	23.00	584.20

With the geometry determined, the pulleys were designed, and the required timing belt was selected as 23 [in] long. Figure 63 shows a schematic of the complete assembly for the design.

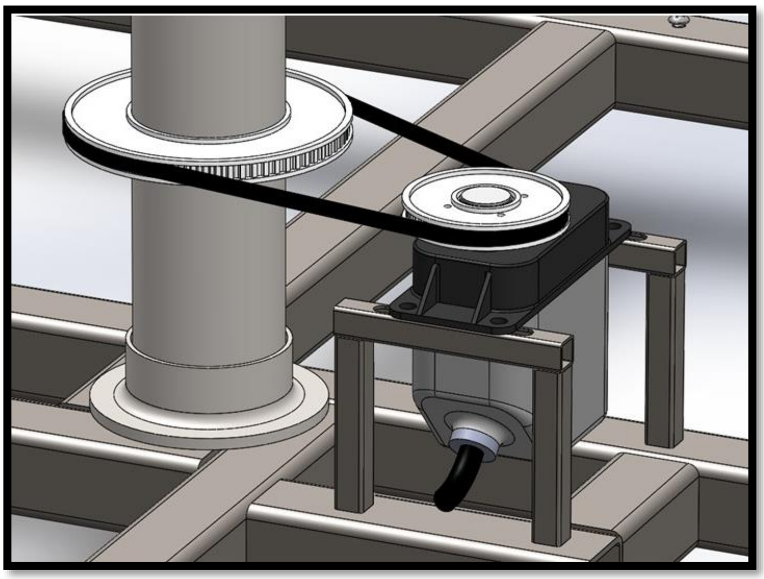


Figure 63: Complete Timing Belt and DC Electric Motor Base Assembly

As shown in Figure 63, the timing belt assembly is welded to the frame with ½” x ½” A513 steel square tubing with slotted holes cut so the motor can be bolted on the horizontal, while regular tubes can be used for the vertical. The slotted holes ensure the timing belt can have tension on both sides of the belt to reduce any slip or backlash, since the umbrella moves very slowly as it tracks the sun. Figure 64 shows the square tube with slotted holes allowing for +/- 5 [mm] adjustments.

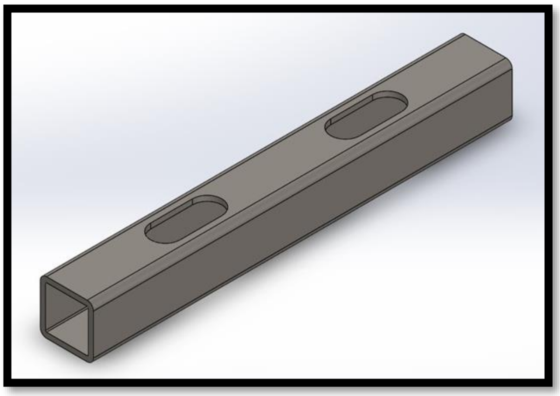


Figure 64: Steel Square Tube with Slots for DC Electric Motor Attachment

Also featured as part of the rotating shaft apparatus is a low friction nylon bushing mounted a distance away from the two-axis bearing. The bushing allows for the shaft to rotate easily about the central axis and provides added stability to the stand-bottom, since the rotating body involves a rather large and heavy umbrella canopy under external loading conditions. The nylon bushing housing is also custom designed from steel and is firmly held into place by welding four ¾” x ¾” 14ga steel square tubes onto the previously mentioned welded square tube steel frame. These 14ga steel tubes further increase the overall stability of the base design and are shown in Figure 65.

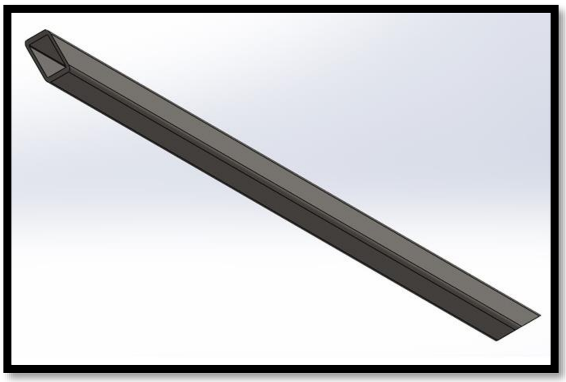


Figure 65: 14ga Square Tube Steel

3.3.3.5 Fixing the Umbrella Stand

Fixing the umbrella stand to the base is accomplished using a hand-tightened tensioning screw within the hollow rotating central shaft apparatus. The tensioning screw is strong enough to hold the umbrella stand into place while the shaft can rotate about the central axis due to the two-axis bearing and low friction nylon bushing. The tensioning screw is shown in Figure 66 below in greater detail.

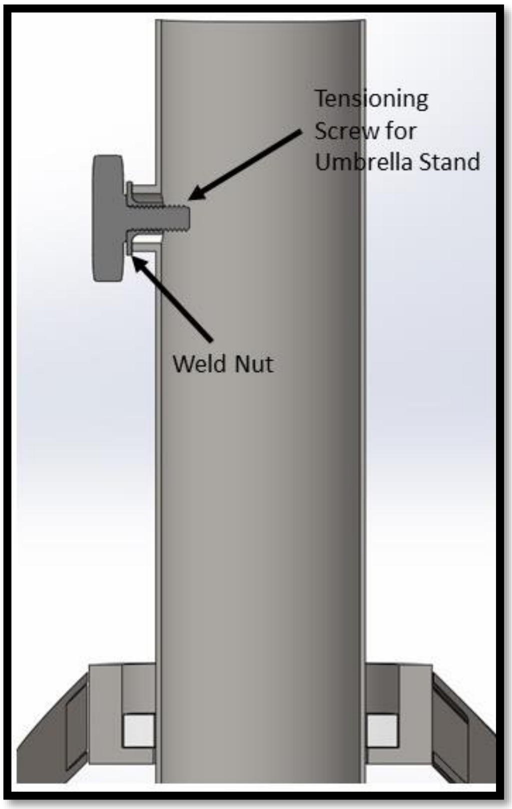


Figure 66: Cut View of Tensioning Screw for Umbrella Stand Connection

The threaded portion of the shaft is from a weld nut welded or brazed onto a hole drilled into the hollow steel tube, and the umbrella stand slides in all the way to the bottom and is tightened into place. The bottom of the tube features a small drain hole for any water or particle accumulation. For easy umbrella storage, the user loosens the tensioning screw to slide out the umbrella stand.

4. Electronic and Software Design

The umbrella consists of a fusion of both mechanical and electrical components and can be categorized as a mechatronic device. In order for the umbrella to first detect the sun and then automatically position itself to provide constant shade for the user(s) an electronic system must be designed to complement the mechanical. A general analogy to an organism can be made to better understand the need and design of the electronic and software components. The mechanical structure detailed in Section 3 is thought of as the body, while the processor and software constitute the system's brain. Actuators are utilized like muscles to move the system and sensors are to observe the environment and provide input information to the brain. Within this section of report the electronic components for the prototype will first be discussed in Section 4.1, followed by the detailed analysis of the systems software in Section 4.2. Section 4.2 is used to describe the necessary alterations to the system required to accommodate the full-scale commercial version.

4.1 Electronics

Within this section, a description for each of the electronic components utilized in the prototype umbrella are provided. Section 4.1.1 introduces the systems microcontroller, Section 4.1.2 details the motors used. Section 4.1.3 describes the umbrella's light detecting sensors and 4.1.4 contains a description of the LCD screen. Section 4.1.5 details the chosen buzzer. Section 4.1.6 briefly covers the purpose of the systems LED. Section 4.1.7 explains the use of the push button. Section 4.1.8 details the need of a potentiometer, and Section 4.1.9 displays the full circuit diagram for the prototype.

4.1.1 Microcontroller

The microcontroller that serves as the brains of the system is a SparkFun RedBoard. This board is an Arduino Uno clone that was chosen based on its simplicity, ease of use and low cost. This board features 14 digital input/output (I/O) pins with 6 being pulse width modulation (PWM) capable, additionally, the board features 6 analog inputs. The board is powered via a USB cable and the on-board power regulator is capable of handling anything from 7 to 15 VDC. The board is programmed using the Arduino IDE in a simple plug-and-code fashion. Programs can be written to the board by connecting it to a computer and uploading. An image of the RedBoard is shown in Figure 67.

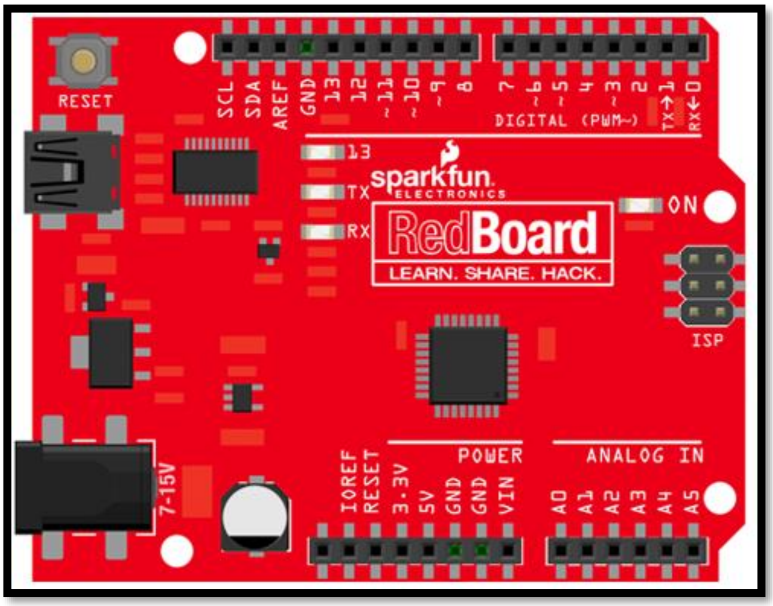


Figure 67: SparkFun RedBoard [11]

4.1.2 Motors

Two DC servo motors are used as the umbrella's actuators to control its position and orientation. Hobby servo motors were chosen due to their ease of use and accurate positional control capabilities. Both motors are identical Tower Pro SG92R servo motors. The motors possess a rated torque of 1.6 [kg cm] and are positionally controlled by the microprocessor by sending PWM signals that specify the desired position in degrees based on the length of the signal. The motors are roughly capable of 180^{o} of rotation and can be commanded with a precision of 1^{o}. As described in Section 2.2, the elbow motor is limited to rotate between 55-125^{o} to maximize the space directly underneath the umbrella and the base motor is restricted to moving within 10-170^{o}. The base motor is slightly limited from its total capable range to reduce the chances of overloading the motor. Figure 68 depicts the available positions of the elbow motor.

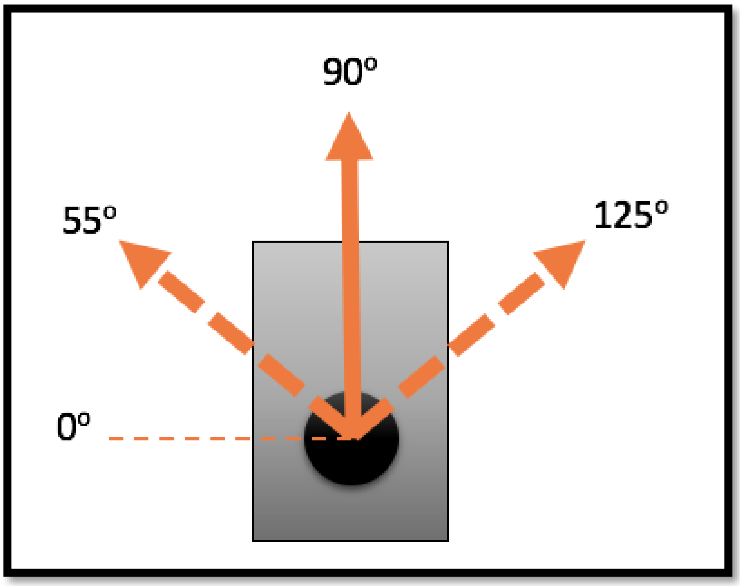


Figure 68: Servo Motor Range of Motion

Included with the servos are horns which can be used for mounting purposes, mounting screws to attach the servo by its side flanges and a screw that can be used to more securely attach a horn to the rotor. Each motor has 3 wires that need to be connected to the microprocessor; Vin, ground and a digital PWM capable output from which command signals are sent. Figure 69 is an image of the servo as well as the included horns and screws.

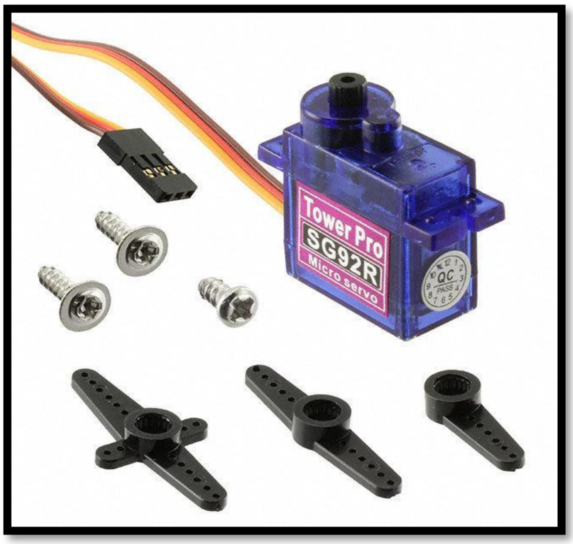


Figure 69: Tower Pro SG92R Servo Motor [12]

4.1.3 Photoresistors

To detect and track the position of the sun, light intensity is measured through the use of 4 identical 16-33 [kohm] photoresistors. These sensors are light dependent resistors (LDR), which depending on the intensity of the light they are exposed to, the resistance value of the sensor will change accordingly. Each LDR is connected to an analog input pin on the microprocessor. The analog input value is digitized by the microcontroller and is read into the Arduino IDE as integer value ranging from 0 to 1023, with zero being the absence of light and 1023 being maximum light intensity. The value of the resistor connected in series with the LDR affects the scaling of the digitized intensity value, for instance, exposing an LDR to the same light source while using a 10 [kohm] resistor could result in a reading of ~900 while at the same distance with the same light source using a 330 [ohm] resistor the sensor could read a value closer to ~600. 330 [ohm] resistors were utilized in the prototype as they provide a reasonable range of scaling when directly exposed to a flashlight (for testing purposes) as well as ambient indoor lighting. An image of one of the LDRs used is show in Figure 70.

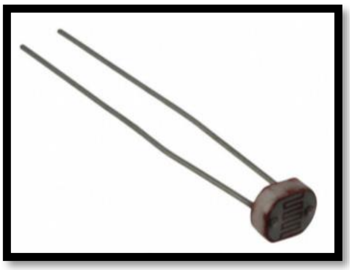


Figure 70: Photoresistor [13]

4.1.4 LCD Screen

To provide the user information in the form of text-based messages, an LCD screen is included in the system. A basic 16x2 character, Hitachi HD44780 white on black screen is used to display messages about the umbrella's current operational state. At start-up, the screen first displays a message instructing the user to press the button to begin calibration. After entering the calibration state the screen is updated and informs the user to stand back from the umbrella while it is in motion. The active tracking state informs the user each time that the umbrella begins to move and in what direction it is adjusting. If a paused state is entered, the screen then informs the user that the system is paused and to press the button to resume. The LCD screen has a total of 16 pins. Figure 71 provides a picture of the screen accompanied with a description for each pin.

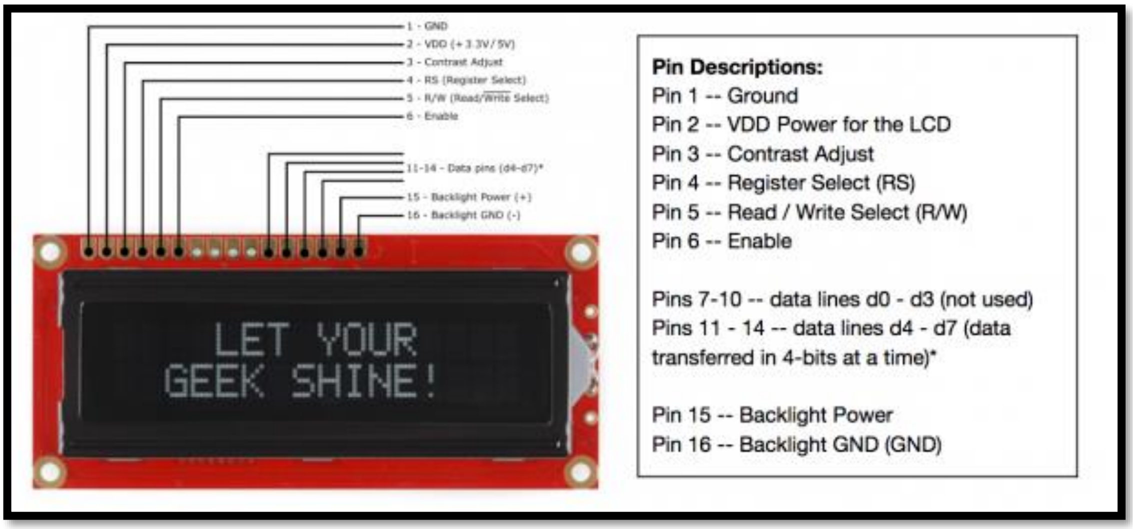


Figure 71: 16x2 LCD Screen [14]

4.1.5 Buzzer

To provide situational feedback to the user, a piezoelectric buzzer (or magnetic buzzer) is included in the umbrellas system. This buzzer works by using an electromagnet to drive a thin metal sheet that is vibrated at certain frequencies in order to obtain specific pitches. The buzzer plays short jingles at the start-up, calibration, pausing and resuming. The function that controls the buzzer was based on an example provided from the open source SparkFun Inventors Kit Guide V4.0 [15]. The buzzer function used for the umbrella is programmed with frequencies that correspond to a 2-octave C major scale. Jingles can be composed by commanding the buzzer to ring at a certain note's frequency for the desired amount of time. The buzzer is controlled through PWM signals. Figure 72 depicts an image of the buzzer.

Figure 72: Piezoeletric Buzzer [16]

4.1.6 LED

A standard LED is included as a means of visual feedback to alert the user of the umbrella's movement. A green 5 [mm] LED turns on whenever the umbrella is about to move. After the umbrella has completed its motion, the light turns off. This light provides a visual notification to the user that is eye catching, yet subtle enough as to not be annoying. An image of a similar LED is provided in Figure 73:

Figure 73: LED [17]

4.1.7 Push Button

A simple push button is used as a user input to interact with the system. This button acts as a switch that when untouched is an open circuit but when closed (pushed down) completes the circuit. The button performs different actions depending on the current state of the system. At start-up, pressing the button initiates the system to start. Pressing the button again will pause, then resume the system and holding the button for 5 [s] puts the system into shutdown mode. Figure 74 depicts a collection of similar buttons to the one used in the system:

Figure 74: Push Buttons [18]

4.1.8 Potentiometer

A 10 [kohm] potentiometer is used to control the intensity of the LCD screen as well as the volume of the buzzer. Rotating the dial on the potentiometer changes its resistance. Due to limited space on the breadboard, a single buzzer is used to control both components. Figure 75 depicts the potentiometer.

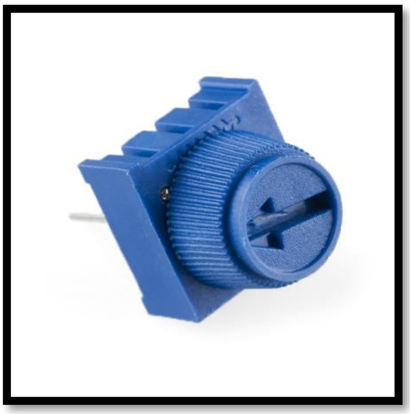


Figure 75: 10 [kohm] Potentiometer [19]

4.1.9 Circuit Diagrams

This section of the report provides a detailed description of the wiring and connections of the prototype system. Figure 76 displays the RedBoard microcontroller along with the solderless breadboard that connects all the previously mentioned components.

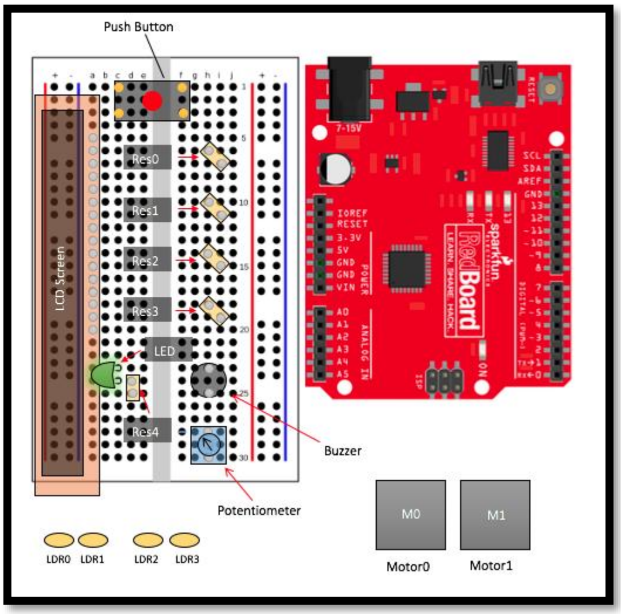


Figure 76: Component Labelled Prototype Circuit Diagram

Figure 77 features the same components and layout as Figure 76 with the addition of the wires that are used to connect the system together.

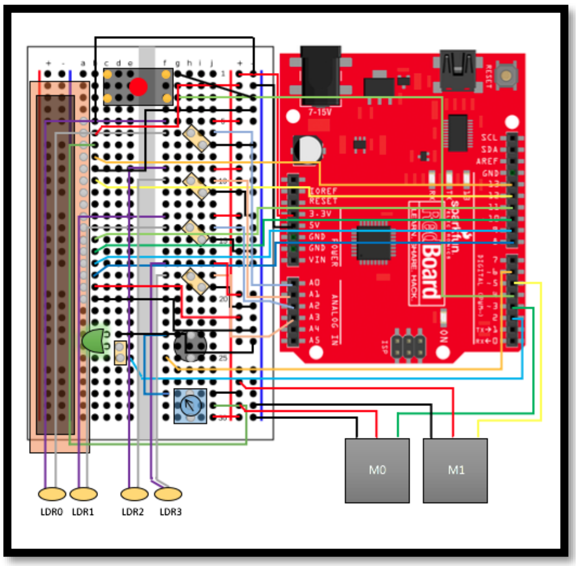


Figure 77: Prototype Circuit Diagram

TABLE VII outlines the locations on the breadboard where each circuit element is connected

TABLE VII: CIRCUIT ELEMENT LOCATIONS

Circuit Element Locations	
Push Button	c1, c3, f1, f3
Resistor 0	n6, i7
Resistor 1	n10, i11
Resistor 2	n14, i15
Resistor 3	n18, i19
Resistor 4	d24, d25
LCD Screen	a5 : a20
Buzzer	n23, n25
Potentiometer	n28, n29, n30
LED	c23, c24

TABLE VIII outlines the paths of current flow through each of the circuits in the system

TABLE VIII: CIRCUIT WIRING PATHS

Circuit Wiring Paths	
Push Button	Dout4 -> g3 -> Push Button -> g1 -> Ground
Resistor 0 & LDR0	Vin -> j5 -> f5 -> LDR0 -> f6 -> Resistor 0
	- Resistor 0 -> j6 -> Ain0
	- Resistor 0 -> j7 -> Ground
Resistor 1 & LDR2	Vin -> j9 -> f9 -> LDR2 -> f10 -> Resistor 1
	- Resistor 1 -> j10 -> Ain1
	- Resistor 1 -> j11 -> Ground
Resistor 2 & LDR1	Vin -> j13 -> f13 -> LDR1 -> f14 -> Resistor 2
	- Resistor 2 -> j14 -> Ain2
	- Resistor 2 -> j15 -> Ground
Resistor 3 & LDR3	Vin -> j17 -> f17 -> LDR3 -> f18 -> Resistor 3
	- Resistor 3 -> j19 -> Ain3
	- Resistor 3 -> 20 -> Ground
LED & Resistor 4	Dout2 -> e25 -> Resistor 4 -> LED -> d23 -> Ground
LCD Screen	Ground -> b5 -> LCD
	Vin -> b6 -> LCD
	Potentiometer -> j29 -> b7 -> LCD
	Dout13 -> b8 -> LCD
	Ground -> b9 -> LCD
	Dout12 -> b10 -> LCD
	Dout11 -> b15 -> LCD
	Dout10 -> b16 -> LCD
	Dout9 -> b17 -> LCD
	Dout8 -> b18 -> LCD
	Vin -> b19 -> LCD
	Ground -> b20 -> LCD
Buzzer	Dout6 -> f25 -> Buzzer -> f23 -> f28 -> Potentiometer

Circuit Wiring Paths	
Potentiometer	Vin -> j30 -> Potentiometer
	LCD -> b7 -> j29 -> Potentiometer
	Ground -> j27 -> Potentiometer
	Buzzer -> f23 -> f28 -> Potentiometer
Motor 0	Dout3 -> Motor 0 -> Vin, ground
Motor 1	Dout5 -> Motor 1 -> Vin, ground

4.2 Software

The system's software component is comprised of the program that is stored onto the microcontroller. The program is written in the style of C/C++ using the Arduino IDE. The software architecture has the programs divided into four phases. At start-up, the umbrella begins in the set-up state, transitions into the calibration state, and then transitions into the active tracking state. At any point during either the calibration or tracking states, the program's execution can be temporarily halted by entering the pause state. The program will remain paused until the necessary conditions are met at which point the program will continue from where it left off. The tracking state will repeat infinitely until the umbrella has been shut down. Throughout this section several direct references are made to the code of the program which is included in its entirety in APPENDIX D. Figure 78 is the total system's process flow diagram for the system that visually explains the flow of logic, actions and decisions that take place during execution.

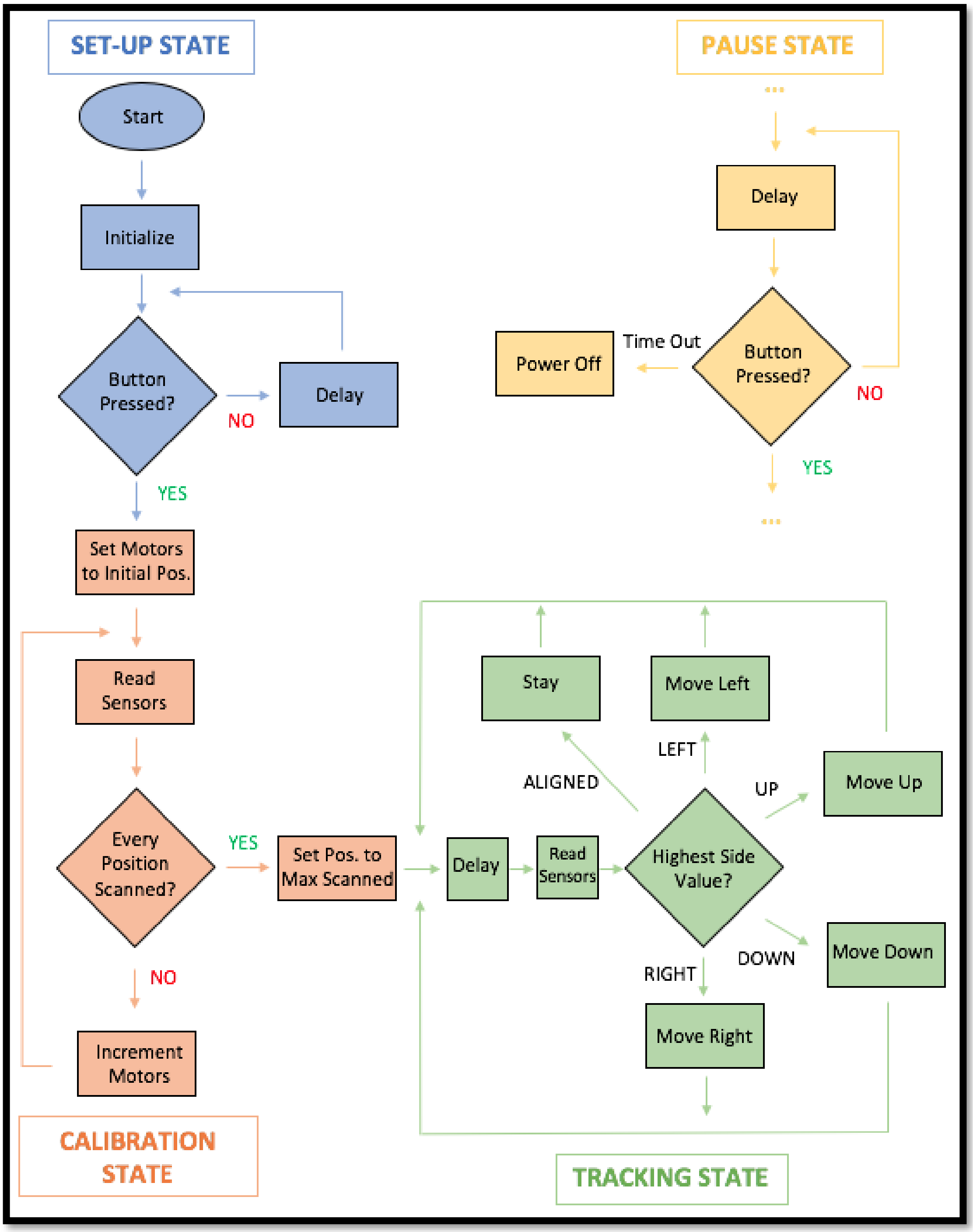


Figure 78: Total Process Flow Diagram

Section 4.2.1 describes the structure of how the program was written. Sections 4.2.2, 4.2.3, 4.2.4, and 4.2.5 describe the Set-Up, Calibration, Tracking, and Pause States respectively. Section 4.2.6 details additional functions not core to any of the main states, and Section 4.2.7 explains any alterations to the code that the client may want to make.

4.2.1 Program Structure

A single program is contained within the microcontroller at a time. This program is executed in a cyclic executive fashion in which there is one task that is infinitely repeated within the program's main function. Given the procedural nature of the umbrella's design in which it needs to sequentially enter various operational states, process control techniques are implemented in order to achieve these desired states. In addition to the program's main function, several additional supporting functions are utilized. These additional functions branch off from the main function using conditional statements that check for the status of control flags and user input. The following sub-sections expand in detail upon the structure and control of each of the program's states.

4.2.2 Set-Up State

The Set-Up State as defined in Figure 78 contains four functional blocks the program's start, an initialization and a decision loop that either delays the programs execution or continues onto the calibration state. Figure 79 displays the Set-Up State's flow diagram for reference.

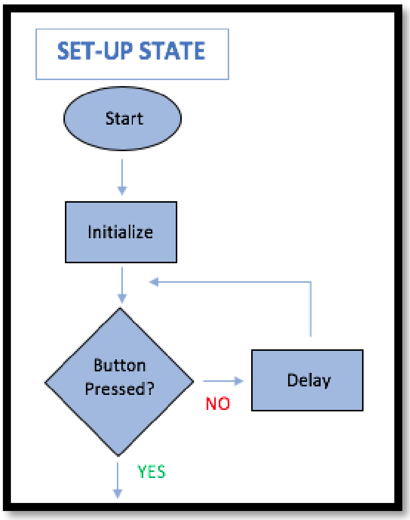


Figure 79: Set-Up State Process Flow Diagram

4.2.2.1 Initialization

Upon powering up the program the first lines of code executed are those that are not contained within any function space. These initial commands are used for the loading of additional libraries, creating global variables and creating named objects for the circuit elements. The umbrella's program requires two additional libraries, those being the standard servo control (Servo.h), and liquid crystal display (LiquidCrystal.h) libraries. Including these two additional libraries grants the program access to dedicated sets of functions that allow for easier operation of these devices. Global variables are those that can be accessed from anywhere within the program. In total, the program uses 14 global variables that range in use from positional trackers that are used to set desired positions for the servo motors, to input pin markers for the RedBoard, to values to store each sensor's readings, and various control flags used to assist in the transition between the program's various operational states. Within the non-function space, objects for circuit elements are created. This entails making an object for each of the servo motors as well as one for the LCD screen. These global objects allow for each of the specified circuit elements to be interacted with at any point in the program's execution.

The first function of the program is the setup. The setup function, different from the Set-Up State, is a mandatory piece of code that is used to establish connections and set objects to initialized states before entering into the program's main loop. This entails specifying which inputs/outputs are located in which pins of the RedBoard, attaching and setting the servos to initial positions and determining the size of the LCD display. When the particular servos that were utilized are first attached to the RedBoard, they initialize their position by automatically setting to 90^o. This is done at full speed and is an unavoidable limitation of the motors, as such it is of vital importance to manually move the motors as close to 90^o as possible when first booting up they system. Following the execution of the setup function the program immediately begins executing the code contained with its main loop.

4.2.2.2 Set-Up State Control Loop

Due to the cyclic nature of the main loop's execution, a major structural challenge is in designing the program such that its progression can flow seamlessly between states while constantly cycling back through the code. Upon entering into the main loop, the system checks if it meets the conditions of several process control states. If so, then the particular state is entered, its code is executed, and the main loop continues until it eventually repeats itself. The first of these processes is a series of three if statements that perform the starting procedures of the umbrella. Using a global variable called "countState" as well as the state of the push button, one of the three if statements will be entered. These three if statements are represented in Figure 79 by the Button Pressed? / Delay looping control blocks. The first of the three initializing if statements checks to see if the countState variable is set to 0. This variable is initialized to 0 at its creation and therefore this first statement is always executed upon start-up. This first if statement when entered sets the LCD screen to display a message informing the user to push the button to start the umbrella, plays a small start-up jingle, and changes the value of countState from 0 to 2. This effectively prevents the main loop from ever entering back into the first if statement.

The second and third of the three if statements check for the conditions of the countState variable equaling 2 (which it always will at this point) and look for the status of the push button. If the button is not pressed (HIGH), then the second of the three if statements will be entered in which the program simply experiences a short delay and loops back to itself (the NO branch from the Button Pressed? block). If the button is pressed (LOW), then the third if statement is entered (YES branch of Button Pressed?). For protection against bugs/glitches the program waits indefinitely until the push button has been released until it continues its execution. Within the third if statement a new process control variable called startState is initialized to true and countState is changed to a value of 1 so that none of the previous if statements can be entered. A new message is displayed on the LCD screen informing the user that the system is about to enter into the calibration state and that they should temporarily step away from the umbrella for safety, the LED is turned on to signify motion and a jingle is played on the buzzer that counts down the start of the calibration state. This concludes the Set-Up State.

4.2.3 Calibration State

The Calibration State performs the operations associated with finding the sun and positioning the umbrella to the ideal initial position for active tracking. To accomplish these tasks the umbrella performs a scan by traversing through its entire work envelop taking sensor readings at each position. The position in which the sensors read their highest total sum is stored in memory and updated each time a higher value is recorded. After the umbrella has traversed through its entire work envelope it then positions the motors to the location where the highest sensor readings were recorded. Figure 80 displays the entire Calibration State flow diagram for reference.

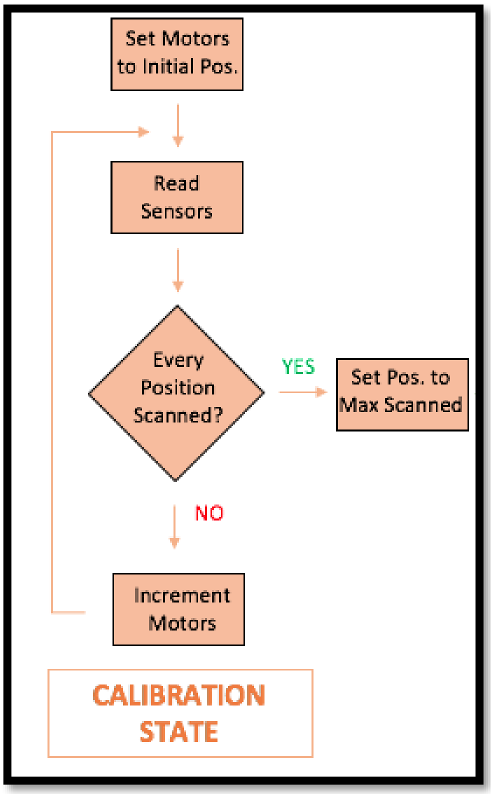


Figure 80: Calibration State Process Flow Diagram

4.2.3.1 Motor Initialization

Continuing from where the Set-Up State left off in the main loop, the program can now enter into the final process controlling if statement that checks for the condition of the previously initialized startState being true. The program then calls the initialStartup function in which the entirety of the Calibration State is contained. The initialStartup function begins by changing the LCD screen to display a message that informs the user that the system is calibrating, and the motors are set to their starting positions to begin calibration. Due to the nature of how the servo motors operate, they cannot simply be sent directly to a desired position. When a servo.write("desired_position") command is sent to a motor it will travel to the desired position at its maximum speed. This is undesirable as having the umbrella travel at this fast of a speed could present a potential safety risk and fast-jerky movements would induce cyclic stresses to the system. To combat these adverse effects an alternative approach is taken where instead of sending a motor directly to the desired position it moves in a rapid succession of very small steps towards the end position. Using a for loop the motor can be sent in 1^{o} increments towards the desired position, stepping for the number of times that it takes for the servos current position to match the desired. This same approach that allows for smoother movements is utilized throughout the program in every instance that a command is sent to a motor. The starting position for calibration has the base motor set to its extreme minimum at 10^0 and the elbow to its decided minimum of 55^o.

4.2.3.2 Calibration Process Loop

After both motors have been set to their initial starting positions the umbrella then travels through its entire work envelop. This is accomplished by several successive calls to the sendMotorCommand function. This function takes as input the desired position in degrees and which motor to send to this position. When sendMotorCommand is called the LCD screen displays a message saying “Calibrating… please wait” and using the previously described incremental stepping method that allows for smooth motion, the motor being commanded makes adjustments of 1^o at a time towards the direction of the desired end position. Each time before the motor is adjusted a call is made to yet another function, this being the sensorReadingCalibration function. sensorReadingCalibration is the section of code that takes the analog input reading of each of the four sensors and totals them, then the current total is compared against the global variable called LDRTotal in which the highest sum is recorded. If a new highest total is found, then LDRTotal is updated and the motor positions that resulted in this highest state are also stored in global variables.

The assumption of the calibration is that if the umbrella does not initially know where the sun is, it can then look in every possible direction to find it. The LDRs provide an approximation of where the sun is based off of the principle that their collective readings will be higher the more closely, they are facing the direction of the sun. Once the umbrellas work envelop has been traversed and a reading has been taken at each point, going back to the orientation where the highest reading occurred will have the umbrella facing in the most likely direction of the sun.

4.2.3.3 Work Envelop Traversal

The process flow diagram of Figure 80 represents the calibration process loop as a repeating section of code that is based around a decision block and whether or not the entire work envelope has been scanned. This representation of the process flow is in fact not an entirely accurate way of representing the actual process of traversing the umbrellas work envelop but visually it is a more succinct method that clearly conveys the underlying process. The scanning of the umbrellas work envelop is accomplished as previously mentioned by performing a series of successive calls to the sendMotorComman function. This function is utilized eleven times each time using different values and alternating motors to get the umbrella to smoothly sweep through its work envelope. The umbrellas work envelope can be approximated to a roughly semi-spherical shape about the elbow motor. The method utilized to traverse this area is to slice the space into three tiered sections. With the elbow motor held at an extreme position the base can go through 160^{o} (-10^{o} at either end) of rotation to cover one half of a single slice, flipping the elbow motor to its opposite extreme then returning the base motor to its initial position effectively covers the other half of the tiered section. This process can be repeated twice more, each time adjusting the elbow motor such that it points more towards 90^{o} (straight up). Figure 81 is a graphical representation of the calibration process.

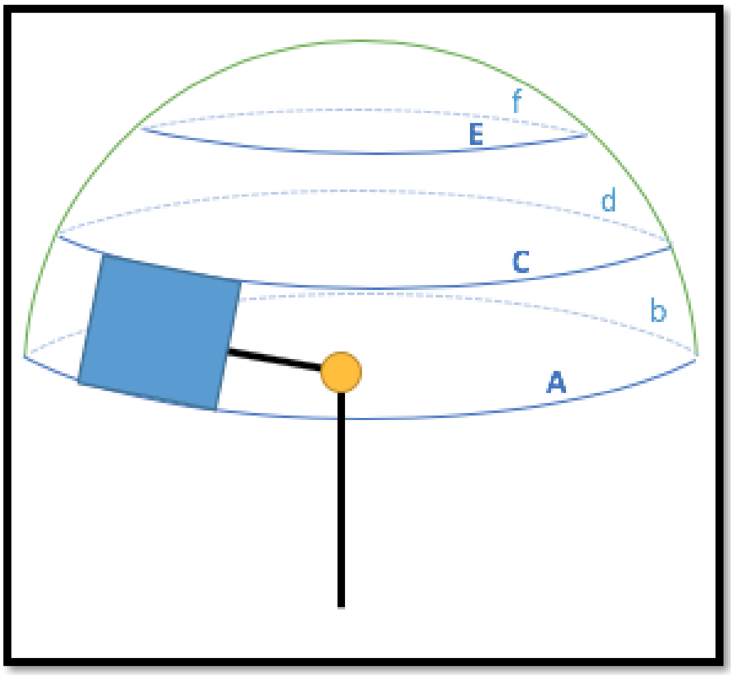
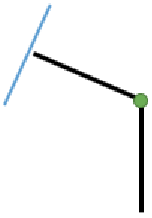
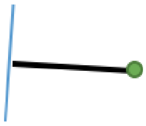
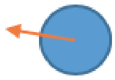
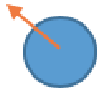
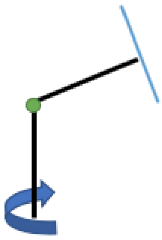
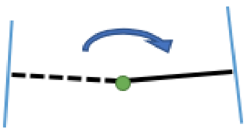
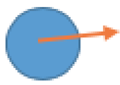
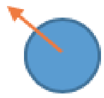
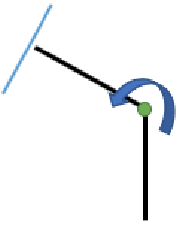
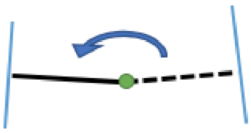
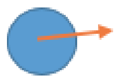
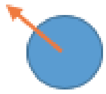
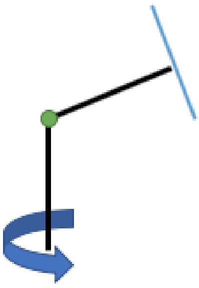
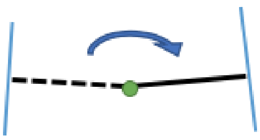
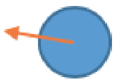
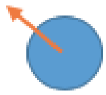
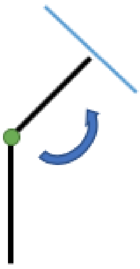
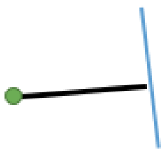
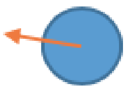
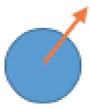


Figure 81: Work Envelop Traversal

In Figure 81 the umbrella will begin by sweeping though slice A, then flipping about the elbow to sweep back over slice b. Then the elbow will be raised, and slice C is covered. The elbow is flipped once more but is also raised by the same amount as slice C, turning about the base allows for slice d to be covered. A similar process is used to cover slice E followed by slice f. Due to the base motor angle restrictions there is a small section of the semi-sphere missing on either side. Starting from the initial position of base=10^{o}, elbow=55^{o}, the series of motor commands are to set base=170^{o}, elbow=125^{o}, base=10^{o}, elbow=108^{o}, base=170^{o}, elbow=72º, base=10º, elbow=85º, base=170º, elbow=95º, base=10º. After this process the umbrella is set back to the maximum sensor reading position and the Calibration State is completed. The entire process takes about ~12-15[s] for the prototype. TABLE IX depicts the first few positions in detail of the calibration sweeping process.

TABLE IX: WORK ENVELOPE TRAVERSAL BREAKDOWN

Side View	Top View	Base Motor	Elbow Motor	Description
				Starting position
				Rotate base from 10º to 170º
				Rotate elbow from 55º to 125º
				Rotate base from 170º to 10º
				Rotate elbow from 125º to 108º

4.2.4 Tracking State

The Tracking State is the final state of the programs process flow. After the sun has been located, this section is repeated infinitely while performing small adjustments to keep the umbrella in line with the sun to provide maximum shade. Given that the relative position of the sun from the umbrella will take time until a noticeable change is detected by the sensors, the position of the umbrella only needs to be updated on a periodic interval. This is done to reduce the workload on the motors and make using the umbrella more enjoyable as constant movements may be annoying to most users. Figure 82 displays the entire Tracking State process flow diagram for reference.

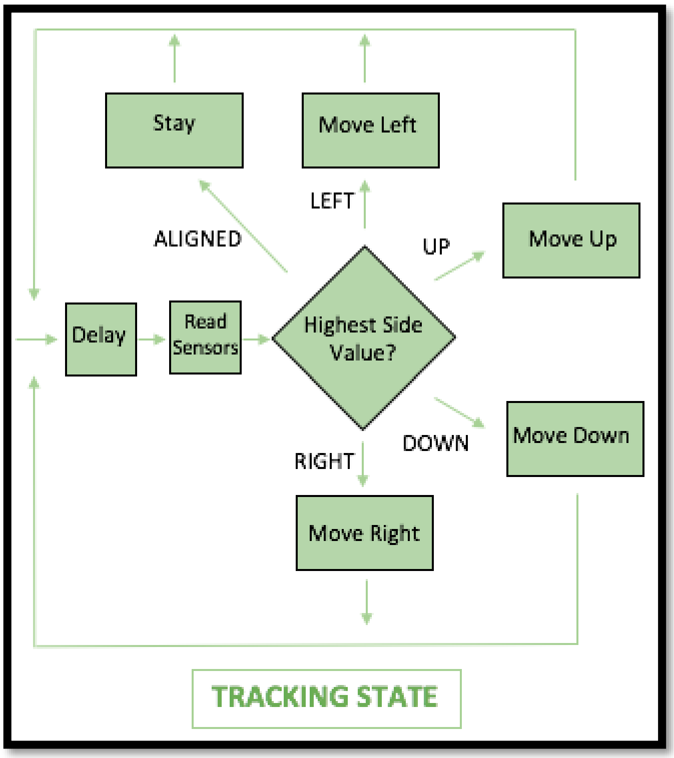


Figure 82: Tracking State Calibration

4.2.4.1 Tracking Process Loop

The Tracking State is entered immediately from the main loop after the initialStartup (calibration) function has finished its execution. A local variable called trackConst is created to control the tracking process flow, additionally an integer called delayCount is initialized, this variable is used to set the interval at which the sensors will be sampled and motors will be adjusted at. A while loop is used to check whether the newly created trackConst evaluates to true, this statement will remain true for the remainder of the program's execution, this is the mechanism by which the umbrella remains in the Tracking State. Within the while loop a delay is used in conjunction with the delayCount integer.

An if statement is used to encapsulate the call to the activeTracking function that handles the umbrella's tracking adjustments. During each cycle of the while loop the program delays for the specified amount, the delayCount is increased by 1 and the if statement checks if delayCount equates to the desired value. Once the program has delayed enough times and delayCount has reached the necessary value, a call is made to activeTracking and delayCount is reset to 0. The reason why this approach was taken using very small delays that add up to the desired time instead of a single long delay of the same length has to do with being able to reliably enter the Pause State that will be touched upon in Section 4.2.4. The length of the delay will be discussed further in Section 4.2.7.1, but for the prototype a relatively short delay is used to allow for more "real-time" adjustments purely for demonstrative purposes, for the commercial version the delay should be much longer. It should also be mentioned that a small amount of time will be added on top of the delay due to the microprocessors clock time and the rate at which it can execute through the program. This total value is negligible compared to the delay itself and can be ignored.

4.2.4.2 Active Tracking

The principles behind the activeTracking function make use of the umbrella's geometry to track the sun. The square shape of the umbrella's canopy with a sensor placed at each corner allows for sensors to be paired along each of the square's sides. The canopy is divided into 4 sections, the top, bottom, left, and right. Figure 83 details a simplified diagram of the umbrella with the sides labelled accordingly.

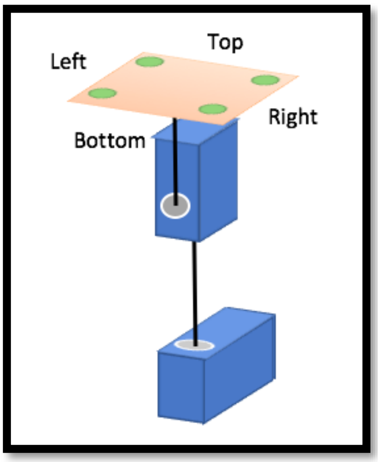


Figure 83: Motor Configuration Canopy Labelling

When called, the activeTracking function initializes a local variable called moveCounter, the rest of the function is contained within a while loop whose condition is based on moveCounter being greater than zero. Within each iteration of the while loop the umbrella will calculate which direction to move in, make a small adjustment and then moveCounter will be decreased by 1. This allows for several moves to be made in rapid succession within a single call of activeTracking. For example, if the delay for the commercial umbrella is set on a 10-minute timer and moveCounter is set to 3, then every 10 minutes the umbrella will make 3 adjustments at once. Similar to the delay itself, determining the optimal number for moveCouner can only be determined through experimentation and will be discussed further in Section 4.2.7.1.

Continuing within activeTracking's while loop, the LCD screen is updated to read "Tracking mode enabled", the LED will turn on to indicate movement, a small delay elapses to ensure smoothness of movement and a reading is taken for each of the four sensors. The sensors are placed as follows: LDR0 on the top right corner, LDR1 on the bottom right corner, LDR2 on the bottom left corner, and LDR3 on the top left corner. Figure 84 depicts the canopy as viewed from above with the sensors and sides labelled.

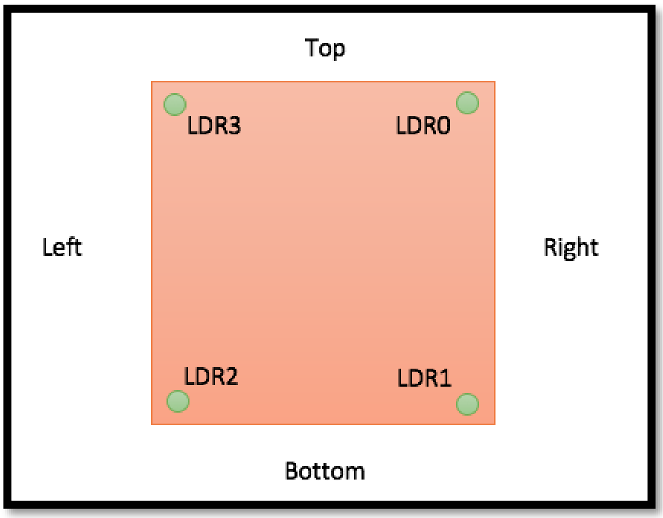


Figure 84: Sensor and Side Labelling

Five local integer variables are created: top = (LDR0+LDR3), bottom = (LDR2+LDR1), left = (LDR2+LDR0), right = (LDR1+LDR3), and sum = (left+right+top+bottom). Additionally, a floating-point value is created to take the average of the sum. The remainder of the ativeTracking function is divided into six if else statements that correspond to each of the possible movements. Firstly, the program checks to see if the umbrella is correctly aligned, this is accomplished via an if statement that evaluates if each of the squares four side values is sufficiently close to the average of the four sides. This amounts to taking the absolute value difference between the average and each of the sides and using a minimum inequality threshold. For the prototype the experimentally determined value was that the difference between the average and each side should be at least 7.

Correct alignment can also be determined by keeping a previous sum variable that is updated after each sensor reading, if the previous sum is sufficiently close to the current sum (difference between both is < 10), this an indication that the umbrella is as aligned as it can be for a particular orientation but it may not be able to move further to equalize the average due to the angle restrictions. If the umbrella is deemed to be correctly aligned, then the LCD screen states as such, and the moveCounter is automatically set to 0 so that no other adjustments take place during this periodic interval.

The other four else if statements determine which side of the umbrella has the highest sensor readings, the side that is the highest indicates which direction the umbrella should be adjusted towards in attempt to balance out the sensors. Due to the configuration of the servo motors a different approach needs to be taken to adjust up/down versus left/right. The elbow motors direction of rotation aligns directly with left/right movements of the canopy, for this reason accomplishing left/right motions is trivial. Adjusting either left or right invokes the same mechanics with the only difference being the direction of rotation for the elbow motor, decrease to move left, increase to move right. Both the second and third else if statements function the same with only the difference in direction. In either case either left/right is evaluated to be greater than the other three sides, the LCD screen displays a message indicating the direction of the adjustment, the motor moves 1^o in the corresponding direction, and moveCounter is decreased by 1.

To achieve up/down movement of the canopy a different approach needs to be taken due to the configuration of the motors. If the umbrella needs to move up/down both the elbow motor and the base motor need to be moved simultaneously to pivot the umbrella such that the elbow motor aligns with the direction of the sun's movement. This technique essentially turns what was originally an up/down movement into a left/right movement by manipulating the configuration of the umbrella. The fourth and fifth else if statements first determine if the top/bottom sides have the highest values respectively. Depending on whether the left or right side is greater than the other this will determine the direction that the base motor needs to turn. For example, if the bottom side reads the highest value, and the left side has a higher sensor reading than the right, then the base and elbow motors will simultaneously decrease in position to turn the umbrella so that the left/right axis (and rotation of the elbow motor) is now aligned with what was previously the top/bottom axis. Ideally, the further the base rotates the more either the left or right side will be aligned with the sun and their sensor values will increase. Once necessary rotation in the base has been achieved, then further rotations are accomplished by the elbow motor. Figure 85 details the systems movements to accomplish a bottom-left movement.

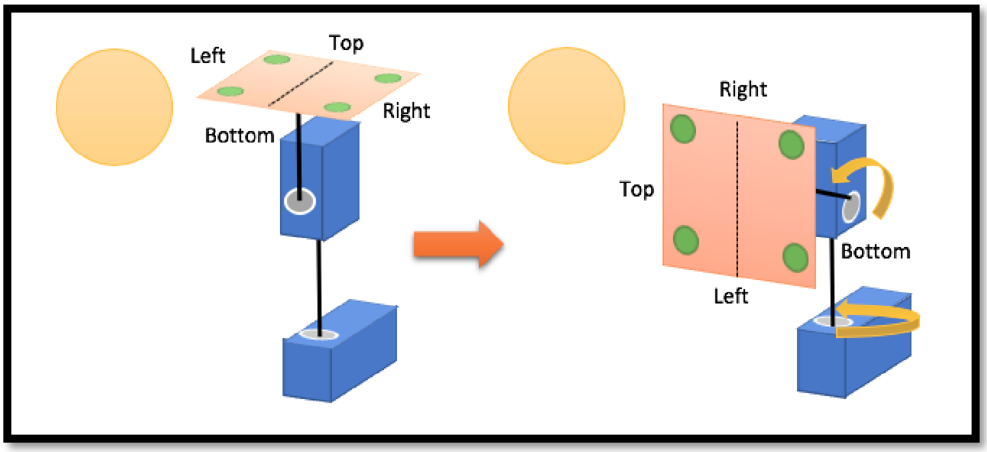


Figure 85: Bottom-Left Rotation Configuration

If the bottom side still possesses the highest sensor reading but instead the sun was more to the right of the umbrella, both motors would simultaneously increase in position to achieve a bottom-right rotation. For the cases where the top side has the highest readings, the elbow motor will rotate in the same direction as in the respective left/right bottom cases, but the base rotation will be reversed. For top-left rotation the elbow decreases while the base increases, and for top-right rotation the elbow increases while the base decreased. For each case, the base motor rotates 2^{o} while the elbow motor only moves 1^{o} per adjustment. The base is rotated faster so that the elbow motor will more quickly align with the sun and left/right motions will be used instead of the more complicated up/down, a step size only of 2^{o} is used as moving any larger reduces the smoothness of the umbrella's movements. After the specified number of adjustments has been made, moveCounter will equal zero, the LED will be turned off, and activeTracking is exited sending the program back into the infinitely repeating while loop within the main function. This process will continue for as long as the system is not interrupted, this is where the umbrellas final operation state comes into play.

4.2.5 Pause State

The umbrella's Pause State is the fourth major operational state and exists outside of the main program process flow. This state is essentially an interrupt that can be activated at any point in either the Calibration or Tracking States. The Pause State halts the execution of the program and pauses it indefinitely until the user either resumes or shuts the system down. Figure 86 depicts the process flow for the Pause State for reference.

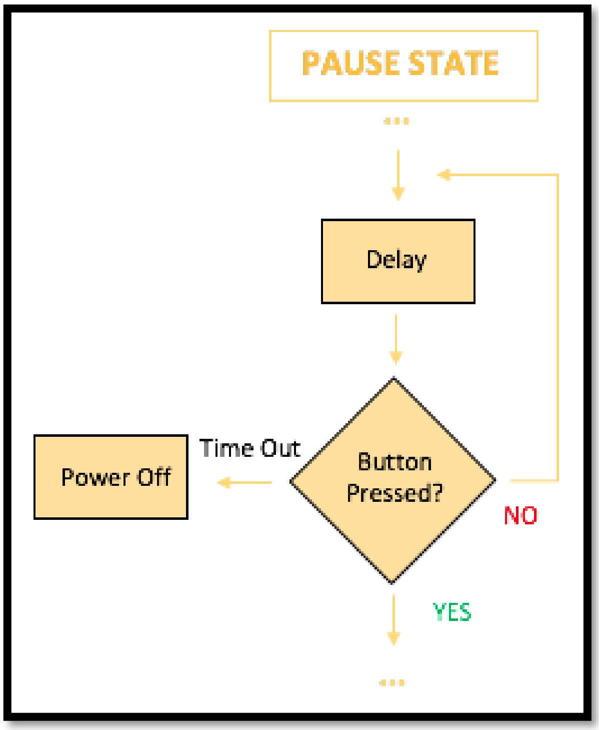


Figure 86: Pause State Process Flow Diagram

4.2.5.1 Pause Control Loop

As mentioned, the Pause State can be entered at any point in the execution of either the Calibration or Tracking states, this is accomplished by the user pressing the push button. Throughout the entirety of the programs code there are frequent checks on the status of the push button, if it is pressed down (LOW) then the pauseMode function is called. The system needs to respond to a press of the button in real time, therefore multiple short delays are used in the Tracking State instead of a single long delay. If the button is pressed during a delay the system will not notice this change in the input status until the delay has elapsed. Decreasing the length of the delays allows for the button press to be recognized in a more responsive manner.

Upon entering into pauseMode, a short descending jingle will play that signifies the system stopping, the LCD screen displays the message “Paused, press button to resume”, the LED will turn off, and a few local variables will be initialized, these being pauseTracker which is used to exit pauseMode, and shutdownCounter and shutdownMarker both of which are utilized to bring the umbrella into its shutdown state. There are two while loops within pauseMode, the first is used to handle the shutdown condition, and the second to exit pauseMode. The first while loop is entered if the button is still pressed down. For the duration that the button is pushed a timer is counted using the shutdownCounter, if the button is held for 5 seconds then using the shutdownMarker the system resets both motors back to a neutral 90^{o} position, the LCD screen displays the message “Please power off...”, and the program enters into an inescapable while loop where the system can be safely taken offline. For the prototype this is accomplished by simply removing the USB cable from the power source. This is also the method used to reset the system in any scenario where the umbrella cannot find or is no longer tracking the sun. The system can be shut down from pauseMode and safely restarted to recalibrate.

The second while loop within pauseMode is automatically entered if the push button is not pressed down, it evaluates the value of the previously inialized pauseTracker variable. Within this while loop the program will simply wait via a short delay until an if statement that looks for the button to be pressed again is satisfied. Once the button is pressed the pause jingle will be played in the reverse order to signify the resuming and the system will wait until the pause button has been released as a logical safety measure. After the button has been released the LED will turn on and pauseTracker will be changed to exit the repeating while loop. The pauseMode function will be exiting and the program will continue operating as noraml from the point after which the button was initially pressed.

4.2.6 Additional Function – Play

An additional function not core to any of the major process operating states is play. This is the function that is used to command the buzzer to play short musical jingles. This function was adapted from an example provided from [15]. The function takes as input the specific note and number of beats for the duration of the note. From within the play function an array is utilized that matches the frequencies of specific tones to the names of notes. As it is currently configured, the umbrella can play the tones of a two-octave C major scale ranging in frequency from 131 Hz (C3) to 494 Hz (B4). The length of a single beat in [ms] is multiplied by the subdivision of a beat that is entered into the function. The buzzer then plays at the specified frequency for the desired duration. Four jingles are utilized to provide audio cues that inform the user of the umbrellas state.

Upon powering on the umbrella, a start-up jingle will play that signifies that the device is ready to be interacted with by the user. Figure 87 is the musical notation of the start-up jingle.

Figure 87: Start-Up Jingle

A jingle is played when pressing the push button to enter into the Calibration State. This calibration jingle mimics a countdown typical for the starting of a race. This allows the user time to step away from the umbrella a safe distance before it begins calibrating. The musical notation of the calibration jingle is show in Figure 88.

Figure 88: Calibration Countdown Jingle

When entering the Pause State a descending jingle play. This pause jingle mimics the shutdown tones of many electronic devices and lets the user know that the umbrella is in a suspending state. The musical notation of the pause jingle is show Figure 89.

Figure 89: Pausing Jingle

The last jingle is played when leaving the Pause State. This resume jingle is the reverse of the pause jingle and uses the same notes and rhythm in ascending order to signify that the device will begin resuming its operation. The musical notation of the resume jingle is shown in Figure 90.

Figure 90: Resuming Jingle

4.2.7 Alterations / Customizability

Throughout the code there are many instances where the client may wish to alter the functionality of the system. The code as it is currently written is tuned for the specific purpose of using the prototype for proof-of-concept demonstrative purposes. When scaled up to the commercial version, many considerations must be made to tailor the systems performance towards a larger, user friendly, functional device. Many of the changes may only be determined through experimentation, therefore the purpose of this section is to highlight the areas of interest that may need to be considered for alteration for the commercial version.

4.2.7.1 Performance Constraining Constants

The first category of items are the constants that directly affect how the device operates. These include things like control variables that dictate how often a procedure will repeat, to the length of delays that will control the speed and smoothness of operation. Depending on the performance characteristics of the motors that are chosen for the commercial version, if possible, it may be beneficial to reduce the step size of the angular increments to the minimum precision that the motors are capable of. This will increase the umbrella's the smoothness of motion; due to the smaller step sizes it is also necessary to reduce the time of any delays between movement commands so that the speed of the system does not slow dramatically. The range of motion of the motors will also depend on the characteristics of the chosen models. If the base motor is capable of exceeding 180^{o} of rotation it would be beneficial to increase the limits set on all commands to the base in order to eliminate the small blind spots that exist in the prototype. The client may also find it necessary to alter the range of motion on the elbow motor, increasing the range of motion would allow for a greater potential area of coverage for the user but will also potentially position the umbrella in positions that may collide with the user or other objects. Lastly, the interval at which activeTracking is called and the number of moves that it makes per interval may be highly subjective. Ideally the umbrella should provide maximum and accurate coverage throughout as much of a day as possible while making the minimum number of adjustments. If the umbrella adjusts frequently and makes several moves to do so it will provide better coverage, but this may be annoying to a user having the umbrella constantly moving and making noise. The ideal combination of delayCount and moveCounter will need to be determined though experimentation with a completed commercial sized prototype.

4.2.7.2 Debugging

If a sensor or some other element becomes faulty it is then necessary to perform debugging procedures to diagnose problems in the system. A powerful tool to accomplish this is to make use of the Arduino IDE's serial monitor when connected to a computer. Using this tool data can be output to the user in real time to provide feedback of the data that is internal to the system. Data can be output to the serial monitor by using Serial.print commands in the programs code. A formatted section for debugging each sensors readings is included within the activeTracking function. A similar format to this block of code can be used elsewhere in the program to provide real time data whenever needed.

4.2.7.3 Flair Customization

The umbrella as currently programmed features a level of customizable aesthetics that the client may wish to change. This include the jingles that are played by the buzzer, messages displayed on the LCD screen, and color of the LED. The jingles can be easily composed using the play function and different themes can be written if desired. Currently the code also has commented out tones programmed to play each time the umbrella makes an adjustment during the Tracking State. The purpose of these beeps was to provide an audio cue of when the umbrella is moving for safety purposes, however this feature may possibly be too annoying to outweigh the potential benefits, as such these tones are currently commented out in the code. Each of the LCD messages can be easily changed to anything else that the client may desire, as long as they fit within the 16x2 character limit. Lastly, the LED currently included in the system was arbitrarily chosen to be green, the client may wish to alter this color choice to better match whatever aesthetic theme choices are made.

4.3 Commercial Umbrella Electronics and Software

Scaling up the umbrella to a full-sized commercial version places drastically different requirements on the systems electronic components. In order to manipulate a longer and heavier umbrella to the same level of precision and responsiveness as the prototype, vastly more powerful actuators need to be sourced and the electronic system overhauled to support them. In this section, the requirements for the commercial umbrella's actuators are calculated, acceptable motors are sourced and a detailed description of alterations that must be made to the system is provided.

4.3.1 Required torque

The major design parameter that will be used as the determining factor for selecting motors to use for the commercial umbrella is torque. Due to the sheer scale of the umbrella, sufficiently high torque motors are required to overcome the concentration of mass situated at the top of the umbrella. The required torque is further increased due to the long lever like linkage of the stand-top which extends the canopy a great distance from the motor. Determining the necessary torque required to manipulate the system can be analytically calculated by first making simplifying assumptions in order to reduce the systems complexity.

When analyzing the umbrella from the elbow the system can be broken into two concentrated masses. The stand-top, support fixture, support arms and required fasteners can be approximated as one mass, while the other concentrated mass is made up of the umbrella fixture, frame arms, cloth and fasteners. The torque required to move the system is a function of the masses of the system and the distances that each mass is located from the motor. The system should be analyzed with the motor rotated to its extreme limit as this is the condition for which maximum torque is required. The upper half of the stand can be considered as a simple rigid link (L_1) that is connected directly to the motor (M_1) with its mass concentrated at its midpoint (W_1). The mentioned canopy parts can be simplified to a point mass (W_2) located at the end of the stand-top. Figure 91 depicts the simplified representation of the system.

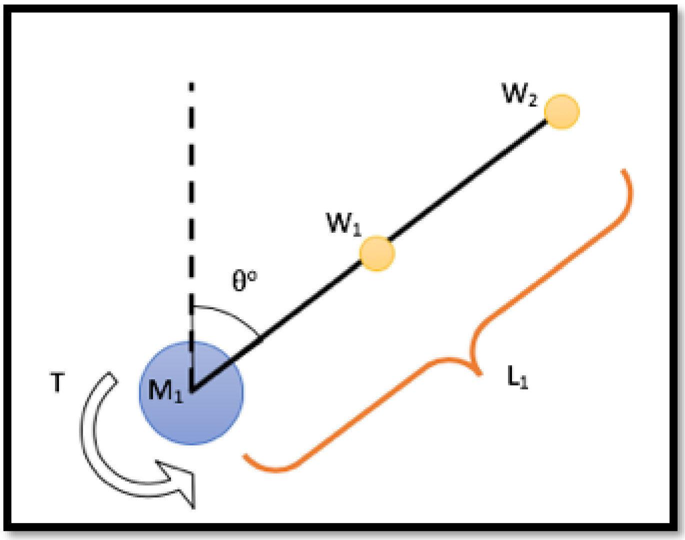


Figure 91: Elbow Motor Torque Diagram

Equation 23 is used to calculate the required torque of the system shown in Figure 91:

Equation 23 [2]

$$T = sin\theta * L_1 * (0.5W_1 + W_2)$$

Before solving Equation 23, it is important to first choose a standard set of units that are convention for describing motor torque. For the analyses in this section torque will be calculated in the units of [kg cm]. The dimensions of the system shown Figure 91 are summarized in TABLE X.

TABLE X: TORQUE DIAGRAM ABBREVIATIONS

Description	Abbreviation	Quantity
Motor 1	M_1	-
Length 1	L_1	137.16 [cm]
Mass 1	W_1	2 .2 [kg]
Mass 2	W_2	2.82 [kg]
Angle of Motor	θ	55°
Torque	T	?

Equation 23 can be solved to determine that the required torque at the elbow motor is 457.28 [kg cm]. Unfortunately, as will be discussed in Section 4.3.2, the selection of readily available servo motors that are capable of producing over 400 [kg cm] of torque is very limited, as such it is recommend that for the commercial umbrella the maximum angle of rotation for the elbow motor be limited instead to 45°. Although this slightly reduces the umbrella's possible range of motion, this change reduces the required torque to only 395 [kg cm] which is a more commonly available torque rating for a motor.

The methods used to determine the required torque for the elbow motor can also be applied to the base motor, however, the base motor similarly simplifies to the same system as described in Figure 91 with negligible differences. This is due to the lower half of the stand being in line with the base motor's axis of rotation as well as the elbow motor being mounted closely to this axis as well. Due to the simplifications of the systems geometry, and negligence of friction and inertia, the calculated torque is merely meant to serve as a guideline for sourcing appropriate motors. Determining the actual required torque for the system is highly dependent on a multitude of factors much of which cannot be accounted for in the general analysis of the commercial umbrella provided in this section.

4.3.2 Commercial Motors

Although torque is the most important attribute for consideration there are other factors that must be discussed before selecting an appropriate motor. By revisiting the client's needs as established in Section 1.3 the selection of available motors can be narrowed by type. To reiterate, it is vital that the overall design is simple, not overly heavy, it is also important that it is priced such that it is affordable to a wide market. High torque AC motors and geared stepper motors can provide the necessary torque, but they are more complicated to use due to requiring additional dedicated motor controllers to be positionally controlled and can be very heavy and expensive. DC servos can also provide the necessary torque, they are often lighter and comparatively cheap. Using a large DC servo would also allow for a more direct implementation of the logic and program described in Section 4.2 as they are controlled and function the same as those used utilized in the prototype. However, an additional microcontroller shield would need to be integrated in order to control these motors with the RedBoard/Arduino microcontroller and a larger external power source to power the motor.

The selection of available DC servo motors that can output 400 [kg cm] of torque is mostly limited to industrial grade products. A suitable motor suggestion is the Happymodel

Super 400 plus Robot Servo [20]. This motor requires a 24 V battery powered (recommended) input voltage and only weighs .765 [kg]. The motor also has a no-load speed of ~037s/60^{o} which is more than sufficient for the umbrella's purposes. Figure 92 is a picture of the motor.

Figure 92: Happymodel Super 400 plus Robot Servo [20]

4.3.3 Motor Shield

In order to control this motor with the RedBoard/Arduino a motor shield is required to protect the microcontroller from the high voltages that are required to power the motor. There are many such devices on the market. A suitable choice is the Arduino Compatible Mega Motor Shield developed by Robot Power [21]. This device utilizes an H-Bridge and is a low-cost method of powering the motor that allows for the convenience of programming with the Arduino IDE to preserved. Figure 93 is a picture of the motor shield.

Figure 93: Mega Motor Shield [21]

4.3.4 Battery

The final major component that requires revision for the commercial umbrella is the systems power source. To power the motors a 24 [V] power source is required, as instructed by the motors manufacturers battery power is recommended. Similar to the shield, there is a large selection of batteries on the market that would be suitable for the umbrella. Lithium-ion batteries, although more expensive than lead acid and other options, are capable of providing high weight and size to power ratios. Determining a specific battery relies on first being able to meet the systems requirements, then the major factors are capacity, size, weight and additionally rechargeability. Determining an estimated operating time in which it would take the system to drain a battery is entirely dependent on the specific batteries capacity usually rated in [Ah], or [mAh] and the intensity of the current pulling from the batteries load, in this case the servo motors. The current that the motors draw varies widely based on the amount of torque required to manipulate the system into any given position. Due to only stalling current (maximum drawn) and no-load current (minimum amount) being listed by the specified motors manufacturer, the estimated battery life for any one particular battery cannot be determined at this time. However, a general recommendation that meets the systems requirements is a High-Power Polymer Li-Ion 22.2 (average) [V] 10 [Ah] rechargeable battery from [22]. This 160x76x72[mm] battery is also lightweight at only 3.3 [lbs]. The battery is also rechargeable via a 22.2V Li/Polymer Battery Smart Charger [23]. Figure 94 is a picture of the battery.

Figure 94: High-Power Polymer Li-Ion Battery [22]

An additional power consideration is the source used to power the systems microcontroller. Due to the convenience of being able to use either a USB cable or a standard power jack many approaches can be taken to solve this problem. Either an additional external battery can be dedicated exclusively for the microcontroller, or the same battery can be shared between the motors although the voltage would need to be stepped down to not fry the board.

4.3.5 Additional Components

Outside of the major components previous discussed in this section, there is a range of smaller components and features that can either be directly carried over from the prototype or re-designed to accommodate the requirements of the commercial version. There are also entirely new components/features previously not included in the prototype that are worth consideration for inclusion in the commercial system.

4.3.5.1 Kill Switch

A deviation from the logic of the prototype is required to perform a full system shutdown for the commercial umbrella. For the prototype, after holding the push button for 5 [s] the system sets the motors to neutral and enters into an infinitely repeating delay where it is safe to remove the power from the microcontroller via unplugging the USB cable. For the commercial umbrella, the power is supplied via a battery stored in the base, in order to fully power off the system a kill switch needs to be integrated that can conveniently de-power both the motors and microcontroller.

4.3.5.2 Light Sensing

The LDRs utilized in the prototype were chosen due to their low cost and simplicity. They sufficiently served their purpose in being able to detect the sun accurately enough to develop the logic and algorithms for automated sun tracking. However, a wide range of advanced sensors can be used to improve the performance of the system. An integrated sensor such as [24] due to its onboard A/D converter can provide more precise readings directly in [lux]. A sensor such as [25] is designed specifically for the purposes of detecting ambient light and is able to detect much smaller changes in light than the LDRs used. Lastly, incorporating a UV detecting sensor such as [26] may be utilized to further validate intended directions of movement based off of light intensity alone. An important consideration when investigating additional and upgraded sensors is the limited amount of inputs on any microcontroller board. If required, an expansion to allow for more inputs or an entirely different board may be required.

4.3.5.3 Display/Interactive Components

The interactive and feedback components utilized in the prototype, namely the LCD screen, buzzer, push button and LED are all elements that can be directly carried over to the commercial umbrella, however, upgrades for each component can be made as required. Larger or touch sensitive display screens may be utilized to display more information to the user or to replace the bush button. More aesthetically pleasing buttons can also be integrated with a marginal increase in cost. Larger and more powerful LEDs and buzzers can also be utilized in conjunction with potentiometer control that is able to control the intensity of each element.

5. User Instructions

This section of the report contains condensed step-by-step instructions detailing how the umbrella is taken from a closed in-active state, to an open and operable state. The instructions are as follows:

1. Base Placement – Determine the desired location to place the umbrella's base. Adjust base legs to level if placed on uneven ground using the bubble level attached to the base.
    - Note: For best performance orient the base such that the umbrella's elbow motor's angle of rotation tracks with the approximate trajectory of the sun.

2. Assembly – Place umbrella into base and secure with tightening screw. Figure 95 displays the umbrella inserted into the base highlighting both the level and tightening screw.

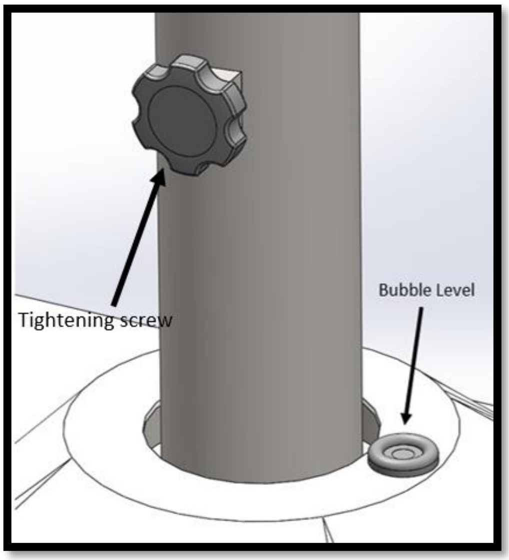


Figure 95: Umbrella Assembly Instruction

3. Open – Raise sliding collar to open umbrella arms, secure in place with locking screw. Figure 96 displays how to extend the umbrella's arms.

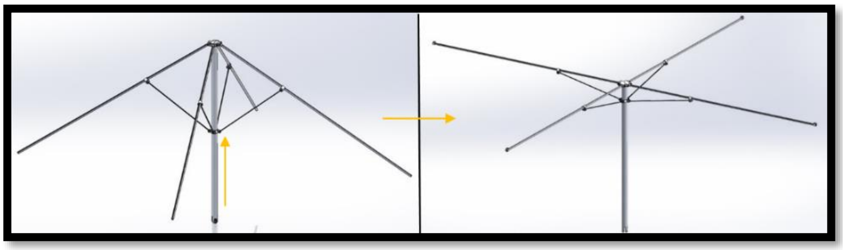


Figure 96: Opening of Umbrella Arms

4. Power On – Activate power to umbrella system
    - Powering up the system will play a start-up jingle and the LCD screen informs user to press push button to start the system.

5. Start – Press push button to activate umbrella
    - A count down jingle plays alerting the user of umbrella's movement
    - For safety, please follow the instructions displayed on LCD screen and do not stand in the way of the umbrella during calibration

6. Calibration – In order to locate the sun, the umbrella will perform a series of wide sweeping motions
    - This procedure takes approximately 10-15 [s]
    - After calibrating the umbrella will position itself in an orientation that directly faces the sun

7. Active Tracking – The umbrella will continue to automatically track the sun for as long as the system is active

8. Pause – To pause the system while in either the calibration or tracking states press and release the push button
    - Resume – Pressing the push button again while paused will allow the umbrella to resume from its previous state
    - Power Off – Holding the pause button for 5 [s] upon initial press will place umbrella into a suspended state where it can be safely powered off

9. Re-Calibration – If umbrella ever loses the position of the sun simply power off and on again and restart the calibration procedure.

6. Bill of Materials

Commercial Umbrella Bill of Materials					
Part Number	Part Name	Accessible	Price per Distance/Unit	Amount Used	Total Price
Base					
T111212	1 1/2" x 1 1/2" 12ga A513 Steel Square Tubing	MetalsDepot.com	$77.28 per 12'	26'	$167.44
T13414	3/4" x 3/4" 14ga A513 Steel Square Tubing	MetalsDepot.com	$13.08 per 12'	12'	$13.08
T2W212065	2 1/2" OD x 16ga A513 Steel	MetalsDepot.com	$43.56 per 4'	18"	$16.34
T11216	1/2" x 1/2" x 16ga A513 Steel	MetalsDepot.com	$3.34 per 2'	2'	$3.34
90596A039	5/8" Steel Round-Base Weld Nut	Mcmaster-carr.com	$8.41 for 10	8	$6.73
90596A240	1/4" Steel Round-Base Weld Nut	Mcmaster-carr.com	$5.70 for 50	1	$0.11
6103K85	Swivel Leveling Mount	Mcmaster-carr.com	$14.76 each	4	$59.04
92620A828	5/8" Zinc Yellow-Chromate Plated Hex Head Screw	Mcmaster-carr.com	$8.16 each	4	$32.64
91363A250	5/8" Oversized-Grip Screw-Head Mount Knob	Mcmaster-carr.com	$16.88 each	4	$67.52
91185A839	1/4" Plastic-Head Thumb Screw	Mcmaster-carr.com	$8.38 each	1	$8.38
6677K51	15mm Tapered-Roller Bearing with Steel Ring	Mcmaster-carr.com	$31.19 each	1	$31.19
92470A242	Phillips Rounded Head Screws for Sheet Metal	Mcmaster-carr.com	$7.17 for 100	12	$0.86
22325A11	High-Temperature Circular Mountable Level	Mcmaster-carr.com	$10.70 each	1	$10.70
6484K134	XL Series Timing Belt, Trade No. 240xL025	Mcmaster-carr.com	$5.55	1	$5.55
				Total:	**$422.92**
Stand					
9056K13	OD 2" Thickness 0.25" Tube 6 ft	Mcmaster-carr.com	$115.67	1	$115.67
9246K524	6" x 12" Thickness 7/16" Sheet	Mcmaster-carr.com	$28.98	1	$28.98
9056K16	OD 2.25" Thickness 0.25" Tube 6ft	Mcmaster-carr.com	$132.10	1	$132.10
91185A839	1/4" Plastic-Head Thumb Screw	Mcmaster-carr.com	$8.38	1	$8.38
8752K833	6"x12" Thickness 1/4" Sheet	Mcmaster-carr.com	$7.7	3	$23.10
90046A109	8-32 3/8" length	Mcmaster-carr.com	$10 for 25	4	$2.00
				Total:	**$310.23**
Canopy					
92290A620	Type 316 SS Socket Head Cap Screw	Mcmaster-carr.com	$3.56 each	8	$28.48
92290A630	Type 316 SS Socket Head Cap Screw	Mcmaster-carr.com	$4.20 each	4	$16.80
94150A360	Type 316 Stainless Steel Hex Nut	Mcmaster-carr.com	$6.45 for 5	12	$19.35
93482A916	Aluminum Rivet Nut	Mcmaster-carr.com	$6.51 for 25	1	$6.51
T3R34065	3/4 OD x .065 wall x .620 ID 6061 Aluminum Round Tube	MetalsDepot.com	$135.04 per 8 '	4	$540.16
SQ312	1/2 x 1/2 6061-T6511 Aluminum Square	MetalsDepot.com	$4.74 per 2'	1	$4.74
SQ314	1/4 x 1/4 6061-T6511 Aluminum Square	MetalsDepot.com	$6.40 per 4'	1	$6.40
8586K81	ABS Sheet 6"x6"1"	Mcmaster-carr.com	$180.00	3	$54.00
	100% Polyester Waterproof Taffeta Fabric	alibaba.com	$1.00 per m2	9	$9.00
				Total:	**$685.44**
Electronics					
33012017698	1PC Happymodel 400KG Large Servo	aliexpess.com	$129.84 each	2	$259.68
-	Arduino Compatible Mega Motor Shield 13A, 5-28V	robotshop.com	$39.99 each	1	$39.99
TE-119-222	High Power Polymer Li-Ion Module 22.2V 10Ah	superdroidrobots.com	$449.9 each	1	$449.90
TE-120-222	Smart Charger for 22.2V Li-Ion/Polymer Battery, 1.5A	superdroidrobots.com	$46.95 each	1	$46.95
15123	SparkFun RedBoard	sparkfun.com	$19.95 each	1	$19.95
00709	16x2 White-on-Black LCD	sparkfun.com	$18.95 each	1	$18.95
PDV-P8103-ND	Photocell 16-33 KOHM	digikey.ca	$0.96 each	4	$3.84
12062	LED - Assorted (20 pack)	digikey.ca	$3.30 each	1	$3.30
09806	Trimpot 10K Ohm with Knob	digikey.ca	$0.95 each	1	$0.95
07950	Mini Speaker - PC Mount 12 mm 2.048 kHz	digikey.ca	$1.95 each	1	$1.95
14460	Tactile Button	sparkfun.com	$1.60 each	1	$1.60
1236428	Sun Ultraviolet UV Spectral Intensity Sensor Module	banggood.com	$5.66 each	4	$22.64
				Total:	**$869.70**
				Full Total:	**$2,288.29**

Figure 97: Bill of Materials

7. Conclusion

For this project, our client Atom Jet Industries desired the design of a self-adjusting sun-tracking umbrella for their research and development division. To prove the validity of the design a small-scale fully-function prototype was created by our team to serve as a proof-of-concept. The prototype is capable of accurately determining the position of the sun and automatically adjust to track a moving light source to provide the optimal amount of shade. Additionally, a design for a full-scale commercial version of the umbrella was developed, including full CAD models, part drawings, and a detailed bill of materials. The elbow joint can bend to 55^o in either direction while still maintaining at least 4 [ft] of clearance from the ground. This design meets the clients design requirements in that it is simple to setup with minimal assembly, an adjustable sliding collar, and a simplistic user interface that utilizes only one button. The umbrella is lightweight, weighing only 44.02 [kg], and can be taken apart for storage and transport. The adjustable base allows for the umbrella to be placed on multiple surfaces. The system is equipped with an LCD screen to provide diagnostic information and a buzzer and LED to provide audio and visually cues respectively that alert and protect the user for when the system is in motion.

From the completion of this project, it is the intention of our team to submit the each of the deliverables with a sense of pride and accomplishment that the quality of the work produced will allow Atom-Jet to further develop this project in hopes of expanding the company into new markets.

8. Recommendations

Although our design did meet all the necessary requirements as specified by the client, there were a few concepts which we had envisioned but were not able to implement due to time constraints. Firstly, the backside of the bottom-stand was to be cut open to allow space for the motor fixture such that the entire top-stand could collapse into the bottom stand. This feature was implemented on the prototype however it was discovered that locking the two parts into place when fully extended placed a large amount of pressure on the structurally weakened bottom-stand where the motor fixture rests. This feature was removed from the commercial version due to not being able to properly re-design to increase the strength of the parts but if properly implemented this could further reduce the size of the umbrella when not in use. Secondly it was envisioned for the wiring to travel through the center of the hollow stand, however, the relative size of the wires on the prototype were far too large to fit through the scaled down components, coupled with the difficulty of not being able to accurately modeling pliable wires in the CAD software, it was difficult to determine how these wires would be affected by motion of the umbrella and properly design this feature. Storing the wires inside the system if implemented correctly would be ideal for their protection. Finally, in addition to incorporating the advanced sensors mentioned in Section 4.3.5.2, incorporating control of the motor's acceleration profiles would allow for even smoother movements.

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Appendices

LIST OF FIGURES

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Appendix A: Additional Design Requirements

This appendix contains a description for each of the umbrella's minor design requirements. These requirements are extra considerations that were suggested by the team. Since they were not explicitly requested by the client, emphasis was not placed on these design requirements for the success of the project.

Table 1: Additional Design Requirements

Design Requirement	**Description of Requirement**
Aesthetics	The design should be visually pleasing, sleek and modern.
Durable	The umbrella should be able to withstand a variety of loads without significant damage. Some of these loads could be caused by the wind, user interaction, or other weather induced forces.
Weather Resistant	The umbrella should be able to function properly during common weather events such as in the rain, in a windy environment or in mild to extreme heats and chills.
Affordable	The commercial design should be reasonably priced to be more affordable than current market alternatives, yet still within the price range of an average consumer.
Weight	The weight of the entire umbrella should be between 5 and 15 [kg].

Appendix B: Umbrella Calculations and Results

Contained within this appendix are the full detailed calculations required for the analyses and their results contained in this report. The calculations for the base's mass and length are included in sections: B.1, B.2, B.3 B.4. The calculations to determine the stand's material and dimensions are included in section B.5. The calculations for the deflection of the umbrella's arms are provided in section B.6.

B.1 Constant Wind Speed, Variable Angle

Umbrella Dimensions	Abbreviation	Size (feet)	Size (m)
Umbrella	$H_{umbrella}$	10.0	3.0
Top Stand	$H_{top\ stand}$	4.5	1.4
Bottom Stand	$H_{bottom\ stand}$	5.5	1.7
Base Width	H_{base}	3.5	1.0
Table Height	H_{table}	2.5	0.8

Constants	
Gravity	9.81
Average Wind Speed (m/s)	4.72
Air Density	1.229

	CONSTANT	VARIABLE										VARIABLE	CONSTANT	
Mass Top (kg)	Base Width	Base Width	Angle (deg)	Wind Speed (km/h)	Wind Speed (m/s)	Wetted Area (m^2)	Wind Force (N)	Wind Moment (Nm)	Top Moment (Nm)	Table Moment (Nm)	Mass Lower Stand (kg)	Mass Base (kg)	Mass Base + Stand (kg)	Mass Base (pounds)
3.14	1.00	0.00	0	17	4.72	0.00	0	0	0	0	5	-5.00	46.00	-11
3.14	1.00	0.16	5	17	4.72	0.78	21	49	4	17	5	2.32	46.00	5
3.14	1.00	0.31	10	17	4.72	1.56	43	98	7	34	5	9.44	46.00	21
3.14	1.00	0.46	15	17	4.72	2.33	64	144	11	51	5	16.18	46.00	36
3.14	1.00	0.59	20	17	4.72	3.08	84	187	15	67	5	22.35	46.00	49
3.14	1.00	0.71	25	17	4.72	3.80	104	226	18	83	5	27.81	46.00	61
3.14	1.00	0.81	30	17	4.72	4.50	123	261	22	99	5	32.39	46.00	71
3.14	1.00	0.89	35	17	4.72	5.16	141	290	25	113	5	36.00	46.00	79
3.14	1.00	0.95	40	17	4.72	5.79	159	313	28	127	5	38.55	46.00	85
3.14	1.00	0.98	45	17	4.72	6.36	174	330	30	140	5	39.97	46.00	88
3.14	1.00	0.98	50	17	4.72	6.89	189	340	33	151	5	40.25	46.00	89
3.14	1.00	0.97	55	17	4.72	7.37	202	344	35	162	5	39.40	46.00	87
3.14	1.00	0.92	60	17	4.72	7.79	214	342	37	171	5	37.45	46.00	82
3.14	1.00	0.86	65	17	4.72	8.16	224	333	39	179	5	34.49	46.00	76
3.14	1.00	0.77	70	17	4.72	8.46	232	320	41	185	5	30.61	46.00	67
3.14	1.00	0.67	75	17	4.72	8.69	238	301	42	191	5	25.95	46.00	57
3.14	1.00	0.56	80	17	4.72	8.86	243	278	42	194	5	20.65	46.00	45
3.14	1.00	0.43	85	17	4.72	8.97	246	251	43	197	5	14.88	46.00	33
3.14	1.00	0.30	90	17	4.72	9.00	247	222	43	197	5	8.82	46.00	19

Figure 1: Results of Constant Wind Speed, Variable Angle Analysis

B.2 Constant Wind Speed, Variable Angle

Umbrella Dimensions	Abbreviation	Size (feet)	Size (m)
Umbrella	$H_{umbrella}$	10.0	3.0
Top Stand	$H_{top\ stand}$	4.5	1.4
Bottom Stand	$H_{bottom\ stand}$	5.5	1.7
Base Width	H_{base}	3.5	1.0
Table Height	H_{table}	2.5	0.8

Constants	
Gravity	9.81
Average Wind Speed (m/s)	4.72
Air Density	1.229

	CONSTANT	VARIABLE										VARIABLE	CONSTANT	
Mass Top (kg)	Base Width	Base Width	Angle (deg)	Wind Speed (km/h)	Wind Speed (m/s)	Wetted Area (m^2)	Wind Force (N)	Wind Moment (Nm)	Top Moment (Nm)	Table Moment (Nm)	Mass Lower Stand (kg)	Mass Base (kg)	Mass Base + Stand (kg)	Mass Base (pounds)
3.14	1.00	0.00	0	17	4.72	0.00	0	0	0	0	5	-5.00	76.00	-11
3.14	1.00	0.14	5	17	4.72	0.78	21	49	4	0	5	5.82	76.00	13
3.14	1.00	0.28	10	17	4.72	1.56	43	98	7	0	5	16.42	76.00	36
3.14	1.00	0.42	15	17	4.72	2.33	64	144	11	0	5	26.59	76.00	58
3.14	1.00	0.54	20	17	4.72	3.08	84	187	15	0	5	36.11	76.00	79
3.14	1.00	0.66	25	17	4.72	3.80	104	226	18	0	5	44.81	76.00	99
3.14	1.00	0.76	30	17	4.72	4.50	123	261	22	0	5	52.51	76.00	116
3.14	1.00	0.84	35	17	4.72	5.16	141	290	25	0	5	59.08	76.00	130
3.14	1.00	0.91	40	17	4.72	5.79	159	313	28	0	5	64.41	76.00	142
3.14	1.00	0.97	45	17	4.72	6.36	174	330	30	0	5	68.42	76.00	151
3.14	1.00	1.00	50	17	4.72	6.89	189	340	33	0	5	71.07	76.00	156
3.14	1.00	1.02	55	17	4.72	7.37	202	344	35	0	5	72.35	76.00	159
3.14	1.00	1.02	60	17	4.72	7.79	214	342	37	0	5	72.29	76.00	159
3.14	1.00	1.00	65	17	4.72	8.16	224	333	39	0	5	70.95	76.00	156
3.14	1.00	0.97	70	17	4.72	8.46	232	320	41	0	5	68.42	76.00	151
3.14	1.00	0.92	75	17	4.72	8.69	238	301	42	0	5	64.81	76.00	143
3.14	1.00	0.86	80	17	4.72	8.86	243	278	42	0	5	60.27	76.00	133
3.14	1.00	0.79	85	17	4.72	8.97	246	251	43	0	5	54.96	76.00	121
3.14	1.00	0.71	90	17	4.72	9.00	247	222	43	0	5	49.05	76.00	108

Figure 2: Results of Constant Wind Speed, Variable Angle Analysis

B.3 Constant Angle, Variable Wind Speed with No Table Attached

Umbrella Dimensions	Abbreviation	Size (feet)	Size (m)
Umbrella	$H_{umbrella}$	10.0	3.0
Top Stand	$H_{top\ stand}$	4.5	1.4
Bottom Stand	$H_{bottom\ stand}$	5.5	1.7
Base Width	H_{base}	3.5	1.0
Table Height	H_{table}	2.5	0.8

Constants	
Gravity	9.81
Average Wind Speed (m/s)	4.72
Air Density	1.229

	CONSTANT	VARIABLE										VARIABLE	CONSTANT	
Mass Top (kg)	Base Width	Base Width	Angle (deg)	Wind Speed (km/h)	Wind Speed (m/s)	Wetted Area (m^2)	Wind Force (N)	Wind Moment (Nm)	Top Moment (Nm)	Table Moment (Nm)	Mass Lower Stand (kg)	Mass Base (kg)	Mass Base + Stand (kg)	Mass Base (pounds)
3.14	1.00	0.00	0	17	4.72	0.00	0	0	0	0	5	-5.00	76.00	-11
3.14	1.00	0.14	5	17	4.72	0.78	21	49	4	0	5	5.82	76.00	13
3.14	1.00	0.28	10	17	4.72	1.56	43	98	7	0	5	16.42	76.00	36
3.14	1.00	0.42	15	17	4.72	2.33	64	144	11	0	5	26.59	76.00	58
3.14	1.00	0.54	20	17	4.72	3.08	84	187	15	0	5	36.11	76.00	79
3.14	1.00	0.66	25	17	4.72	3.80	104	226	18	0	5	44.81	76.00	99
3.14	1.00	0.76	30	17	4.72	4.50	123	261	22	0	5	52.51	76.00	116
3.14	1.00	0.84	35	17	4.72	5.16	141	290	25	0	5	59.08	76.00	130
3.14	1.00	0.91	40	17	4.72	5.79	159	313	28	0	5	64.41	76.00	142
3.14	1.00	0.97	45	17	4.72	6.36	174	330	30	0	5	68.42	76.00	151
3.14	1.00	1.00	50	17	4.72	6.89	189	340	33	0	5	71.07	76.00	156
3.14	1.00	1.02	55	17	4.72	7.37	202	344	35	0	5	72.35	76.00	159
3.14	1.00	1.02	60	17	4.72	7.79	214	342	37	0	5	72.29	76.00	159
3.14	1.00	1.00	65	17	4.72	8.16	224	333	39	0	5	70.95	76.00	156
3.14	1.00	0.97	70	17	4.72	8.46	232	320	41	0	5	68.42	76.00	151
3.14	1.00	0.92	75	17	4.72	8.69	238	301	42	0	5	64.81	76.00	143
3.14	1.00	0.86	80	17	4.72	8.86	243	278	42	0	5	60.27	76.00	133
3.14	1.00	0.79	85	17	4.72	8.97	246	251	43	0	5	54.96	76.00	121
3.14	1.00	0.71	90	17	4.72	9.00	247	222	43	0	5	49.05	76.00	108

Figure 3: Results of Constant Angle, Variable Wind Speed with No Table Attached

B.4 Constant Wind Speed, Variable Angle with No Table Attached

Umbrella Dimensions	Abbreviation	Size (feet)	Size (m)
Umbrella	$H_{umbrella}$	10.0	3.0
Top Stand	$H_{top\ stand}$	4.5	1.4
Bottom Stand	$H_{bottom\ stand}$	5.5	1.7
Base Width	H_{base}	3.5	1.0
Table Height	H_{table}	2.5	0.8

Constants	
Gravity	9.81
Average Wind Speed (m/s)	4.72
Air Density	1.229

	CONSTANT	VARIABLE										VARIABLE	CONSTANT	
Mass Top (kg)	Base Width	Base Width	Angle (deg)	Wind Speed (km/h)	Wind Speed (m/s)	Wetted Area (m^2)	Wind Force (N)	Wind Moment (Nm)	Top Moment (Nm)	Table Moment (Nm)	Mass Lower Stand (kg)	Mass Base (kg)	Mass Base (kg)	Mass Base (pounds)
3.14	1.00	0.09	55	0	0.00	7.37	0	0	35	0	5	2.20	76.00	5
3.14	1.00	0.17	55	5	1.39	7.37	17	30	35	0	5	8.27	76.00	18
3.14	1.00	0.41	55	10	2.78	7.37	70	119	35	0	5	26.48	76.00	58
3.14	1.00	0.81	55	15	4.17	7.37	157	268	35	0	5	56.82	76.00	125
3.14	1.00	1.37	55	20	5.56	7.37	280	476	35	0	5	99.30	76.00	218
3.14	1.00	2.09	55	25	6.94	7.37	437	744	35	0	5	153.91	76.00	339
3.14	1.00	2.97	55	30	8.33	7.37	629	1072	35	0	5	220.66	76.00	485
3.14	1.00	4.01	55	35	9.72	7.37	856	1459	35	0	5	299.55	76.00	659
3.14	1.00	5.20	55	40	11.11	7.37	1119	1905	35	0	5	390.58	76.00	859
3.14	1.00	6.56	55	45	12.50	7.37	1416	2411	35	0	5	493.74	76.00	1086
3.14	1.00	8.08	55	50	13.89	7.37	1748	2977	35	0	5	609.04	76.00	1340

Figure 4: Results of Constant Wind Speed, Variable Angle with No Table Attached

B.5 Umbrella Stand Dimensional Calculations

	Diameter stand-top [in]	Diameter [m]	hickness [in	Thickness [m]	Moment of inertia [m^4]	mass of stand-top [kg]	moment stand-top [Nm]	Total moment [Nm]	shear stress [MPa]	Safety Factor
Aluminum-6061										
desity = 2700 kg/m^3	1	0.0254	0.25	0.00635	1.91547E-08	1.03	7.01	1107	733.97	0.33
Yield strength = 35,000psi=241.3165 Mpa	1.25	0.03175	0.25	0.00635	4.34174E-08	1.37	9.34	1109	405.62	0.59
Based on 30 km/h wind speed	1.5	0.0381	0.25	0.00635	8.30038E-08	1.71	11.68	1112	255.14	0.94
	1.75	0.04445	0.25	0.00635	1.41745E-07	2.05	14.02	1114	174.67	1.38
	2	0.0508	0.25	0.00635	2.23472E-07	2.39	16.35	1116	126.89	1.90
	Diameter stand-top [in]	Diameter [m]	hickness [in	Thickness [m]	Moment of inertia [m^4]	mass of stand-top [kg]	moment stand-top [Nm]	Total moment [Nm]	shear stress [MPa]	Safety Factor
	1	0.0254	0.5	0.0127	2.04317E-08	1.37	9.34	1109	689.55	0.35
	1.25	0.03175	0.5	0.0127	4.98023E-08	2.05	14.02	1114	355.10	0.68
	1.5	0.0381	0.5	0.0127	1.02159E-07	2.74	18.69	1119	208.61	1.16
	1.75	0.04445	0.5	0.0127	1.85162E-07	3.42	23.36	1123	134.84	1.79
	2	0.0508	0.5	0.0127	3.06476E-07	4.10	28.03	1128	93.49	2.58
Stand top chosen	2	0.0508	0.25	0.00635	2.23472E-07	2.39	16.35	1949	221.57	1.09
Based on 40 km/h wind speed										
Maximum wind speed stand can bearing at maximum angle										

Figure 5: Umbrella Stand Dimensional Calculation Results

B.6 Umbrella Arm Deflection Analysis

In Figure 6: Free-Body Diagram of Arm with Forces, the resolved reaction supports and distributed load are shown:

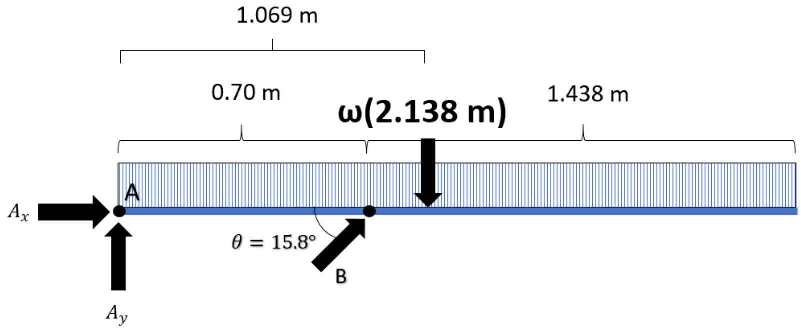


Figure 6: Free-Body Diagram of Arm with Forces

Applying a force equilibrium in the y-direction produces the following expression:

Equation 1

$$\sum F_y = 0 \rightarrow B \sin 15.8° - \omega(2.138) - A_y = 0$$

$$A_y = B \sin 15.8° - \omega(2.138)$$

Applying a moment equilibrium at point A produces the following expression:

Equation 2

$$\sum M_A = 0 \rightarrow (0.7)B \sin 15.8° - \omega(1.069)(2.138) = 0$$

$$B = \omega(11.991)$$

Solving for A_y:

$$A_y = \omega(11.991) \sin 15.8° - \omega(2.138) = 1.1269\omega$$

The moment distribution along the extended arm is determined by taking a section cut along the simulated beam. The section cut is shown in Figure 7:

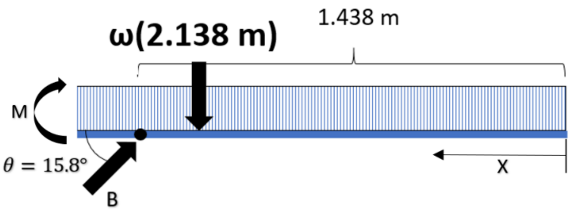


Figure 7: The Section Cut Along the Arm

Taking a moment about the section cut yields the following expression:

Equation 3

$$\sum M = 0 \rightarrow M + \frac{\omega x^2}{2} - B\sin 15.8°(x - 0.7) = 0$$

$$M(x) = -\frac{\omega x^2}{2} + 1.8075\omega(x - 0.7)$$

$$EI\frac{dy}{dx} = \int_0^x M(x) + C_1$$

Substituting Equation 3 into the expression that defines the slope of the deflection curve [1] of produces the following expression:

Equation 4

$$EI\frac{dy}{dx} = \int_0^x -\frac{\omega x^2}{2} + 1.8075\omega(x - 0.7) + C_1$$

$$EI\frac{dy}{dx} = -\frac{\omega x^3}{6} + \frac{1.8075\omega(x - 0.7)^2}{2} + C_1$$

Substituting Equation 4 into the equation that defines the deflection of the arm [1] produces the following expression:

Equation 5

$$EIy = \int_0^x \left(-\frac{\omega x^3}{6} + \frac{1.8075\omega(x - 0.7)^2}{2} + C_1\right)dx + C_2$$

$$EIy = -\frac{\omega x^4}{24} + \frac{1.8075\omega(x - 0.7)^3}{6} + C_1 x + C_2$$

Rearranging the expression to solve for the deflection:

Equation 6

$$y(x) = \frac{1}{EI}\left[\int_0^x \left(\int_0^x M(x) + C_1\right)dx + C_2\right]$$

$$y(x) = \frac{1}{EI}\left[-\frac{\omega x^4}{24} + \frac{1.8075\omega(x - 0.7)^3}{6} + C_1 x + C_2\right]$$

Applying boundary conditions (x = 1.438 [m]; y = 0 [m]):

$$0 = \frac{1}{EI}\left[-\frac{\omega(1.438)^4}{24} + \frac{1.8075\omega(1.438-0.7)^3}{6} + C_1(1.438) + C_2\right]$$

$$C_2 = 0.05708\omega - C_1(1.438)$$

Applying boundary conditions (x = 2.138 [m]; y = 0 [m]):

$$0 = \frac{1}{EI}\left[-\frac{\omega(2.138)^4}{24} + \frac{1.8075\omega(2.138-0.7)^3}{6} + C_1(2.138) + C_2\right]$$

$$C_2 = -0.02518\omega - C_1(2.138)$$

Equating the two expression of C_2 to solve for constant C_1:

Equation 7

$$0.05708\omega - C_1(1.438) = -0.02518\omega - C_1(2.138)$$

$$C_1(0.7) = -0.08226\omega$$

$$C_1 = -0.011751\omega$$

Solving for C_2:

Equation 8

$$C_2 = -0.02518\omega - 0.011751\omega(2.138) = 0.22606\omega$$

The resulting equation for the deflection of the arm is shown as:

Equation 9

$$y(x) = \frac{1}{EI}\left[-\frac{\omega x^4}{24} + \frac{1.8075\omega(x-0.7)^3}{6} - 0.011751\omega x + 0.22606\omega\right]$$

The calculations for deflection along the arm with the rectangular cross-sections are shown in Figure 8:

Distributed Load (w)	Mass (m)	Distance (x)	Deflection y(x)	Moment of Inertia (I)	Modulus of Elasticity (E)
1.718677128	0.37457	0	0.2292776	1.33333E-11	69000000000
		0.15	0.295712294		
		0.25	0.315845842		
		0.35	0.320185151		
		0.45	0.311546424		
		0.55	0.292559051		
		0.65	0.265665607		
		0.75	0.233121856		
		0.85	0.19699675		
		0.95	0.159172426		
		1.05	0.12134421		
		1.15	0.085020615		
		1.25	0.05152334		
		1.35	0.021987275		
		1.45	-0.002639508		
		1.55	-0.021595746		
		1.65	-0.034306991		
		1.75	-0.040385604		
		1.85	-0.039630764		
		1.95	-0.032028459		
		2.05	-0.017751491		
		2.15	0.002840526		

Figure 8: Deflection Results for Rectangular Cross-Section

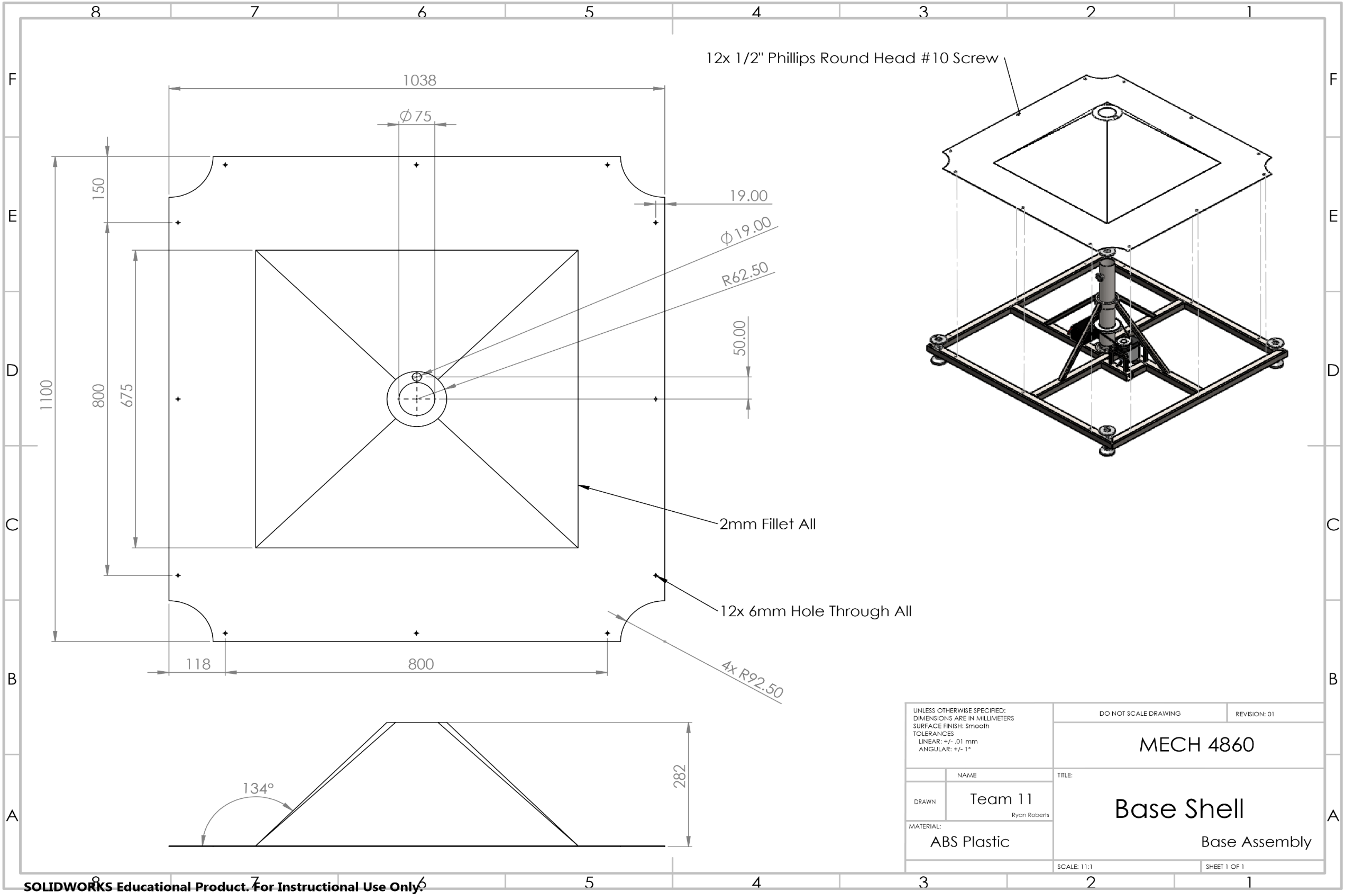
The calculations for deflection along the arm with the rectangular cross-sections are shown in Figure 9Figure 8:

Distributed Load (w)	Mass (m)	Distance (x)	Deflection y(x)	Moment of Inertia (I)	Modulus of Elasticity (E)
2.899869036	0.632	0	0.001496965	3.44566E-09	69000000000
		0.15	0.00193072		
		0.25	0.002062173		
		0.35	0.002090505		
		0.45	0.002034102		
		0.55	0.001910133		
		0.65	0.001734544		
		0.75	0.001522064		
		0.85	0.001286202		
		0.95	0.001039245		
		1.05	0.000792262		
		1.15	0.000555104		
		1.25	0.000336398		
		1.35	0.000143556		
		1.45	-1.72335E-05		
		1.55	-0.000141		
		1.65	-0.000223992		
		1.75	-0.00026368		
		1.85	-0.000258751		
		1.95	-0.000209115		
		2.05	-0.0001159		
		2.15	1.85459E-05		

Figure 9: Deflection Results for Hollow Cylinder Cross-Section

Appendix C: Drawings

Contained within this appendix are the detailed drawings for each design component featured in the commercial design.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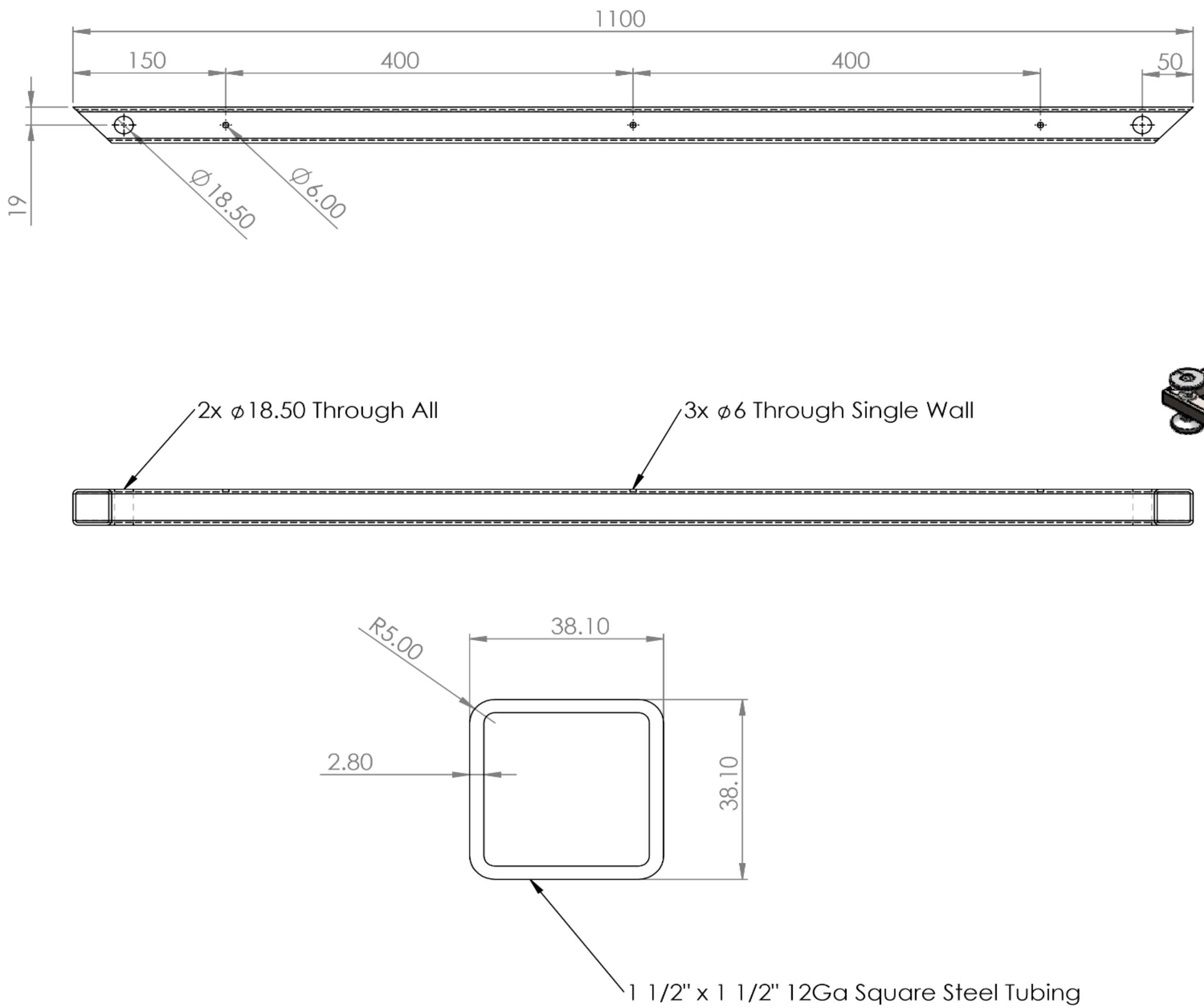
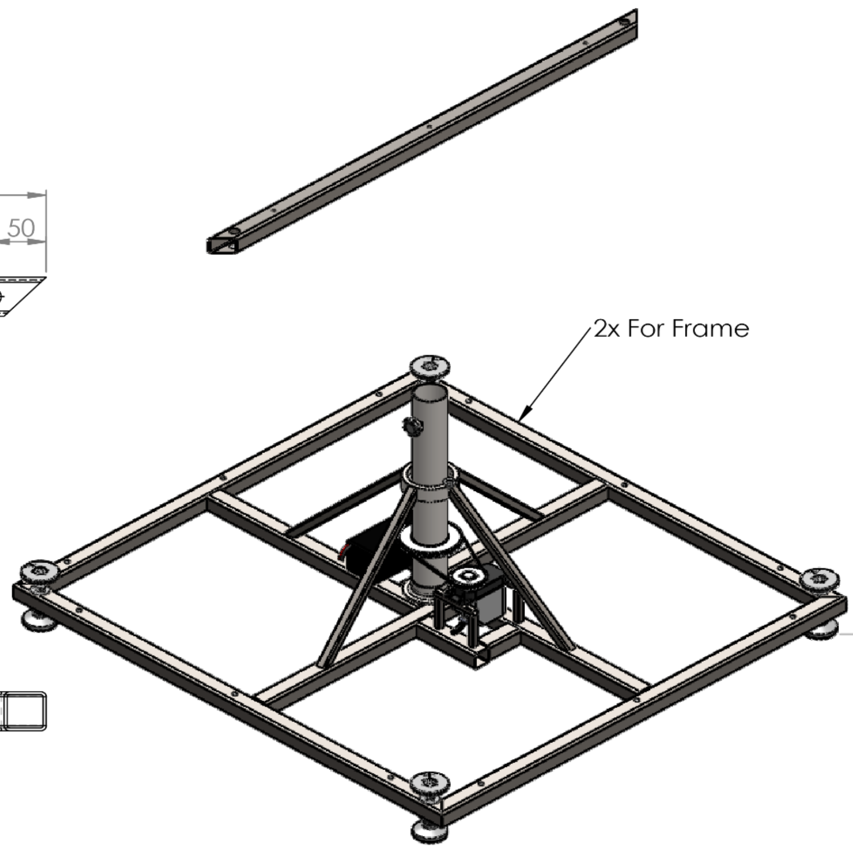
Ø19.00
R62.50
50.00
1100
800
675
2mm Fillet All
12x 6mm Hole Through All
118
800
4x R92.50
134°
282
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°
DO NOT SCALE DRAWING
REVISION: 01
MECH 4860
NAME
DRAWN
Team 11
Ryan Roberts
TITLE:
Base Shell
Base Assembly
MATERIAL:
ABS Plastic
SCALE: 11:1
SHEET 1 OF 1





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	MECH 4860	
NAME	TITLE:	
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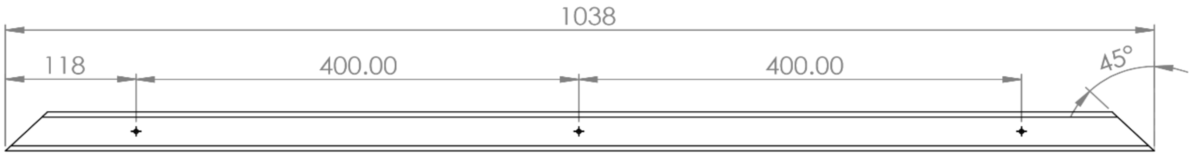
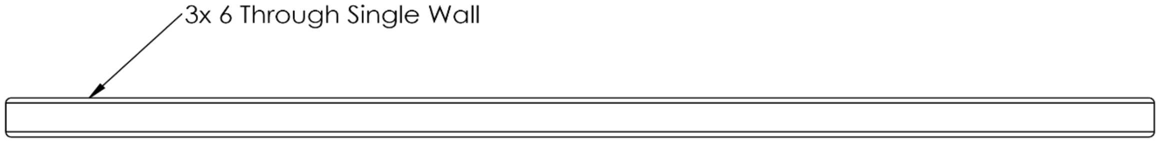
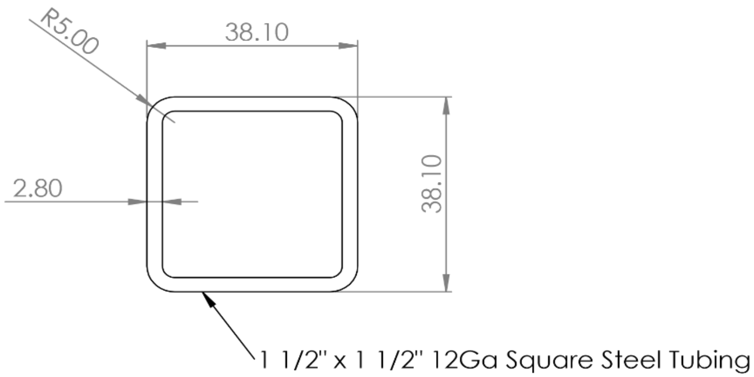
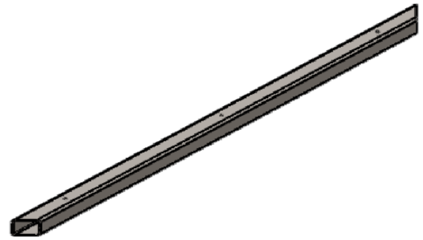
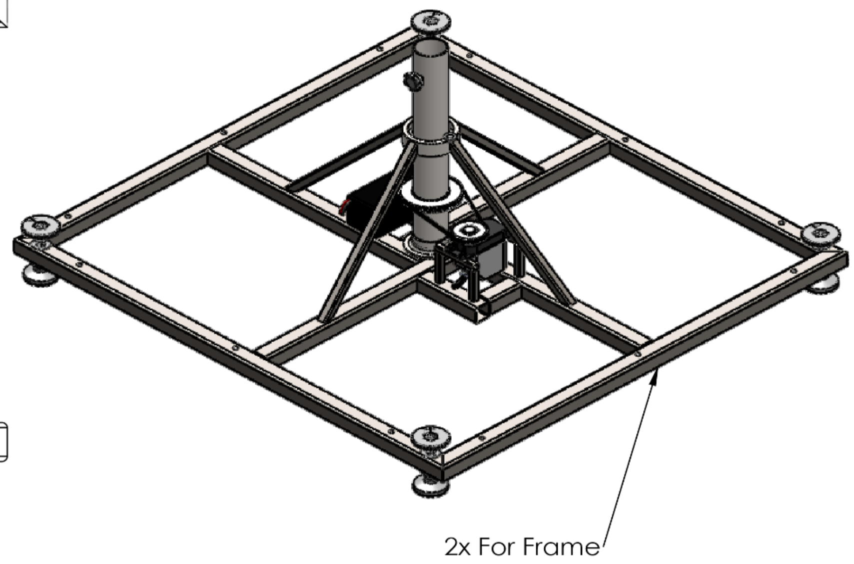
MATERIAL: A513 Steel	Base Assembly	
	SCALE: 11:1	SHEET 1 OF 1











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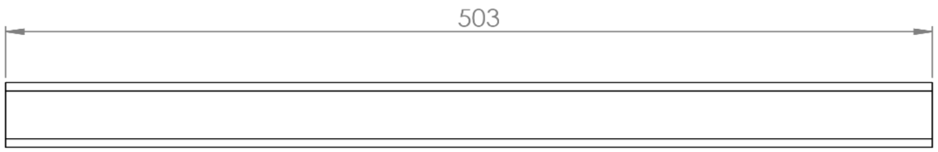
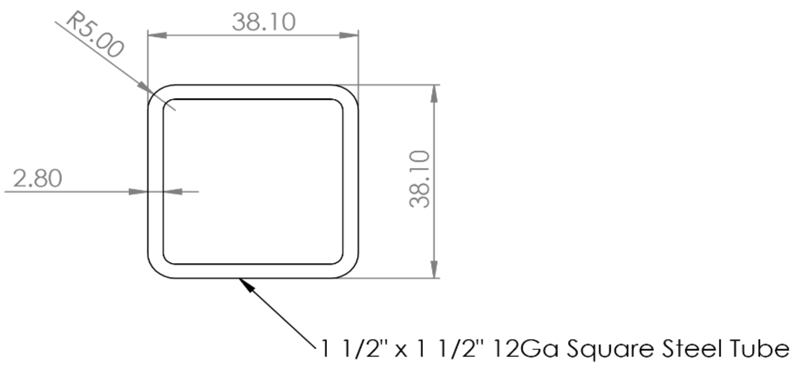
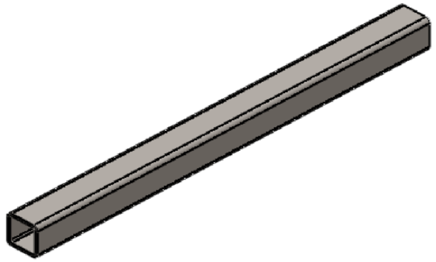
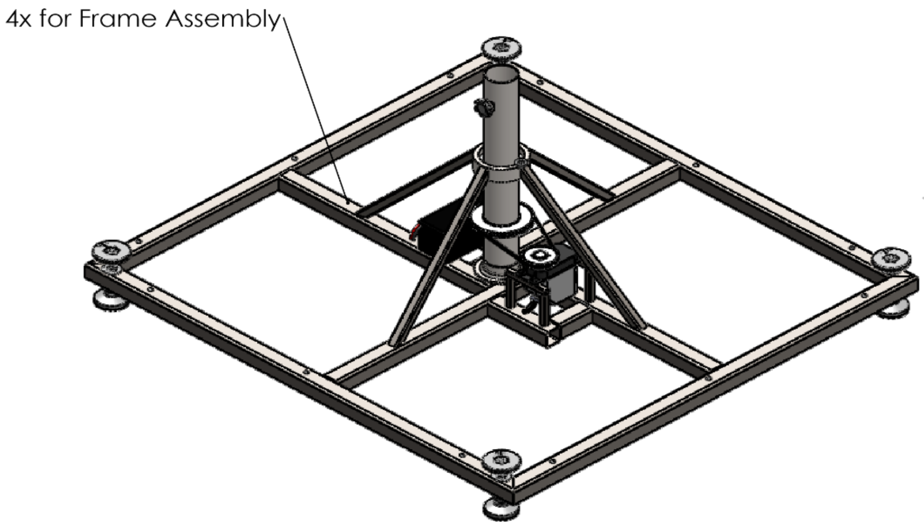
DRAWN	Team 11 Ryan Roberts	Base Frame Square Tube	
MATERIAL: A513 Steel		Base Assembly	
		SCALE: 11:1	SHEET 1 OF 1









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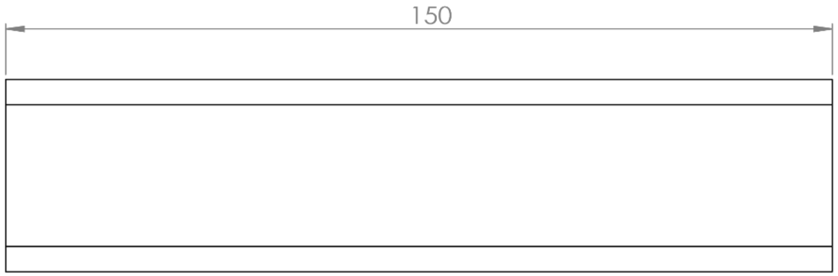
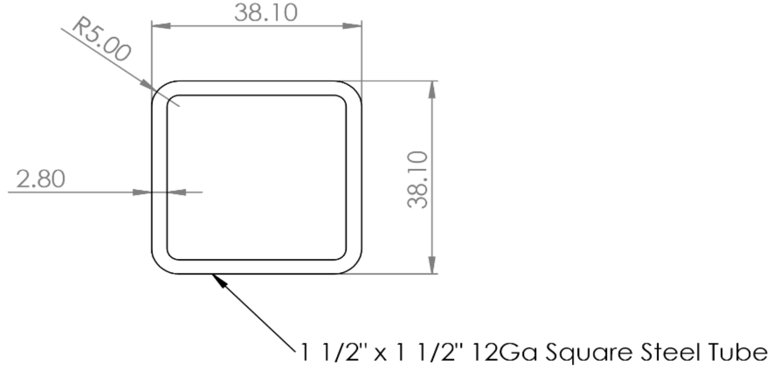
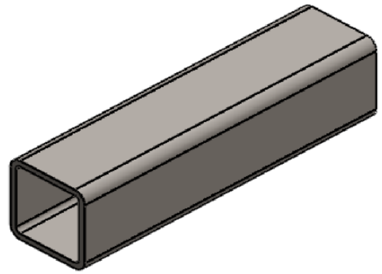
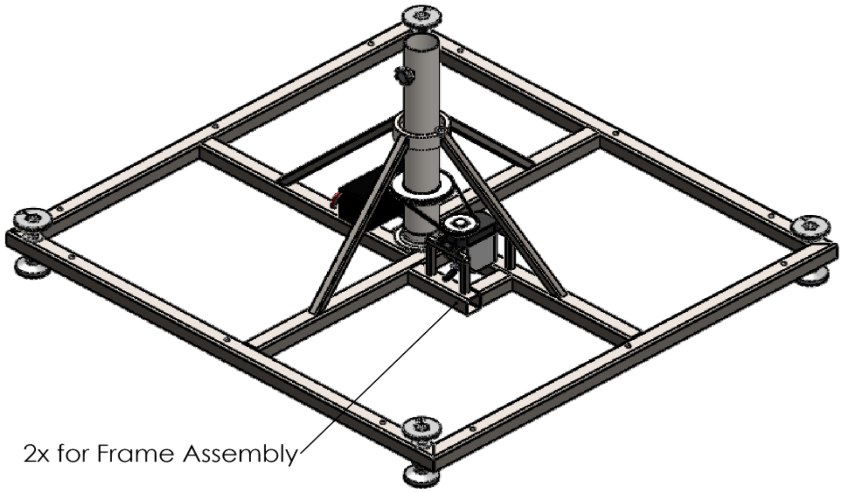
MATERIAL: A513 Steel	SCALE: 11:1 — SHEET 1 OF 1









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SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

TITLE:

Base Frame Motor Tube 1

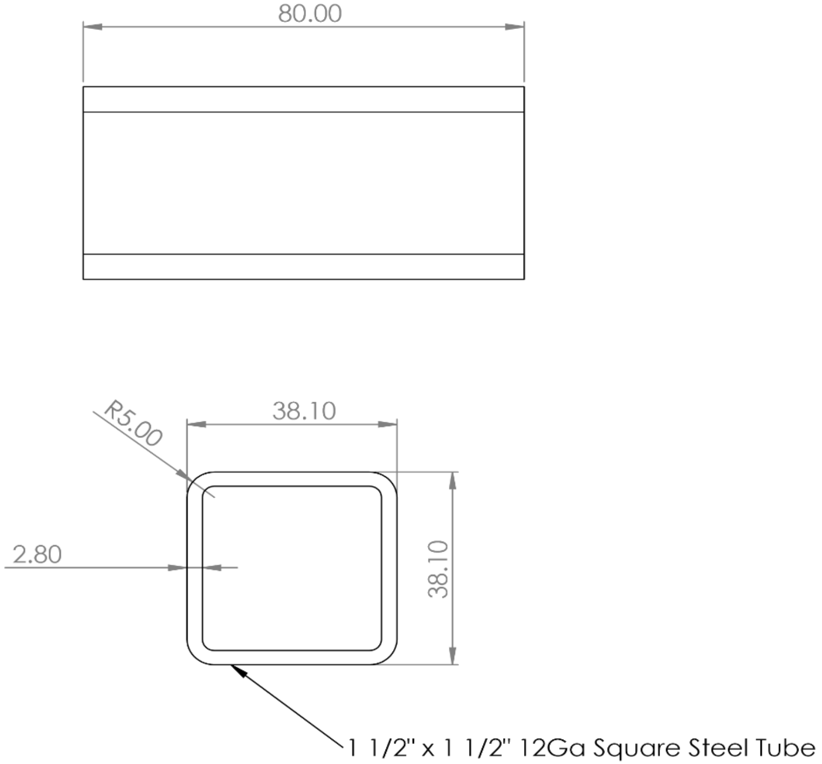
Base Assembly

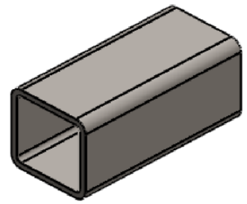
MATERIAL:

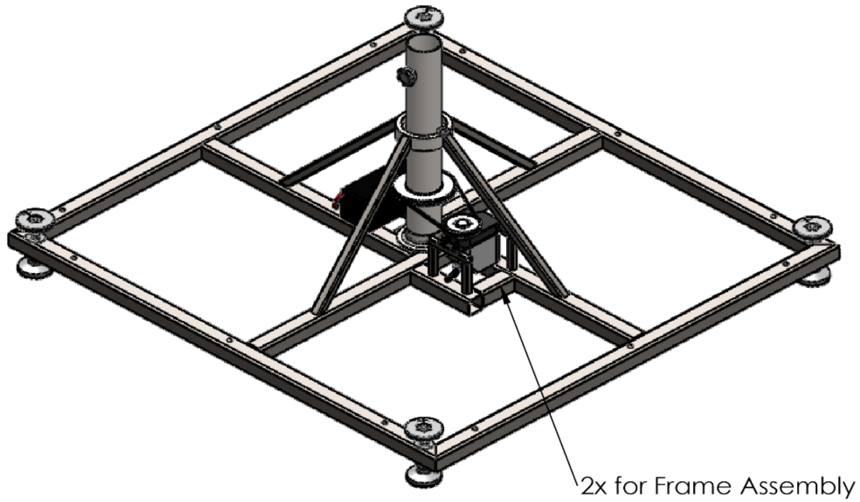
A513 Steel

SCALE: 11:1

SHEET 1 OF 1







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ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

TITLE:

Base Frame Motor Tube 2

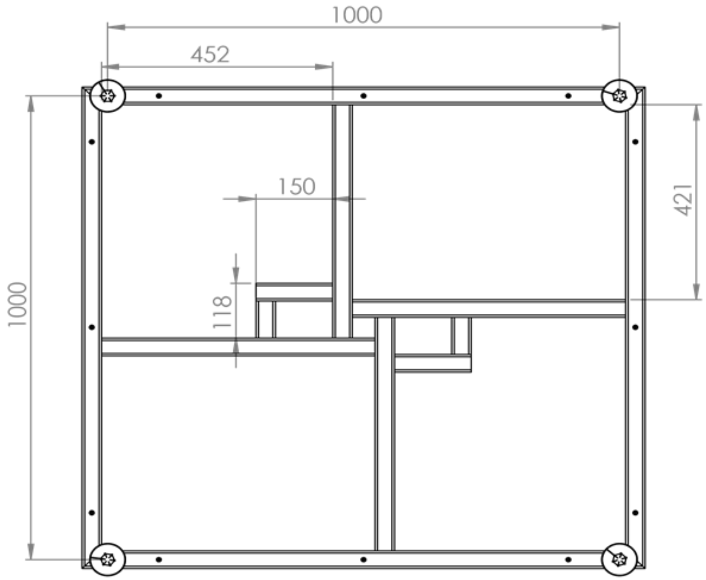
Base Assembly

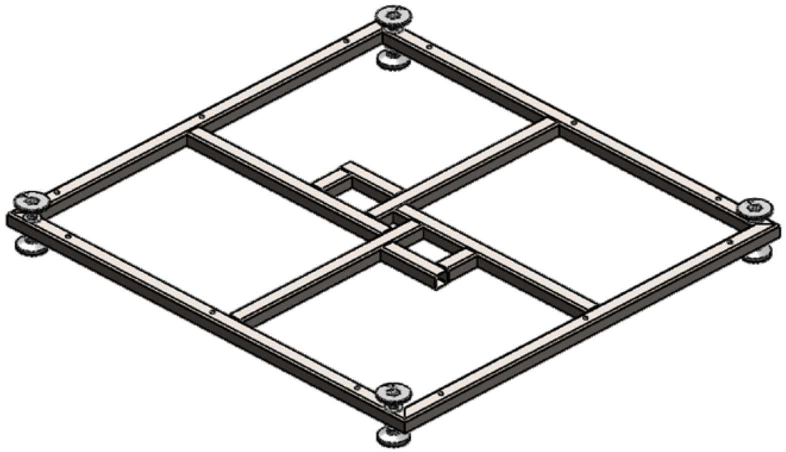
MATERIAL:

A513 Steel

SCALE: 11:1

SHEET 1 OF 1





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DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

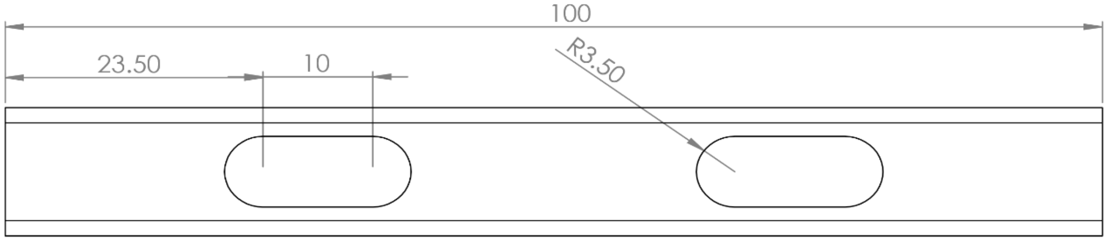
TITLE:

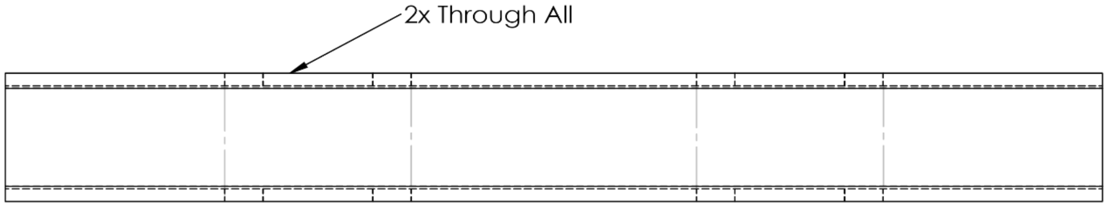
Base Frame Assembly

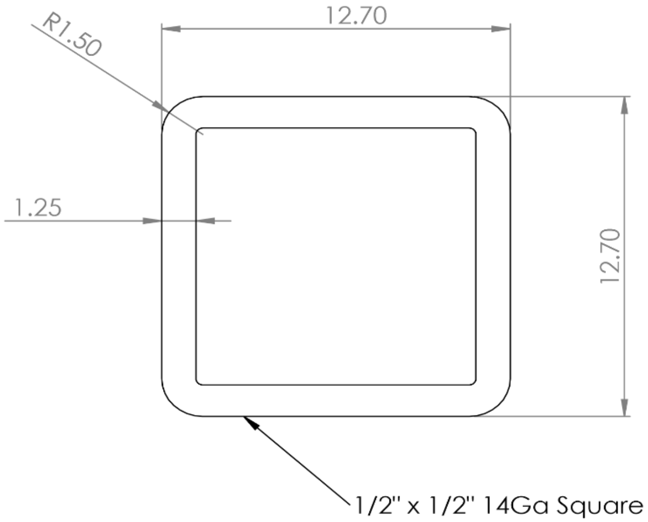
MATERIAL:
A513 Steel

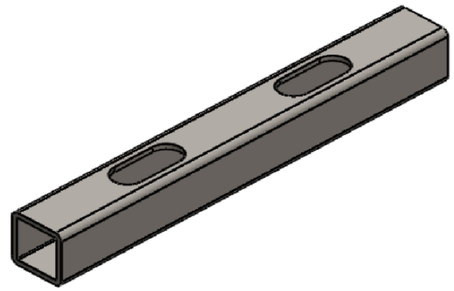
SCALE: 11:1

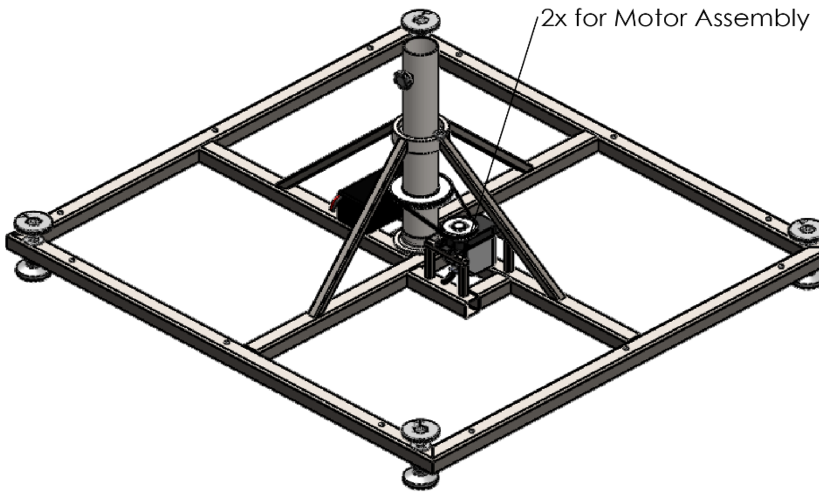
SHEET 1 OF 1











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ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

TITLE:

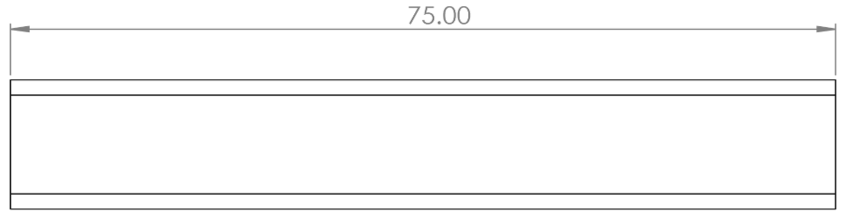
Motor Horizontal Support

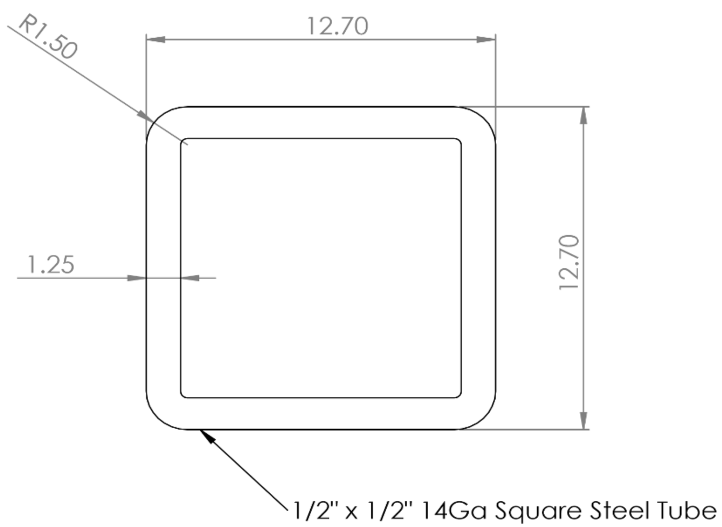
Base Assembly

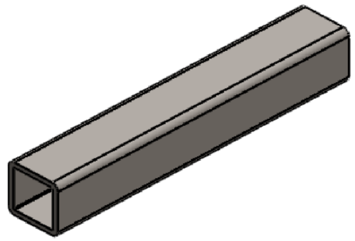
MATERIAL:
A513 Steel

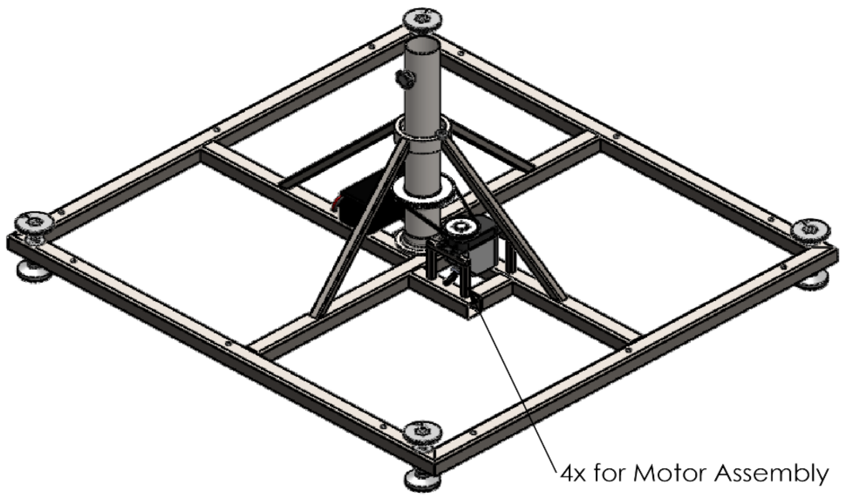
SCALE: 11:1

SHEET 1 OF 1









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TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

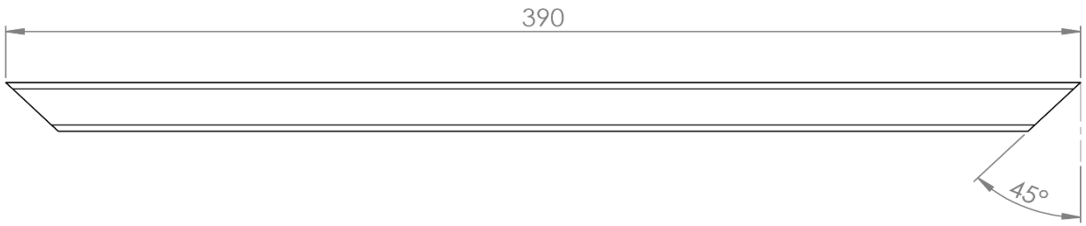
MECH 4860

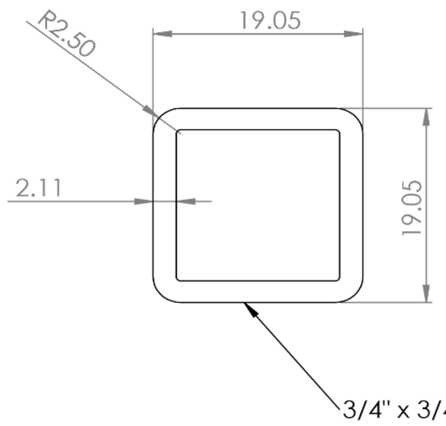
	NAME
DRAWN	Team 11 Ryan Roberts

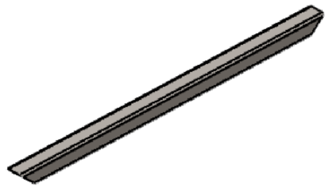
MATERIAL:
A513 Steel

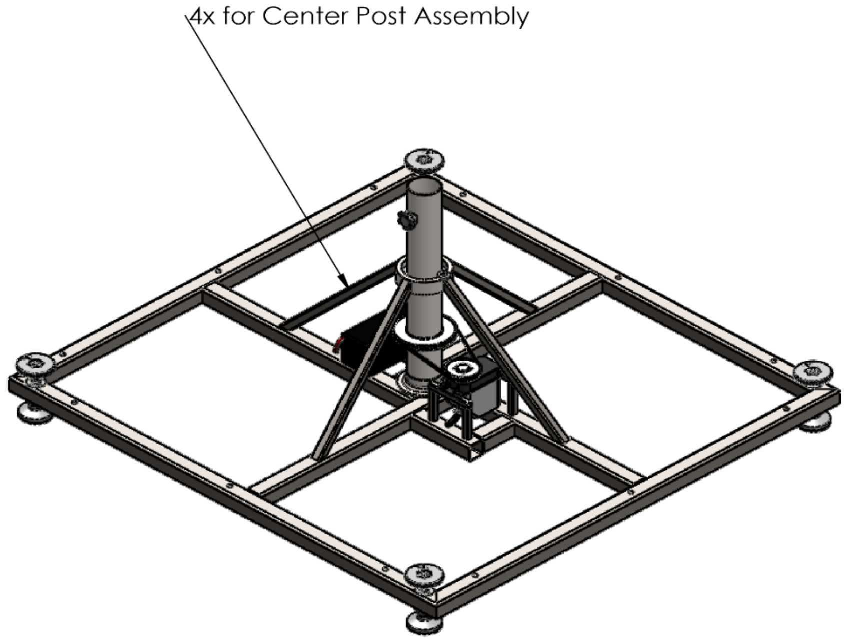
TITLE:
Base Motor Vertical Support
Base Assembly

SCALE: 11:1 SHEET 1 OF 1









UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°		DO NOT SCALE DRAWING	REVISION: 01
		MECH 4860	
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DRAWN	Team 11 Ryan Roberts	Bushing Support Arm	
MATERIAL: A513 Steel		Base Assembly	
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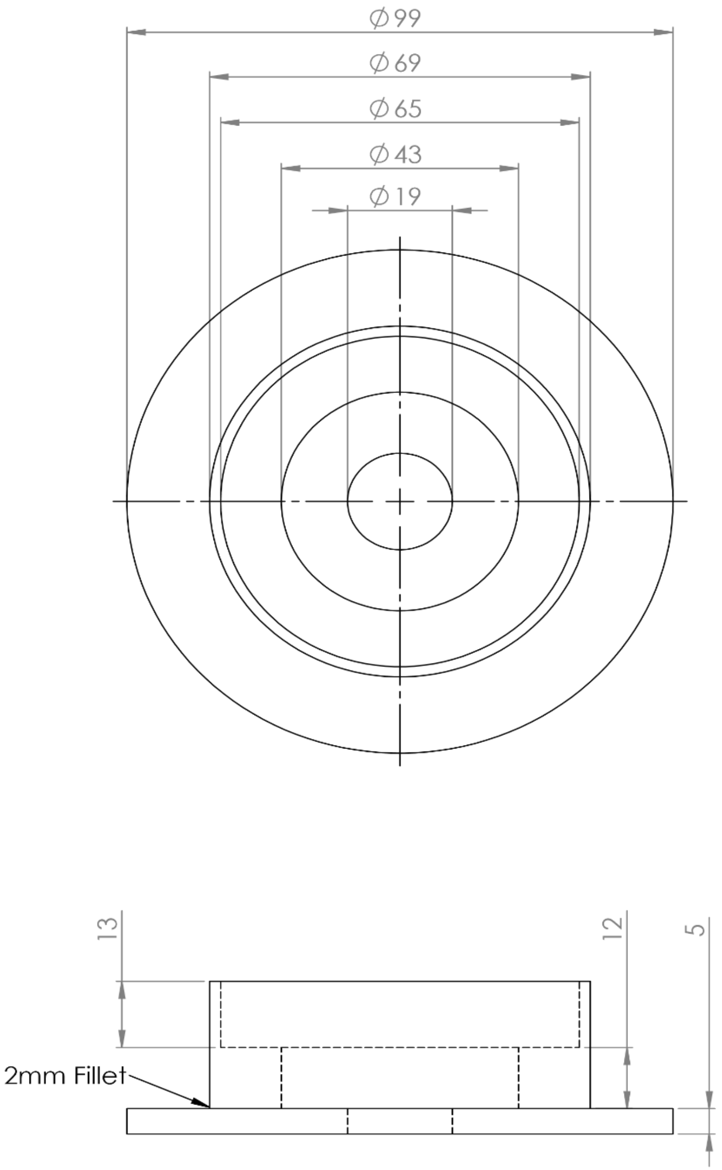

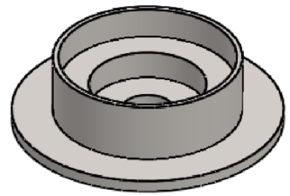

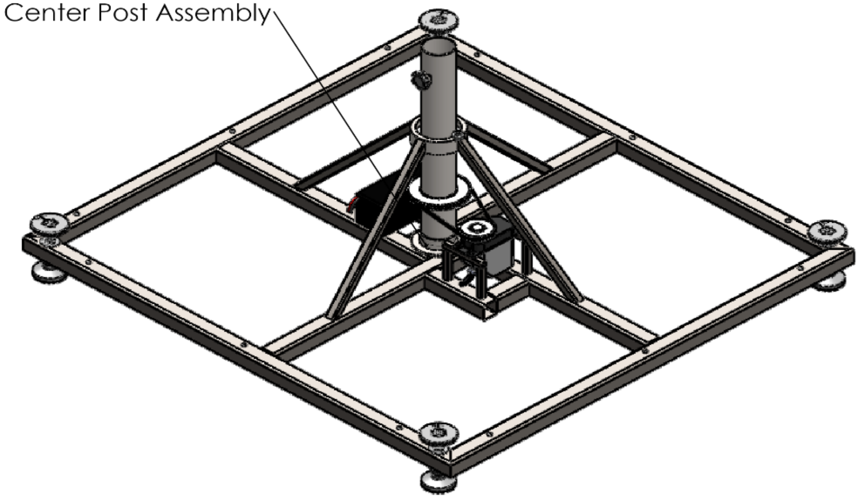

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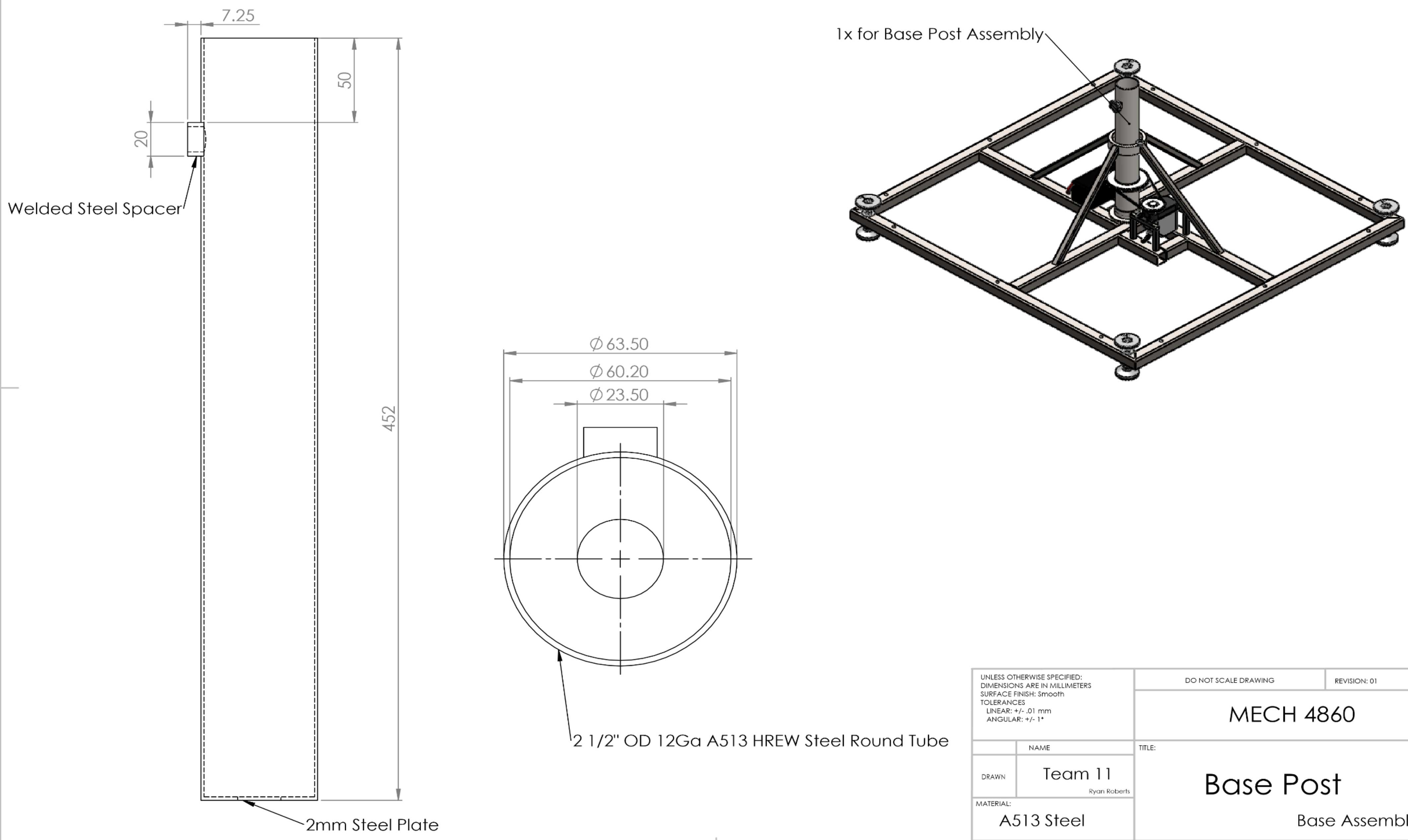
MATERIAL: Plain Carbon Steel	SCALE: 11:1	SHEET 1 OF 1



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	MECH 4860	
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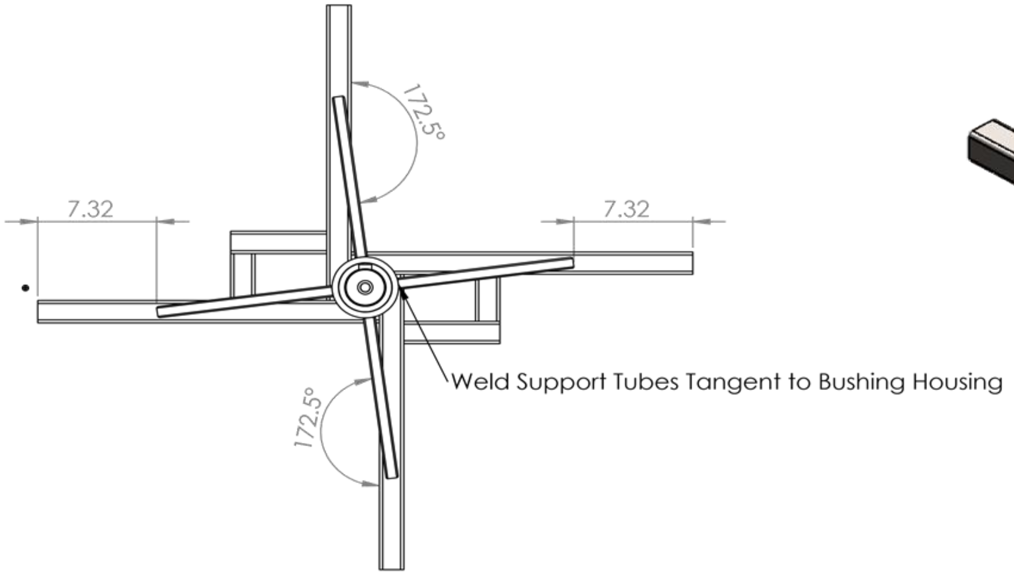
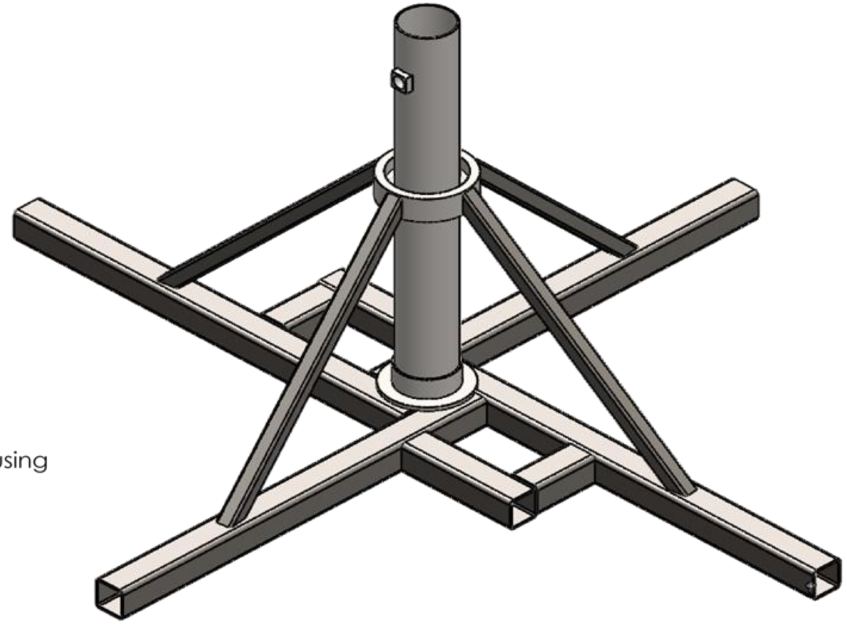
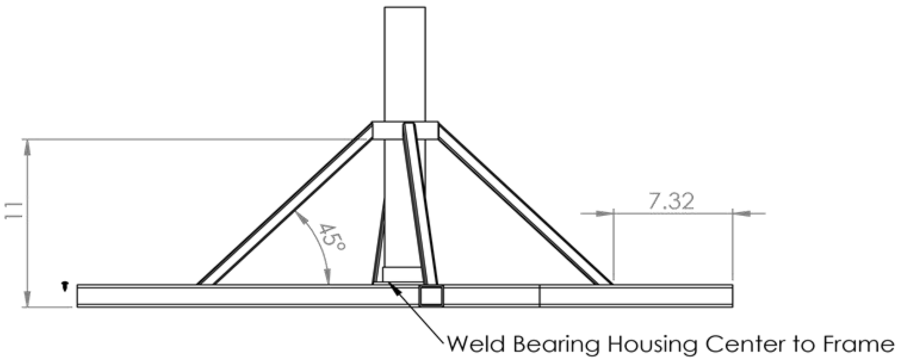
DRAWN: Team 11 (Ryan Roberts)	Base Post	
MATERIAL: A513 Steel	Base Assembly	
	SCALE: 11:1	SHEET 1 OF 1







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TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

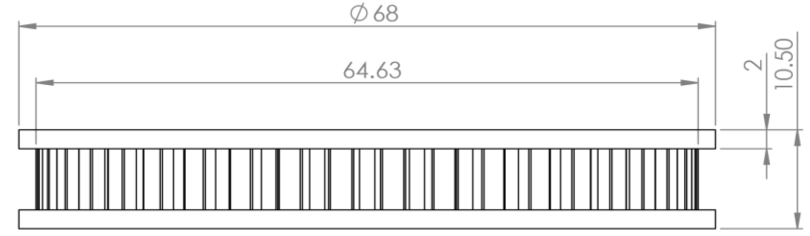
TITLE:

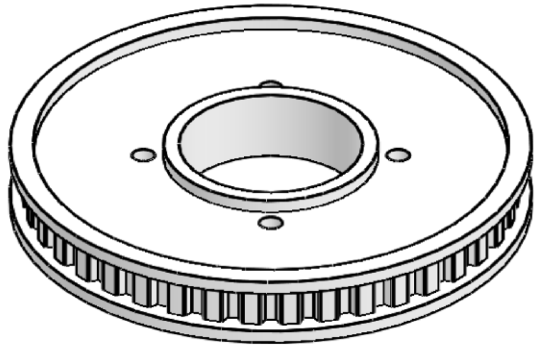
Rotating Post Assembly

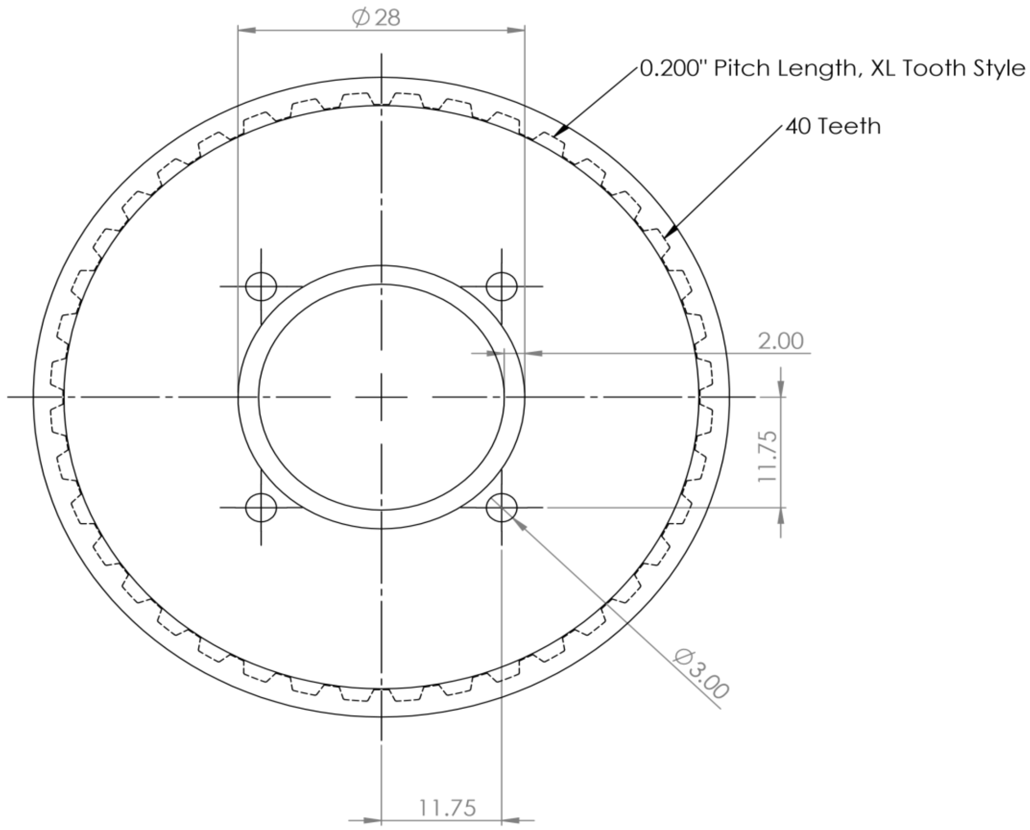
MATERIAL:
A513 Steel

SCALE: 11:1

SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11 Ryan Roberts

MATERIAL:
ABS Plastic

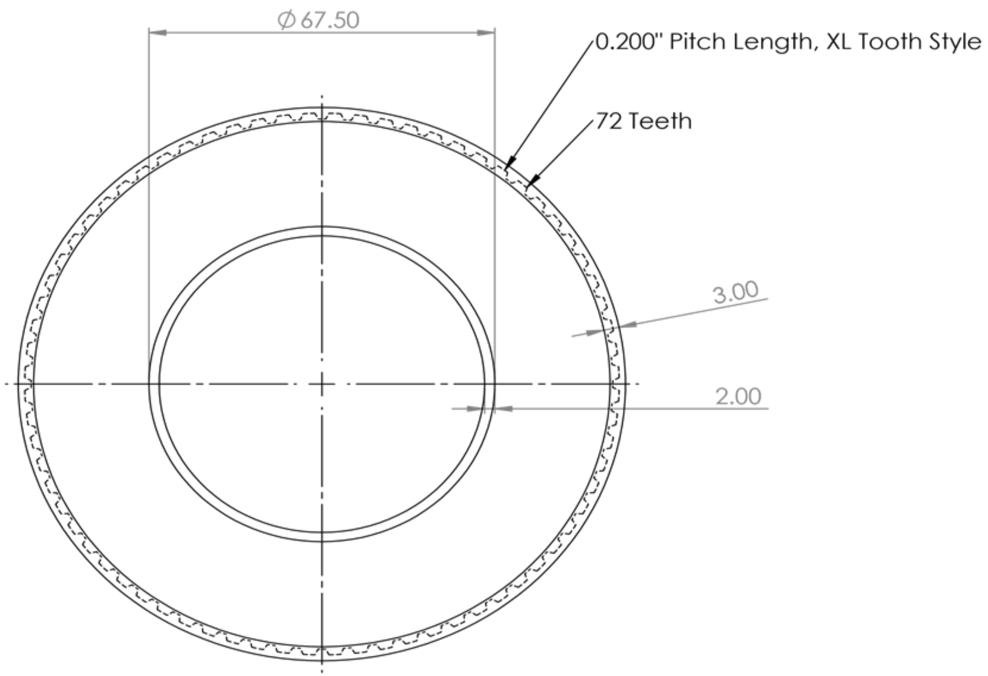
TITLE:

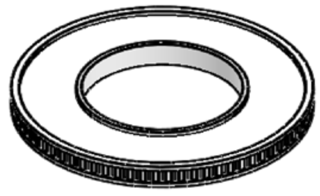
Motor Mount Gear

Base Assembly

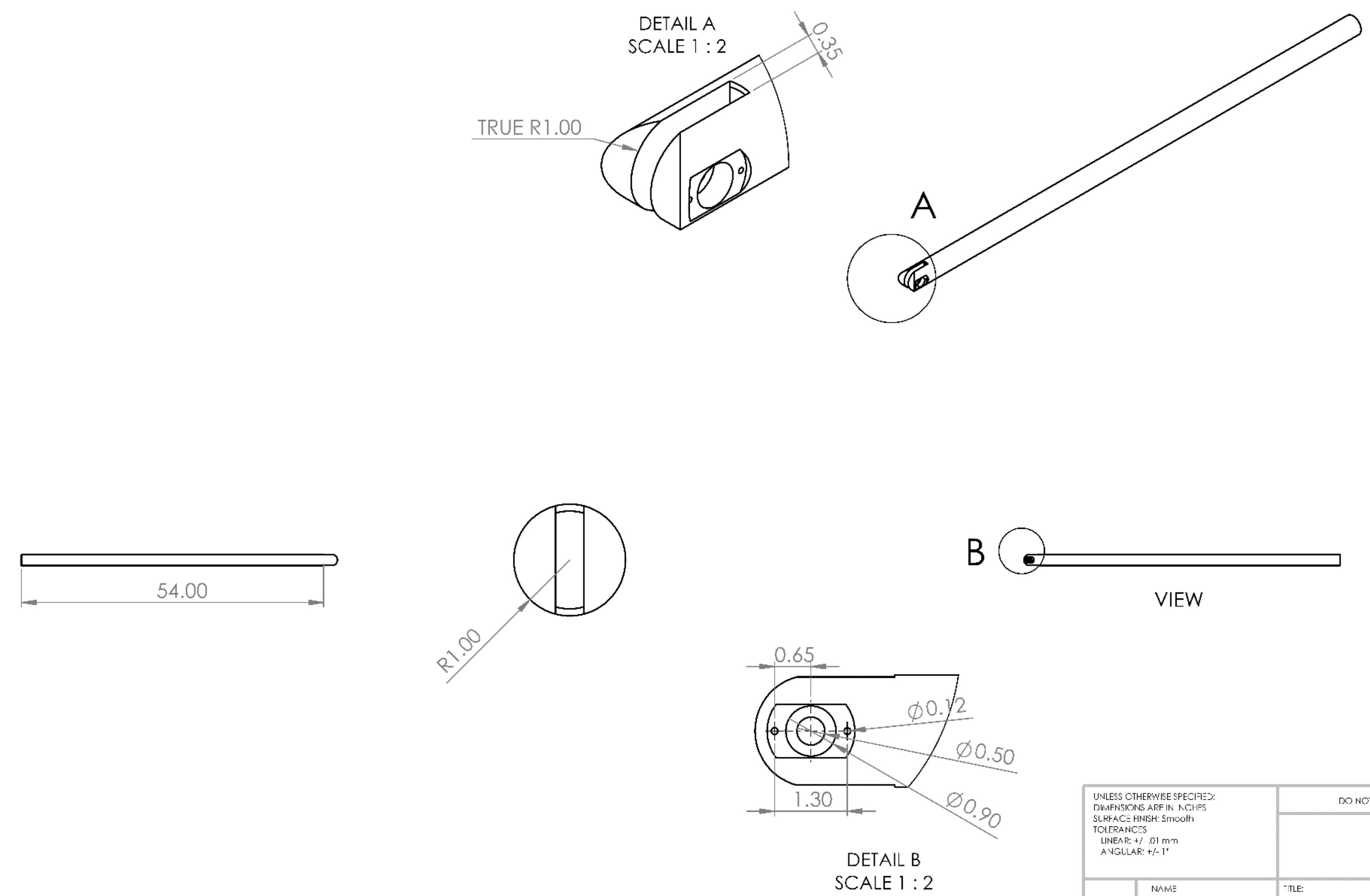
SCALE: 11:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°		DO NOT SCALE DRAWING	REVISION: 01
		MECH 4860	
	NAME	TITLE:	
DRAWN	Team 11 Ryan Roberts	Shaft Gear Base Assembly	
MATERIAL: ABS Plastic			
		SCALE: 11:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING | REVISION: 01

MECH 4860

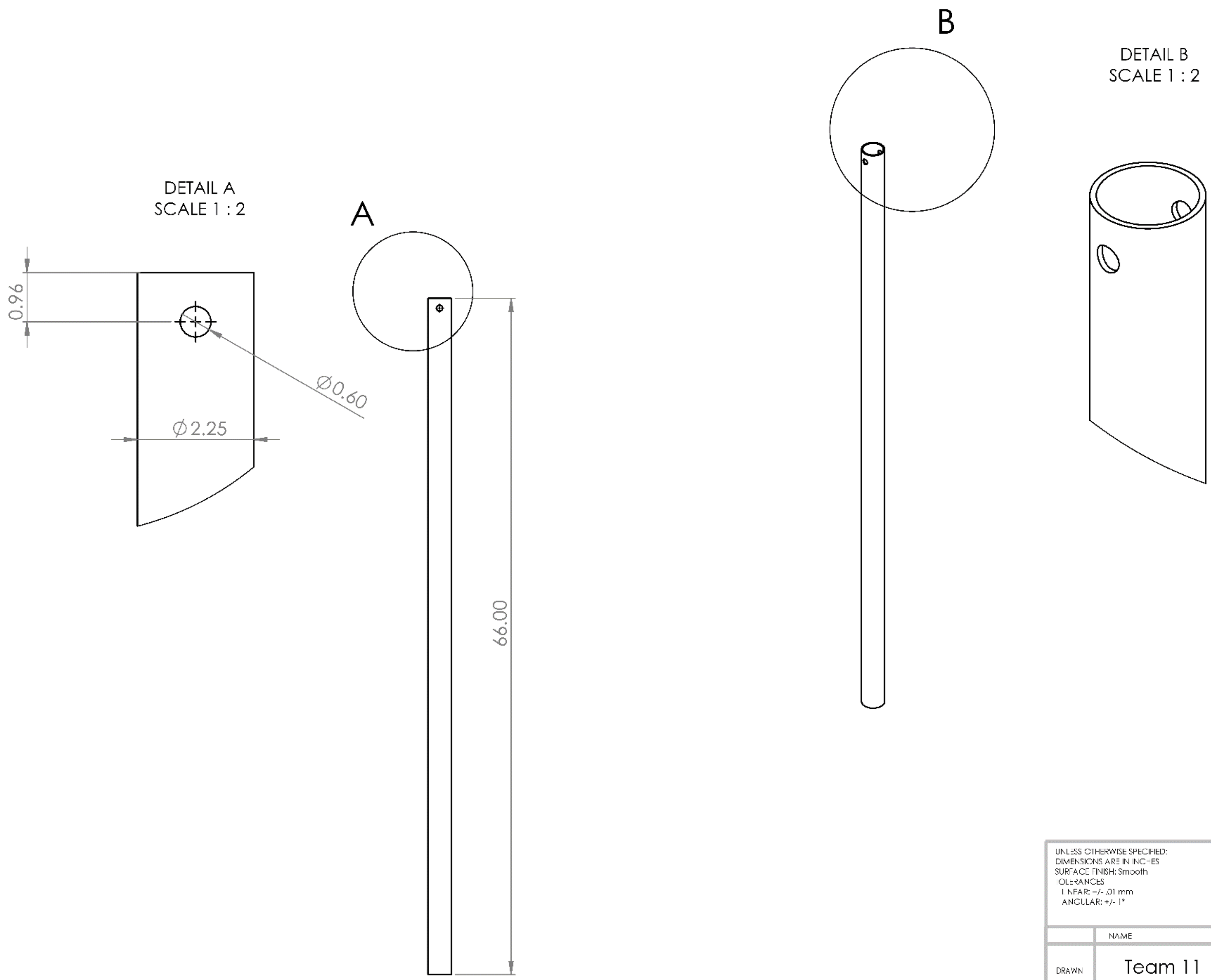
	NAME
DRAWN	Team 11

MATERIAL:

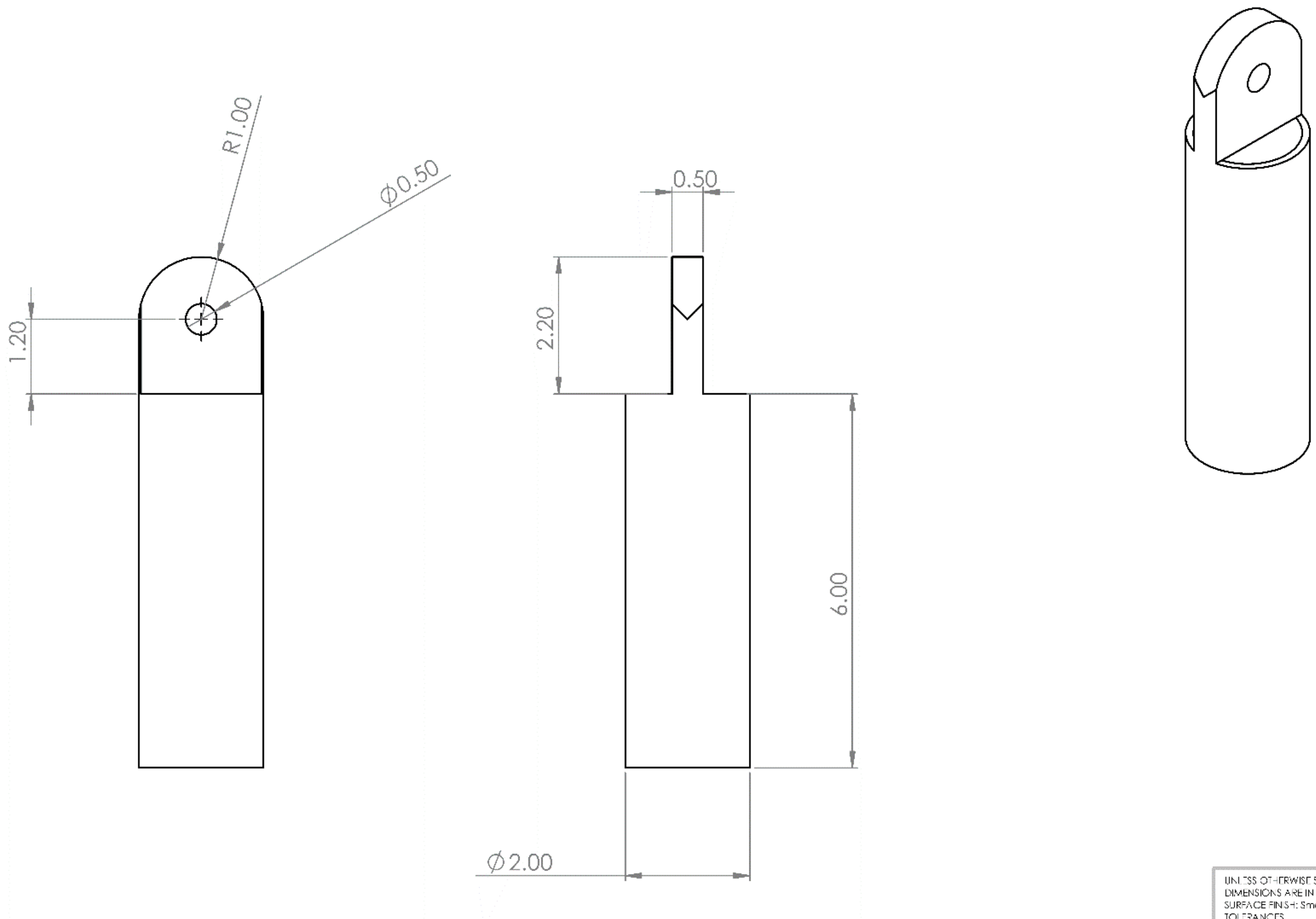
TITLE:

Stand-top

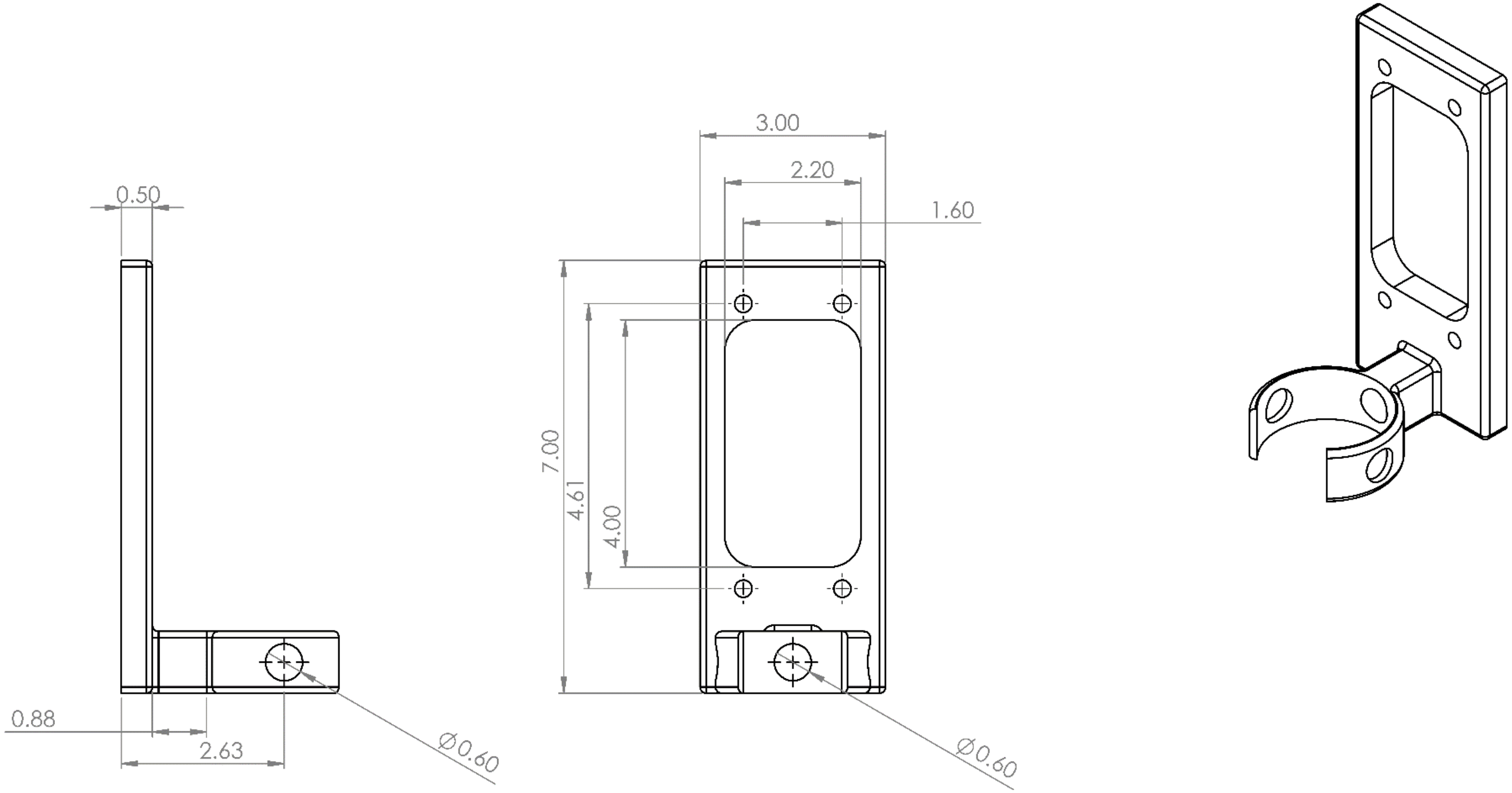
SCALE: 1:1 | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°		DO NOT SCALE DRAWING	REVISION: 01
		MECH 4860	
	NAME	TITLE:	
DRAWN	Team 11	Stand-bottom	
MATERIAL:			
		SCALE: 1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°	DO NOT SCALE DRAWING — REVISION: 01 MECH 4860
NAME DRAWN: Team 11	TITLE: Stand-middle
MATERIAL:	
	SCALE: 1:1 — SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

NAME

DRAWN Team 11

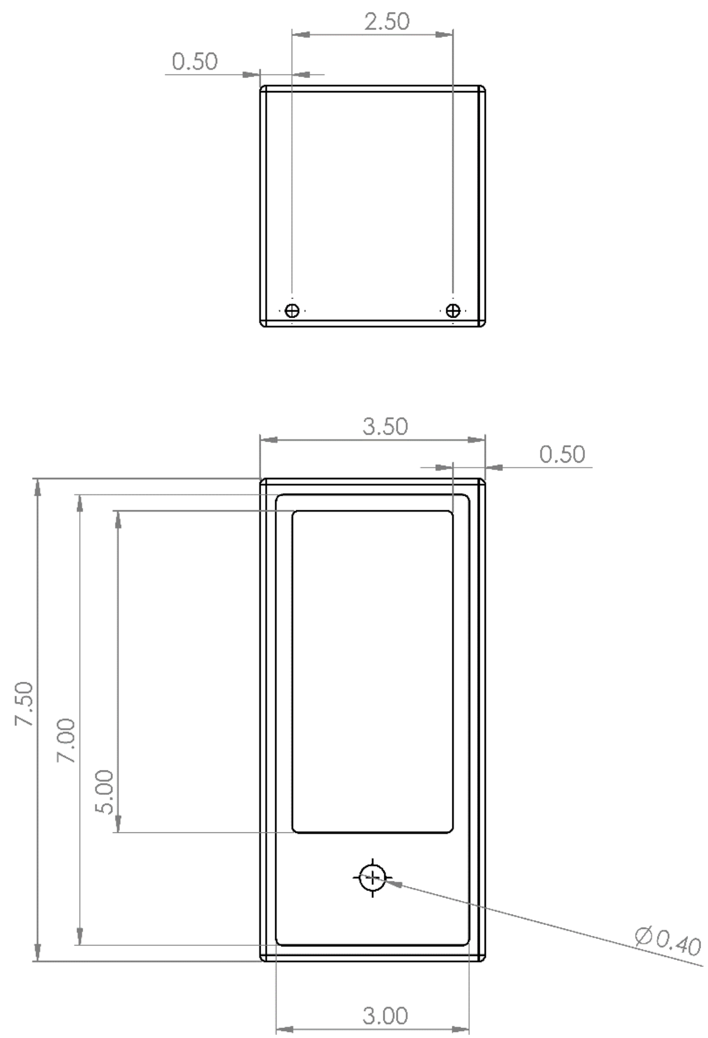
TITLE:

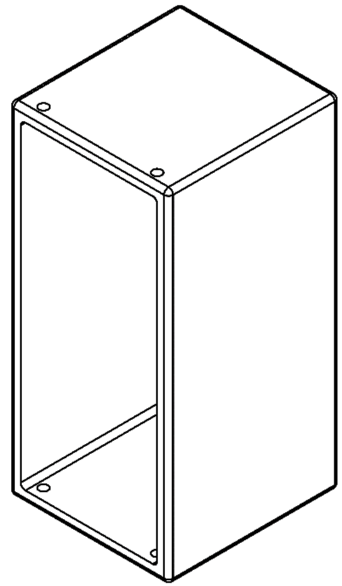
motor-supp

MATERIAL:

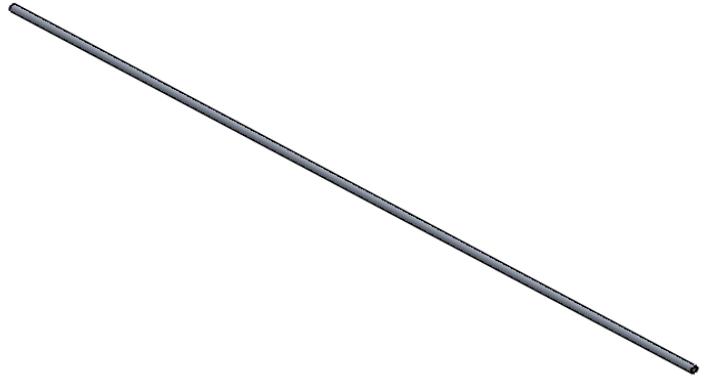
SCALE: 1:1

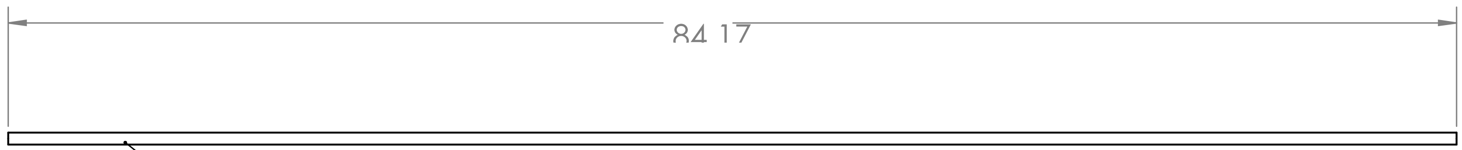
SHEET 1 OF 1





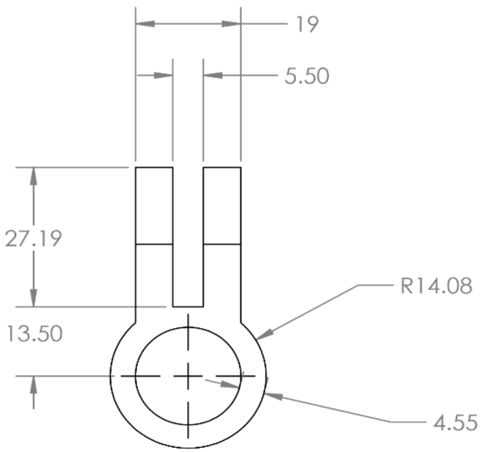
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°		DO NOT SCALE DRAWING	REVISION: 01
		MECH 4860	
	NAME	TITLE:	
DRAWN	Team 11	motor-cover	
MATERIAL:			
		SCALE: 1:1	SHEET 1 OF 1

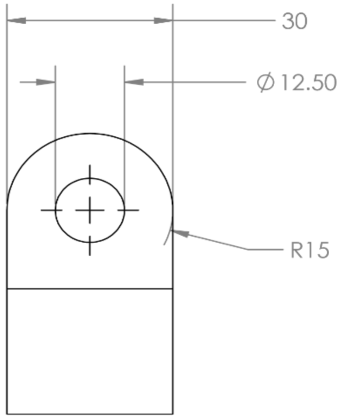


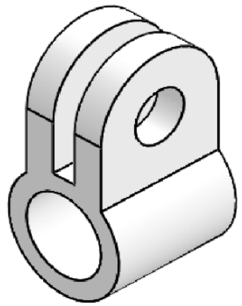


3/4" OD 0.065" Wall Thickness 1060 Aluminum Round

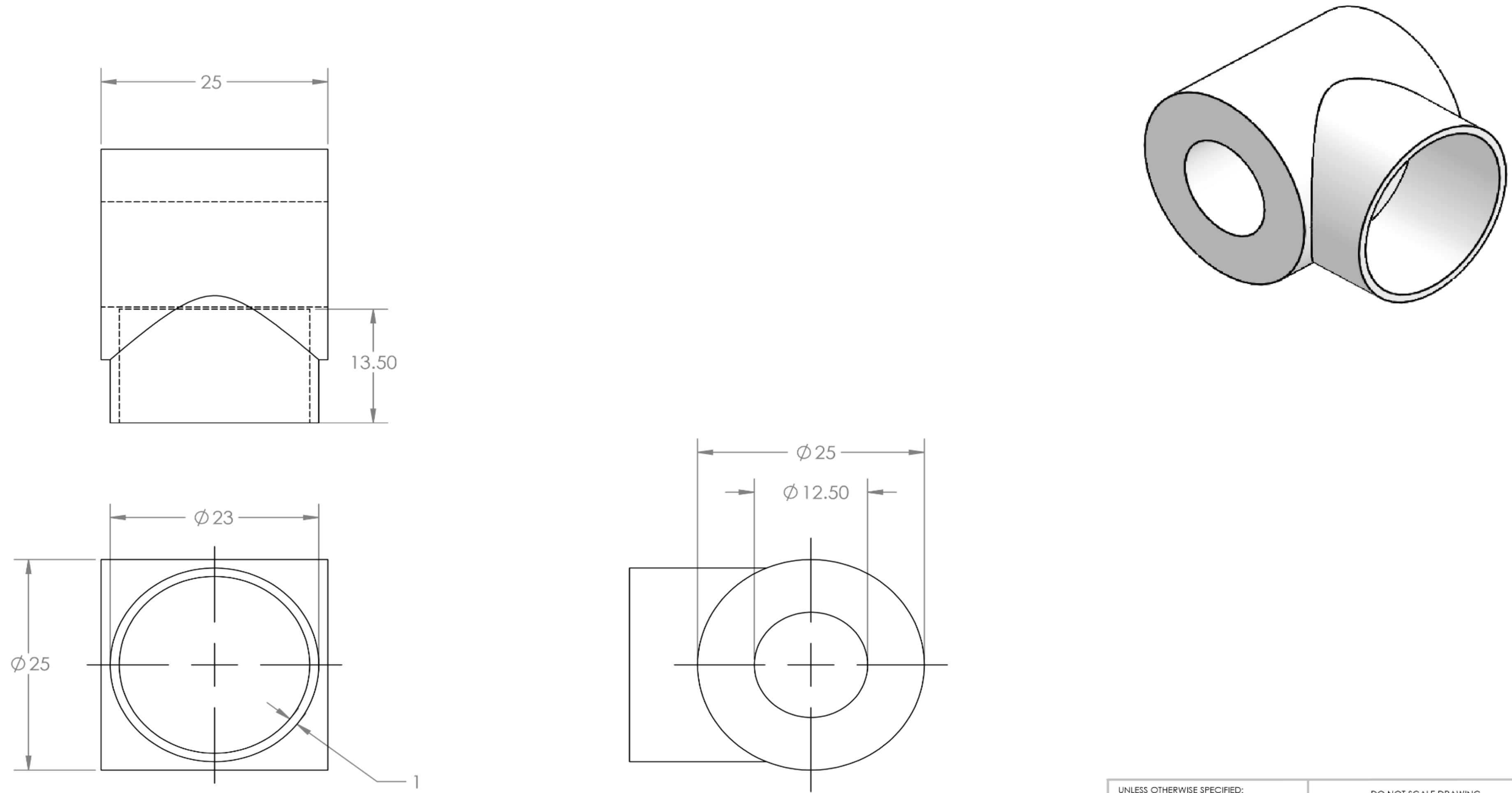
UNLESS OTHERWISE DIMENSIONS ARE IN SURFACE FINISH: TOLERANCE LINEAR: +/- .01 ANGULAR: +/-	DO NOT SCALE / REVISION:
	MECH 4860
NAME / DRAW: Team 11	TITLE: Umbrella Arm
MATERIAL: 1060 Aluminum	
	SCALE: / SHEET 1 OF



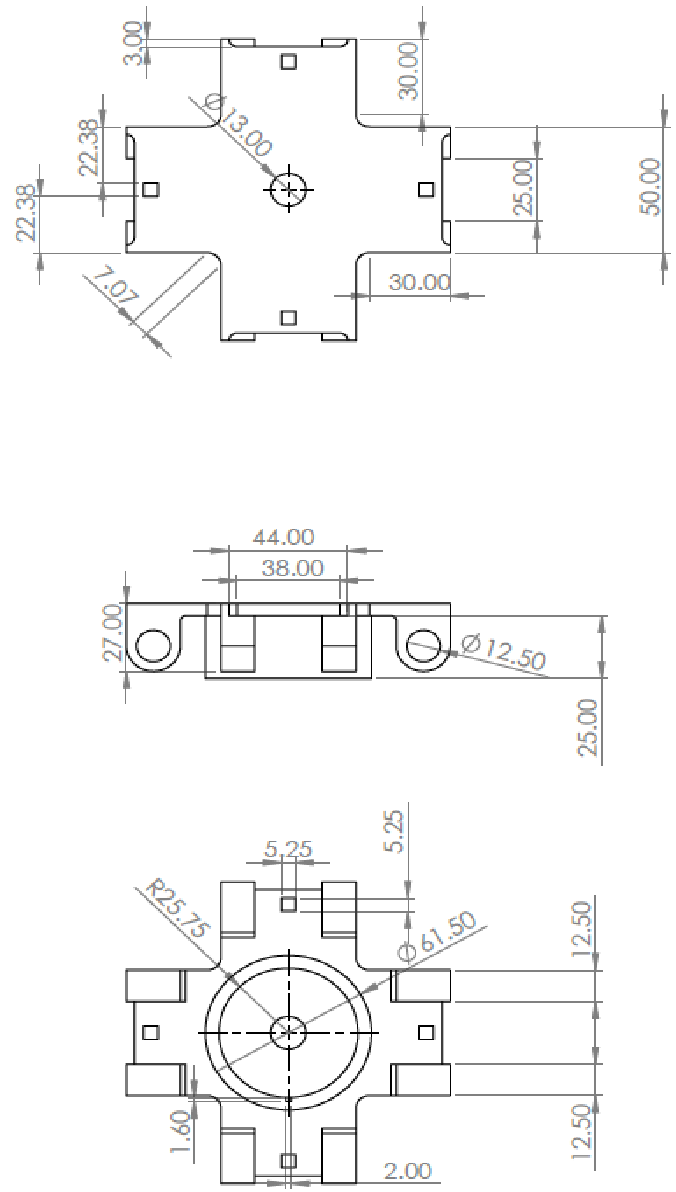


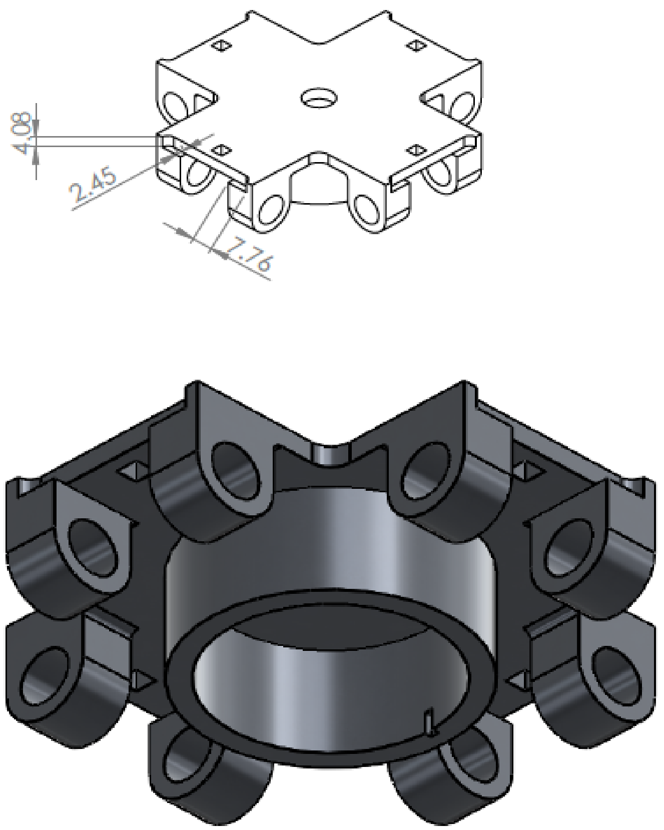


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°	DO NOT SCALE DRAWING	REVISION: 01
	MECH 4860	
NAME	TITLE:	
DRAWN: Team 11	Arm Collar Bushing	
MATERIAL: ABS Plastic		
	SCALE: 11:1	SHEET 1 OF 1

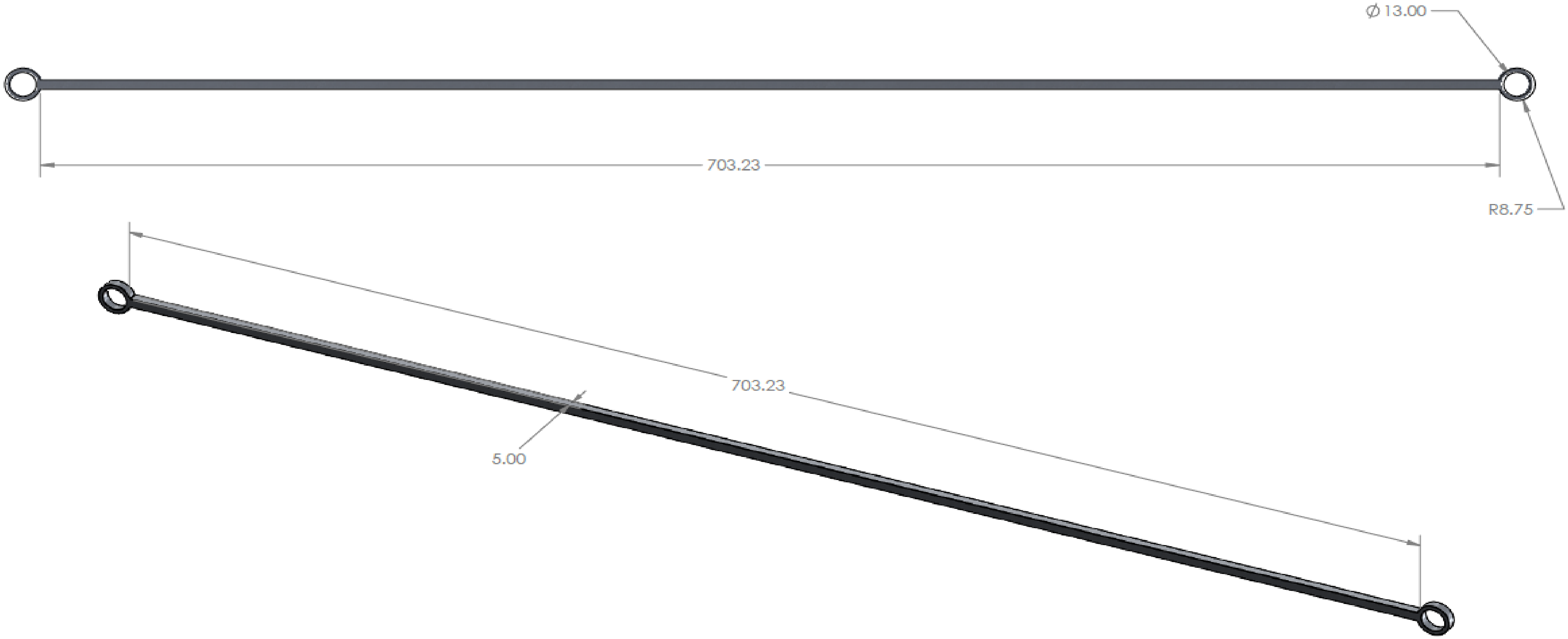


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°	DO NOT SCALE DRAWING	REVISION: 01
	MECH 4860	
NAME	TITLE:	
DRAWN: Team 11	Upper Fixture Bushing	
MATERIAL: ABS Plastic		
	SCALE: 11:1	SHEET 1 OF 1

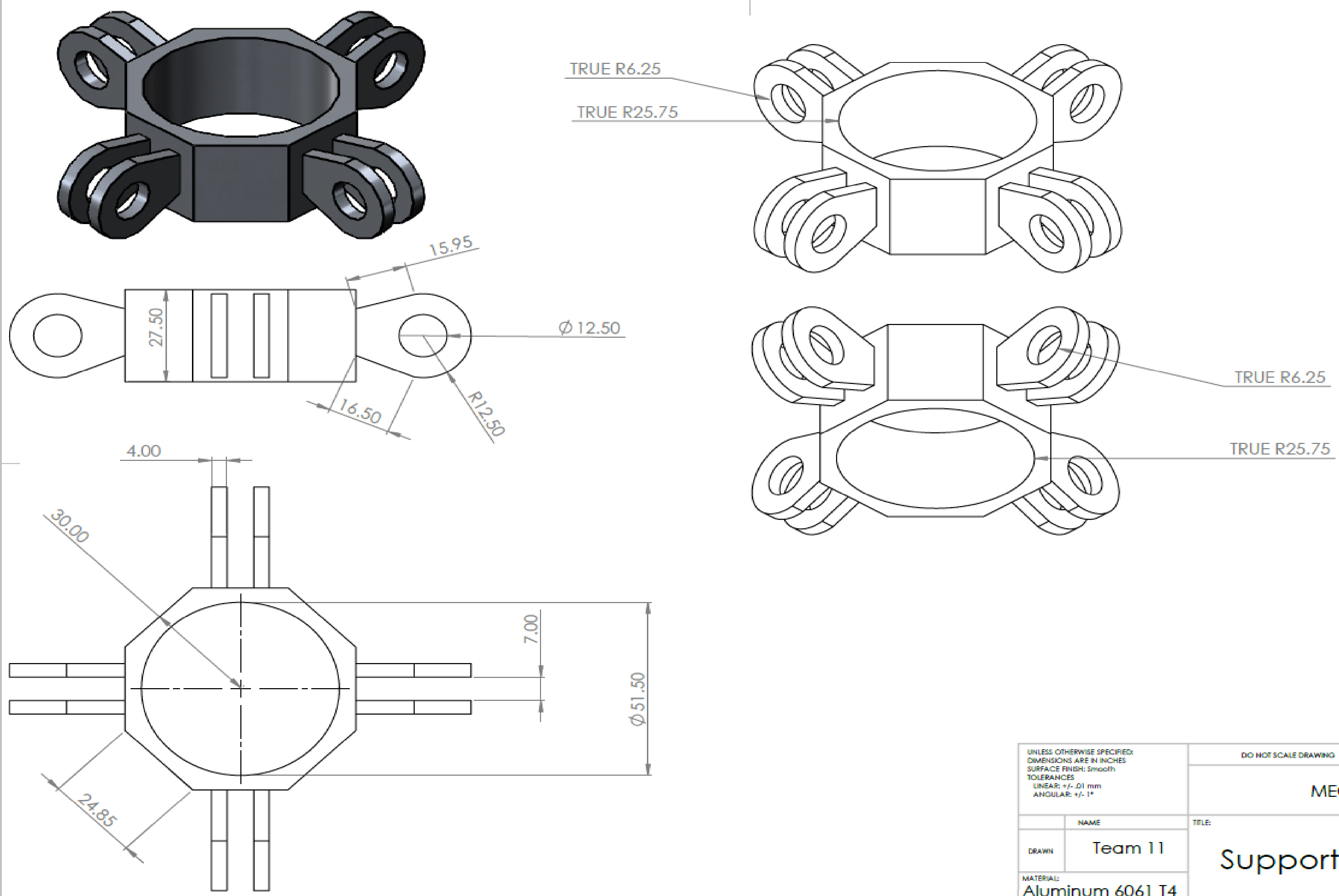




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°	DO NOT SCALE DRAWING	REVISION: 01
	MECH 4860	
NAME	TITLE:	
DRAWN: Team 11	Umbrella Fixture	
MATERIAL: Aluminum 6061 T4		
	SCALE: 1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: Smooth TOLERANCES LINEAR: +/- .01 mm ANGULAR: +/- 1°		DO NOT SCALE DRAWING	REVISION: 01
		MECH 4860	
	NAME	TITLE:	
DRAWN	Team 11	Support Arm	
MATERIAL: Aluminum 6061 T4			
		SCALE: 11:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH: Smooth
TOLERANCES
LINEAR: +/- .01 mm
ANGULAR: +/- 1°

DO NOT SCALE DRAWING

REVISION: 01

MECH 4860

	NAME
DRAWN	Team 11

MATERIAL:
Aluminum 6061 T4

TITLE:

Support Fixture

SCALE: 11:1

SHEET 1 OF 1

Appendix D: Program Code

Contained within this appendix is the full Arduino IDE program that controls the prototype. The code is fully commented to provide insight into the program.

```
#include <Servo.h> //servo control library
#include <LiquidCrystal.h> //LCD Library

int servoPos0 = 95; //elbow servo
int servoPos1 = 100; //base servo
int startPos0 = 0; //starting position of elbow servo
int startPos1 = 0; //starting position of base servo
int speakerPin = 6; //buzzer input pin
int LDR0 = 0; //bottom left sensor
int LDR1 = 0; //top left sensor
int LDR2 = 0; //top right sensor
int LDR3 = 0; //bottom right sensor
int LDRTotal = 0; //summation of all sensors
int threshold = 650; //sensor light threshold value
int button = 4; //button input pin
bool startState = false; //start state flag
int countState = 0; //state counting variable
bool pauseTracker = 0; //pause state flag
int runningTotal = 0;

Servo myServo0; //elbow servo object
Servo myServo1; //base servo object
LiquidCrystal lcd(13, 12, 11, 10, 9, 8); //LCD screen object

void setup()
{
  Serial.begin(9600); //start a serial connection with the computer
  pinMode(button, INPUT_PULLUP); //set button as input
  pinMode(4, OUTPUT); //set pin 4 as an output that can be set to HIGH or LOW
  pinMode(2, OUTPUT); //green LED
  myServo0.write(servoPos0);
  myServo1.write(servoPos1);
  myServo0.attach(3); //attach elbow servo to pin 3
  myServo1.attach(5); //attach base servo to pin 5
  lcd.begin(16, 2); //set size of LCD output
  lcd.clear(); //clear LCD screen
  pinMode(speakerPin, OUTPUT); //set buzzer pin as output
}

void loop() //main program control loop
{
  if (countState == 0) //if in initial starting state
  {
    Serial.println("Press button to start"); //output to serial
    Serial.println("");
    lcd.setCursor(0,0); //print to LCD screen
    lcd.print("                ");
    lcd.setCursor(0,1);
    lcd.print("                ");
    lcd.setCursor(0,0);
    lcd.print("Please press");
    lcd.setCursor(0,1);
```

```
  lcd.print("button to start");
  play('c', 2.66); //play starting jingle
  play('a', 2.66);
  play('b', 2.66);
  play('D', 4);
  countState = 2; //change state to enter next
  delay(1000);
}
else if ((digitalRead(button) == HIGH ) && (countState == 2)) //if button not pressed
{
  delay(100);
}
else if ((digitalRead(button) == LOW) && (countState == 2)) //if button pressed
{
  startState = true; //change start-up state flag
  countState = 1; //change state
  Serial.println("Beginning, please wait a moment");
  Serial.println("");
  while (digitalRead(button) == LOW) // wait until button is released to continue
  {
    delay(10);
  }
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Beginning,");
  lcd.setCursor(0,1);
  lcd.print("please step back");
  digitalWrite(2, HIGH); //turn on LED
  play('b', 0.5); //play pre-calibration jingle
  play('b', 0.5);
  play(' ', 1);
  play('b', 0.5);
  play('b', 0.5);
  play(' ', 1);
  play('b', 0.5);
  play('b', 0.5);
  play(' ', 1);
  play('B', 2);
  delay(1000);
}

if (startState == true) //enter calibration state/ exit setup
{
    initialStartup(); //call calibration start-up routine

    bool trackConst = true; //tracking phase flag
    int delayCount = 0; //delaying variable
    while (trackConst == true) //while in tracking phase
    {
      if ((digitalRead(button) == LOW) && (pauseTracker == 0)) //if button pressed
      {
        pauseMode(); //call pausing routine
      }
      delay(5);
      delayCount += 1; //loop through and increment to control time period
      if (delayCount == 100) //if looped desired number of times
      {
```

```
        activeTracking(); //call active tracking to update position
        delayCount = 0; //reset count to start new timed interval
      }
    }
  }
}

void play( char note, int beats) //music playing function
{
  int numNotes = 14; //number of notes in our note and frequency array
  char notes[] = { 'c', 'd', 'e', 'f', 'g', 'a', 'b', 'C', 'D', 'E', 'F', 'G', 'A', 'B', ' '};
  //notes are in key of C major
  int frequencies[] = {131, 147, 165, 175, 196, 220, 247, 262, 294, 330, 349, 392, 440, 494, 0};
  int currentFrequency = 0; //frequency pointer for array
  int beatLength = 160; //the length of one beat in ms
  for (int i = 0; i < numNotes; i++) //check each value in notes from 0 to 14
  {
    if (notes[i] == note) //does the letter passed to the play function match the letter in the array?
    {
      currentFrequency = frequencies[i]; //set the current frequency to match that note
    }
  }
  //play the frequency that matched our letter for the number of beats passed to the play function
  tone(speakerPin, currentFrequency, beats * beatLength);
  delay(beats* beatLength); //wait for the length of the tone so that it has time to play
  delay(50); //a little delay between the notes makes the song sound more natural
}

void sensorReadingCalibration() //read sensor inputs and set new highes total if found
{
  int currentTotal = 0;
  LDR0 = analogRead(A0); //top left corner
  LDR1 = analogRead(A1); //bottom right corner
  LDR2 = analogRead(A2); //bottom left corner
  LDR3 = analogRead(A3); //top right corner
  currentTotal = LDR0 + LDR1 + LDR2 + LDR3; //summation of all LDRs
  if (currentTotal > LDRTotal) //if current reading is higher than previous best
  {
    LDRTotal = currentTotal; //sets new highest combination
    startPos0 = servoPos0; //store elbow angle of highest position
    startPos1 = servoPos1; //store base angle of highest position
   }
}

void sendMotorCommand(int desiredAngle, int motorSelector) //motor poition commmand function
{
  digitalWrite(2, HIGH); //turn on LED
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Calibrating...");
  lcd.setCursor(0,1);
  lcd.print("please wait");
  if (motorSelector == 0) //if elbow motor selected
  {
    //Serial.println("Motor 0: " + desiredAngle);
    Serial.println();
    if (desiredAngle > servoPos0) //if need to increase position from current
```

```
  {
    for (int angle = desiredAngle; servoPos0 < angle; servoPos0 += 1) //increment until desired position
    {
      if ((digitalRead(button) == LOW) && (pauseTracker == 0)) //if button is pressed
      {
        pauseMode(); //call pausing function
      }
      sensorReadingCalibration(); //read sensors
      myServo0.write(servoPos0); //update motor position
      delay(10);
    }
  }
  else if (desiredAngle <= servoPos0) //if need to decrease from current position
  {
    for (int angle = desiredAngle; servoPos0 > angle; servoPos0 -= 1) //decrement until desired position
    {
      if ((digitalRead(button) == LOW) && (pauseTracker == 0))
      {
        pauseMode();
      }
      sensorReadingCalibration(); //read sensors
      myServo0.write(servoPos0); //update motor position
      delay(10);
    }
  }
}
else if (motorSelector == 1)
{
  //Serial.println("Motor 1: " + desiredAngle);
  Serial.println();
  if (desiredAngle > servoPos1)
  {
    for (int angle = desiredAngle; servoPos1 < angle; servoPos1 += 1)
    {
      if ((digitalRead(button) == LOW) && (pauseTracker == 0))
      {
        pauseMode();
      }
      sensorReadingCalibration(); //read sensors
      myServo1.write(servoPos1); //update motor position
      delay(10);
      //Serial.println("servoPos1: " + servoPos1);
    }
  }
  else if (desiredAngle <= servoPos1)
  {
    for (int angle = desiredAngle; servoPos1 > angle; servoPos1 -= 1)
    {
      if ((digitalRead(button) == LOW) && (pauseTracker == 0))
      {
        pauseMode();
      }
      sensorReadingCalibration();
      myServo1.write(servoPos1);
      delay(10);
    }
  }
}
else
{
```

```
    Serial.println("error");
  }
}

void pauseMode() //pausing state function
{
  pauseTracker = 1; //update pasuing state tracker to currently pasued
  Serial.println("Paused, press button to resume");
  Serial.println("");
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Paused press");
  lcd.setCursor(0,1);
  lcd.print("button to resume");
  digitalWrite(2, LOW); //turn off LED
  play('B', .5); //play shut-down jingle
  play('A', .5);
  play('G', .5);
  play('E', .5);
  play('C', .5);
  play('e', 1);
  play(' ', 1);
  int shutdownCounter = 0;
  bool shutdowmMarker = false;
  while (digitalRead(button) == LOW) //wait until button is released
  {
    delay(10);
    shutdownCounter += 1; //counter for time button is held
    if (shutdownCounter == 500) //if button held for 5 seconds
    {
      sendMotorCommand(90, 0); //set elbow to neutral
      sendMotorCommand(90, 1); //set base to neutral
      bool shutdownMarker = true; //marker to enter infinite shutdown loop
      lcd.setCursor(0,0);
      lcd.print("                ");
      lcd.setCursor(0,1);
      lcd.print("                ");
      lcd.setCursor(0,0);
      lcd.write("Please power");
      lcd.setCursor(0,1);
      lcd.write("off...");
      while (shutdownMarker == true) //enter loop and never leave until power is turned off
      {
        delay(100);
      }
    }
  }
  while (pauseTracker == 1) //always enter loop
  {
    delay(10);
    if ((digitalRead(button) == LOW) && (pauseTracker == 1)) //if button pressed again
    {
      play('e', .5); //play resume jingle
      play('C', .5);
      play('E', .5);
      play('G', .5);
      play('A', .5);
```

```
      play('B', 1);
      play(' ', 1);
      while (digitalRead(button) == LOW) //wait until button is released
      {
        delay(10);
      }
      lcd.setCursor(0,0);
      lcd.print("                ");
      lcd.setCursor(0,1);
      lcd.print("                ");
      lcd.setCursor(0,0);
      digitalWrite(2, LOW); //turn off LED
      delay(1000);
      pauseTracker = 0; //exit while loop
     }
   }
}

void initialStartup() //initial calibration function
{
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Calibrating...");
  lcd.setCursor(0,1);
  lcd.print("please wait");
  digitalWrite(2, HIGH); //turn on LED

  for (int angle1 = 10; servoPos1 > angle1; servoPos1 -= 1) // quick set base and elbow to start poitions
  {
    myServo1.write(servoPos1);
    if (servoPos0 > 55)
    {
      servoPos0 = servoPos1;
      myServo0.write(servoPos0);
    }

    delay(10);
  }

  sendMotorCommand(170, 1); //set base to 170
  sendMotorCommand(125, 0); //set elbow to 125
  sendMotorCommand(10, 1);  //set base to 10
  sendMotorCommand(108, 0); //set elbow to 108
  sendMotorCommand(170, 1); //set base to 170
  sendMotorCommand(72, 0);  //set elbow to 72
  sendMotorCommand(10, 1);  //set base to 10
  sendMotorCommand(85, 0);  //set elbow to 85
  sendMotorCommand(170, 1); //set base to 170
  sendMotorCommand(95, 0);  //set elbow to 95
  sendMotorCommand(10, 1);  //set base to 10
  if (servoPos0 < startPos0) //determine which was to move to reach post-calibration poition
  {
    for(int angle = startPos0; servoPos0 < angle; servoPos0 += 1)
    {
      myServo0.write(servoPos0);
      delay(10);
    }
```

```
  }
  else if (servoPos0 > startPos0)
  {
    for(int angle = startPos0; servoPos0 > angle; servoPos0 -= 1)
    {
      myServo0.write(servoPos0);
      delay(10);
    }
  }
  if (servoPos1 < startPos1)
  {
    for(int angle = startPos1; servoPos1 < angle; servoPos1 += 1)
    {
      myServo1.write(servoPos1);
      delay(10);
    }
  }

  else if (servoPos1 > startPos1)
  {
    for(int angle = startPos1; servoPos1 > angle; servoPos1 -= 1)
    {
      myServo1.write(servoPos1);
      delay(10);
    }
  }

}

void activeTracking() //active tracking function
{
  int moveCounter = 2; //# of continuous movements
  while (moveCounter > 0) //while still have movements
  {
    digitalWrite(2, HIGH); //turn on green LED
    lcd.setCursor(0,0);
    lcd.print("                ");
    lcd.setCursor(0,1);
    lcd.print("                ");
    lcd.setCursor(0,0);
    lcd.print("Tracking mode");
    lcd.setCursor(0,1);
    lcd.print("enabled");
    delay(50);
    LDR0 = analogRead(A0);
    LDR1 = analogRead(A1);
    LDR2 = analogRead(A2);
    LDR3 = analogRead(A3);
    int bottom = LDR2 + LDR1; //top side
    int top = LDR3 + LDR0; //bottom side
    int left = LDR2 + LDR3; //left side
    int right = LDR1 + LDR0; //right side
    int sum = left + right + top + bottom;
    float average = sum / 4.0;


     //For debugging sensors
    Serial.print("Left: "); //serial print readings
    Serial.print(left);
    Serial.print("\t");
```

```
  Serial.print("Right: ");
  Serial.print(right);
  Serial.print("\t");
  Serial.print("Top: ");
  Serial.print(top);
  Serial.print("\t");
  Serial.print("Bottom: ");
  Serial.print(bottom);
  Serial.print("\t");
  Serial.print("Average: ");
  Serial.print(average);
  Serial.println("\t");
  /*
  Serial.print("LDR0: ");
  Serial.print(LDR0);
  Serial.print("\t");
  Serial.print("LDR1: ");
  Serial.print(LDR1);
  Serial.print("\t");
  Serial.print("LDR2: ");
  Serial.print(LDR2);
  Serial.print("\t");
  Serial.print("LDR3: ");
  Serial.print(LDR3);
  Serial.print("\t");
  Serial.print("Average: ");
  Serial.print(average);
  Serial.println("");
  */

  if ((abs(average - top) <= 7) && (abs(average - bottom) <= 7) && (abs(average - left) <= 7) && (abs(average
- right) <= 7))
  { //if all sides are roughly equal do nothing and wait
   lcd.setCursor(0,0);
   lcd.print("                ");
   lcd.setCursor(0,1);
   lcd.print("                ");
   lcd.setCursor(0,0);
   lcd.print("Correctly");
   lcd.setCursor(0,1);
   lcd.print("aligned");
   Serial.println("Correctly aligned");
   if ((digitalRead(button) == LOW) && (pauseTracker == 0))
     {
      pauseMode();
     }
   moveCounter = 0;
   runningTotal = sum;
  }

  else if (abs(runningTotal - sum) < 7)
  {
   lcd.setCursor(0,0);
   lcd.print("                ");
   lcd.setCursor(0,1);
   lcd.print("                ");
   lcd.setCursor(0,0);
   lcd.print("Correctly");
   lcd.setCursor(0,1);
   lcd.print("aligned");
```

```
  Serial.println("Correctly aligned");
  if ((digitalRead(button) == LOW) && (pauseTracker == 0))
  {
    pauseMode();
  }
  moveCounter = 0;
  runningTotal = sum;
}

else if ((left>right+5)&&(left>top)&&(left>bottom))
{
  //Left Greatest adjust left
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Adjusting left");
  lcd.setCursor(0,1);
  lcd.print("remain still");
  //play('a', 1);
  //play('E', 1);
  //delay(100);
  if (servoPos0 < 125) // elbow <-
  {
    servoPos0 += 1;
  }
  if ((digitalRead(button) == LOW) && (pauseTracker == 0))
    {
      pauseMode();
    }
  myServo0.write(servoPos0);
  Serial.println("Adjusting Left");
  Serial.println("");
  runningTotal = sum;
}
else if ((right>left+5)&&(right>top)&&(right>bottom))
{
  //Right Greatest adjust right
  lcd.setCursor(0,0);
  lcd.print("                ");
  lcd.setCursor(0,1);
  lcd.print("                ");
  lcd.setCursor(0,0);
  lcd.print("Adjusting right");
  lcd.setCursor(0,1);
  lcd.print("remain still");
  //play('a', 1);
  //play('E', 1);
  //delay(100);
  if (servoPos0 > 55) // elbow ->
  {
    servoPos0 -= 1;
  }
  if ((digitalRead(button) == LOW) && (pauseTracker == 0))
    {
      pauseMode();
    }
  myServo0.write(servoPos0);
  Serial.println("Adjusting Right");
```

```
  Serial.println("");
  runningTotal = sum;
}
else if ((bottom>top+5)&&(bottom>right)&&(bottom>left))
{
  //Bottom Greatest adjust down
  if ((bottom > top)&&(right > left))
  //swerve to right
  {
    lcd.setCursor(0,0);
    lcd.print("                ");
    lcd.setCursor(0,1);
    lcd.print("                ");
    lcd.setCursor(0,0);
    lcd.print("Adjusting down");
    lcd.setCursor(0,1);
    lcd.print("remain still");
    //play('a', 1);
    //play('E', 1);
    //delay(100);
    if (servoPos0 > 55)
    {
      servoPos0 -= 1;
    }
    if (servoPos1 > 10)
    {
      servoPos1 -= 2;
    }
    if ((digitalRead(button) == LOW) && (pauseTracker == 0))
    {
      pauseMode();
    }
    myServo0.write(servoPos0);
    myServo1.write(servoPos1);
    Serial.println("Adjusting Down");
    Serial.println("");
    runningTotal = sum;
  }
  else if ((bottom > top)&&(left > right))
  {
    //swerve to left
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Adjusting down");
    lcd.setCursor(0,1);
    lcd.print("remain still");
    //play('a', 1);
    //play('E', 1);
    //delay(100);
    if (servoPos0 < 125)
    {
      servoPos0 += 1;
    }
    if (servoPos1 < 170)
    {
      servoPos1 += 2;
    }
    if ((digitalRead(button) == LOW) && (pauseTracker == 0))
    {
      pauseMode();
```

```
    }
    myServo0.write(servoPos0);
    myServo1.write(servoPos1);
    Serial.println("Adjusting Down");
    Serial.println("");
    runningTotal = sum;
  }
}
else if ((top>bottom+5)&&(top>left)&&(top>right))
{
  //Top Greatest move up
  if ((top > bottom)&&(right > left))
  {
    //swerve right
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Adjusting up");
    lcd.setCursor(0,1);
    lcd.print("remain still");
    //play('a', 1);
    //play('E', 1);
    //delay(100);
    if (servoPos0 > 55)
    {
      servoPos0 -= 1;
    }
    if (servoPos1 < 170)
    {
      servoPos1 += 2;
    }
    if ((digitalRead(button) == LOW) && (pauseTracker == 0))
    {
      pauseMode();
    }
    myServo0.write(servoPos0);
    myServo1.write(servoPos1);
    Serial.println("Adjusting Up");
    Serial.println("");
    runningTotal = sum;
  }
  else if ((top > bottom)&&(left > right))
  {
    //swerve left
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Adjusting up");
    lcd.setCursor(0,1);
    lcd.print("remain still");
    //play('a', 1);
    //play('E', 1);
    //delay(100);
    if (servoPos0 < 125)
    {
      servoPos0 += 1;
    }
    if (servoPos1 > 10)
    {
      servoPos1 -= 2;
    }
    if ((digitalRead(button) == LOW) && (pauseTracker == 0))
```

```
        {
          pauseMode();
        }
        myServo0.write(servoPos0);
        myServo1.write(servoPos1);
        Serial.println("Adjusting Up");
        Serial.println("");
        runningTotal = sum;
      }
    }

    moveCounter -= 1;
    digitalWrite(2, LOW);
  }
  digitalWrite(2, LOW); //turn off LED
}
```

References

[1] J.D.M Beer, Mechanics of Materials 7th Edition, New York: McGraw-Hill Education, 2015.