The Passive Solar Energy Initiative

A Solar Heliostat Reflecting System with Passive Solar Seeking Technology

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Abstract

Students during the winter of 2009 began researching the possibility of implementing solar reflectors to aid in energy cost savings. The team did a great deal of analysis on the amount of solar energy available and the possibility of a brainless system to track the Sun and reflect solar energy into north-facing buildings – surfaces that do not normally receive Sun light. Our challenge is to bring these preliminary ideas to fruition and determine if this system has the potential to be mass-produced. Our design is different from other market heliostats because it uses a novel error correction system and can be produced at low cost. Thus, we developed a testing method to quantitatively justify the implementation of a brainless system.

Executive Summary

The purpose of the Passive Solar Energy Initiative (PSEI) is to provide an inexpensive and visually pleasing method of reflecting solar energy into buildings (specifically north-facing building sides that do not normally receive Sun light) with the intent to heat them in cold climates. Inspiration for this project was derived from a previous ME 450 project titled "SolarFocus" in the winter of 2009, which sought to achieve similar goals. With the help of Professor Stephen Skerlos, the PSEI intended to design a system that utilizes brainless control technology to reflectively direct the Sun's rays at a designated target.

Further motivation for this project is driven by the current lack of low-cost options for persons interested in harnessing the free and environmentally friendly energy delivered by the Sun. Today, photovoltaic (PV) solar cell systems are expensive and require charge controllers, batteries and charge inverters in order to convert the solar energy into usable electrical energy that can be transferred to a building's power grid. Furthermore, the current Sun tracking technology utilized in heliostats on the market is expensive and has a high probability of failure due to design complexity. Our design aimed to implement a simple novel error correction based on LED sensors to a marketable heliostat.

Our preliminary design process was focused towards making a simple unit with a low-cost, low-power consuming control system. Several brainstorming sessions led us to several possible solutions based on the customer requirements, functional decomposition and engineering specifications. We analyzed each design for feasibility, cost-effectiveness, and energy transfer efficiency, and ultimately developed an alpha design that incorporated features from multiple initial concepts. The design's foremost components include the reflector, sensor and control system, and gear train.

During the preliminary design process we focused the project primarily on the application of a passive solar reflection system to a new G.G Brown atrium, but we changed the scope during design iterations to focus on determining if this is a practical mass producible product applicable to a variety of instances including residential and commercial uses. We aimed to test the error of our system to directly correspond to a cost comparison of our product and benchmarked heliostats. Therefore, for the prototype, we modeled one-axis of rotation for simplicity and testing purposes.

We built a test set-up to validate such a product quantitatively. The test focused on measuring the error associated with the sensor tracking abilities by utilizing a 400-watt metal halide bulb to mimic the sun in a controlled environment. We were then able to determine the error of the set-up by comparing the angle the reflector should be at to properly redirect the solar energy and the angle that it actually was at. For this product to be feasible, it was necessary that the system tracked the Sun with less than five degrees of error, and this was our target specification during testing. After scaling our analyzing our testing data and scaling the results to actual settings we compared the results to the original engineering specifications. We also vigorously critiqued our design and recommended optimization procedure for future design iterations.

The impact of implementing the PSEI would offset $537.10 dollars in annual heating costs of the future G.G. Brown Atrium. The reflector array will pay for itself in 7.1 years based on a final design cost of $384.11 per square meter. The final design is, on average, 63% less expensive than its competitive reflector counterparts and is expected to last 30 years. Based on energy costs, the dollar amount offset stands for 11% of the building's energy requirements, and therefore our design would earn G.G. Brown 4.4 points toward LEED Certification.

Table of Contents

Abstract 1

Executive Summary 2

Problem Description 6

Information Sources 6

  Previous Design 6

  Benchmarking from Previous Report 6

  Benchmarking of Competitive Market Heliostat Reflectors 7

    Leo Gerst Heliostats 7

    The HelioTrack Heliostat Reflector 8

    Practical Solar HE500 9

  Benchmarking Alternative Heliostat Functions 9

    Solar Water Heating 9

    Solar DC Cooling Fans 10

    Solar Air Conditioning 11

  Light Sensors 11

    LED Solar Tracking System 12

  Systems to Increase Heliostat Functionality 12

    Light Shelf 13

    Thermal Body 13

Project Requirements and Engineering Specifications 14

  Customer Requirements 14

  Engineering Specifications 15

Alpha Design and Testing 18

  Functional Decomposition 18

  Concept Generation 18

  Concept Selection 21

  Alpha Design 23

Selected Concept Description 25

  Prototype Description 25

  Parameter Analysis 27

  Final Design Description 29

Validation of Approach 31
    Validation of Prototype 31
    Validation of System Energy Supply 37
    Performance against Benchmarked Heliostat Reflectors 38
    Cost Analysis against Benchmarked Heliostat Reflectors 38
Fabrication Plan 39
Discussion 40
Benefit Analysis 40
Design Critique 41
Recommendations 42
Conclusion 42
Acknowledgements 43
References 44
Appendix 46
Appendix A: Bill of Materials 46
    Table A.1: Final Design Bill of Materials 46
    Table A.2:Prototype Bill of Materials 48
    Table A.3:Testing Bill of Materials 49
Appendix B: Description of Engineering Changes since Design Review #3 50
Appendix C: Design Analysis Assignment 62
    Material Selection Assignment (Functional Performance) 62
    Material Selection Assignment (Environmental Performance) 68
    Manufacturing Process Selection Assignment 71
Appendix D: QFD Diagram 72
Appendix E: Gantt Chart 73
Appendix F: Concept Generation 74
Appendix G: CAD Model of Alpha Prototype 80
Appendix H: LED Solar Sensor Circuit Diagram 81
Appendix I: Preliminary Test Diagram 82
Appendix J: Detailed Analysis 83
    Heat Transfer Analysis 83
    Detailed Torque and Gear Analysis 83

Appendix K: Fabrication Plan 86
  Manufacturing Overview for Prototype 86
  Manufacturing Steps and Drawings for Prototype 88
  Manufacturing Overview for Test Set-up 98
Appendix L: Assembly Overview 105
  Assembly Overview of Prototype 105
  Assembly Overview for Test Set-up 121
Appendix M: Final Design Drawings. 128
Bios 130

Problem Description

This project will harness solar energy to reduce the energy costs associated with a building by refining and adding to the SolarFocus project produced by Team 25 of ME 450 Winter 2009. This group developed the idea of a theoretical reflector to focus light and thermal energy into the north-facing windows of the possible G.G. Brown building renovations. Our sponsor and course lead Steven Skerlos has asked us to adapt this current theoretical system. The previous group compiled a large amount of data to determine engineering specifications and requirements needed to create a solar reflector, but they did not focus on a detailed design of a functional prototype or final design. Furthermore, our project aimed to adapt a mass producible heliostat to all applications.

Information Sources

Previous Design

The main source of information of our project was the previous design for the solar reflector created by the SolarFocus group of ME 450 in winter of 2009. Their report provided us with a large amount of information regarding solar location and availability in the state of Michigan. Their design was focused primarily on designing a device to re-direct solar heat and light within a potential G.G. Brown atrium that would not normally receive direct Sunlight. They devised an “innovative, brainless, control circuit” [1] to track the location of the Sun in the sky at any given time. They had measureable impacts of their design, namely $240 of annual energy savings, which equates to 5.3% of the annual atrium costs, and 1.6 metric tons of annual carbon dioxide offsets [1]. We found several areas to improve upon this preliminary design that we would like to emphasize. Most importantly, the solar tracking device was a complicated system that we greatly simplified without loss of functionality. We also believed that some of SolarFocus cost calculations required some refinement, and improvements upon their design helped to reduce the costs as well as shorten the pay-back time of the product.

Benchmarking from Previous Report

We gathered a significant amount of engineering information on other solar energy devices to adequately benchmark our design. The benchmarks have been developed by comparing initial costs of photovoltaic cells and their payback time without government subsidy. The SolarFocus team determined that the there is 1100 kWh/m^2 of reflector area to be annually harnessed by their proposed reflector [1]. The current price per kWh used from the electrical power grid in Michigan is $0.0843 [2]. The money saved each year with the solar reflector would then be $93.83 per 1 m^2 of reflector. The payback time can then be calculated by dividing the initial investment by the price saved each year. Other benchmarks relate the Sun tracking system. Current market heliostats use a “smart” system that calculates the exact position of the Sun based on the year, day and time. These systems are very complex and require memory and constant power to function. We aimed to implement a tracking system that locates the position of the by finding the brightest area in the sky rather than by calculation and programming.

We found a few relevant patents such as 4419981. It is a Sun tracking apparatus that uses symmetrically placed photo sensors to detect Sunlight. When there is a difference between outputs of symmetrical sensors the driving means will operate to realign the apparatus [3]. Another related patent is 4146784 where a series of sensors face outwards on a square structure inside a hemisphere so that the entire sky is visible to detect the position of the Sun in the sky [4]. Both show unique ways of solving the Sun tracking problem.

Benchmarking of Competitive Market Heliostat Reflectors

There are three notable heliostats available on the market that we would compare our system against. They include the Leo Gerst, the HelioTrack, and the Practical Solar HE 500.

Leo Gerst Heliostats

Fig. 1: Side View of Leo Gerst Heliostat [28]

Fig. 2: Array of Leo Gerst Heliostats [28]

Leo Gerst has developed an in-line solar tracker that drives a T-Pole heliostat seen above in Fig. 1 and 2 [28]. His design quotes a total cost of $128.05 for the structure and the tracking control device. The control system for the unit is called a RASP and costs $25.97. It is a device that takes the sun's reflection off the mirror to align it with the target. The structure is made of a series of PVC pipes that affix to a wooden mount that support an actual mirror. PVC also supports the RASP tracking system in front of the mirror. Though the system can very cheaply deliver reflected solar radiation to a target, it is inherently flawed for long-term or harsh climate use. Potential problems may arise if the system were exposed to moderate winds which may crack the mirror and craze the PVC. Ice could also coat the system and prevent motion of the linear actuators from moving. Also, the unit is powered by a conventional 120V power outlet which means that it is not free-standing and must be within a certain range of the target to receive the motor driving energy. Furthermore, the RASP system is positioned in front of the reflector, blocking some radiation from being transmitted to the target. Leo Gerst's system is highly affordable, but lacks many of the elements of a more elegant, long lasting heliostat reflector.

The HelioTrack Heliostat Reflector


Fig. 3: Heliotrack Rear View [29]


Fig. 4: Heliotrack Front View [29]

The HelioTrack is a solar heliostat tracking device and reflector. It employs a dual axis solar tracking controller with a remote sun sensor and can be seen above in Fig. 3 and 4 [29]. Together, the tracking control and the remote sun sensor locate the position of the sun and direct the one meter squared reflector with one linear and one rotary actuator. The reflector mount is made of painted wood to allow for mirror or reflective material mounting. The system supports are made of steel and the circular stand was designed so that sand bags can be placed on the unit to prevent it from blowing away in the wind. The complex tracking system costs $175 which does not include the motors, the support structure, or the photovoltaic cell used to power the device. It features two motor inputs, a power input, adjustable duty cycle, duty frequency, time delay and sensitivity. It also features a remote control interface to allow for manual or automated controls. The powerful, slow rotating motor used by the HelioTrack costs $700 alone. The HelioTrack needs a 12-36 Volt DC power source to function, and because the device is so heavy, the motors powering the motion need to have a higher torque output than other heliostat trackers. Typically, the makers of the HelioTrack power the device using a 12 Volt garden tractor battery that is recharged by a 5 Watt solar battery charger. It consumes 8 milliamps of current, and each actuator draws approximately 0.5 Amps while in use.

Practical Solar HE500

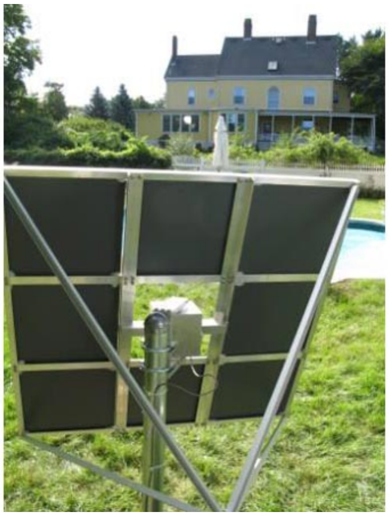


Fig. 5: Practical Solar Heliostat Rear View [30]

Fig. 6: Practical Solar Heliostat Front View [30]

Practical Solar's answer to the heliostat tracking system is called the HE500 and can be seen above in Fig. 5 and 6 [30]. The reflector panel is subdivided into nine aluminum framed segments, eight of which contain square mirrors and one that is empty to allow space for the motor. Each heliostat housing and mirror frame costs $995 and that price does not include wiring, the mirrors themselves, the 2-3/8 inch support pole, or cement to mount the unit into the ground. The control system includes interactive software with a user-friendly interface, a driver box, and accessories and costs $345. It functions while attached to a computer that is equipped with Windows '95 or later. This system claims to have an accuracy of 0.11 degrees, and that one control system can control up to 200 heliostats. The performance of the unit is excellent, but its cost is exorbitant and its reflector is missing a reflective panel in the center of the heliostat which, if in place, could reflect more valuable energy to the target.

Benchmarking Alternative Heliostat Functions

An initial sub-component of the project was to develop a summer function for the reflector when space heating is not required. This section outlines some of the possible alternative uses but does not claim to be an exhaustive list.

Solar Water Heating

One solution to the problem of a summer function would be to implement solar water heating. Nearly one third of the average residential electric bill is devoted to heating water [5]. Therefore, adding a solar water heating device to our design would be an effective way to reduce energy costs in the summertime. There are many devices on the market that are capable of using the Suns energy and heating up water for building occupants to use warm water. One such device, created by Solar Panels Plus, uses copper pipes and glass tubes to heat water that provide enough hot water to supply a family of six [6]. Pictured in Fig. 7 below, is the SPP-30, containing 30 glass tubes with water to be heated. Using a device such as this on the roof of the building would allow a way to use the reflected solar energy in the summer.

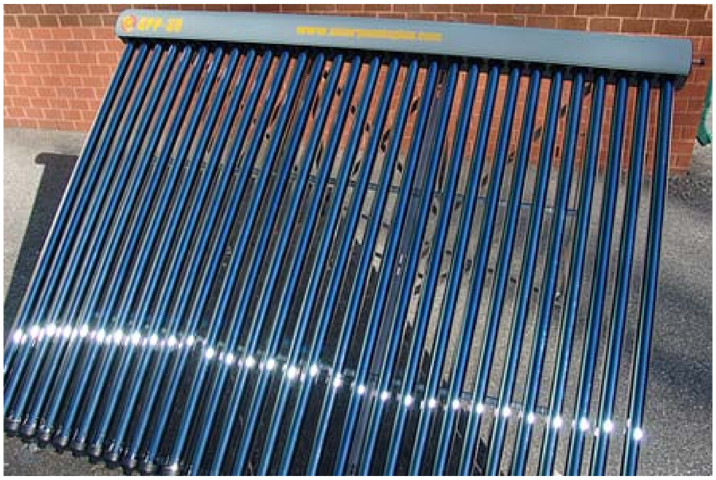


Fig. 7: SPP-30 by Solar Panels Plus uses solar energy to heat water [5]

Another such device is a passive solar water heating system called the ProgressivTube [7]. This system is a passive system because it does not have any moving parts of its own, and it depends only on the local water pressure and solar radiation. Fig 8, below, demonstrates how the ProgressivTube system works. Water is pumped through the lines into the solar heater where the water is heated.

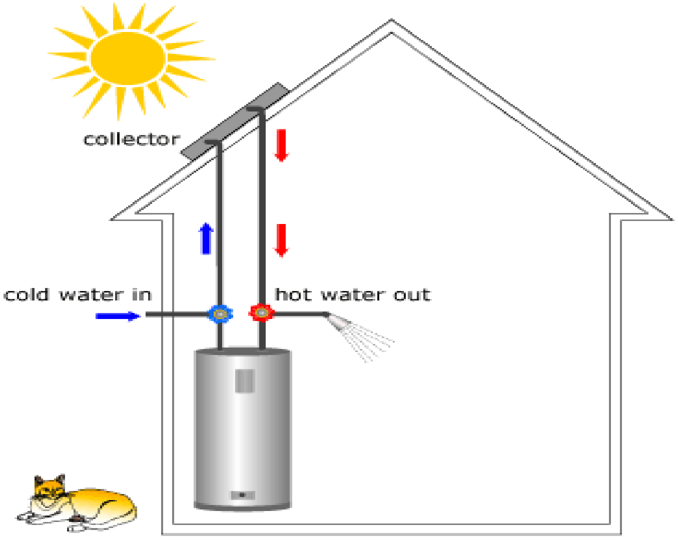


Fig. 8: ProgressivTube uses a passive system to heat the water [7]

The water is then returned to a copper storage tank that is insulated with closed cell foam and double glazed to increase heat retention. This system is even more ideal because of its simplicity.

Solar DC Cooling Fans

Another alternative for solar energy in the summer months would be to use the solar energy to power cooling fans. Simple technology exists to power fans using solar power loads. One such of these systems is attic venting. Advanced Energy Solutions has several types of solar powered attic fans on the market [8]. These fans run directly off of DC and run when they are needed most – when the Sun is shining. These fans are cost effective and relatively noise-free. Pictured below in Fig. 9 is a model of one of the fans, which can produce up to 1000 cubic feet per minute when the model is in full Sunlight. Using the ideas from these attic fans, larger systems could be used to provide cooling to a room during the summer months with the solar reflector design.

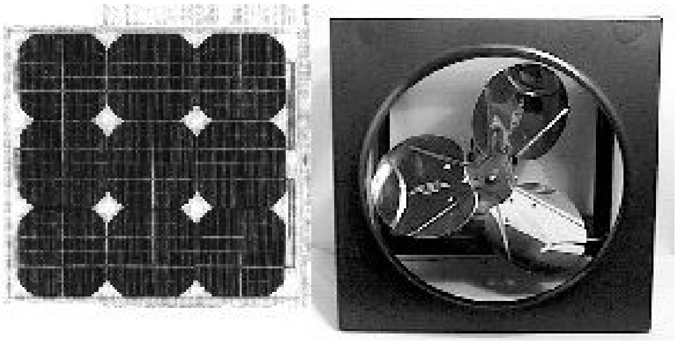


Fig. 9: Solar Powered Fan Kit [8]

Solar Air Conditioning

One way to use solar energy that may sound counter-intuitive is solar air conditioning. This system works by incorporating absorption chillers that are powered by hot water. The thermal powered air conditioners are a well established technology, especially in Japan, where up to 40% of installed commercial air conditioning is done using an absorption chiller [9]. Solar Panels Plus has a system based off of chillers made by Yazaki. Below in Fig. 10 is an image of an absorption chiller. Fig. 11, below, demonstrates how the solar air conditioning system works. The heat from the solar field is used in the chiller to cool air entering the building. These devices are simple and dependable, and operate without using harmful chlorofluorocarbons. This system would work alongside the heating aspect of the solar reflector to have a building that would heat and cool based solely on solar energy.

Fig. 10: Absorption chiller by Solar Panels Plus [9]

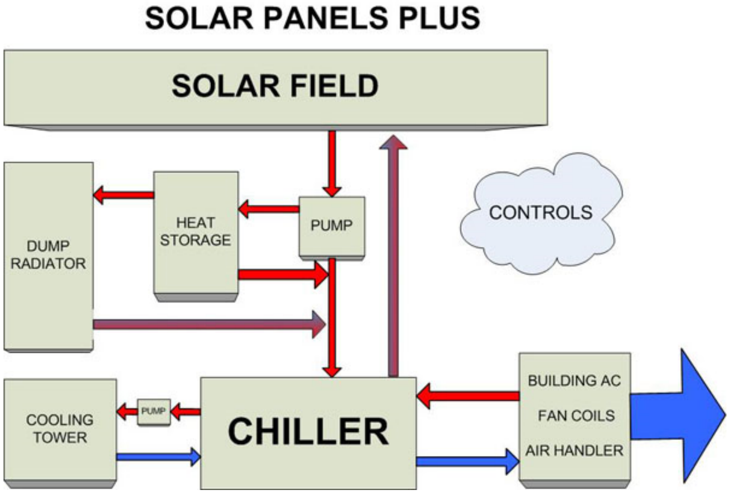


Fig. 11: Solar Air Conditioning System [9]

Light Sensors

The most critical component in our design is the sensor responsible for locating the Sun in the sky, and translating this data to a mechanical movement designed to redirect the solar energy at a target. The fly's eye design must implement some sort of light sensor. The optimal sensor for our purposes would be compact, inexpensive, sense light in the 600nm-700nm range (644nm for optimal solar PV cell function) [10], and have a narrow viewing angle to increase the angular accuracy of the control system. We have considered phototransistors, bipolar photodiodes, and photoresistors as a means of sensing the position of the Sun. The first two have a general function of reversing current flow over the element when exposed to light, and the third has a variable resistance based on the amount of light it is exposed to [11]. Each of the individual circuit elements considered is very inexpensive.

LED Solar Tracking System

In order to track the Sun with a cost effective passive system, we must create a circuit system that does not involve the use of a microprocessor. In order to do this, we looked into other systems that exist to establish a possible starting point for our circuit. One such system that exists is circuits created by Duane C. Johnson and Red Rock Energy [21]. Red Rock Energy has several examples of simple circuit systems that are used to track the Sun for PV solar panels. One system that we feel we can use as a stepping stone is the LED3X solar tracker, as seen in Fig. 12. This solar tracking system is designed to drive linear satellite dish actuator which is an actuation system that is commonly chosen when designing and building solar tracking systems for PV cells. The circuit uses 2 LEDs that compare the strength of the Sun and signal a motor to move the LEDs until the light hitting both is equal. These LEDs generate voltage in Sunlight due to the semiconductor located inside the LED. The system can operate in a voltage range from 10.5 volts to 91 volts for a high voltage version [21]. The circuits of all the systems created by Red Rock Energy are relatively inexpensive; several are composed of parts equaling a total under $2.50. This would be ideal for our design as we are looking to create the most inexpensive passive system. A circuit diagram for the LED system can be found in the Appendix. The circuit takes in electrical signal from the LEDs and uses transistors, capacitors, resistors, and diodes to send signal to the motor of which direction to turn. When light is impingent on an LED, the voltage across the LED reverses direction. The circuit instructs the motor to turn until the voltages across both LEDs are equal and the theoretical amount of light impingent upon both LEDs is equal. In theory, this will position the system to point directly at the spot in the sky that is the brightest.

Fig. 12: LED3X solar tracking system [21]

Systems to Increase Heliostat Functionality

There are systems available that can increase the effectiveness of a heliostat when installed to work together as a single unit. This section discusses light shelves and thermal masses as possible systems to work in conjunction with the heliostat system.

Light Shelf

One way to bring lighting into a room through the pre-existing windows is to use light shelves. A light shelf is a horizontal surface placed inside or outside a window that allows light to be reflected upward into the room to distribute the light throughout the entire room [24]. These are typically used on south facing windows and help to reduce the need of electrical lighting inside buildings. The shelf has a highly reflective upper surface to work effectively. Most light shelf systems are aesthetically pleasing to better blend into the pre-existing window system needing little to integrate into the system in a building. Fig. 13 shows an example of interior light shelves. Fig. 14 shows an example of exterior shelves. When used with a solar reflecting system, these shelves can be used on any window to distribute the light reflected into the non-south facing window throughout the entire room.

Fig. 13: Interior Light Shelves [24]

Fig. 14: Exterior Light Shelves[25]

Thermal Body

In order to properly heat the room the reflector redirects energy into, the room must be designed to store the energy and gradually release heat throughout the room. One such way of making sure this happens is to have a wall that acts as a thermal body. This means the wall is designed and built from a material that will readily absorb heat. Brick and concrete can both absorb heat, but brick is much better at doing so because it has higher thermal conductivity [26]. Another way to have walls that absorb heat well is to have interior walls of water. Water walls are much more efficient at thermal collection and storage than masonry walls [26]. Incorporating a wall with a waterfall into a design with a solar reflector would allow the heat to be absorbed in the room and also add an aesthetic appeal to the room. Fig. 15 demonstrates how a wall of water works within a greenhouse system. The same principle can be applied to any building or room to distribute the solar energy in the room.

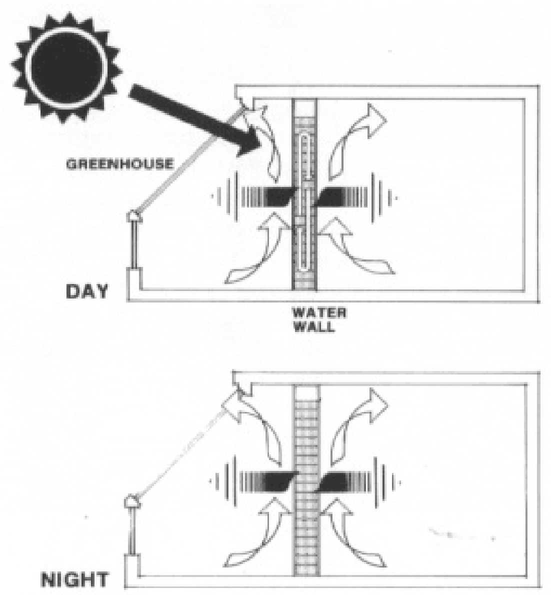


Fig. 15: Greenhouse with water storage wall [26]

Project Requirements and Engineering Specifications

Customer Requirements

We created an elaborate list of customer requirements after we finalized the scope of our design project to focus more on the building and testing of a passive system. As a team, we rated each requirement relative to the each other using a QFD diagram in order to determine the relative importance of each. If a requirement was more important than another requirement it was given a point. After each requirement had been compared directly to all other requirements, the points were added together, and the total number of points a requirement received was then called the QFD score. The complete list is shown in Table 1. One requirement, implementing passive solar energy technology, gained importance as our scope was refined as this is a major component of our design. We felt feasibility and safety are important aspects to our design since meeting these produce a product that will be easy to make and safe to test. We want to ensure that our design will reduce energy requirements of G.G. Brown and reflect the light into the building in an acceptable range of light intensity. We must also have a durable design capable of surviving the harsh winter conditions in Michigan. Further significant requirements include long lifetime and cost effectiveness of the design. Our aim was to create a more passive solar energy system that is less sophisticated so that the initial investment is low and more attractive than other solar energy options [12-13]. We incorporated these requirements when creating our test procedure for our design so that we can ensure that we meet all of these requirements. The full QFD can be found in the Appendix D.

Table 1: Customer Requirements and Score for Each

Project Requirement	QFD Score
Design is feasible	20
Design is safe	19
Implements passive solar energy technology	18
Reduces Energy Requirements of GGBL	17
Light reflected into room remains within acceptable range	16
Durable	15
Maintains efficiency over lifespan	14
Long lifetime	13
Easy to use and maintain	11
Cost effective	10
Minimize production emissions	10
Produces its own electrical power	10
Aid in LEED certification of GGBL	8
Minimize manual reflector adjustments	8
Functional during summer months	6
Aesthetically pleasing	5
Adaptable to different locations	4
Low initial investment	3
Mass producible	2

Engineering Specifications

We altered our engineering specifications to reflect our change in scope of our project. The scores shown in Table 2 that can be seen in the QFD in Appendix D were developed based on a comparison method in which each requirement was directly evaluated against all other requirements and received a point if it was considered more important to our project. The final score was a compilation of all comparisons. These requirements included targets that were developed by Team 25 for SolarFocus, as well as new, vital specifications pertinent to our design and goals.

One of our most important specifications was to quantify the energy cost savings in the G.G. Brown building due to the implementation of the system. It was recommended to design a building to reduce energy use and aid in silver LEED certification to increase the likeliness of implementation. The energy costs should ultimately be reduced by at least 2.5% annually, which corresponds to one LEED certification point [14].

The reflector should be large enough to transmit thermal and visible energy from the Sun to the atrium to meet the 11,000 kWh energy specifications. However, we also intended the implementation of our system on smaller scale home and office application. These two requirements dictated that we must design a reflector with a size that can be scaled easily for use in a variety of areas. A mirror that was too large hinders installation, takes up a lot of space and may detract from the object's visual appeal. Furthermore, a large mirror would require a larger motor to power the system and a larger structure to hold the reflectors weight. We chose a reflector with a surface area of 1 m^2 because it can be scale easily for multiple applications and because the area is relatively small the structure and motor costs are kept low. We can use an array of the reflectors to meet the total energy consumption reduction required for the G.G. Brown atrium.

A previous group designed a sun detecting reflector system that requires an initial investment of $400 per square meter. Based on the data that the unit installed in front of G.G. Brown would provide at least 11,000 kWh per year [1] to the building and operate at an efficiency of at least 40% at current energy costs, it would pay for itself in 4 years. Actual calculations led to an actual payback time of over ten years. We chose a specification of less than four years payback time because we wanted to have a competitive edge over the benchmarked systems available on the market.

In order to ensure that reflection of the Sun's rays are entering the north-facing windows of the atrium, our system must be able to track the Sun within ±5° of its actual location. This allows the system to capture adequate energy to maintain our energy reduction requirements based on a simple geometric analysis of a reflecting mirror 150 feet away from an atrium with a width of 26 feet. This 150 foot distance was based on the specification that the reflector must be 5.6 feet away from the building per foot of building height [1]. Again, developing a proper testing procedure allowed us determine what type of motor resolution would be needed in order to obtain our ±5° tracking error.

To accurately refocus light from the Sun into the atrium (or any other building) the reflector must be equipped to rotate in two axes; the axis of altitude and the axis of azimuth. Making the assumption that the Earth can be modeled as a flat surface, the axis of azimuth would be represented by an imaginary line projecting from the ground to the sky normal to the Earth. The axis of altitude would be represented by an infinite imaginary line normal to the axis of azimuth that projects to the left and right parallel to the Earth's surface. Rotation about the axis of azimuth will result in left to right motion of the preconceived reflector, and rotation about the axis of altitude will result up and down tilting of the reflector. The rotational motion in these axial directions will be controlled by rotational motors. In order to simplify our design for testing purposes, we created a unit that has only one axis of rotation in the azimuth direction. We then would test the unit against one location of the Sun in the altitude direction, tracking the Sun as it moves horizontally across the sky.

The range of motion of our reflector is vital to correctly reflecting the Sunlight into the atrium. Since the altitude angle of the Sun varies between 0° and 20° during the winter solstice and 0° and 70° during the summer solstice, we need a self adjusting system to account for the seasonal and daily angular change. Furthermore, the Sun moves from -122° to +122° in the axis of azimuth [1]. Thus, we need our mirror to be able to move from -61° to +61° since the law of reflection dictates that the angle between the incident ray and normal is equal to that of the angle between the reflection ray and normal [16]. We added an extra 4° to the range of motion as a safety factor which changed the azimuth rotational specification to -65° to +65°.

It is vital that the support of the system does not allow the light reflection to damage pedestrian's vision. Also, the height of the support can make maintenance of the system much more difficult. The support diameter and height must be of adequate dimensions because both are factors in the structure's stability. Preconceived design suggests the support height and diameter are fifteen feet and eight inches, respectively [1].

A guard to protect our new structure against severe weather was necessary in the state of Michigan and other harsh global climates. Our 1 m^2 structure must be able to withstand at least 50 pounds [1] of snow to avoid failure and to give time for the maintenance crew to provide snow removal. It should also be able to handle the occasional strong wind gusts that occur in certain regions of the world. We aim to have our system handle gusts up to 100 mph [15].

Using sun detection (passive), rather than sun location calculation (active), was a key factor in the design of the solar energy system because it will reduce the initial investment cost and lower the payback time. Calculating the location of the sun requires the system to have memory and programming. By eliminating this factor we will also eliminate much of the cost associated uniquely with an active system. Another factor we considered was the energy consumption of the system. Energy consumption increases with an active system relative to a passive system because microcontrollers need more energy to operate than simple circuits. For instance, an Arduino Mega, running continuously will deplete a 9V battery in approximately 40 hours assuming the average 9V battery can supply 0.55 amp-hours [23]. This does not include the energy required to power the motor of the system. By using less energy controlling and maintaining the unit, the system will be able to reduce the energy consumption of G.G. Brown even further because it will not need to pull energy from the G.G Brown power grid in order to function.

The system must be durable enough to withstand the harsh temperature fluctuations it will be subject to in the Michigan climate which means it must operate properly in temperatures ranging from -25° to 115° F [17]. As with any solar system, efficiency decreases as the cleanliness of the panel or reflector decreases. To combat this problem, the system was allowed bi-monthly maintenance which will incorporate a brief cleaning and troubleshooting session (if needed). Furthermore, for the system to match benchmarked current solar technology, and to make a continued energy need reduction in G.G. Brown, it should have a lifetime of at least 30 years [18].

In order to assure the inhabitants of the G.G. Brown atrium are comfortable, some engineering constraints must be applied to the solar energy project. For instance, according to IESNA it is recommended that the maximum light intensity in a room not exceed 850 lux to prevent eye damage or discomfort [19]. Furthermore, if building inhabitants occupied the atrium for extended periods, they may be subject to increased ultraviolet rays which could lead to Sunburn or other skin damage if the maximum light intensity specification is not followed. The possibility of overheating the atrium is very real, therefore the system should be constrained to heat the atrium to a maximum temperature of 72°F in the winter and 78°F during the summer months [20]. Should the system impart too much light or too much radiant heat energy, it should also be designed to be adjustable. For instance, heat and light sensors could detect if a threshold value were reached and signal a screen to drop down from the window to partially shield the atrium.

In order to create our alpha prototype, we had to account for all of these specifications, specifically those which we will verify through testing procedures. Our first task was to develop concepts that matched our requirements and specifications.

Table 2: Top 6 Engineering Specifications

Rank	Engineering Specification	Target [Units]
1	Reduces Building Energy	> 2.5%
2	Investment Payback Time	< 4 Years
3	Energy Production	> 11,000 kWh
4	Tracks Sun With Minimized Error	< 5°
5	Motion	2-axis
6	Reflector Area	1 m^2

Alpha Design and Testing

Functional Decomposition

Prior to generating concepts of our design, we created a functional decomposition to address the main and sub-components to meet the requirements and specifications outlined in the previous sections. Our system involves multiple subsystems that must all work together in order to direct light and thermal energy into G.G. Brown. We created a functional decomposition of our Alpha Design, as seen in Fig. 16, to understand how the subsystems will work together. Solar energy is taken in by the light sensors and compared between the LEDs to determine the location of the Sun. A signal is sent to the motor from the circuit telling the motor a certain distance to reflect the solar energy into the building. We must understand that there will be energy loss within the system and may therefore have to look into altercations so that these energy losses will be minimal. This can involve using bearing to reduce the effect of friction on the rotating shafts and possibly minimizing the length of the wires used in the electronic system to reduce the system's electronic resistance. When we tested the system we used a power supply to power the rotational motor instead of a PV cell. The functional decomposition below models the potential mass producible unit as opposed to our test simulation prototype.

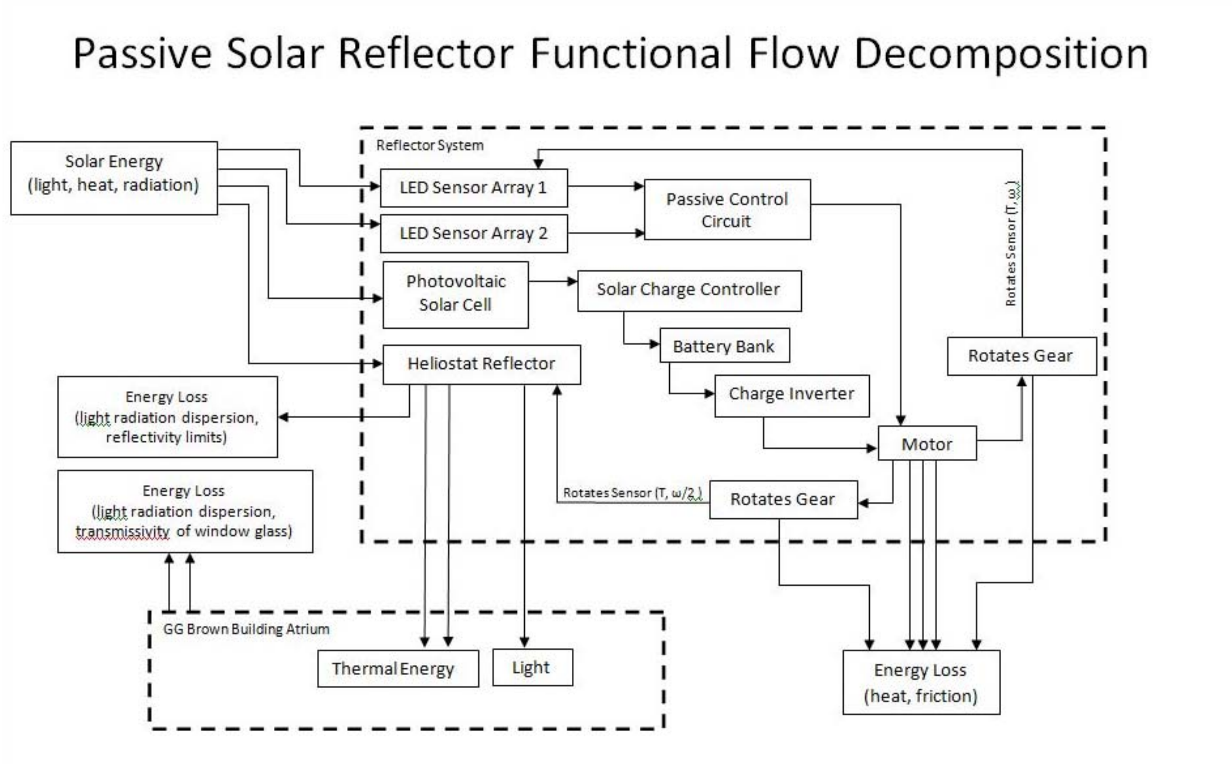


Fig. 16: Functional Decomposition of Alpha Design

Concept Generation

Information gathered from our design requirements, engineering specifications, and functions described by our functional decomposition helped us generate ideas for our solar reflector. According to our functional decomposition, our ideas needed to focus on reflector movement and tracking the Sun's position.

Multiple circuit ideas to control our passive solar tracking device without the use of a microprocessor were researched. One of these circuits created and sold by Red Rock uses LEDs to track the Sun and provide information to the control motors [21]. Ultimately, a circuit similar to this is the most cost-effective way to track the Sun, as the expected loss in tracking error is low enough to produce a low pay-back time, which justifies the implementation of a passive system that functions without a microprocessor. Other ideas that were discussed include the use of a web camera to be able to identify the location of the Sun in the sky.

Moving the reflector was also an area we focused our concept generation around. We had to determine what would be the best way to move the reflector with little error and allow for easy adjustments for tracking the Sun. Our concepts included linear and rotational motors that would move the reflector in the horizontal and vertical directions. We also researched using a satellite actuator motor for our reflector, as the motion our reflector will have will be similar to the motion used by a satellite dish.

Fig. 17, below, shows one concept generated using a linear motor for the reflector movement. Attaching the motor to the stationary structure would rotate the reflector clockwise as it extended and counter-clockwise as it retracted. However, this design would require a second motor to rotate the sensor and make it very difficult to calculate where the reflector would be located relative to the building and the sensor.

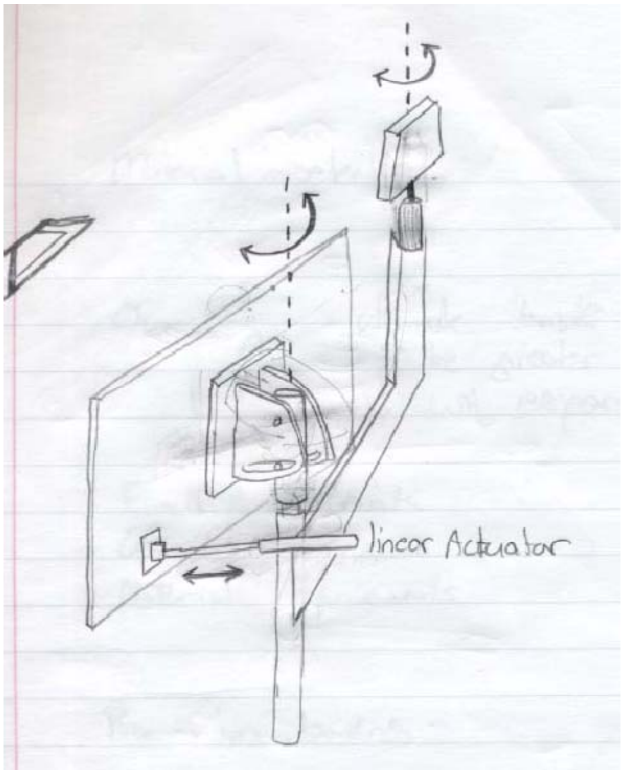


Fig. 17: Linear Actuator Concept

Fig. 18, below, shows a second concept generated for the solar reflector. This design included a tri-pod type base that would allow the system to be moved around with ease, which is ideal for us to be able to test our system. Also included are LEDs that display a block M at night for aesthetics.

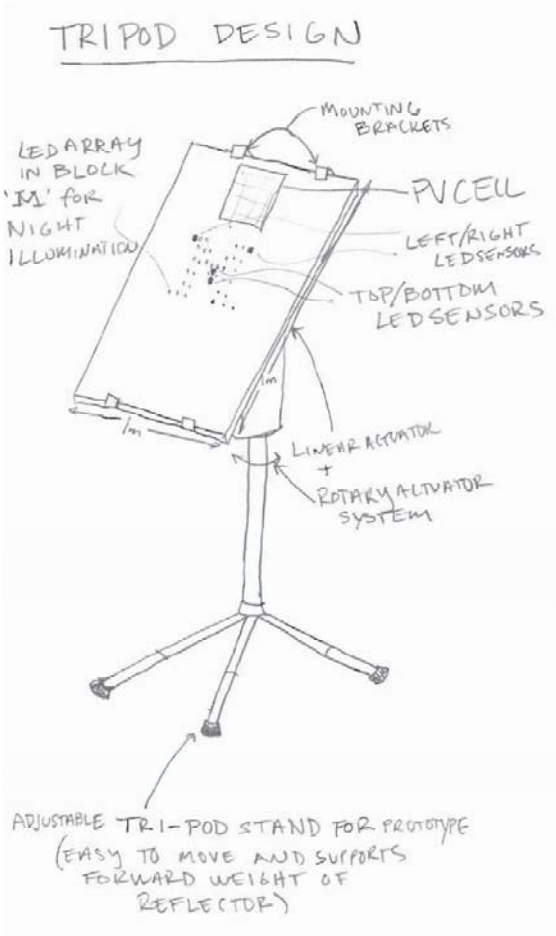


Fig. 18: Tri-pod Base Concept

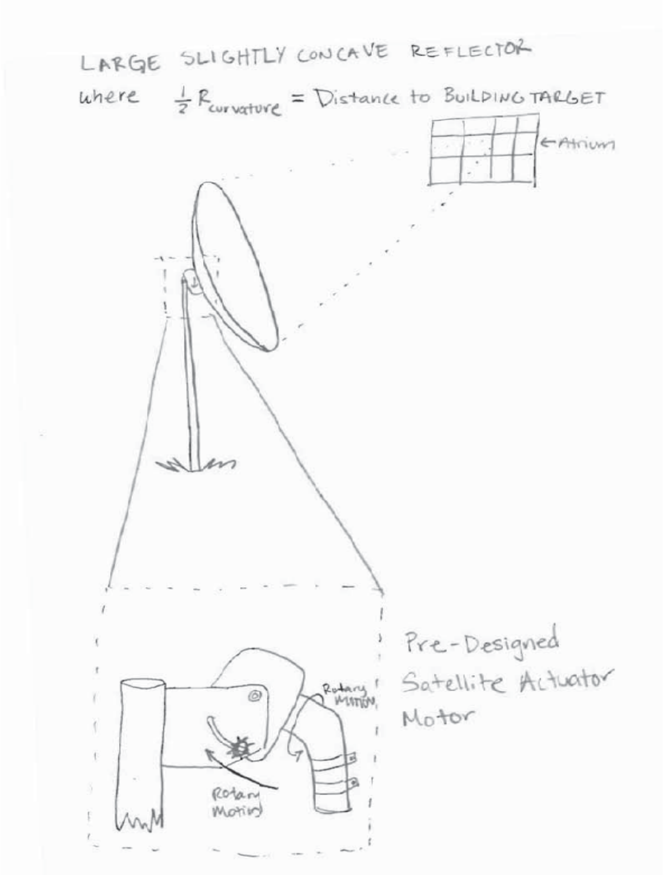


Fig. 19: Satellite Actuator Concept

Fig. 19, above, illustrates a design concept using a satellite actuator for reflector rotation. This design also used a reflector with a slight curve to it, where the focal point is located a distance that is equal to half of the radius of curvature of the reflector.

Although these three concepts were great in helping us determine how we want to meet our requirements, we felt that they would not be the best. We narrowed our selection down to two designs that we felt best met our requirements, and we compared these two and reduced them to one final design. Other concepts we generated can be found in the Concept Generation section in Appendix F.

Concept Selection

We first decided to select the design for the solar tracking system since it would limit other portions of the design. We discovered that the operation temperature for the web camera was not ideal for the temperatures in which we wanted to operate our reflecting system. We then decided to use the LED circuit for our passive solar tracker. The circuit incorporates two LEDs in which the light intensity incident on each LED causes the voltage flow to reverse across the diode. The circuit then compares the voltages and provides the motor with a command to move the sensor so that the highest intensity will be directly between the LEDs as shown in Fig. 20.

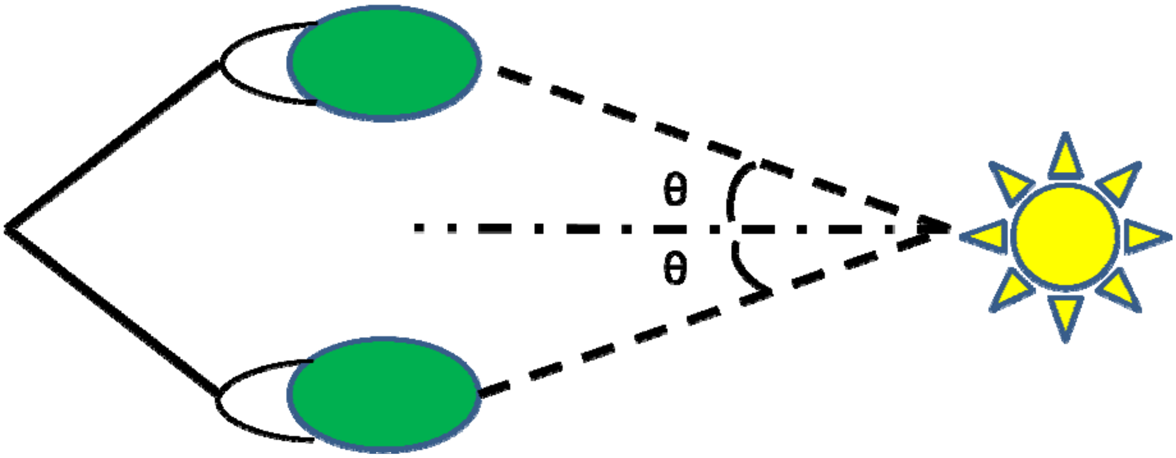


Fig. 20: LED Light Intensity Detector

This system causes a problem because the sensor needs to be pointed directly at the Sun, but the reflector needs to be angled exactly half way between the sensor and the building in order to direct the solar energy into the building or a similar target. This was an important aspect in creating our design because it added complexity to the system. In an attempt to solve this problem we created a design that includes a double rack and pinion in which the lower rack and pinion is grounded as shown in Fig. 21, p. 21.

In this concept the reflector rotates at the same speed as the gear that is attached to the motor shaft, and the sensor rotates at twice the speed, solving the off-set issue. Furthermore, the design has aesthetic appeal and could potentially be part of a summer function. The downside of this concept was that it would be extremely difficult to account for the change in the altitude angle. Also, the stability of the structure would be an issue as the gear rotates through its path and the top pinion becomes off-center.

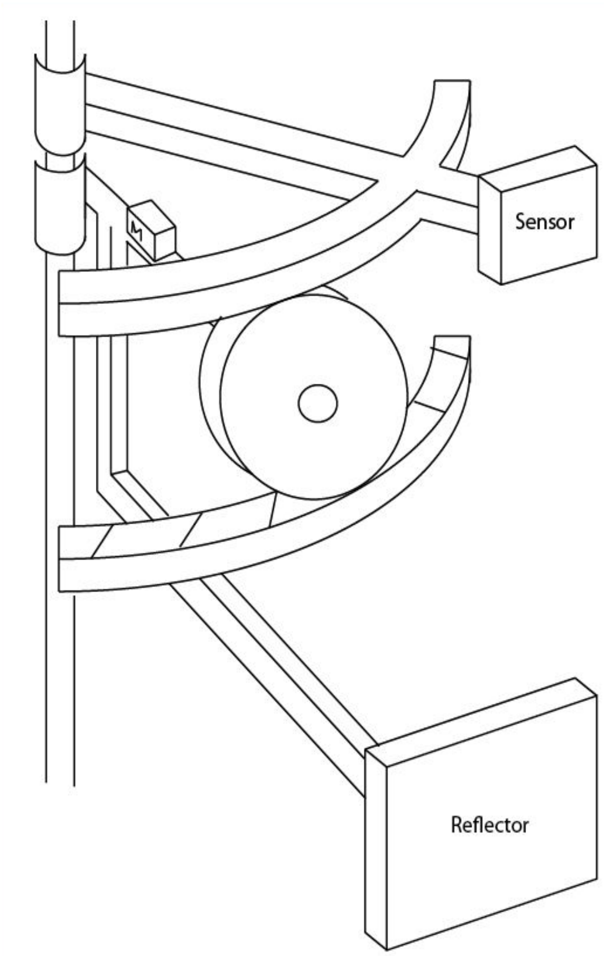


Fig. 21: Alpha Concept Design One

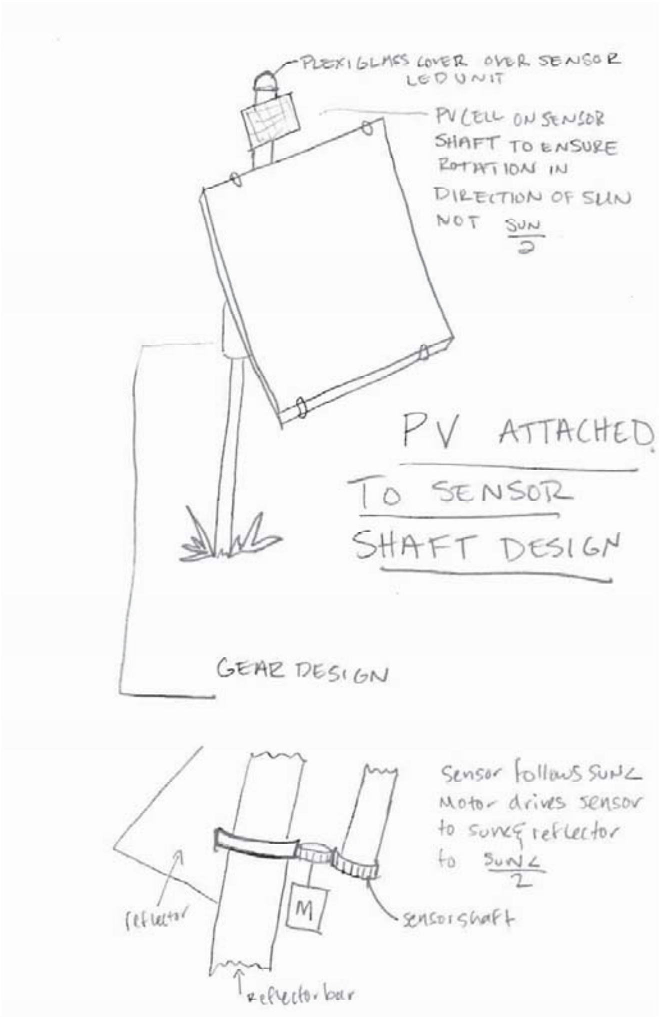


Fig. 22: Alpha Design Concept Two

The next concept (Fig. 22, above) we created was simpler in design and involves attaching two gears directly to a centralized gear on the motor shaft. The two gears have a 2:1 ratio where the gear for the reflector shaft is twice the size of the sensor shaft gear. The motor gear is in the middle, therefore the sensor and reflector gear will turn in the same direction, and the sensor gear will always turn twice as far as the reflector gear. This allows the reflector to remain half-way between the target and the power source and the energy to be directed at the target. The sensor is oriented behind and above the reflector so that its viewing angle is not obstructed and so that it is not affected by light noise off of the reflector.

This concept does not have the aesthetic appeal as the first concept, but it is does have the versatility to adapt the altitude angle into its design easily. Another gear system could be placed behind the reflector and below the sensor to add a vertical LED system to track the altitude angle.

Although concept one is more visually appealing, we selected concept two for its simplicity in functionality for testing as well as its ability to accommodate an altitude angle adjustment for mass production purposes both of which were vital to our project requirements and engineering specifications.

Alpha Design

After selecting the best concepts generated, we were able to create an Alpha Design for our passive solar reflecting system. Fig. 23, below, shows our design featuring our rotational motor connected to both the reflector and tracking system. Our Alpha Design incorporated only one axis of rotation, the azimuth direction. We chose to do this so that we could test our system to obtain data to determine how well our passive system will track the Sun.

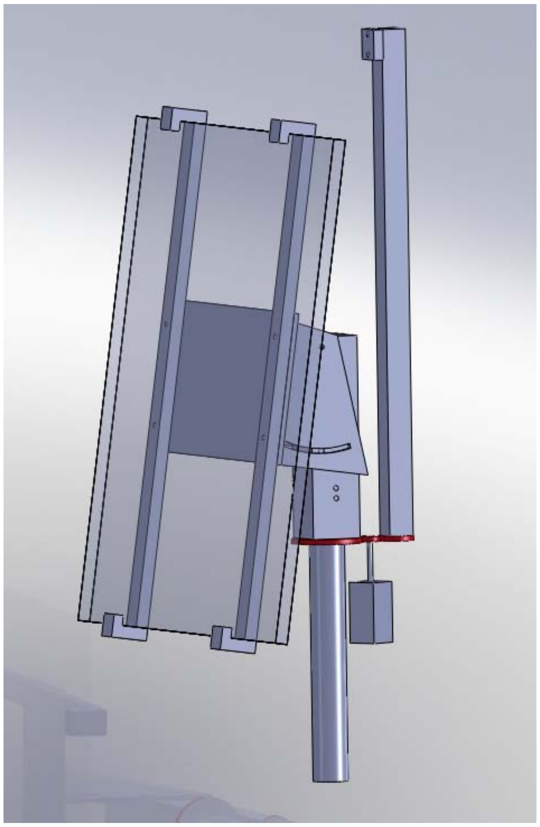


Fig. 23: Alpha Design

Fig. 24 illustrates the inner workings of the moving shaft connected to the reflector panel. The inner shaft is connected to the motor via a gear. This shaft is connected to the upper shaft which is attached to the reflector panel. The lower shaft allows the inner shaft to rotate but still keep the system in a stationary position. A bearing is used to reduce the loads and friction involved in the moving system.

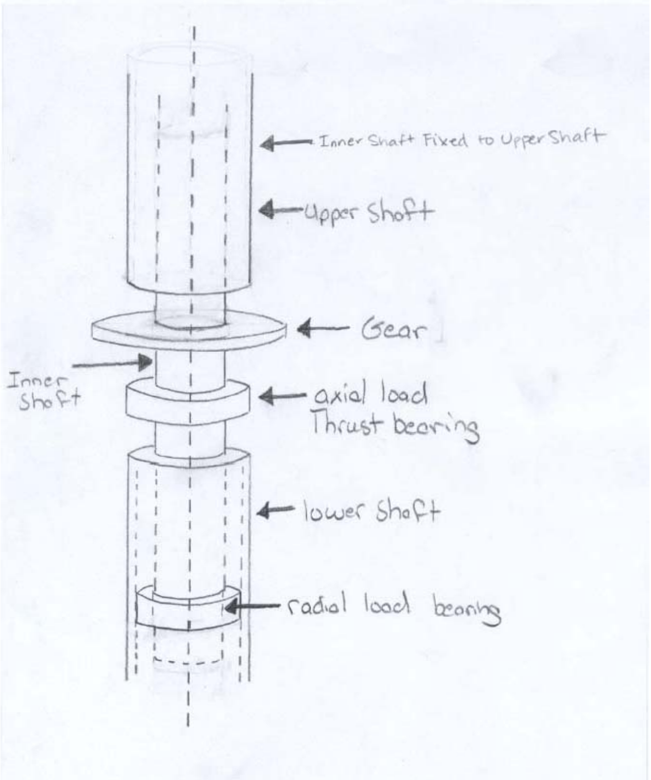


Fig. 24: Reflector Panel Shaft

Accurate motor positioning was important to have a properly functioning system. Fig. 25 shows the motor placed between the shaft for the reflector and the shaft for the tracking device. It is mounted to both shafts for stability. Both shafts are attached to the support base of our system. The base of our design follows a tripod design to allow for stability and portability for testing purposes. It was vital that we considered the implications of backlash and sticking in our design as these factors could cause problems. Possible problems with this system are increased torque and motor size requirements and reflector misalignment. Either factor could prohibit meeting the specifications.

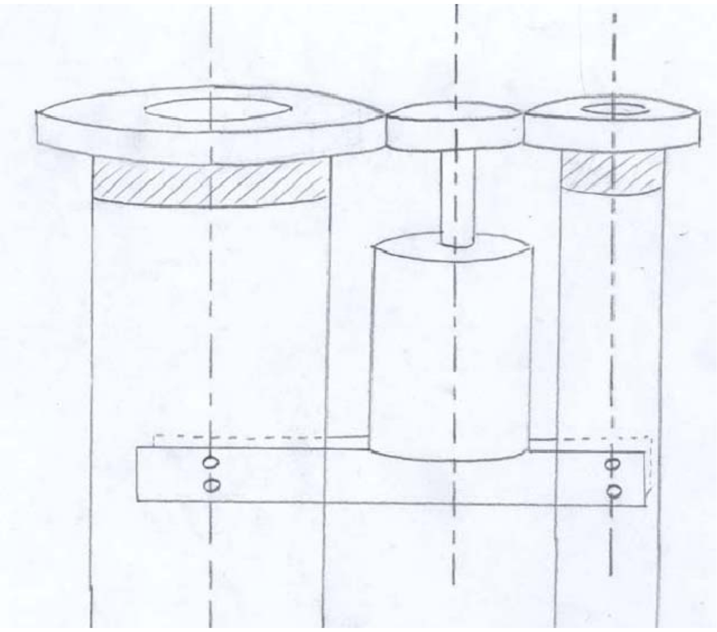


Fig. 25: Motor Location

Selected Concept Description

Prototype Description

To ensure that the requirements and specifications are met, a testable prototype was manufactured. This prototype demonstrated the important aspects of our design, namely the effectiveness of the passive tracking system and the potential solar energy transfer from the system into the building. The prototype tracked the Sun in only one direction – the azimuth direction. This required only one motor to rotate the reflector and LED solar tracking circuit for the passive system. The prototype was also much smaller than the final design, having a reflector area of 0.25 m^2, allowing for ease of transport during testing. Fig. 26 shows a three-dimensional view of the prototype that was fabricated. The fabrication process is addressed in the Initial Fabrication Plan section.

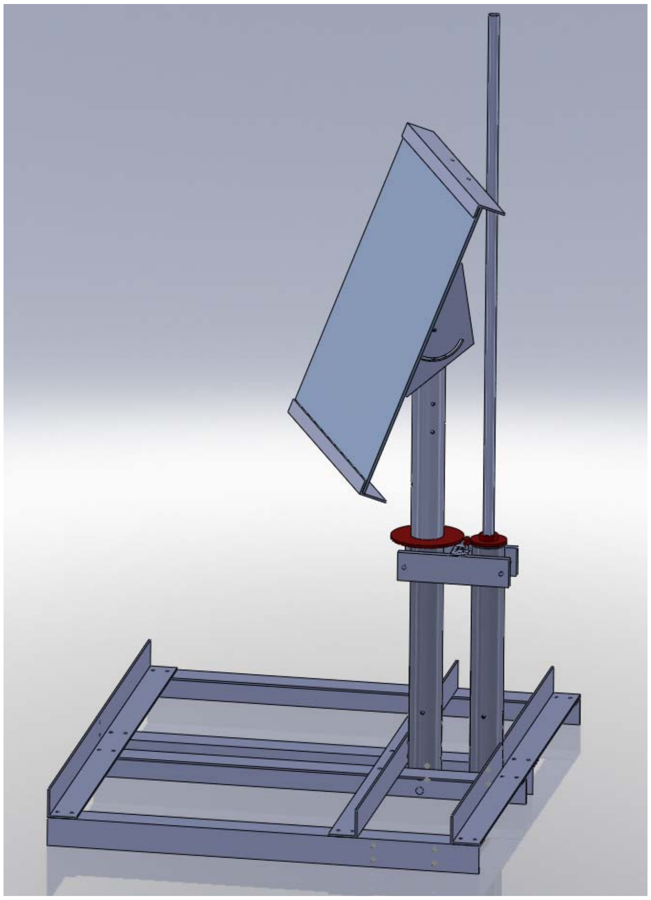


Fig. 26: Final Prototype for Fabrication

A Bill of Material of the prototype can be found in Appendix A. A majority of the parts used to construct our prototype were readily available for our use in the Machine Shop on the first floor of G.G. Brown. We had permission from Bob Coury, the shop manager, to use some of the scrap in the shop for our prototype. Testing supplies, including the thermocouples and devices to take reading from the thermocouples, were available for use from Professor Steven Skerlos' lab. A laptop to run LabView and take measurements during our test was borrowed from the Electronic Reservation Department in G.G. Brown. The availability of these materials allows us to save a substantial amount of money when building and testing our prototype.

After determining which items we could get cost-free, we determined the remaining items that needed to be purchased. The high cost items that drive the cost of our prototype up included the bearings and gears used for rotating both the reflector and sensor. We also included items that must be purchased for testing purposes, such as lumber for the test track and Styrofoam for the insulated box. With the current prices, we determined the cost of our prototype to be $246.60. When we included the cost of the prototype supplies as well as the testing materials, our total cost came to $360.00. This value was below the established goal of $400 for the costs associated with the project. The Bill of Material for both the test apparatus and the prototype, with cost calculations, can be found in Appendix A. Images of the manufactured prototype can be seen in Fig. 27 and 28.

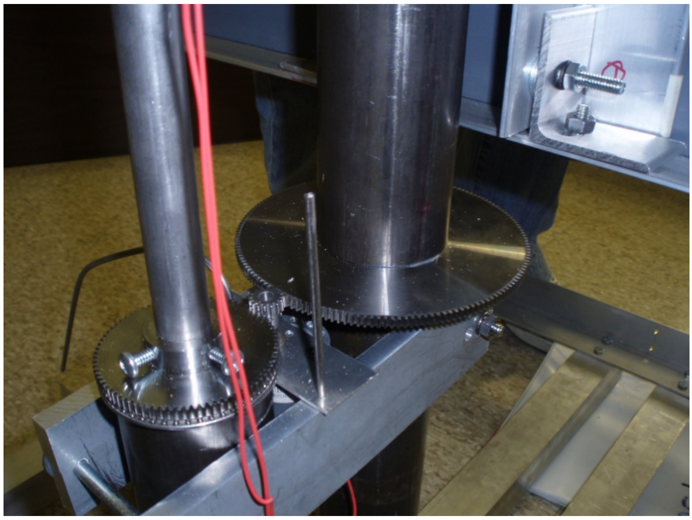


Fig. 27: Prototype Gear Assembly

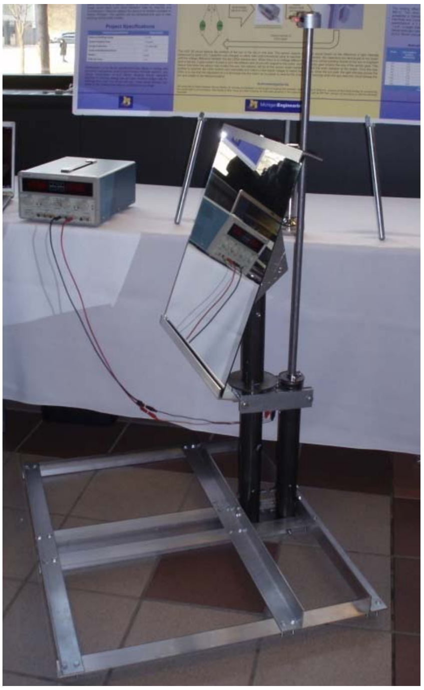


Fig. 28: Prototype

Parameter Analysis

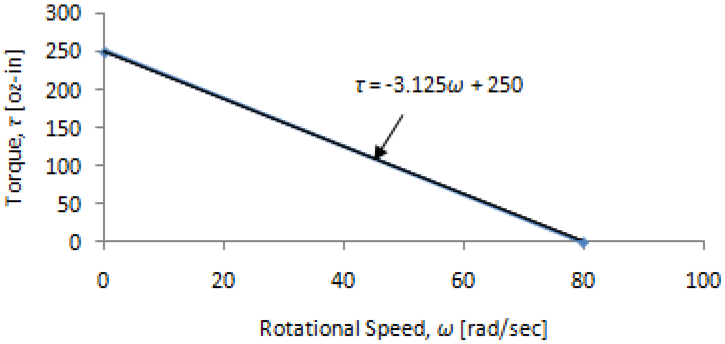
The concept chosen successfully completed the functions necessary of a passive solar reflector and it allowed us to quantitatively determine the validity of our initial requirements and specifications through testing. The alpha design was focused on a testable prototype rather than a final design. The parameters had to be validated to determine the characteristics of a final design. The approach to refine the alpha design is outlined below.

To create our prototype, it was necessary to minimize the amount of materials purchased. The most costly components of the design were the gears and motor. Several materials that could be used for the prototype and test set-up were found in the Machine Shop. Steel pipes, aluminum plates, L-beams, Plexiglas and various fasteners were among the available items. Angular and thrust bearings that match the dimensions of the scrap materials were found which lowered our total prototype cost. Further details were discussed in the Prototype Description section. Also, we obtained K-type thermocouples, a signal conditioning unit, a DAQ card and a laptop cost free from Professor Steven Skerlos' lab and the University of Michigan. These materials allowed us to quantitatively measure the energy transmitted to the insulated box by each system as described in the Validation of Approach section.

A testing procedure was developed to quantitatively compare the active, static, and passive systems, and measure and compare the energy transfer by each system into an insulated box. The main component that affected our design parameters was a 400 watt metal halide light bulb that our team already had in our possession. This light represented a radiation-emitting energy source, which quantitatively compared to the irradiative energy emitted to Earth by the Sun. The temperature change was found to be 92 Kelvin assuming perfect tracking during the entire thirty minute test with no significant energy losses. The detailed calculation can be found in Appendix J. We used this reference temperature as a measure of efficiency during the analysis of our testing results.

Another important component vital to our design was the prototype's ability to rotate the sensor and reflector at the correct angles and speeds necessary to effectively track light. We were required to rotate the sensor at a two to one ratio to the reflector, and we needed a motor to power this function. A motor from Pololu Robotics and Electronics was used with 250 oz-in of stall torque and free-run angular velocity of 80 RPM at 12 Volts [22]. The torque curve for the selected motor can be seen in Fig. 29. This curve was used to ensure that the required torque at the desired rotational speed will not stall the motor. Based on a test time of thirty minutes, the motor needed a gear ratio of 10:1 to provide adequate torque to the reflector. The detailed calculations for this can be found in the Appendix. The analysis allowed us to detail and refine our alpha design, and to prepare an initial fabrication plan.

Fig. 29: Theoretical Motor Torque Curve



A material selection and environmental analysis was performed on the materials to be used for the reflector backing and the support structure for the system. First, it was determined what the desired qualities of each material must be in order to have a durable and functioning design. Some of the important characteristics include high yield strength, high corrosion resistance, and price. Next, this information was inputted into CES software to determine the best material to use. Using the software, it was determined that polycarbonate was ideal for the reflector backing and steel was ideal for the support structure. The environmental impacts of these chosen materials were then identified using SimaPro 7 software. SimaPro calculated and plotted the regions that production of this material would impact. Such areas of interest included the human health impact and emissions from creating the materials. It was determined that the polycarbonate for the reflector backing has a large impact on the environment, much larger than that of steel. Although the environmental impact of the polycarbonate is high, having a long lifetime will help to reduce the amount of this material needed for manufacturing, such that reflector backings do not need replacing throughout the lifetime of the system. The impacts of polycarbonate are similar to those of other thermoplastics that could be used instead of the polycarbonate, such as polystyrene and polyethylene. But these materials have slightly lower yield strengths which is an area which we want to have a higher value. A more detailed description of the material and environmental analysis can be found in Appendix C.

A safety analysis was performed for the prototype in order to determine which areas of the build were of high interest for failures that could cause us harm. The light bulb used for testing was determined to be the area of most interest, as the light contained gases that were not good to inhale. Extra caution was used when handling the light to ensure it was not dropped. Another area of interest was the mirror, in that breaking the mirror could cause problems. Again extra caution was used when handling the mirror to ensure it was not broken. A Failure Mode Effects Analysis (FMEA) was performed to determine which areas of the design needed more focus to ensure they did not fail. Other than the two previously mentioned issues, no other glaring problems were brought out through the analysis. DesignSafe software was used to perform a risk assessment on all the parts that would be machined. It concluded that the highest risk situation included retinal eye damage to the user due to the light intensity involved. To this point light shelves would be implemented to prevent a user from having eye damage. Other than the normal safety issues that must be taken when machining parts, there were no extra safety steps that needed to be taken when creating the prototype and this carries over to machining the final design.

Final Design Description

Our final design involves a 1 m^2 solar reflector with two LED solar tracking circuits. This is an expanded version of the prototype developed and tested. The final design uses cement to fix both of the supporting poles into the location desired for the reflector. A separate sensor and gear system similar to the one used for tracking the azimuth direction of Sun was applied to the altitude direction. Both motors and gear systems are covered by a protective housing. Dimensioned drawings of the new parts different from the prototype can be found in Appendix M.

The test results were used to determine the error associated with our solar reflecting system. We established whether or not our system was cost-effective enough to become mass producible and in what fashion. Because the atrium project is not finalized and the date of completion is still uncertain, incorporating the design into the atrium project may be irrelevant. To this point we looked into using our passive system to heating the offices and other rooms located in G.G. Brown and other buildings that do not have south facing windows. This was the original idea that brought about the project completed by team SolarFocus from Winter 2009. Implementing an array of the passive solar reflectors to bring light and heat from the Sun into offices in the winter months would help to reduce energy costs of a building. In applying the reflector to the atrium, we must ensure that the system is above eye level from people passing by and in the building so that no one is injured. The same safety concerns must be applied to the office design, and a light shelf may be incorporated in order to achieve this in the office situation. For either real-world situation, the mechanics and electronics of our design are the same. For this design the passive system's costs would be lower with respect to the active system's costs because multiple reflector systems would be required. This is because the active system's costs would greatly increase as the number of reflector systems increases. This would reduce the payback period for the system and make the passive system that much more enticing. Upon completion of the testing we can compare the energy gained by our system and the energy usage of a standard office to determine if the passive system would bring down the overall energy costs in a time-effective manner.

Fig. 30 shows a CAD drawing of the final design. The original sensor pole from the prototype has been changed to incorporate a banana curve to allow greater degrees of rotation for the mirror in the azimuth direction. There will be a housing used to protect the gears and the motor from the elements, seen in Fig. 31. The housing will be attached to the stationary base poles so that it does not rotate. Small coverings, pictured in Fig. 32, will be attached to the rotating poles to prevent rain or debris from falling into the gear Housing. The slot for manual adjustment on the prototype was eliminated on the final design because the motion in the azimuth direction will be controlled by a second motor, as seen in Fig. 33.

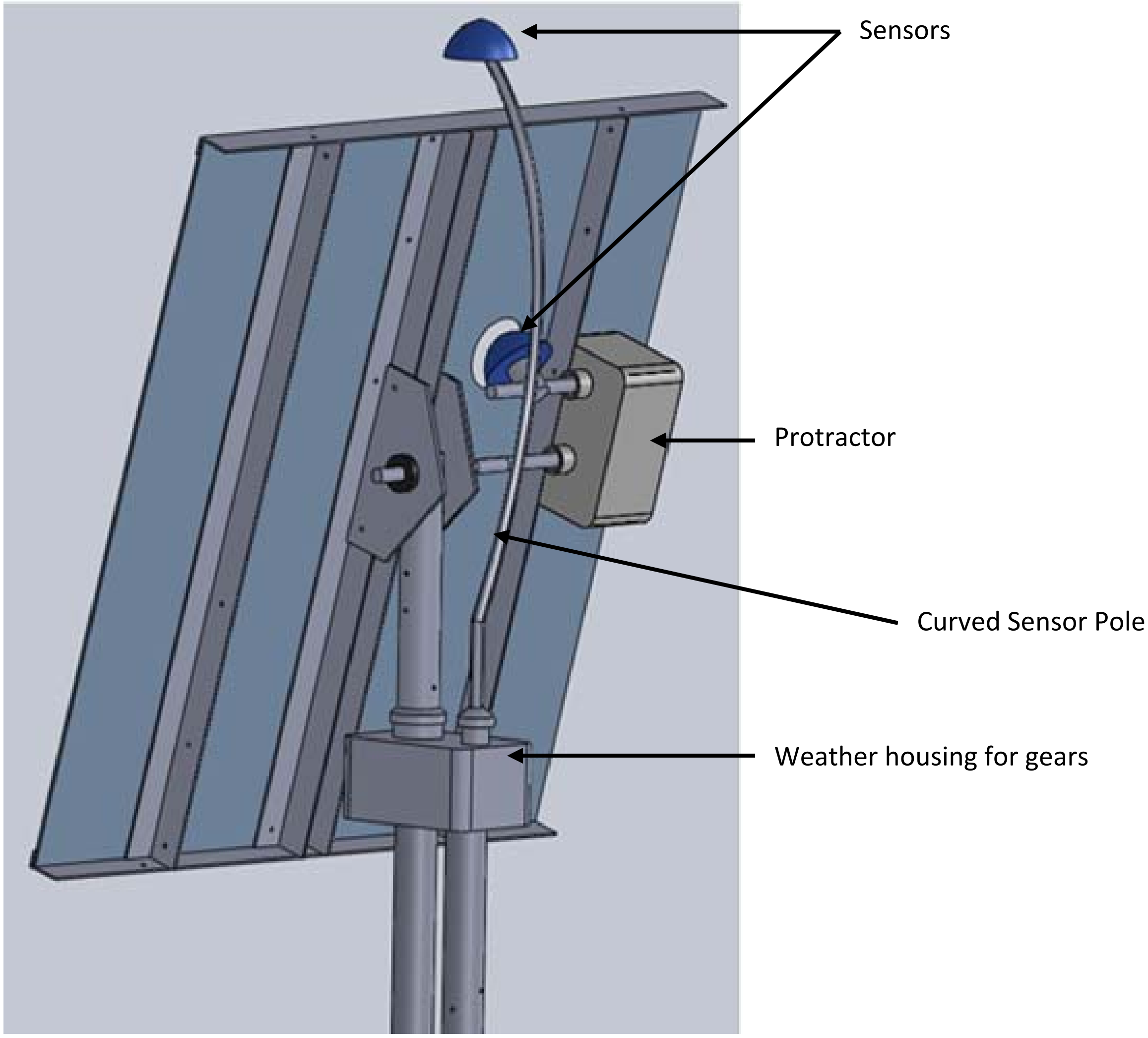


Fig. 30: Final Design CAD Model

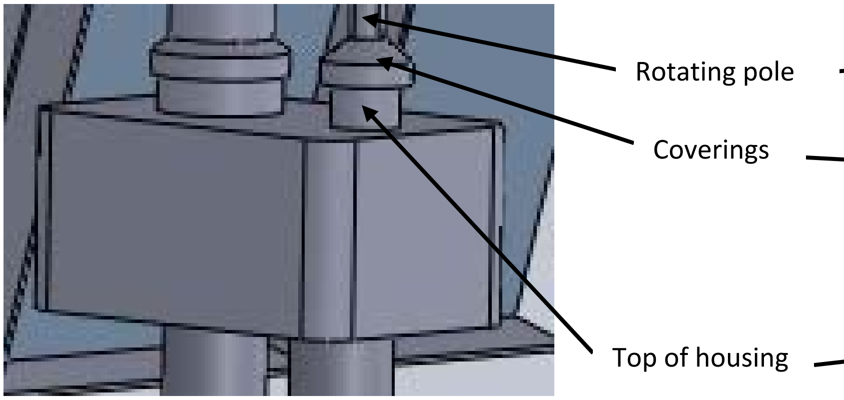


Fig. 31: Gear Housing

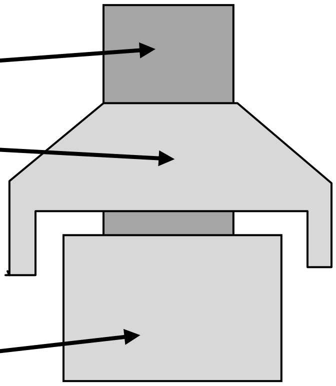
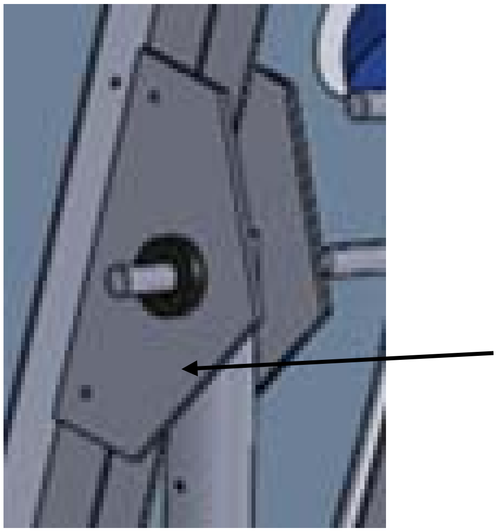


Fig. 32: Covering Concept



Manual Adjustment slot
has been eliminated

Fig. 33: Final Design for Bracket

Validation of Approach

To demonstrate that our design would meet the specifications, we performed tests and analysis to validate the performance of our design. The validation through testing, power analysis, performance against the benchmarked heliostat reflectors, and cost analysis can be found in this section.

Validation of Prototype

In order to prove that our concept was feasible and met specifications, we developed a plan that would verify the electric tracking abilities, mechanical functionality, and support the dimensions of our prototype. We were to first test the efficiency of our passive solar tracking method against an active and static system. A cost-analysis was then done to compare the energy gains of the passive system against the active and static system, and we also compared the costs to typical building heating and lighting systems. However, upon attempting to perform the test we realized that the measured results were not significant enough to extract valid conclusions. A manual method of measuring the error associated with our tracking system was then developed to allow a cost-analysis to still be validated. The inconclusive and manual tests are both discussed below.

The first test developed consisted of a powerful light to imitate the Sun, a reflector, and an insulated box. Specifically, we used a 400 Watt Metal Halide light bulb with attached reflector that followed an elevated linear track made out of two by four pieces of lumber. The light was attached to a wheeled platform that was then attached to a rope. The rope's other end attached to the drive shaft of a motor so that when the motor runs, the string wound around the drive shaft and the wheeled platform, light, and reflector were pulled at a constant speed across the track. This system simplifies the motion of the Sun by holding the altitude angle constant, and our original concept is depicted in Fig. 34, below.

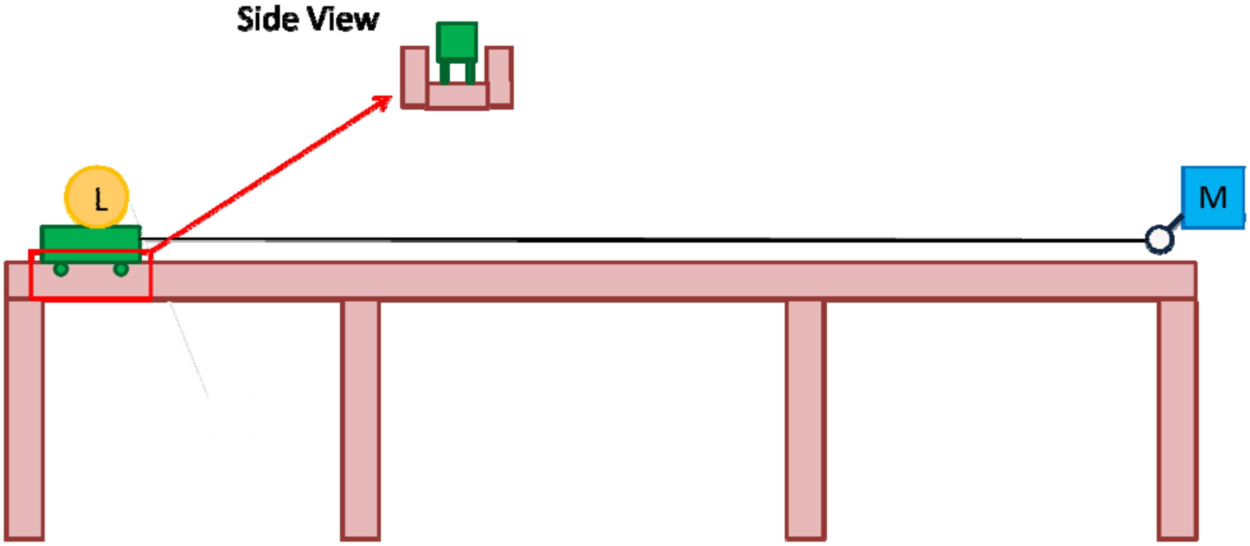


Fig. 34: Original Test Set-up for Lighting Track

The light was directed onto a reflector which redirected the energy into an insulated box. This box was made out of Styrofoam due to its insulation properties with its sixth side made out of Plexiglas to allow for energy transfer into the box. Each side of the Plexiglas face of the box had a length of 0.5 m. The reflector of the prototype also had the same dimensions of the Plexiglas face. Based on thermodynamic calculations we determined the thermocouple must have ± 0.5° accuracy.

We modified this general approach after design review two, with refinements to the car and track. A curved track made out of seven, 2.2 m long 2x4 was used. Each section had a base at the middle for support consisting of a 1 m high vertical 2x4 with three additional 0.75 m 2x4s. The ends of the track had a second base for added support. The base is depicted in Fig. 35. The base on its own is not stable but when attached to the other bases in the semi circle formation it cannot tip over.

Each 2.2 m long section was at an angle of 154.28° from the previous, creating a focal point 5 m away. This was the location of the reflector. The purpose of the curved track was to maintain a constant distance between the reflector and the light. This reduced the possibility that the system would track the light with greater efficiency as the light moves closer to the sensor. This test forced the reflector to track from -61° to +61° in the azimuth angle while keeping the altitude angle constant. Holes were drilled into the top of the track at the 2.1 m mark of each 2x4. A dowel rod was placed into each hole for the string to wind around to guide the car down the track. During testing, we manually removed the dowel rods as the car got close to them so that it continued on to the next part of the track. We used a DC motor that was available in the X50 lab in the basement of G.G. Brown to pull the car, and it will be controlled by a power source set to a specific voltage to pull the car at a constant speed. A rendering of the refined track is shown in Fig. 36.

Fig. 35: Base for Test Track

Fig. 36: Refined Test Track

The car for the light was modified to fit on the refined track. The car is shown in Fig. 37. The car had a total of six wheels: two wheels on each side and two wheels directly between the top of the track and the bottom of the car. This design allowed for minimal friction as well as stability during the test. There was a small gap between the side wheels and the track that allowed for easier transition between the boards of the track.

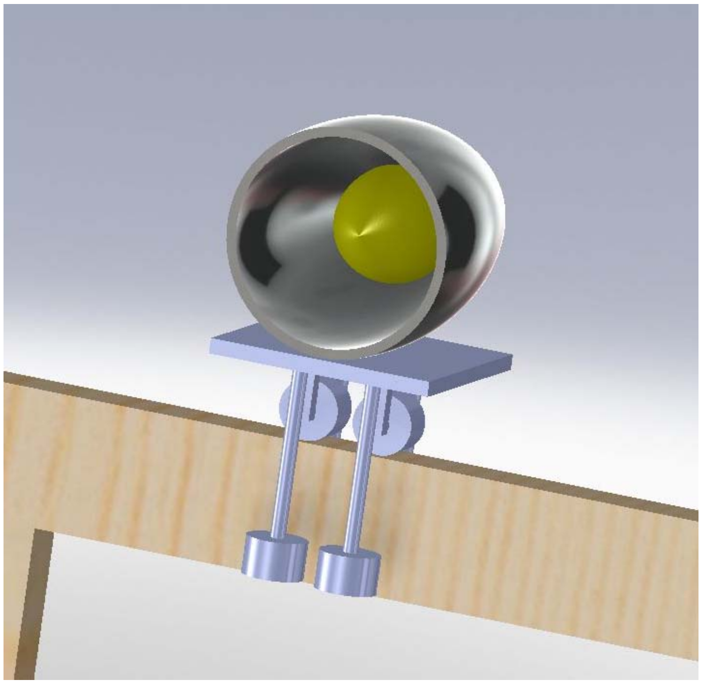


Fig. 37: Light-carrying Car on Track

The insulated box was also refined. The concept of adding a fan to the box with a sole thermocouple would add energy to the system, and would therefore be a poor choice. Instead two K-type thermocouples were used that were wired to a signal conditioning box. This box converted the analog signal to digital and fed data to a PC via a Data Acquisition Card (DAQ). This information was inputted into LabView where we could save and modify the data. We considered attaching the thermocouples directly to a multi-meter and taking the data by hand during the test, but this would be tedious and could add error to the measurements. Two thermocouples were used to eliminate error associated with temperature variance within the box. The set-up for the insulated box is shown below, in Fig. 38.

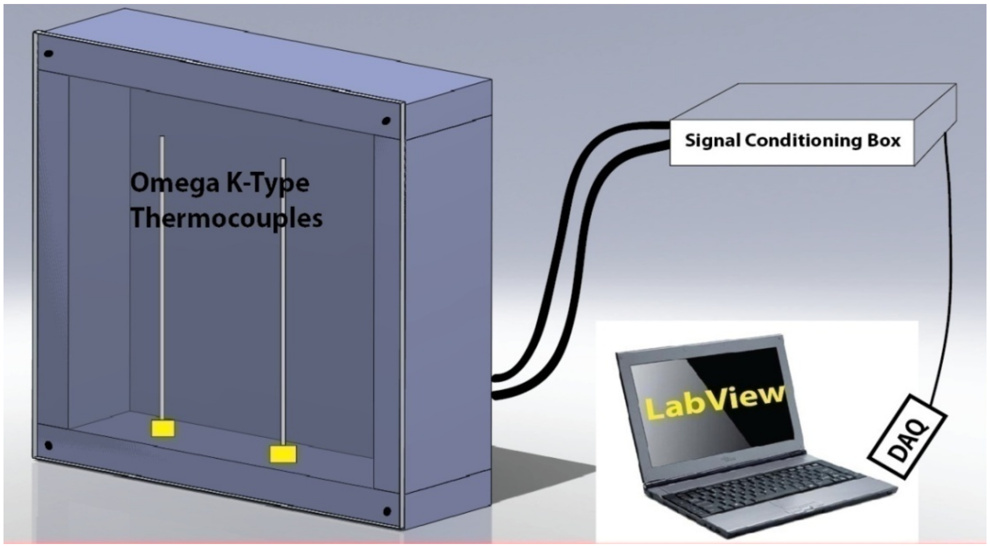


Fig. 38: Insulated Box with Thermocouples connected to a Signal Conditioning Box and PC

The passive system was measured against both an active and static system. The static system does not have motors or any electronics, and is simply a reflector on a pole. The purpose of this system was to represent the most basic possible system, and is shown below in Fig. 39 and 40.

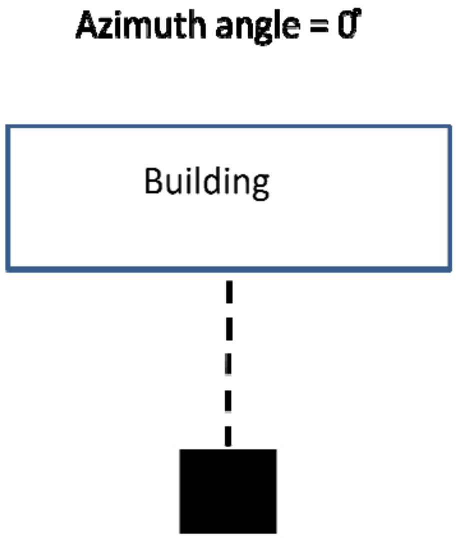


Fig. 39: Azimuth Angle of Static System

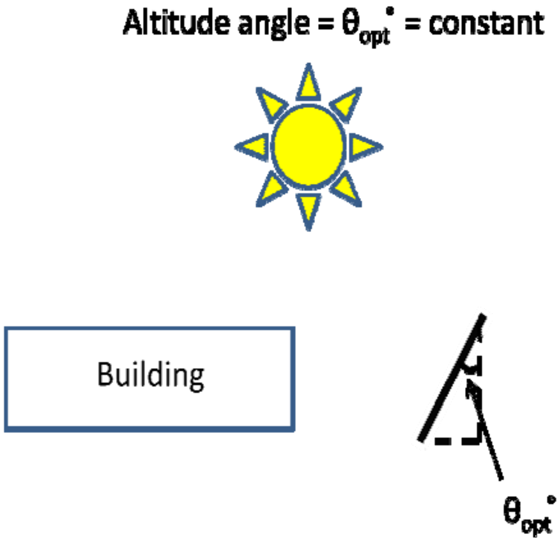


Fig. 40: Altitude Angle of Static System

First, the static system was tested. The light on the track traveled around the track in 30 minutes. Next, the passive system was tested. The passive circuit was activated and was used to control the rotational motor. The test was run in the same 30 minute time segment. Finally, the active system was tested. In active solar tracking systems, a microcontroller is programmed with the location of the Sun. In the case of this test an Arduino Mega microcontroller was programmed to rotate the reflector at the exact same speed the light is moving along the track. The passive circuitry was disconnected during this test. Again, the test was run in the same 30 minute time segment. Before each test, the light was given time to warm up to its maximum temperature. After each test the insulated box was allowed to cool to the ambient temperature. Each system was tested with three trials of the 30 minutes each to reduce the uncertainty in the precision of the values obtained.

By the end of testing we had hoped to be able to quantitatively determine the most efficient tracking method based on energy transfer and cost. However, the poor data prevented us from making valid conclusions about the energy transfer. We believe that there was a great amount of heat loss due to convection in the air and a poorly insulated box that prevented accurate results from being measured by the thermal couples.

A second test was then developed to verify the performance of the solar tracking system by measuring the error between the light, mirror, and target, specifically, comparing the angle the sensor should have moved to with respect to the light position and the angle it actually moved to. A protractor was attached to the reflector when the mirror and the sensor were directed at the target. A string was then attached to the center of the protractor and to the center of the target. A second string was attached to the center of the protractor and to the light. It was the same light and test track used in the previous test. The light was then moved along the track until the desired degree of rotation was met. The angle of rotation was determined by measuring the angle between the two strings attached to target and the light, as seen in Fig. 41. The string attached to the target does not move because the target location remains constant. Fifteen degree intervals were chosen so measurements were taken when the alpha angle was 15, 30, 45, and 60 degrees. At each interval theta was measured. Theta is the angle between the target and the line normal to the reflector face and is the measurement of how far the reflector physically moved while the system was tracking the light, shown in Fig. 42, where theta (θ) is the degrees the reflector physically rotated and alpha (α) is the degrees the light moved along the track. The ideal tracking movement is equal to one half of alpha (α/2), so that the line normal to the reflector face should always be halfway between the light and the target. The error in the system was calculated using these two angles, specifically as the ideal movement (α/2) minus the actual movement (θ). The average error demonstrated by our system while tracking the Sun was 2.9°. This is well below the specification of 5° we were looking to achieve.

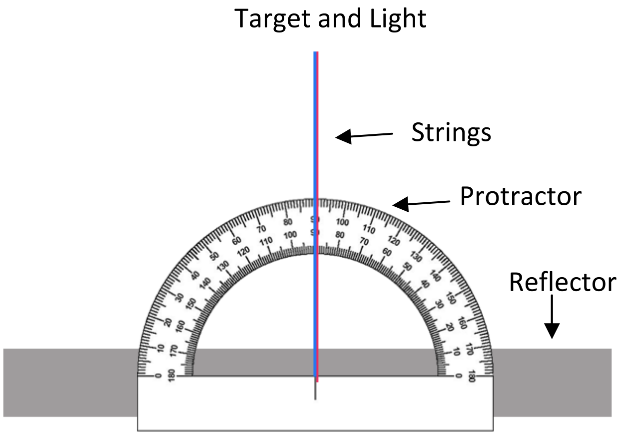


Fig. 41: Setup for measuring angles of movement while the system tracks the light

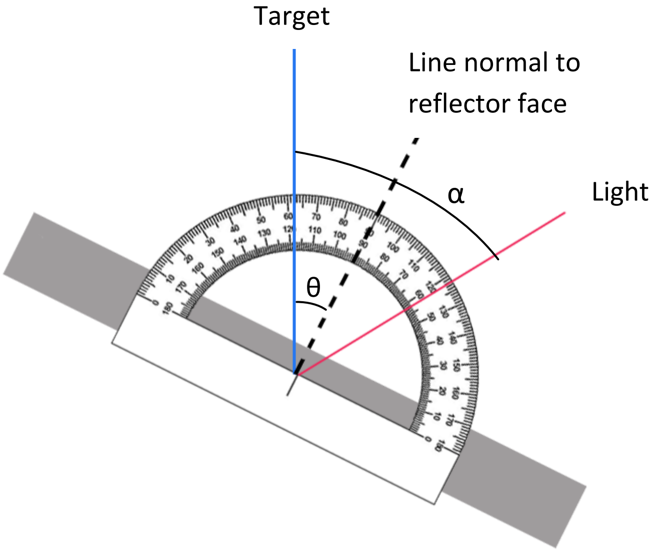


Fig. 42: Rotated reflector after light movement

It was assumed that the “active” system would behave like that of an ideal tracker because it calculates where the suns location will be at all times. Therefore, the error in our system was the difference between the ideal reflector movement and what our system physically moved.

By analyzing the error data, we were be able to decide the most practical method of production for our passive system; whether it should be designed for large scale purposes such as an atrium, or if it should be used for small scale purposes such as individual offices. Furthermore, we were able to quantify the heating and lighting costs reduced from typical natural gas heating and electric lighting and determine the payback time.

Validation of System Energy Supply

For G. G. Brown, specifically, an array of ten, one meter squared reflectors described as the final design is recommended. Instead of powering each reflector with its own small battery and small photovoltaic cell it would be more cost-effective to have a singular large 40 Watt photovoltaic cell with a bank of five larger 12 Volt, 8 Amp-hour (28800 Amp-Seconds) batteries that each reflector could draw power from. Based on prototype testing, the system re-adjusted its position approximately every 2.9 degrees of light source motion and took approximately 0.5 seconds to adjust to the new position. Our test track was 122° and each test lasted thirty minutes. This data suggests that the light adjusted itself on average 42 times per test for a total duty cycle time of 21 seconds. Assuming that the circuit will adjust the same number of times a day, the energy use of each motor in the system can be determined.

The control motors for the final design have a 30 mA free run current draw at 6 Volts. By multiplying the energy draw of the motor and the control circuit (30mA + 3mA) by the Voltage that is supplied to the system (6V), and by the number of hours the sun is expected to be up per day (10 hrs), the energy daily maximum energy requirement for each one meter by one meter reflector was determined to be 1.98 Watt-hours per day. The proposed array of 10 reflectors suggests that the total array daily energy requirement is 19.8 Watt-hours/day.

The proposed 40 Watt photovoltaic cell is expected to function at 85% of its rated value throughout its lifetime. Therefore, it can be expected that on a perfectly sunny day, 34 Watts will be produced. The time to charge the battery array on a totally sunny day is therefore 14.12 hours, while the time to drain the battery array (assuming no daily input from the photovoltaic cell) is 12.66 days and is based on our 19.8 Watt daily requirement, and the number of Amp-Seconds the battery array can hold, and the drain rate due to the array’s motors (1.58 Joules/Second). We intend to start the system with a full battery charge, and expect that on heavily cloud covered days that the photovoltaic cell will still yield at least 1.7 Watts of energy production which will only mean that the battery array would take 11.76 days of 95% reflectance cloud covered days (5% light transmittance) to fully charge even given the 12.66 day battery array drain time. Though this calculation was done to model the extreme of cloud cover, average clouds have a reflectance range of 70-95% [31], therefore the calculation of slightly more transparent clouds suggests that the battery array only takes 1.96 days to charge under lighter cloud cover. Based on these calculations and a sizable safety consideration, the photovoltaic cell will provide plenty of energy for our system to function without being tied to the power grid.

Performance against Benchmarked Heliostat Reflectors

In order to determine how well our design did against other heliostat reflectors, we first had to compare the advantages and disadvantages of our design against the benchmarked heliostat reflectors. Table 3 lists the advantages and disadvantages found for each solar heliostat reflecting system. The areas of interest included cost, durability, and solar tracking ability. While the Leo Gerst reflector had the lowest overall cost, the durability of the system is too low to be implemented. The Practical Solar and HelioTrack heliostats both have very little error in their ability to track the Sun, but their system prices are very high and unaffordable to customers looking to install the system in their home. We determined that between cost and durability, our system beats the other heliostat reflectors found on the market today.

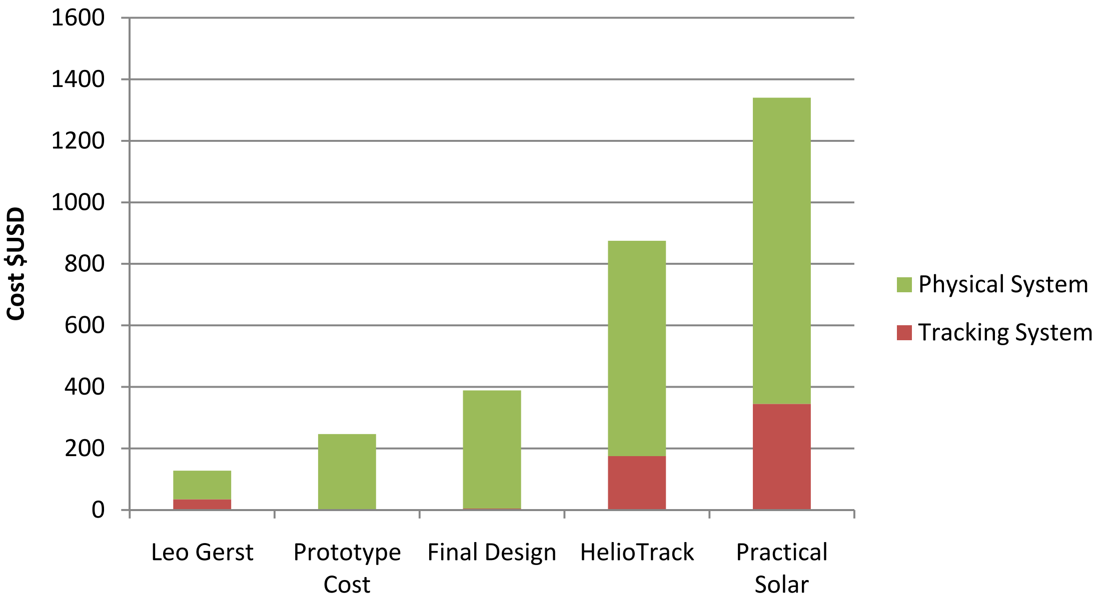
Table 3: Advantages and Disadvantages of each Heliostat Reflector

System	Advantages	Disadvantages
Practical Solar	➢ 0.11 Degree Tracking Error ➢ Can Set New Targets Easily ➢ Multiple Heliostats can Work Together ➢ Durable	➢ High Cost
HelioTrack	➢ Durable ➢ Sub-degree Tracking Error	➢ High Cost
Leo Gerst	➢ Low Cost	➢ Not Robust ➢ Accuracy Unknown ➢ No Assembly Directions
Solar Initiative	➢ Low Cost ➢ Durable ➢ Comparable Tracking Error	➢ 2.9° Error ➢ Array needed for large applications

Cost Analysis against Benchmarked Heliostat Reflectors

Next we did an in-depth cost analysis between each of the benchmarked reflectors and our own reflector design. We separated the cost associated with the tracking system and the costs associated with the support system for the reflector. Fig. 43 shows the results of the cost analysis. The total cost of the final design for the Passive Solar Energy Initiative reflector came to $384.11. This falls between the cost of the Leo Gerst reflector and the HelioTrack reflector. We determined the best way to keep costs low and maintain a competitive edge in the market without jeopardizing the strength of the structure was to keep the reflector area small. This was how we validated the use of a $1m^2$ area. Reducing the size of the reflector kept the price of the motors and support system down. The high cost of the HelioTrack and Practical Solar designs is dominated by the cost of the support and reflector system the designs employ. The Practical Solar design also uses an expensive tracking system that has 0.11 degree tracking error. We feel our system met our goal of designing a cost-effective solar reflector by incorporating a design with low error that is lower in cost and still very durable. It is important to note that costs for labor and production were not included in the total cost of the reflector system. In a realistic business setting, we would estimate a salary for each design engineer, consider facility costs, and set a 200% overhead cost on labor.

Fig. 43: Costs of Competing Heliostat Reflecting Systems



Fabrication Plan

The fabrication plan for the prototype includes both the machining and assembly of the solar reflector prototype as well as the test track and apparatus. The plan is centered around the components and supplies available in the Machine Shop that we used with no cost. The prototype, specifically, was made out of scrap L-beams, metal poles, and metal sheets. To satisfy the specifications and requirements we utilized these scrap pieces to develop our machining processes. The fabrication plan is very detailed and will help to minimize errors during manufacturing and assembly. Each part has been grouped into a sub-component category consisting of L-beams, support shafts, sheet metal, gears, and the reflector. Each sub-component lists the order of fabrication along with the tools, materials, feeds, and speeds needed for manufacturing the part in Tables K.1 and K.3. The quantity displayed in the part list (Table I.2) dictates how many of each part will need to be manufactured. After all the parts have been created the assembly process can begin. Appendix K details all the steps needed for the correct assembly of the prototype.

Similarly to the prototype, a large amount of materials necessary for the test set-up was readily available, specifically for the insulated box. We were given Plexiglas from Bob Curry, and we obtained the temperature measurement equipment from Professor Skerlos' lab. The remaining five sides of the box were made out of Styrofoam to form a 0.5 m x 0.5 m x 0.25 m box and were assembled using epoxy.

The track was developed using 2x4s to create nine base set-ups which each included four separate pieces of lumber each. Seven tracking pieces of 2x4s were attached to the top of the base frames for support during testing. All 2x4s were assembled with a power drill and wood screws. The top of the tracking pieces had one ¼" diameter hole drilled into them in where a dowel rod was placed to allow the car to follow a direct path as described in earlier sections. Finally, a motor was attached to one end of the track using wood screws and brackets

The last part of the set-up was the car. There were six wheels purchased that were attached to metal scrap rods of 1/8” diameter that were cut down using a band saw. There were two different axle types, four of which were significantly longer than the other two. There was two connecting pieces made out of scrap metal to hold the top wheels and two shorter axles in place with the support. A detailed description of all manufacturing and assembly steps for the test set-up can be found in the Appendix.

Discussion

To determine how well our design performed, we took the cost analysis and error measurements and utilized them to determine the benefit our system will have depending on its application. This helped us to determine how we met some of the specifications set before the design process. We also critiqued the final design and listed areas that could use improvement.

Benefit Analysis

After completing cost analysis and angle accuracy measurements along with data provided to us by the report completed by SolarFocus, we determined the energy savings and payback period for our system. We calculated the daily electric heating offset that our system could produce based on solar radiation availability numbers provided to us by SolarFocus [1]. Table 4 outlines the costs saved for both the home or office use and the G.G. Brown atrium use. We calculated an annual building heating offset cost for G.G. Brown to be $53.71. The offset was calculated for months where the reflector would be used to heat the building, namely the fall, winter, and spring months in Michigan.

Table 4: Cost Benefit for Home/Office Use and for G.G. Brown Atrium

		Home or Office Use		**G.G. Brown or Atrium Use**	
Month	Solar Radiation Availible kWh/m^2/day	Error Scaled Radiation Availible kWh/m^2/day	Daily Electric Heating Energy Cost Offset (USD)	Error Scaled Radiation Availible kWh/m^2/day	Daily Electric Heating Energy Cost Offset (USD)
Oct	3.73	2.46	0.38	3.18	0.51
Nov	2.52	1.70	0.26	2.20	0.35
Dec	2.24	1.52	0.24	1.97	0.32
Jan	2.7	1.82	0.28	2.35	0.38
Feb	3.2	2.11	0.33	2.72	0.44
Mar	3.74	2.39	0.37	3.08	0.49
Apr	4.3	2.60	0.40	3.35	0.54
May	4.69	2.70	0.42	3.49	0.56
		Annual Building Heating Cost Offset	$80.12		$107.41
(because 50% of sun's radiation is in the form of light energy, and the other 50% is heat energy)		Actual Annual Building Heating Cost Offset	$40.06		$53.71

We determined the reflector design to pay for itself in 7.1 years for the design for G.G. Brown. This is based on the annual heating cost offsets and the total cost of the reflector system. While this did not achieve the goal of 4 years we had as a specification, it is lower than the payback time of 10 years for the design proposed by SolarFocus from the previous term. Using an array of 10 reflectors that we have proposed, the reflector system would offset $537.10 dollars in annual heating costs of the future G.G. Brown Atrium. The final design is, on average, 63% less expensive than it's more expensive competitive reflector counterparts and is expected to last 30 years. Based on energy costs, the dollar amount offset stands for 11% of the building's energy requirements, and therefore our design would earn G.G. Brown 4.4 points toward LEED Certification. This meets the specifications for both the reducing the building's energy requirements and contributing towards LEED certification.

Design Critique

Upon completion of our final design, we assessed our work for strengths and weaknesses. The gearing train complements the sensor equipment very well, and with the low errors associated with the system the design concept is validated. The integration of the electrical components and mechanical components together was the biggest hurdle in our design process, but meeting our error specifications we believe that the prototype is a successful indicator of final design functionality. Through iterations of material selection the final design will be able to utilize components that can withstand severe weather conditions common in Southeast Michigan. Further, the implementation of the advanced LED 5S5V in the final design provides for greater sky coverage and increases the capabilities of the system.

There are two drawbacks to using a gear system where the first is the risk of backlash, but this property is unavoidable in reversing mechanical couplings [27]. Since the system must be able to reverse each time the sun rises, this is a requirement of the final design. If the backlash becomes non-negligible, the error of the tracking method will increase and the system may redirect the sunlight to an undesirable target. This is a potential safety hazard for locations such as pedestrian walkways where bystanders would be at risk of eye damage described in our safety report. It is important to note that this situation is highly unlikely as the error would accumulate over an extended period of time, and a maintenance worker or home owner would have ample time to adjust the system to its correct target before a safety issue occurred.

The second problem with the gearing system is alignment. By cementing down the system for use, the target becomes locked in the azimuth direction. The three gears must be aligned with each of their midpoints in the same plane to ensure proper functionality, and once the system is "locked" by cement it is not possible to adjust. This can be seen in Figure X1. Thus, the target can only be changed in the altitude angle, and reduces the utilization of the system when space heating is not necessary. To fix this issue the sensor pole would be fastened only to the gear housing rather than to the ground. This allows the housing and sensor pole to be rotated relative to the reflector pole by simple mechanical processes that any home owner could complete quickly and easily. Material selection of the sensor pole would be vital in this modification because the pole must be able to withstand the elements while remaining at a low weight to prevent tipping due to added torque requirements.

Finally, the system must be located outdoors to be functional, and it could be a bit of an eye sore. The aesthetics around the design could be improved so that it does not resemble simply a "mirror on a stick". This issue does not affect the functionality of the system, and is a secondary drawback.

Recommendations

From the data measured and determined from the previous ME 450 report along with the cost and test data generated from the tests performed on a working prototype, the design proposed by the Passive Solar Energy Initiative would be a benefit to any building seeking to reduce its energy consumption from a nonrenewable source. The design that has been created is suitable in an array format for the new proposed G.G. Brown atrium, if the atrium project becomes a reality. The design is also suitable for general office or home use and can be adapted for many locations.

For this project to become a reality, we recommend that the exact placement and foundation structure be finalized for installing the system for the proposed G.G. Brown atrium. Analysis should be done to ensure the system of reflectors will work for the atrium. Research must be done to finalize the method of absorbing and releasing the heat into the atrium, using some sort of thermal body to do so. Window refraction and transmissivity must also be determined to calculate the exact gains that can be realized using the solar reflecting system. Knowing more about the exact dimensions of the atrium are also necessary to understand how many reflectors would be needed to heat the room.

We recommend that more research be done on an application for the solar reflecting system in locations with warmer climates. There are many other systems that can use solar energy to cool or heat water, as we have researched for this project. We feel having a use for our design in the summer or in a location with warmer temperatures, where the heating of a room is not necessary, is vital to meet the demands of more consumers. This would allow more consumers to use renewable energy in their everyday lives and help the consumers to save money in the long run.

Conclusion

The purpose of the Passive Solar Energy Initiative (PSEI) is to provide an inexpensive and visually pleasing method of reflecting solar energy into buildings with north-facing windows with the intent to heat them in cold climates. Inspiration for this project was derived from a previous ME 450 project titled “SolarFocus” in the winter of 2009, which sought to achieve similar goals. With the help of Professor Stephen Skerlos, the PSEI intended to design a system that utilizes brainless control technology to reflectively direct the Sun’s rays at a designated target. Through design iterations the scope of the design moved towards creating a reflecting system that could be mass produced and applicable to many buildings.

We designed a solar reflecting system that is low in cost and low in power consumption. The system incorporates a LED circuitry system to track the Sun’s position. This system is integrated with mechanical components to reflect the Sun’s energy at a target with minimized error. The impact of implementing the PSEI would offset $537.10 dollars in annual heating costs of the future G.G. Brown Atrium based on an average tracking error of 2.9^{o}. The reflector array will pay for itself in 7.1 years based on a final design cost of $384.11. Our system is more inexpensive than the leading competition and should be put into production. Based on energy costs, the dollar amount offset stands for 11% of the building’s energy requirements, and therefore our design would earn G.G. Brown 4.4 points toward LEED Certification. We exceed our specification of reducing the building’s energy requirements and have validated the proposed design through testing, error calculations, and cost analysis.

Acknowledgements

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Appendix

Appendix A: Bill of Materials

Table A.1: Final Design Bill of Materials

Item	Qty	Units	Source	Catalogue No.	Unit Cost	Total Cost	Contact	Notes
Altitude/Azimuth Control Motors	2	Motors	Pololu Robotics &Electronics	1094	$11.96	$23.92	www.pololu.com	298:1 Micro Metal Gearmotor
Altitude Small Gear	2	Gears	SDP-SI	A 1C 2-N32016	$5.30	$10.60	sdp-si.com	º14.5° Pressure Angle, 0.5" Pitch Diameter
Altitude Medium Gear	2	Gears	SDP-SI	A 1C 2-N32080	$12.56	$25.12	sdp-si.com	º14.5° Pressure Angle, 2.5" Pitch Diameter
Altitude Large Gear	2	Gears	SDP-SI	A 1C 2-N32160	$26.34	$52.68	sdp-si.com	º14.5° Pressure Angle, 5" Pitch Diameter
Tracking Circuit	2	Circuits	DigiKey	N/A	$2.24	$4.48	www.digikey.com	Individual Circuit Elements Can Be Viewed On Pg XX
Tracking Circuit Mount	0.083	Linear Feet	McMaster Carr	87025K62	$20.70	$1.72	McMaster.com	2 PVC Discs Cut from Rod Stock-Each 0.5" Thick, 2.75" in Diameter
Tracking Circuit Clear Plastic Housing	2	Hemispheres	Factory Direct Craft	110595	$0.62	$1.24	www.amazon.com	60mm Clear Plastic Acrylic Fillable Ball Ornaments
Reflector Polycarbonate	10.76	Square Feet	Ecologic Technologies	N/A	$3.30	$35.51	cloudtops.com	Clear, 16mm thick
U Shaped End Caps	13.12	Linear Feet	Ecologic Technologies	N/A	$1.17	$15.35	cloudtops.com	To Seal Cut Ends of Polycarbonate Sheet
Reflective Thin Film	1	Square Meter	ReflecTech Mirror Film	N/A	32.29	$32.29	www.reflectechsolar.com	94% reflectivity, .1mm thick, adhesive backing
Electrical Wire	30	Linear Feet	RadioShack	278-1224	$0.09	$2.61	radioshack.com	Insulated 22 Gauge Copper Hookup Wire
Reflector/Sensor Outer Support Shaft	49	Linear Inches	McMaster Carr	7750K236	$0.92	$45.08	McMaster.com	2" I.D. - 2.375" O.D. Steel
Reflector/Sensor Inner Support Shaft	115	Linear Inches	McMaster Carr	7750K231	$0.26	$29.90	McMaster.com	0.75" O.D. Steel
Thrust Cage-Needle Assembly	2	Bearings	MSC Industrial Supply Co.	3380995	$4.63	$9.26	www1.mscdirect.com	1.75" I.D. x 2.5" O.D. Steel

Thrust Washer-Flat Needle	4	Washers	MSC Industrial Supply Co.	3381175	$2.28	$9.12	www1.mscdirect.com	1.75" I.D. x 2.5" O.D. Steel
PVC Spacers	0.25	Linear Feet	McMaster Carr	8497K431	$15.36	$3.84	McMaster.com	4 Discs Cut from Rod Stock - Each 3/4" Thick, 2" Diameter - 3/4" Center Bore for Inner Support Rod
Aluminum Frame Supports	240	Linear Inches	Cut2SizeMetals.com	N/A	$0.13	$31.63	cut2sizemetals.com	6061-T6 Aluminum Alloy
Fasteners (1" long, .25" diameter bolts)	25	Bolts	BoltDepot.com	832	$0.06	$1.50	BoltDepot.com	
Fasteners (3" long, .25" diameter bolts)	4	Bolts	BoltDepot.com	837	$0.14	$0.56	BoltDepot.com	
Nuts (.25" diameter)	29	Nuts	BoltDepot.com	2648	$0.05	$1.45	BoltDepot.com	
Washers (.25" diameter)	29	Washers	BoltDepot.com	2947	$0.06	$1.74	BoltDepot.com	
Rust Protective Paint	1	Can	Raybuck Auto Body Parts	ASL-BLK	$8.50	$8.50	raybuck.com	
40 Watt Framed Solar Battery Charger PV Cell	1	Cell	BatteryStuff.com	BSP40W	$295.00	$295.00	BatteryStuff.com	
Solar Battery Charge Controller	1	Module	BatteryStuff.com	CC10000	$35.00	$35.00	BatteryStuff.com	
12 V Battery	5	Battery	Cabela's	9IS-018049	$14.99	$74.95	www.cabelas.com	
				Power Subtotal		**$404.95**		
				(1/10) Power Subtotal		**$40.50**		
			Grand Total (per square meter)			**$388.59**		

Table A.2:Prototype Bill of Materials

Item	Quantity	Vendor	Unit Cost	Total Cost	Notes
Thrust Bearing	2	MSC	$28.55	$57.10	Thrust Cage Needle Assembly
Angular Bearing	2	MSC	$10.12	$20.24	Sealed Underground Retainer Angular Bearing
Shaft	2	Bob's Shop	N/A	$0.00	Available in Bob's Shop
Mirror	1	Pictures Plus	$16.00	$16.00	550.8x500mm
LED Circuit	1	Red Rock Energy	$24.00	$24.00	Built by Red Rock Energy
DC Motor	1	Pololu	$24.95	$24.95	122:1 Metal Gearmotor
Small Gear	1	SDP SI	$42.41	$42.41	14.5^o Pitch Angle, 0.5" Pitch Diameter
Medium Gear	1	SDP SI	$22.00	$22.00	14.5^o Pitch Angle, 2.5" Pitch Diameter
Large Gear	1	SDP SI	$11.10	$11.10	14.5^o Pitch Angle, 5" Pitch Diameter
Bracket	7	Bob's Shop	N/A	$0.00	Available in Bob's Shop
Bolt	40	Bob's Shop	N/A	$0.00	Available in Bob's Shop
Toy Wheels	3	Tower Hobbies	$5.79	$17.37	2 Wheels per pack
PVC	1	Bob's Shop	N/A	$0.00	2-1" Discs Cut From Rod Stock For Circuit Housing
Plastic Paint and Primer	1	Bob's Shop	N/A	$0.00	Circuit Housing Paint
3M Felt Tape	1	Kmart	$4.44	$4.44	Used to cushion mirror against brackets
22 Gauge Electrical Wire	1	Radioshack	$6.99	$6.99	Three Copper Insulated Spools Included
		Total Prototype Cost		**$246.60**	

Table A.3:Testing Bill of Materials

Item	Quantity	Source	Unit Cost	Total Cost	Notes
Styrofoam	1	Lowe's	$34.22	$34.22	2" x 48" x 96"
Lumber	21	Lowe's	$1.89	$39.69	2" x 4" x 96"
Plexiglas	1	Bob's Shop	N/A	$0.00	Available in Bob's Shop
Thermocouple	2	Skerlos Lab	N/A	$0.00	Available in Prof. Skerlos' Lab
Thermocouple Input Block	1	Skerlos Lab	N/A	$0.00	Available in Prof. Skerlos' Lab
Connector Block	1	Skerlos Lab	N/A	$0.00	Available in Prof. Skerlos' Lab
DAQ Card	1	Skerlos Lab	N/A	$0.00	Available in Prof. Skerlos' Lab
Toy Wheels	3	Tower Hobbies	$5.79	$17.37	2 Wheels per pack
Adjustable Power Supply	1	X50 Lab	N/A	$0.00	Available in Lab on Loan
400 Watt MH Bulb	1	Cathryn	N/A	$0.00	Provided by Cathryn
Toy Motor	1	X50 Lab	N/A	$0.00	Available in Lab on Loan
Insulating Foam	1	Lowe's	$4.49	$4.49	Sprayable
3/8x48 HRDWD Dowel	2	Carpenter Brothers	$1.19	$2.38	Tow Line Supports
M1425 Fish Line	1	Carpenter Brothers	$3.29	$3.29	25lb Test
2 1/2" Deck Screws	2	Lowe's	$5.98	$11.96	Lumber Fasteners
	Total Testing Supply Cost			**$113.40**	

Appendix B: Description of Engineering Changes since Design Review #3

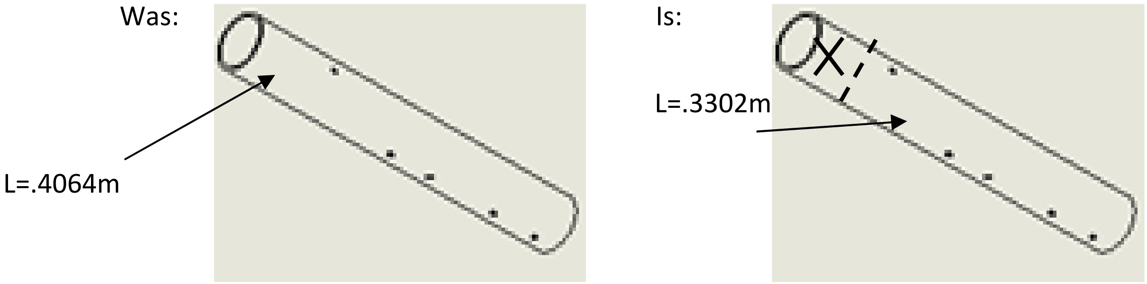
After finishing design review three, we began manufacturing the prototype detailed by our manufacturing plan. Over the course of the manufacturing and into the assembly of the prototype, there were many components that needed refinement or initial creation. Each deviation from the original manufacturing and assembly plans prompted an Engineering Change Notice (ECN), which can all be found in Appendix B, Engineering Change Notices.

The first divergence from our original manufacturing plan was forced by the lack of stock material used for the bracket pole, and we were forced to shorten the pole from .406m to .330m. Further, we had to add a .0635m by .1905m slot into the sensor bracket pole to allow sufficient room for the motor. Neither of these changes affected the functionality of the prototype. A final modification to the bracket poles was the reduction in bolt holes and the addition of two press-fit spacers made out of PVC, one for each pole. This was a more effective way of keeping the poles in the correct position. We were able to reduce the holes required in the motor mount as its position was locked with only two holes rather than four. Changes to the gear train include adding a second set screw hole to the sensor and reflector gears to decrease the chance of slipping, and the size of the set screw hole on the motor gear was changed from a 5 – 40 thread to a 4 – 40 thread.

As a team, we obtained two mirrors to serve as the reflector in the prototype, and we attempted to cut the glass to .5m by .55m. We failed with both mirrors as the glass cutting tool available was dull, and we were forced to purchase a new mirror and outsource the cutting. The backing for this mirror had numerous gaps between the L-brackets, and we implemented washers with .00635m inner diameters to fit around the bolts and serve as spacers. Also, as a safety factor against glass fracture we added soft felt to the L-brackets at the points of contact with the mirror. This reduced the friction and impact forces between the mirror and the aluminum.

At this point, we completed the assembly of the prototype, and discovered two areas that still needed refinement. First, there was human error in measurement and manufacturing of the bolt holes in the L-brackets, and a power drill was required to widen the holes so that a bolt could fit through and secure the base of the system. Second, for aesthetic and functionality reasons we created a sensor holder for the LED 3X circuit. The component was made out of two pieces of PVC piping with a hole for the wiring and a hole for the LEDs. Since this component is the top of the structure and the most noticeable part, we painted it with a metallic gray.

Fig. B.1: Engineering Change Notice 1

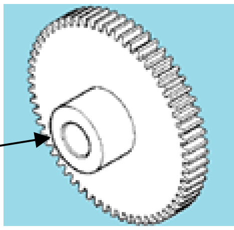


Notes: We were forced to shorten the bracket pole for the prototype due to lack of material available at no cost in Bob’s office. The length dimension was not a critical component to the functionality of the prototype and this restriction was not a obstacle in further manufacturing or assembly.

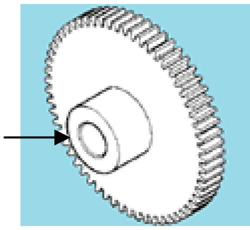
Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/1/2009
Proj. Lead: C. Fageros	12/1/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.2: Engineering Change Notice 2

Was:



Is:



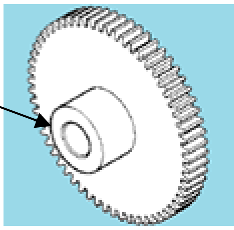
Notes: The original thread we designed for the set screw for the motor gear hub was not sufficient because the screws available at the specified size did not hold the gear in place sufficiently. Therefore, we used a new thread size of 4-40 that solved the problem.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/3/2009
Proj. Lead: C. Fageros	12/3/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.3: Engineering Change Notice 3

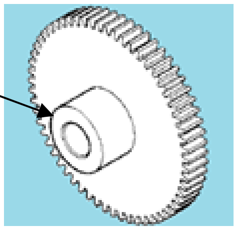
Was:

1 hole in hub
(8 – 32 thread)



Is:

2 holes in hub
(8 – 32 thread)

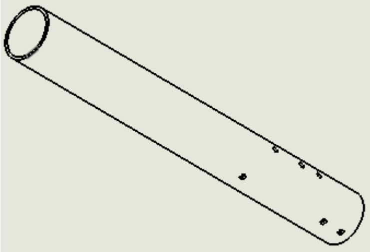


Notes: We added a second threaded hole to each hub with an 8 – 32 thread to increase the safety factor in the functionality of the gears for the sensor and reflector poles. This was to ensure that the poles would rotate with the gears without slipping.

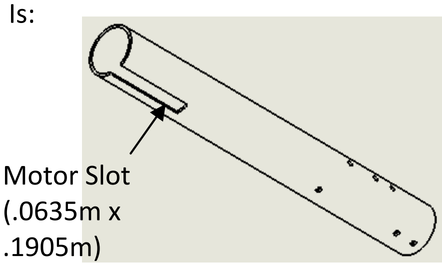
Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: C. Fageros	12/3/2009
Proj. Lead: C. Fageros	12/3/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.4: Engineering Change Notice 4

Was:



Is:

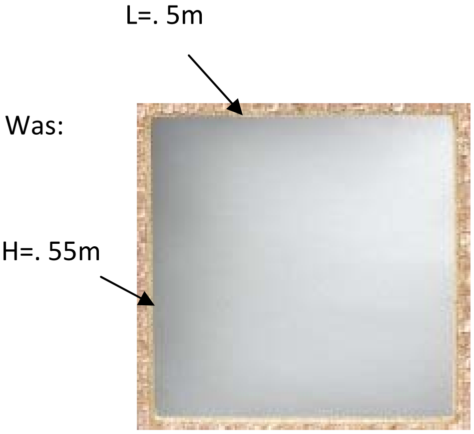


Notes: Due to the position of the sensor and reflector poles, it was necessary to mill out a slot in the sensor pole to allow the gear train to line up properly. This slot is positioned .0127m from the top of the bracket pole.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/3/2009
Proj. Lead: C. Fageros	12/3/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.5: Engineering Change Notice 5

Was:



Is: Same dimensions, new mirror

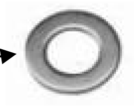
Notes: We were unable to cut the glass ourselves and broke the original mirror we had obtained in the process. Thus, we outsourced the cutting of the mirror.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: C. Fageros	12/3/2009
Proj. Lead: C. Fageros	12/3/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.6: Engineering Change Notice 6

Was: The part did not previously exist.

Is:



ϕ_{inner}=.00635m

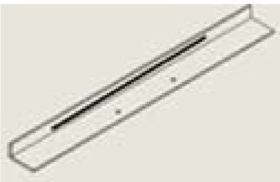
Notes: Washers were required to properly space the backings for the reflector once we began assembly.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/3/2009
Proj. Lead: C. Fageros	12/3/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.7: Engineering Change Notice 7

Was:

Is:



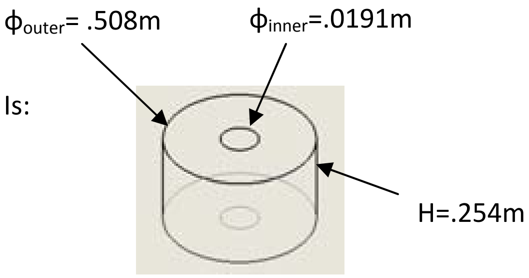
Notes: Added soft felt to aluminum L-bracket to reduce friction and impact forces between glass mirror and bracket.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: C. Fageros	12/6/2009
Proj. Lead: C. Fageros	12/6/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.8: Engineering Change Notice 8

Was: Part did not previously exist.

Is:



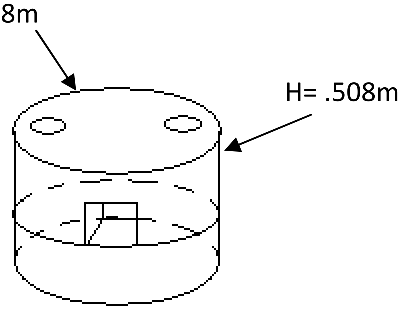
Notes: The sensor pole and reflector pole required another spacer (PVC) to ensure position necessary for correct functionality.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/7/2009
Proj. Lead: C. Fageros	12/7/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.9: Engineering Change Notice 9

Was: Part did not previously exist.

Is:

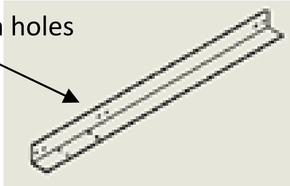


Notes: The sensor was originally going to be attached directly to the top of the sensor pole, but a holder was developed for aesthetic and durability purposes.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: C. Fageros	12/9/2009
Proj. Lead: C. Fageros	12/9/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.10: Engineering Change Notice 10

Was:



Original .0064m holes

Is:

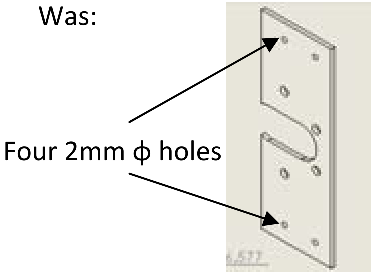
Refined holes to allow for structure to fit together properly

Notes: After constructing the base for the reflector, some of the holes did not line up correctly due to human error in measurement, drilling, and cutting. Therefore it was necessary to use a power drill to make the holes slightly larger in diameter so that the base could be assembled properly.

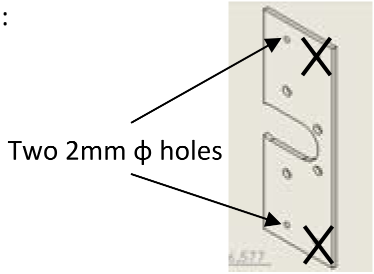
Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: C. Bence	12/9/2009
Proj. Lead: C. Fageros	12/9/2009
Mgmt/Proj. Sponsor	12/10/2009

Fig. B.11: Engineering Change Notice 11

Was:



Is:



Notes: The original design required four 2mm holes to hold the motor in position between the reflector and sensor poles, but in reality only two holes were required, one on each side.

Solar Innovators	
Project: Manufacturing of Solar Reflector Prototype	
Stud. Engineer: J. Hummel	12/9/2009
Proj. Lead: C. Fageros	12/9/2009
Mgmt/Proj. Sponsor	12/10/2009

Appendix C: Design Analysis Assignment

Material Selection Assignment (Functional Performance)

Design Requirement for the Reflector	
Function	Reflect solar radiation energy at target
Objective	Maximize strength to weight ratio Maximize fracture toughness Minimize cost
Constraints	Dimensions, L and W, specified Cost C_m < \$3/lb Fracture toughness $G_c > 3$ ksi/in^2

Design Requirement for Base Structure	
Function	Hold reflector
Objective	Maximize strength Minimize cost Corrosion resistant
Constraints	Height, H specified Cost C_m < \$0.50/lb Fracture toughness $G_c > 20$ ksi/in^2

1. Reflector Material

This material must support a reflective film. It needs to be durable to be able to withstand the elements of weather conditions and it must be cost effective. The CES EduPak 2009 was used to compare price and fracture toughness, and the top five choices for this function are: PPC (unfilled), Alumina (85), PET (unfilled, semi-chrystalline), ethyl acrylate terpolymer and styrene acrylonitrile. Our final choice was the polycarbonate, PPC (unfilled), due to its low cost and durability for outdoor applications.

PPC (unfilled)

General properties

Designation

Polyestercarbonate or polyphthalate carbonate

Density		1.19e3	-	1.2e3	kg/m^3
Price	*	4.6	-	5.06	USD/kg

Tradenames

Lexan

Composition overview

Composition (summary)

Copolymer of bisphenol-A polycarbonate and terephthalic acid.

Base	Polymer
Polymer class	Thermoplastic : amorphous
Polymer type	PPC

% filler		0			%
Filler type		Unfilled			

Composition detail

Polymer		100			%

Mechanical properties

Young's modulus	*	2.02e9	-	2.33e9	Pa
Compressive modulus	*	2.02e9	-	2.33e9	Pa
Flexural modulus		2.02e9	-	2.33e9	Pa
Shear modulus	*	7.19e8	-	8.39e8	Pa
Bulk modulus	*	3.71e9	-	3.89e9	Pa
Poisson's ratio	*	0.388	-	0.404	
Shape factor		4.5			
Yield strength (elastic limit)		6.34e7	-	6.66e7	Pa
Tensile strength		7.1e7	-	7.7e7	Pa
Compressive strength	*	7.42e7	-	8.19e7	Pa
Flexural strength (modulus of rupture)	*	1.11e8	-	1.2e8	Pa
Shear strength	*	5.68e7	-	7.7e7	Pa
Elongation		78	-	122	%
Hardness - Vickers	*	1.82e8	-	2.01e8	Pa
Hardness - Rockwell M		85	-	92	
Hardness - Rockwell R		121	-	127	
Hardness - Shore D	*	79	-	87	
Hardness - Shore A	*	90	-	100	
Fatigue strength at 10^7 cycles	*	2.84e7	-	3.08e7	Pa
Fracture toughness	*	3.36e6	-	3.71e6	Pa.m^1/2
Mechanical loss coefficient (tan delta)	*	0.0208	-	0.0232	

Impact properties

Impact strength, notched 23 °C		3.73e4	-	6.4e4	J/m^2
Impact strength, unnotched 23 °C		1.9e5	-	2e5	J/m^2

Thermal properties

Glass temperature	*	155	-	171	°C
Heat deflection temperature 0.45MPa	*	153	-	158	°C
Heat deflection temperature 1.8MPa		143	-	148	°C
Maximum service temperature	*	117	-	137	°C
Minimum service temperature	*	-48	-	-28	°C
Thermal conductivity		0.206	-	0.214	W/m.K
Specific heat capacity		1.24e3	-	1.26e3	J/kg.K
Thermal expansion coefficient		8.1e-5	-	9.18e-5	/K
Vicat softening point	*	157	-	162	°C

Processing properties

Linear mold shrinkage		0.7	-	1	%
Melt temperature		340	-	370	°C
Mold temperature		80	-	115	°C

Electrical properties

Electrical resistivity		2.6e14	-	2.5e15	ohm.m
Dielectric constant (relative permittivity)		3	-	3.27	
Dissipation factor (dielectric loss tangent)		0.0012	-	0.0016	
Dielectric strength (dielectric breakdown)		1.97e7	-	2.05e7	V/m

Optical properties

Refractive index		1.59	-	1.61	

Transparency		Transparent			

Absorption, permeability

Water absorption @ 24 hrs		0.16	-	0.19	%
Water absorption @ sat	*	0.968	-	1.15	%
Humidity absorption @ sat	*	0.291	-	0.344	%

Durability: flammability

Flammability		Slow-burning			

Durability: fluids and sunlight

Water (fresh)		Acceptable			
Water (salt)		Acceptable			
Weak acids		Acceptable			
Strong acids		Unacceptable			
Weak alkalis		Limited use			
Strong alkalis		Unacceptable			
Organic solvents		Limited use			
UV radiation (sunlight)		Fair			
Oxidation at 500C		Unacceptable			

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	1.06e8	-	1.17e8	J/kg
CO2 footprint, primary production	*	4.27	-	4.71	kg/kg
Water usage	*	0.29	-	0.32	m^3/kg

Material processing: energy

Polymer molding energy	*	1.05e7	-	1.16e7	J/kg
Polymer extrusion energy	*	4.06e6	-	4.48e6	J/kg
Polymer machining energy (per unit wt removed)	*	2.06e6	-	2.27e6	J/kg

Material processing: CO2 footprint

Polymer molding CO2	*	0.84	-	0.928	kg/kg
Polymer extrusion CO2	*	0.325	-	0.358	kg/kg
Polymer machining CO2 (per unit wt removed)	*	0.165	-	0.182	kg/kg

Material recycling: energy, CO2 and recycle fraction

Recycle		√			
Embodied energy, recycling	*	4.44e7	-	4.91e7	J/kg
CO2 footprint, recycling	*	1.79	-	1.98	kg/kg
Recycle fraction in current supply		0.1			%
Downcycle		√			
Combust for energy recovery		√			
Heat of combustion (net)	*	3.04e7	-	3.19e7	J/kg
Combustion CO2	*	2.73	-	2.87	kg/kg
Landfill		√			
Biodegrade		X			
A renewable resource?		X			

2. Base Structure

This material must support the reflector. It needs to be durable to be able to withstand the elements of weather conditions, be inexpensive, and be capable of holding the reflector up. The CES EduPak 2009 was used to compare price and strength, and the top five choices for this function are: low alloy steel, carbon steel, intermediate alloy, stainless steel, and toll steel. Our final choice was the low alloy steel AISI 94B30 (tempered @ 205 C, oil quenched) due to its low cost and durability in outdoor applications.

Low alloy steel, AISI 94B30, tempered at 205°C & oil quenched

General properties

Designation

Low alloy steel, AISI 94B30 (tempered @ 205 C, oil quenched)

UNS number		G94301			
Density		7.8e3	-	7.9e3	kg/m^3
Price	*	0.801	-	0.881	USD/kg

Tradenames

SHARON 8600 SERIES A, Sharon Steel Corp. (USA);

Composition overview

Composition (summary)

Fe/.28-.33C/.3-.5Cr/.3-.6Ni/.75-1Mn/.15-.3Si/.08-.15Mo/P,B,S traces

Base	Fe (Iron)

Composition detail

B (boron)	0			%
C (carbon)	0.28	-	0.33	%
Cr (chromium)	0.3	-	0.5	%
Fe (iron)	97.1	-	98.1	%
Mn (manganese)	0.75	-	1	%
Mo (molybdenum)	0.08	-	0.15	%
Ni (nickel)	0.3	-	0.6	%
P (phosphorus)	0			%
S (sulfur)	0			%
Si (silicon)	0.15	-	0.3	%

Mechanical properties

Young's modulus		2.06e11	-	2.16e11	Pa
Shear modulus		7.9e10	-	8.5e10	Pa
Bulk modulus		1.59e11	-	1.76e11	Pa
Poisson's ratio		0.285	-	0.295	
Shape factor		15			
Yield strength (elastic limit)		1.4e9	-	1.71e9	Pa
Tensile strength		1.55e9	-	1.9e9	Pa
Compressive strength		1.4e9	-	1.71e9	Pa
Flexural strength (modulus of rupture)		1.4e9	-	1.71e9	Pa
Elongation		9	-	15	%
Hardness - Vickers		4.17e9	-	5.15e9	Pa
Fatigue strength at 10^7 cycles	*	5.81e8	-	6.71e8	Pa
Fatigue strength model (stress range) Parameters:Stress Ratio = 0, Number of Cycles = 1e7	*	3.82e8	-	5.37e8	Pa
Fracture toughness	*	2.7e7	-	5.2e7	Pa.m^1/2

Mechanical loss coefficient (tan delta)	*	2.3e-4	-	2.9e-4	

Thermal properties

Melting point		1.46e3	-	1.51e3	°C
Maximum service temperature	*	165	-	195	°C
Minimum service temperature	*	-53	-	-23	°C
Thermal conductivity		46	-	51	W/m.K
Specific heat capacity		425	-	475	J/kg.K
Thermal expansion coefficient		1.1e-5	-	1.3e-5	/K
Latent heat of fusion	*	2.65e5	-	2.8e5	J/kg

Electrical properties

Electrical resistivity	*	1.5e-7	-	3.5e-7	ohm.m

Optical properties

Transparency	Opaque

Durability: flammability

Flammability	Non-flammable

Durability: fluids and sunlight

Water (fresh)	Acceptable
Water (salt)	Limited use
Weak acids	Limited use
Strong acids	Unacceptable
Weak alkalis	Acceptable
Strong alkalis	Limited use
Organic solvents	Excellent
UV radiation (sunlight)	Excellent
Oxidation at 500C	Acceptable

Primary material production: energy, CO2 and water

Embodied energy, primary production		3.2e7	-	3.8e7	J/kg
CO2 footprint, primary production		2.01	-	2.22	kg/kg
Water usage		0.0369	-	0.111	m^3/kg

Material processing: energy

Casting energy	*	3.97e6	-	4.39e6	J/kg
Forging, rolling energy	*	4.69e6	-	5.18e6	J/kg
Metal powder forming energy	*	1.32e7	-	1.46e7	J/kg
Vaporization energy	*	2.46e7	-	2.71e7	J/kg
Conventional machining energy (per unit wt removed)	*	8.63e6	-	9.53e6	J/kg
Non-conventional machining energy (per unit wt removed)	*	4.6e7	-	5.09e7	J/kg

Material processing: CO2 footprint

Casting CO2	*	0.238	-	0.263	kg/kg
Forging, rolling CO2	*	0.375	-	0.414	kg/kg
Metal powder forming CO2	*	1.06	-	1.17	kg/kg
Vaporization CO2	*	1.97	-	2.17	kg/kg
Conventional machining CO2 (per unit wt removed)	*	0.69	-	0.762	kg/kg
Non-conventional machining CO2 (per unit wt removed)	*	3.68	-	4.07	kg/kg

Material recycling: energy, CO2 and recycle fraction

Recycle		√			
Embodied energy, recycling	*	9.28e6	-	1.03e7	J/kg
CO2 footprint, recycling	*	0.562	-	0.621	kg/kg
Recycle fraction in current supply		39.9	-	44	%
Downcycle		√			
Combust for energy recovery		X			

Landfill	√
Biodegrade	X
A renewable resource?	X

Notes

Typical uses

General construction; general mechanical engineering; automotive; tools; axles; gears; springs.

Reference sources

Data compiled from multiple sources. See links to the References table.

Standards with similar compositions

The following information is taken from ASM AlloyFinder 3 - see link to References table for further information.

DGN B-203 94B30 (Mexico)
DGN B-297 94B30 (Mexico)
NMX-B-300(91) 94B30 (Mexico)
ASTM A29/A29M(93) 94B30 (USA)
ASTM A322(96) 94B30 (USA)
ASTM A331(95) 94B30 (USA)
ASTM A519(96) 94B30 (USA)
ASTM A752(93) 94B30 (USA)
SAE 770(84) 94B30 (USA)
AISI 94B30 (USA)
COPANT 514 94B30 (Venezuela)

Material Selection Assignment (Environmental Performance)

Using SimaPro 7 software, the materials selected for both the reflector backing and the support system were compared based on their environmental impacts. SimaPro calculated the amount of raw materials used, the amount of waste produced, the air emissions and the water emissions using EcoIndicator 99 damage classifications. Fig. C.1 shows the results of these calculations for both the polycarbonate and steel. Based on these calculations, it was determined that the polycarbonate for the backing of the reflector surface will have the bigger impact on the environment. It outweighs the impact of the steel in all four of the categories measured. SimaPro also determined the damage impact of the life cycle of the materials. Fig. C.2 illustrates the relative impacts of the life cycle for the materials used in the reflector system. Fig. C.3 shows the three damage categories associated with the life cycle: human health, ecosystem quality, and resources. Fig.C.4 is another way of showing the damage impact from Fig. C.3, but in terms of the materials used. Based on these numbers, the polycarbonate will have a bigger impact on the environment throughout its life cycle. The polycarbonate has a significantly higher point value than the steel as far as damage impact is concerned from Fig. C.4. The human impact of the polycarbonate is also staggering in comparison to the steel, appearing to be an important area of concern when using this material.

The polycarbonate in our system will have a higher total impact on the environment than the steel. It scores higher numbers in almost every category measured. Considering the life cycle of both materials is important in the analysis because both have strong impacts on the environment. The expected lifetime of both the polycarbonate and the steel is designed to be long, therefore both materials should last the same amount of time within the system. One will not have to be produced more than the other in order to compensate for shorter life. Therefore, the environmental impacts should not change relative to one material having a different lifetime than the other. The selection of these materials will be impacted by the environmental impacts of creating them. Looking for a different material to use rather than the polycarbonate for the reflector backing is an area that was looked into. Comparing the impacts of other thermoplastics, such as polystyrene and polyethylene, the polycarbonate scores much higher environmental impacts. Yet, the polycarbonate is the most durable of the thermoplastics, which is why it was selected for the reflector backing. Comparing the polycarbonate to some metals that could be used in as replacements, such as aluminum, the polycarbonate has a much smaller environmental impact.

Fig. C.1: Total Emissions of Materials Selected

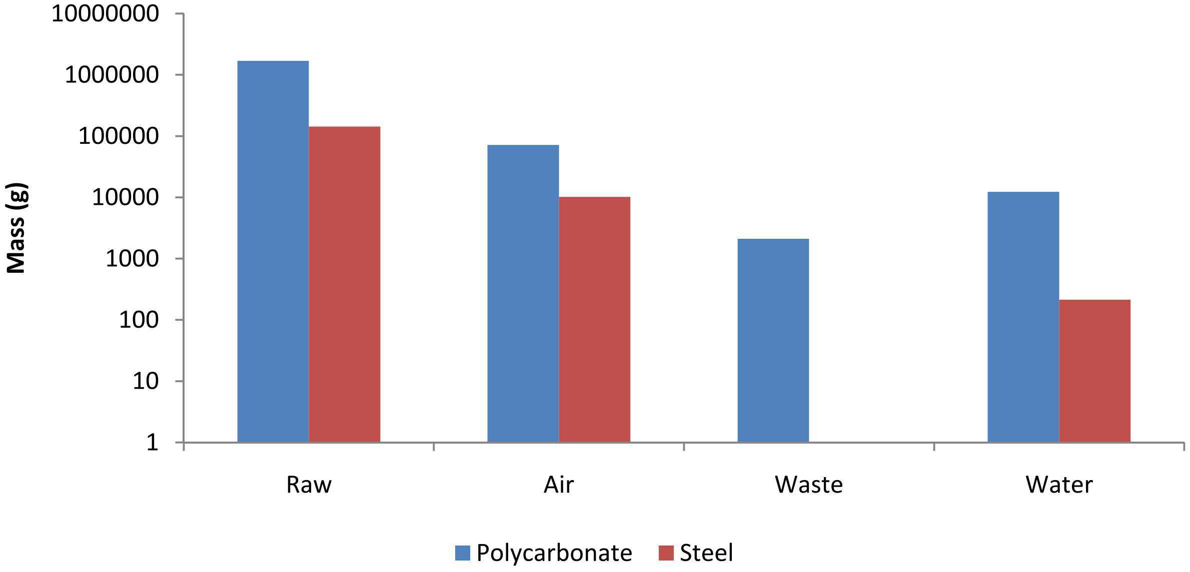
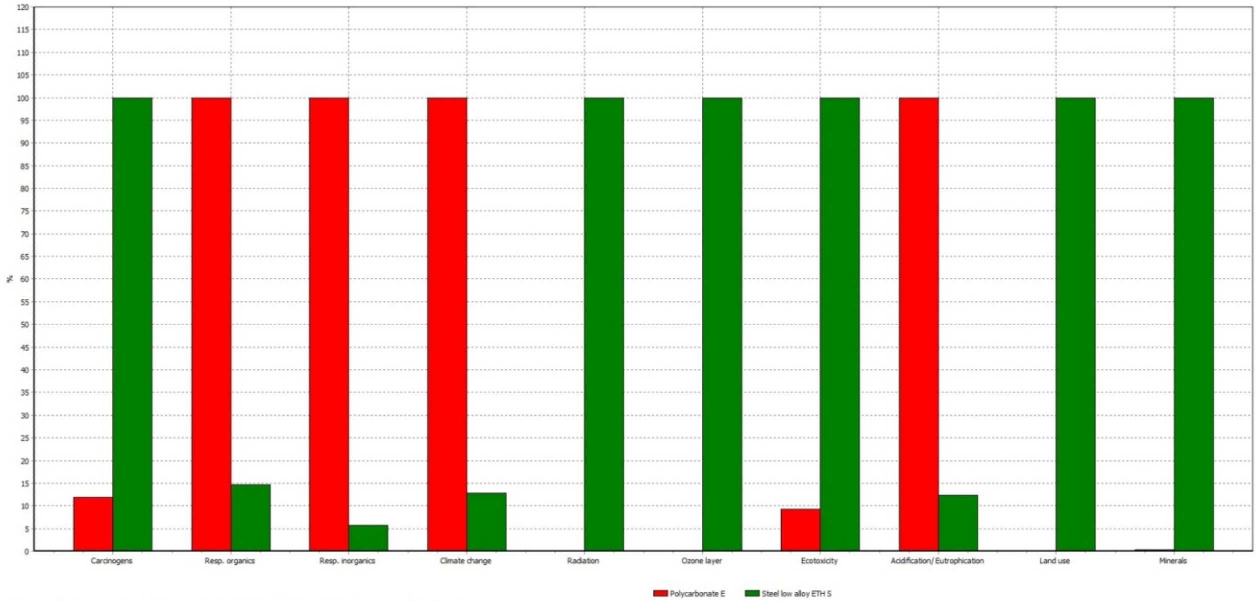
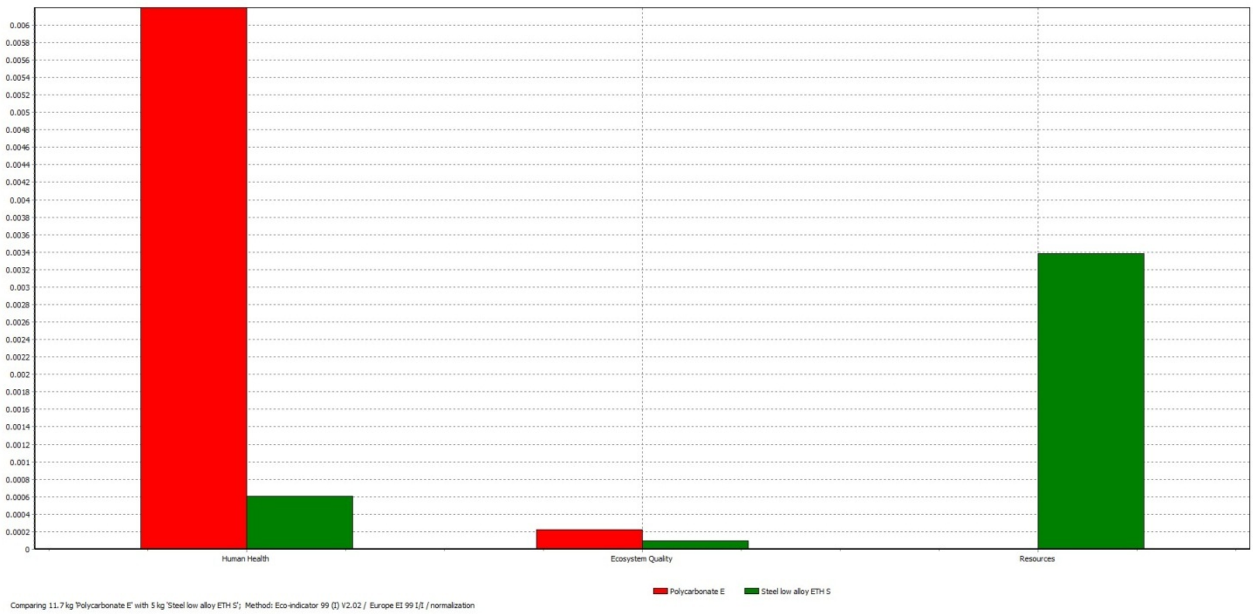


Fig. C.2: Relative Environmental Impacts in Damage Categories



Comparing 11.7 kg 'Polycarbonate E' with 5 kg 'Steel low alloy ETH S'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Fig. C.3: Normalized Environmental Score



Comparing 11.7 kg 'Polycarbonate E' with 5 kg 'Steel low alloy ETH S'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Fig. C.4: Single Environmental Score Comparison

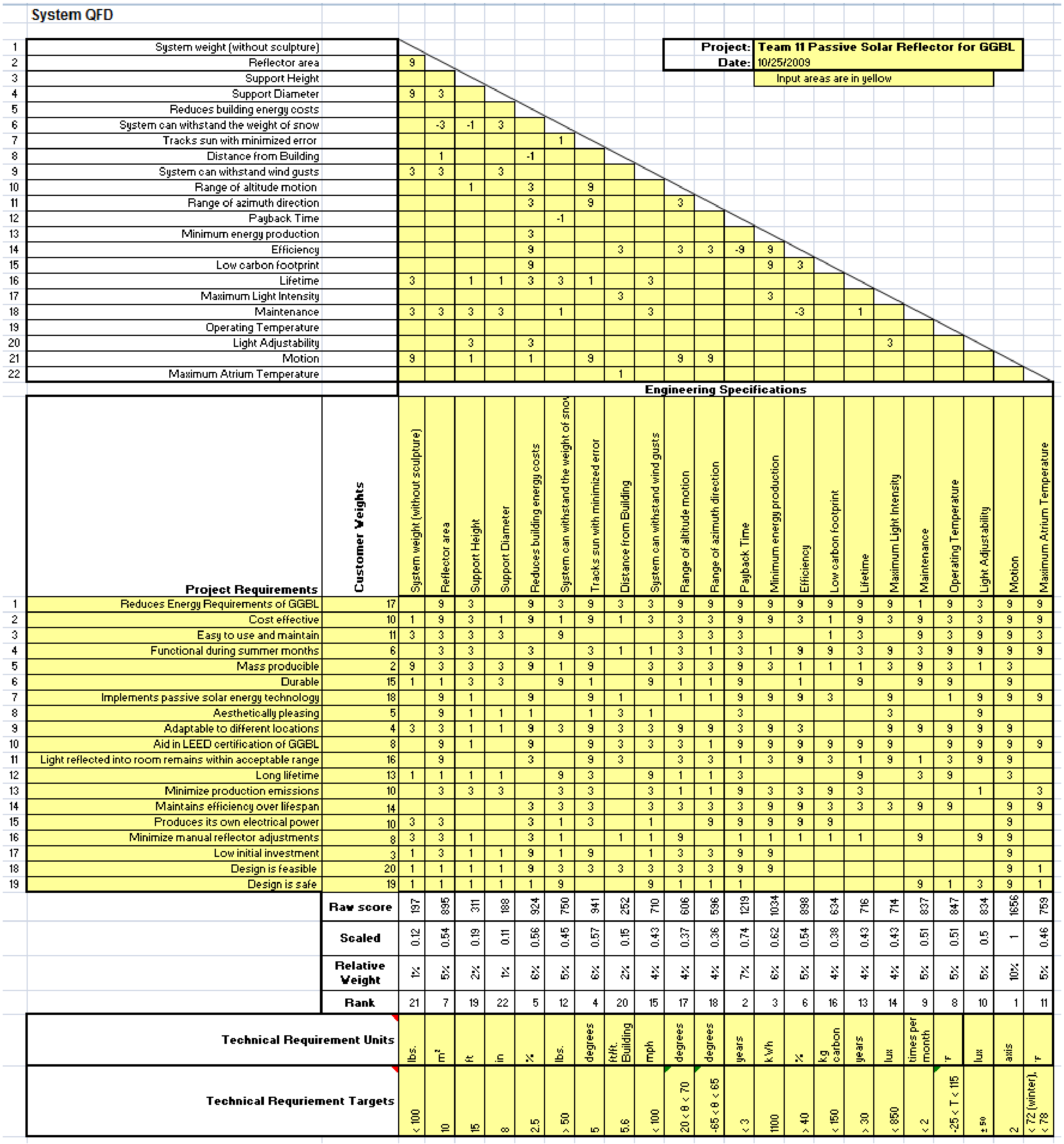
Comparing 11.7 kg 'Polycarbonate E' with 5 kg 'Steel low alloy ETH S'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Manufacturing Process Selection Assignment

The solar reflector created by the Passive Solar Energy Initiative is a system that looks to bring renewable energy into various buildings in many locations. Although the design of the system was centered on a future atrium for the G.G. Brown building at the University of Michigan, the system can be used for many other buildings and homes. For the G.G. Brown, it was proposed to use an array of 10 solar reflectors to heat and light the building. As far as other applications such as buildings and homes, the number to produce is limitless. The demand for such a system depends on the consumer's desire to harness solar energy to reduce the costs associated with heating a room. This system could be used on any building or home, either with a single reflector or an array such as the one proposed for the G.G. Brown atrium project.

The two materials selected for the reflector will have to be manufactured in the proper fashion in order to be used as the reflector backing and supports. For the backing of the solar reflector, polycarbonate will be used. This polycarbonate will cut to size after it has been formed. It will be ideally purchased in sheets that have been possibly injection molded or extruded. It will be cut to the 1 m^2 specified by the final design. For the steel supports, circular support tubes will be purchased and machined to the correct size desired. The length of each pole will be cut to a size specified by the customer based on the location of the window and the distance from the building or home. The brackets needed for the reflector will be machined out of sheets of steel. These will be cut to the dimensions specified in the final design.

Appendix D: QFD Diagram



System QFD

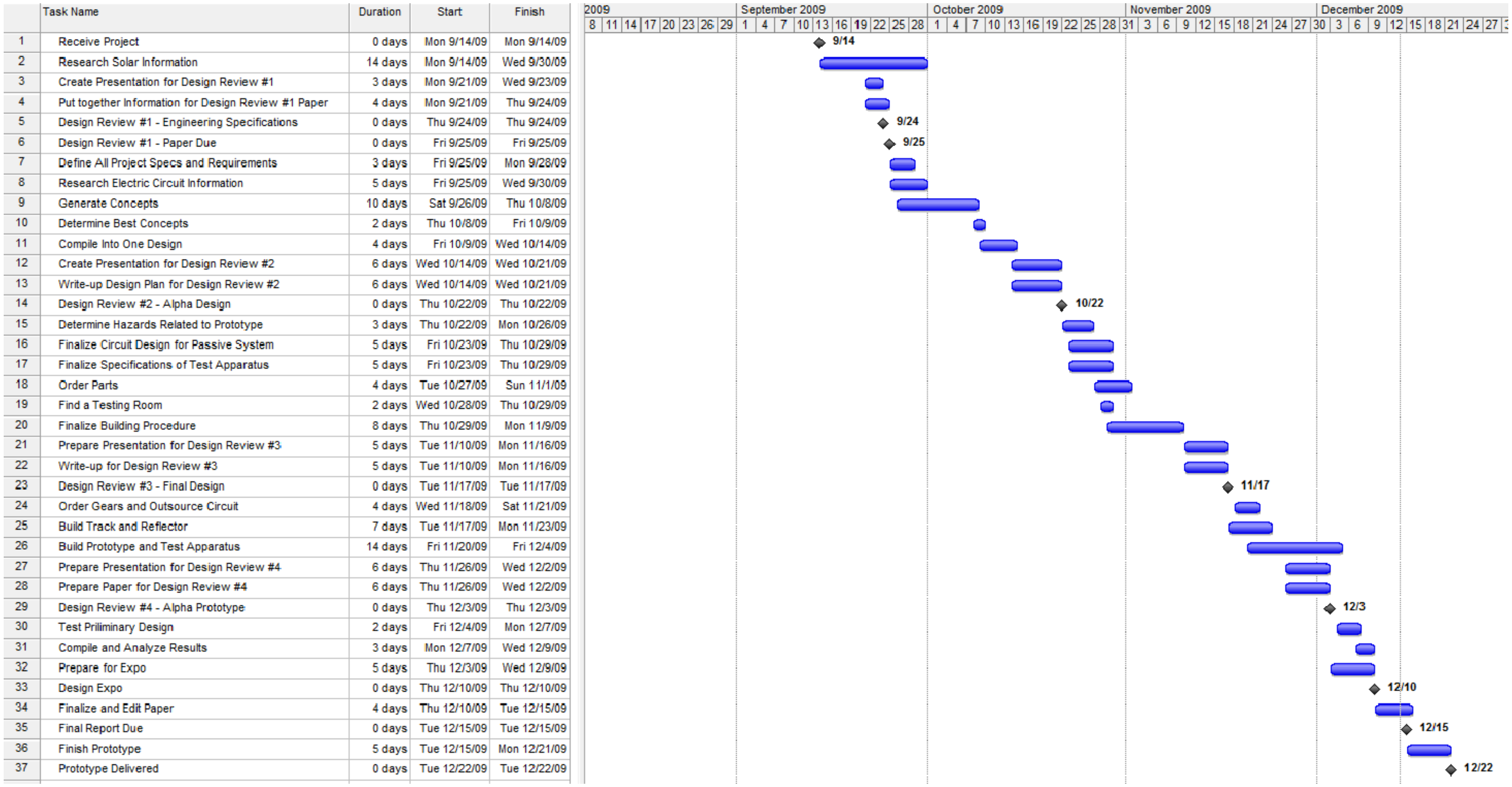
Project: **Team 11 Passive Solar Reflector for GGBL**
Date: 10/25/2009
Input areas are in yellow

1	System weight (without sculpture)																					
2	Reflector area	9																				
3	Support Height																					
4	Support Diameter	9	3																			
5	Reduces building energy costs																					
6	System can withstand the weight of snow		-3	-1	3																	
7	Tracks sun with minimized error						1															
8	Distance from Building		1			-1																
9	System can withstand wind gusts	3	3		3																	
10	Range of altitude motion			1		3		9														
11	Range of azimuth direction					3		9			3											
12	Payback Time						-1															
13	Minimum energy production					3																
14	Efficiency					9			3		3	3	-9	9								
15	Low carbon footprint					9								9	3							
16	Lifetime	3		1	1	3	3	1		3												
17	Maximum Light Intensity								3					3								
18	Maintenance	3	3	3	3		1			3					-3		1					
19	Operating Temperature																					
20	Light Adjustability			3		3												3				
21	Motion	9		1		1		9			9	9										
22	Maximum Atrium Temperature								1													

Engineering Specifications

	Project Requirements	**Customer Weights**	System weight (without sculpture)	Reflector area	Support Height	Support Diameter	Reduces building energy costs	System can withstand the weight of snow	Tracks sun with minimized error	Distance from Building	System can withstand wind gusts	Range of altitude motion	Range of azimuth direction	Payback Time	Minimum energy production	Efficiency	Low carbon footprint	Lifetime	Maximum Light Intensity	Maintenance	Operating Temperature	Light Adjustability	Motion	Maximum Atrium Temperature
1	Reduces Energy Requirements of GGBL	17		9	3		9	3	9	3	3	9	9	9	9	9	9	9	9	1	9	3	9	9
2	Cost effective	10	1	9	3	1	9	1	9	1	3	3	3	9	9	3	1	9	3	9	3	3	9	9
3	Easy to use and maintain	11	3	3	3	3		9				3	3	3			1	3		9	3	9	9	3
4	Functional during summer months	6		3	3		3		3	1	1	3	1	3	1	9	9	3	9	3	9	9	9	9
5	Mass producible	2	9	3	3	3	9	1	9		3	3	3	9	3	1	1	1	3	9	3	1	3	
6	Durable	15	1	1	3	3		9	1		9	1	1	9		1		9		9	9		9	
7	Implements passive solar energy technology	18		9	1		9		9	1		1	1	9	9	9	3		9		1	9	9	9
8	Aesthetically pleasing	5		9	1	1	1		1	3	1			3					3			9		
9	Adaptable to different locations	4	3	3	1	1	9	3	9	3	3	9	9	3	9	3			9	9	9	9	9	
10	Aid in LEED certification of GGBL	8		9	1		9		9	3	3	3	1	9	9	9	9	9	9		9	9	9	9
11	Light reflected into room remains within acceptable range	16		9			3		9	3		3	3	1	3	9	3	1	9	1	3	9	9	
12	Long lifetime	13	1	1	1	1		9	3		9	1	1	3				9		3	9		3	
13	Minimize production emissions	10		3	3	3		3	3		3	1	1	9	3	3	9	3				1		3
14	Maintains efficiency over lifespan	14					3	3	3		3	3	3	3	9	9	3	3	3	9	9		9	9
15	Produces its own electrical power	10	3	3			3	1	3		1		9	9	9	9	9						9	
16	Minimize manual reflector adjustments	8	3	3	1		3	1		1	1	9		1	1	1	1	1		9		9	9	
17	Low initial investment	3	1	3	1	1	9	1	9		1	3	3	9	9								9	
18	Design is feasible	20	1	1	1	1	9	3	3	3	3	3	3	9	9								9	1
19	Design is safe	19	1	1	1	1	1	9			9	1	1	1						9	1	3	9	1
		Raw score	197	895	311	188	924	750	941	252	710	606	596	1219	1034	898	634	716	714	837	847	834	1656	759
		Scaled	0.12	0.54	0.19	0.11	0.56	0.45	0.57	0.15	0.43	0.37	0.36	0.74	0.62	0.54	0.38	0.43	0.43	0.51	0.51	0.5	1	0.46
		Relative Weight	1%	5%	2%	1%	6%	5%	6%	2%	4%	4%	4%	7%	6%	5%	4%	4%	4%	5%	5%	5%	10%	5%
		Rank	21	7	19	22	5	12	4	20	15	17	18	2	3	6	16	13	14	9	8	10	1	11
		Technical Requirement Units	lbs.	m^2	ft	in	%	lbs.	degrees	ft/ft. Building	mph	degrees	degrees	years	kWh	%	kg carbon	years	lux	times per month	°F	lux	axis	°F
		Technical Requriement Targets	< 100	10	15	8	2.5	> 50	5	5.6	< 100	20 < θ < 70	-65 < θ < 65	< 3	1100	> 40	< 150	> 30	< 850	< 2	-25 < T < 115	± 50	2	< 72 (winter), < 78

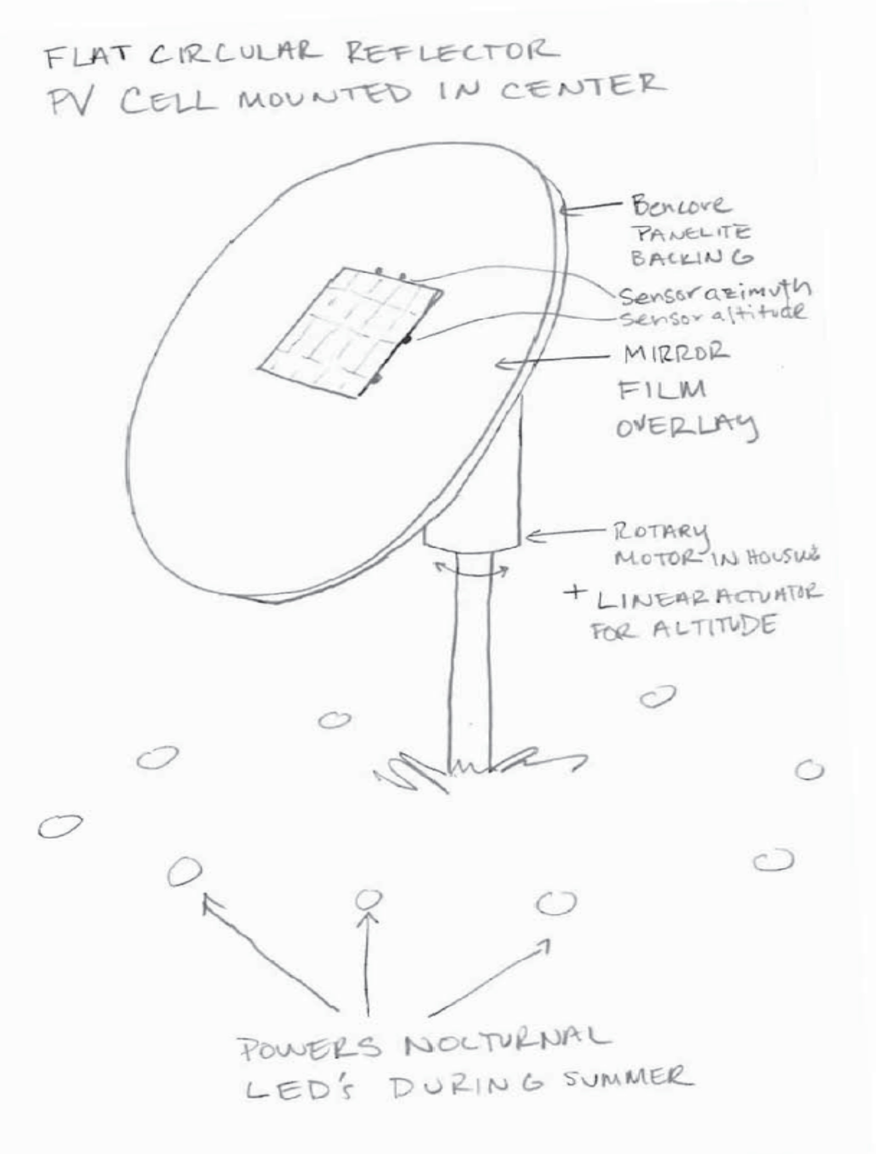
Appendix E: Gantt Chart



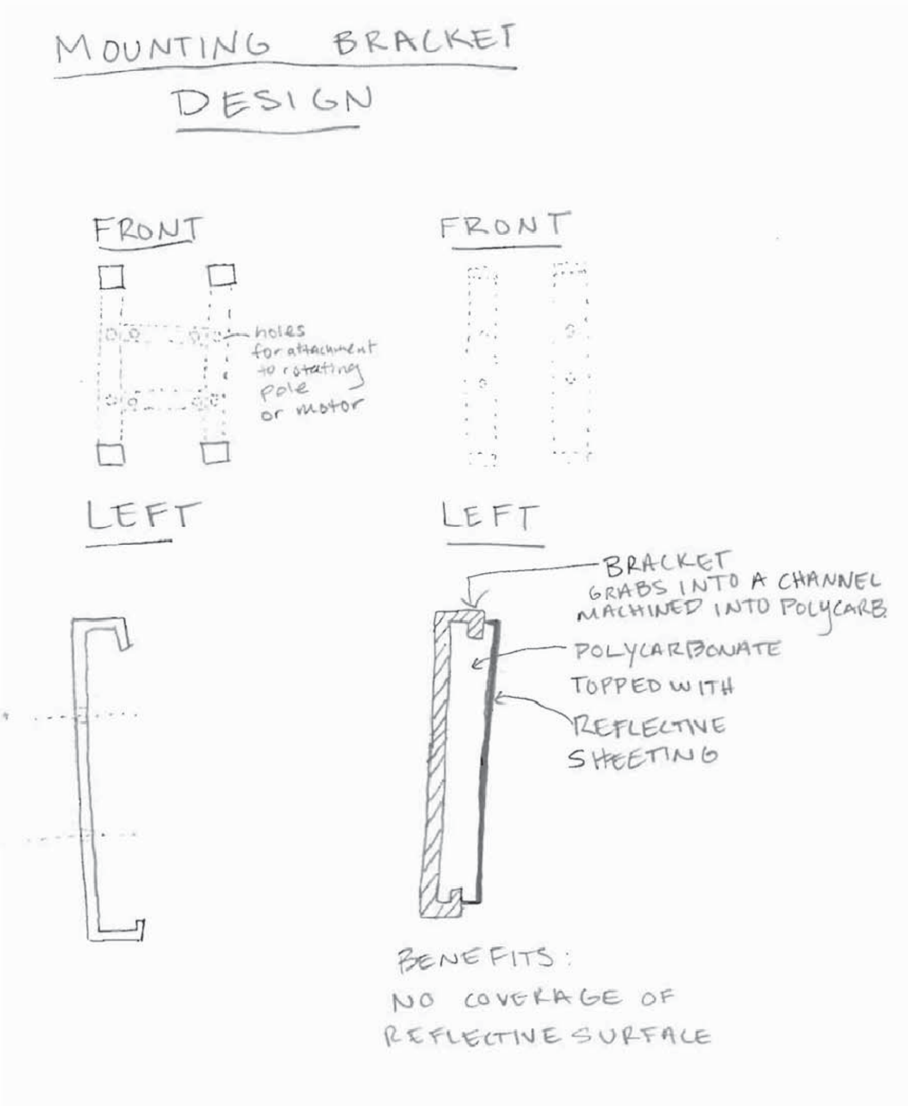
	Task Name	Duration	Start	Finish
1	Receive Project	0 days	Mon 9/14/09	Mon 9/14/09
2	Research Solar Information	14 days	Mon 9/14/09	Wed 9/30/09
3	Create Presentation for Design Review #1	3 days	Mon 9/21/09	Wed 9/23/09
4	Put together Information for Design Review #1 Paper	4 days	Mon 9/21/09	Thu 9/24/09
5	Design Review #1 - Engineering Specifications	0 days	Thu 9/24/09	Thu 9/24/09
6	Design Review #1 - Paper Due	0 days	Fri 9/25/09	Fri 9/25/09
7	Define All Project Specs and Requirements	3 days	Fri 9/25/09	Mon 9/28/09
8	Research Electric Circuit Information	5 days	Fri 9/25/09	Wed 9/30/09
9	Generate Concepts	10 days	Sat 9/26/09	Thu 10/8/09
10	Determine Best Concepts	2 days	Thu 10/8/09	Fri 10/9/09
11	Compile Into One Design	4 days	Fri 10/9/09	Wed 10/14/09
12	Create Presentation for Design Review #2	6 days	Wed 10/14/09	Wed 10/21/09
13	Write-up Design Plan for Design Review #2	6 days	Wed 10/14/09	Wed 10/21/09
14	Design Review #2 - Alpha Design	0 days	Thu 10/22/09	Thu 10/22/09
15	Determine Hazards Related to Prototype	3 days	Thu 10/22/09	Mon 10/26/09
16	Finalize Circuit Design for Passive System	5 days	Fri 10/23/09	Thu 10/29/09
17	Finalize Specifications of Test Apparatus	5 days	Fri 10/23/09	Thu 10/29/09
18	Order Parts	4 days	Tue 10/27/09	Sun 11/1/09
19	Find a Testing Room	2 days	Wed 10/28/09	Thu 10/29/09
20	Finalize Building Procedure	8 days	Thu 10/29/09	Mon 11/9/09
21	Prepare Presentation for Design Review #3	5 days	Tue 11/10/09	Mon 11/16/09
22	Write-up for Design Review #3	5 days	Tue 11/10/09	Mon 11/16/09
23	Design Review #3 - Final Design	0 days	Tue 11/17/09	Tue 11/17/09
24	Order Gears and Outsource Circuit	4 days	Wed 11/18/09	Sat 11/21/09
25	Build Track and Reflector	7 days	Tue 11/17/09	Mon 11/23/09
26	Build Prototype and Test Apparatus	14 days	Fri 11/20/09	Fri 12/4/09
27	Prepare Presentation for Design Review #4	6 days	Thu 11/26/09	Wed 12/2/09
28	Prepare Paper for Design Review #4	6 days	Thu 11/26/09	Wed 12/2/09
29	Design Review #4 - Alpha Prototype	0 days	Thu 12/3/09	Thu 12/3/09
30	Test Priliminary Design	2 days	Fri 12/4/09	Mon 12/7/09
31	Compile and Analyze Results	3 days	Mon 12/7/09	Wed 12/9/09
32	Prepare for Expo	5 days	Thu 12/3/09	Wed 12/9/09
33	Design Expo	0 days	Thu 12/10/09	Thu 12/10/09
34	Finalize and Edit Paper	4 days	Thu 12/10/09	Tue 12/15/09
35	Final Report Due	0 days	Tue 12/15/09	Tue 12/15/09
36	Finish Prototype	5 days	Tue 12/15/09	Mon 12/21/09
37	Prototype Delivered	0 days	Tue 12/22/09	Tue 12/22/09

Appendix F: Concept Generation

Concept 1: Flat circular reflector that features LEDs for lighting at night. This concept uses both a linear actuator and a rotary motor for motion.

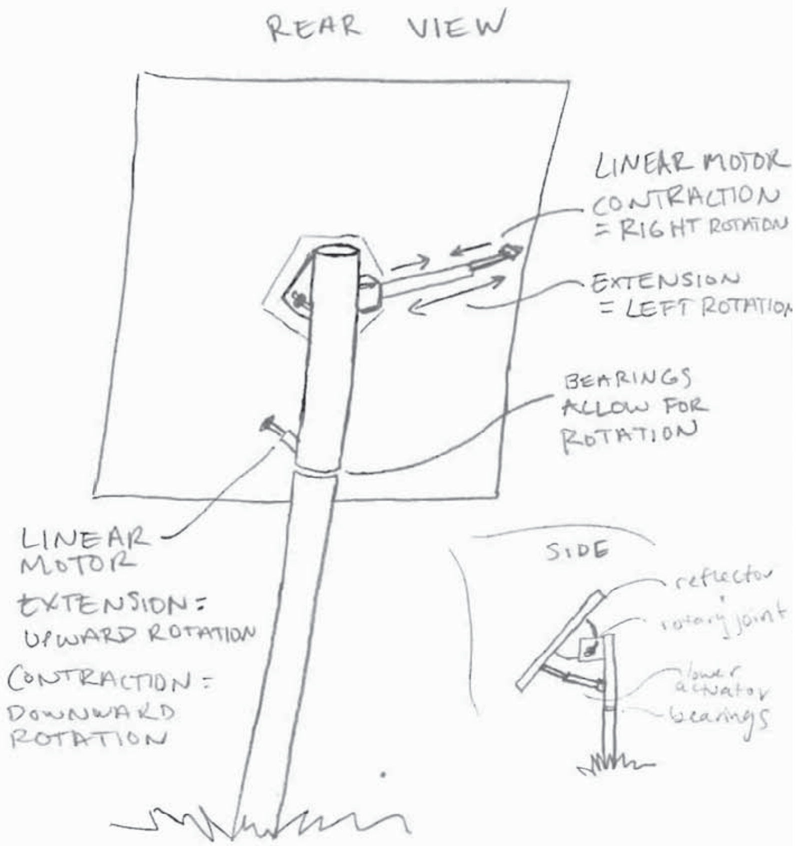


Concept 2: This concept deals with mounting possibilities for the reflector panel. We must decide how we want to mount the mirror to the system, if we will drill through the material or make brackets to hold it. We also must take into consideration if the mounting will reduce the size of the reflective surface.



Concept 3: This concept uses linear actuators for both the azimuth and altitude motion. The linear actuators may not work in the weather conditions we are requiring due to the lack of protective housing.

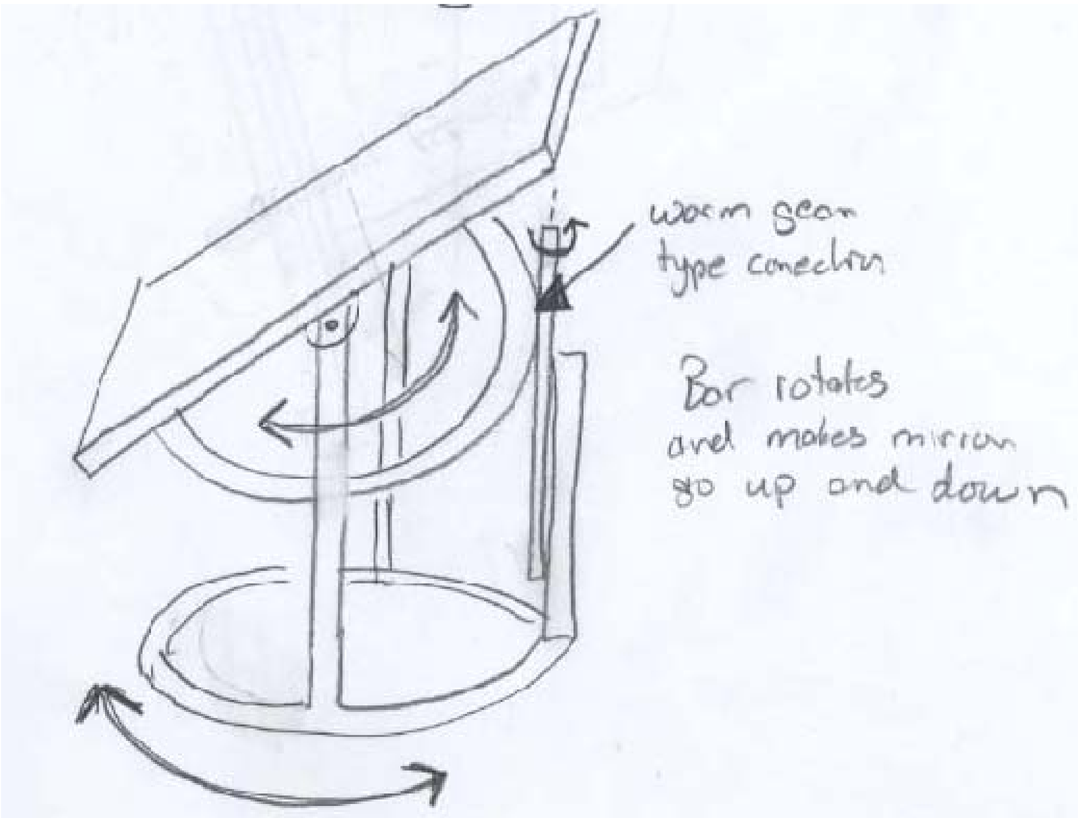
BI - LINEAR ACTUATOR



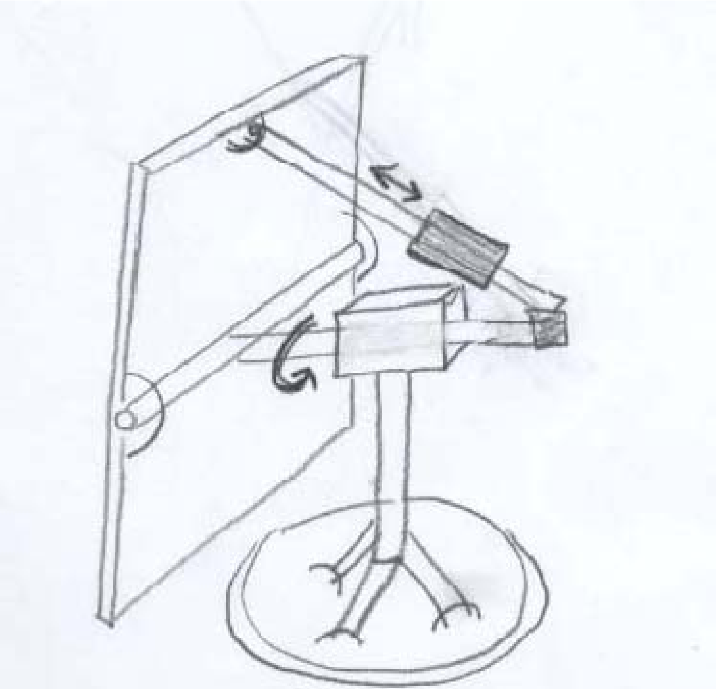
CONSIDERATIONS:

LINEAR ACTUATORS MAY BECOME ENCRUSTED IN ICE AND CEASE TO FUNCTION. SIGNIFICANT PROTECTIVE HOUSING IS REQUIRED!

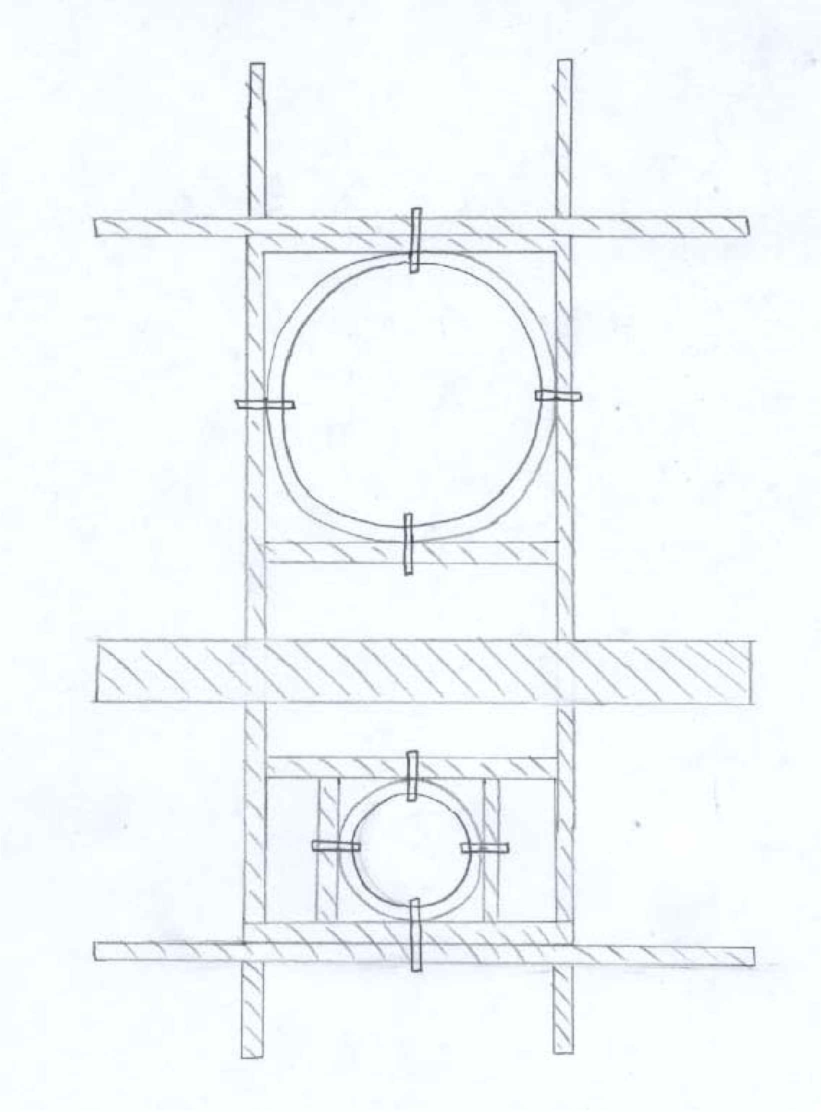
Concept 4: This concept uses a worm gear in order to move the reflector up and down in the altitude direction. The entire system would then move around the base in order to account for the azimuth direction.



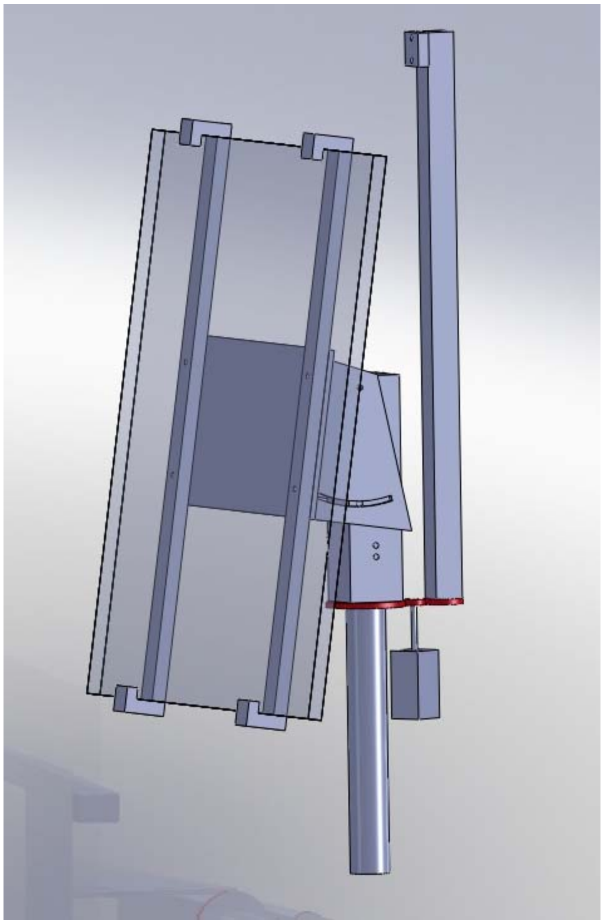
Concept 5: This concept uses a linear actuator to adjust the pitch of the reflector while the reflector would spin about the center shaft. This concept would probably involve programming so that the system would move correctly.

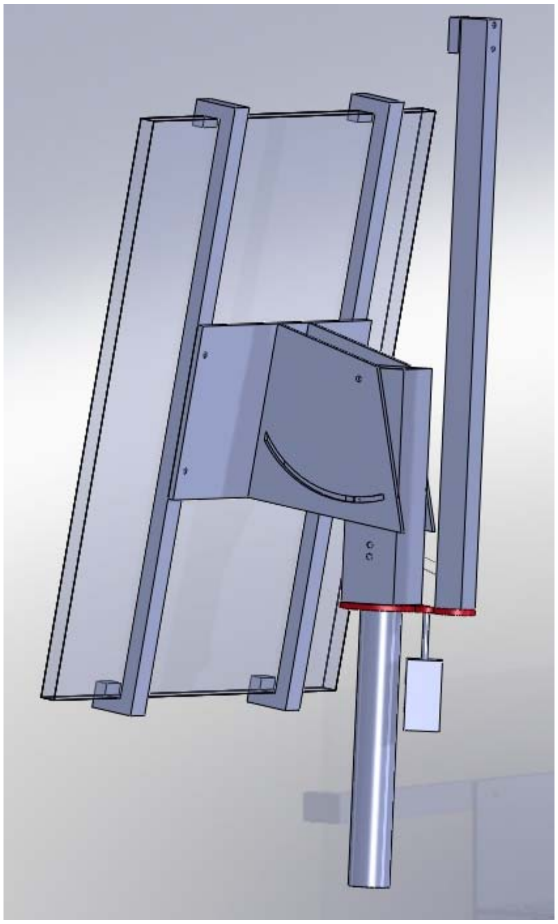


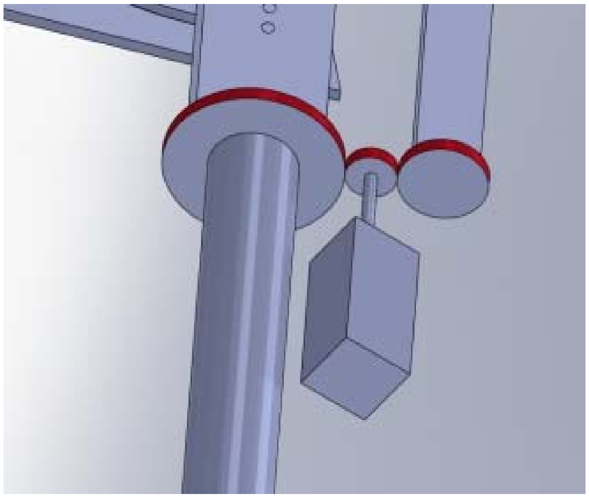
Concept 6: This is a concept for the base of the alpha design, where the larger diameter circle is the shaft for reflector and the smaller diameter circle is the shaft for the tracking system.



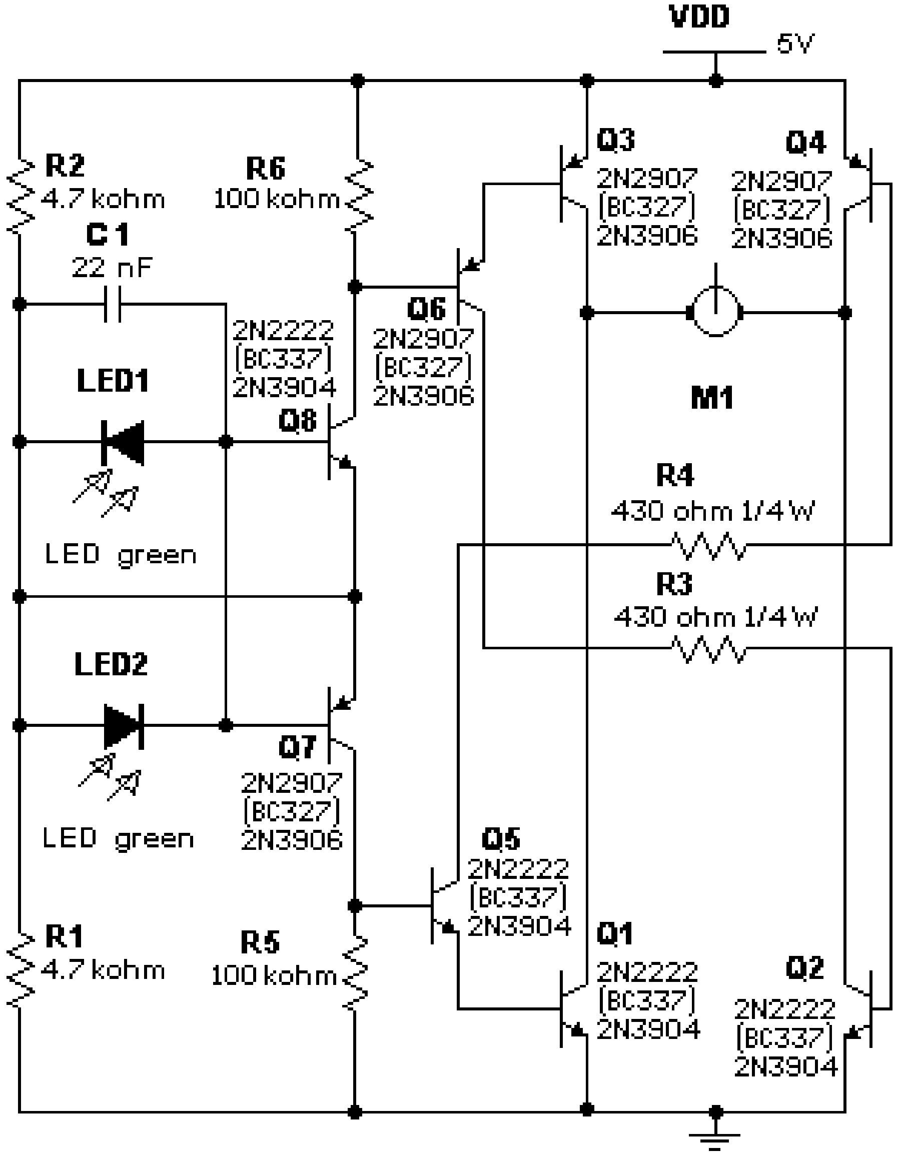
Appendix G: CAD Model of Alpha Prototype





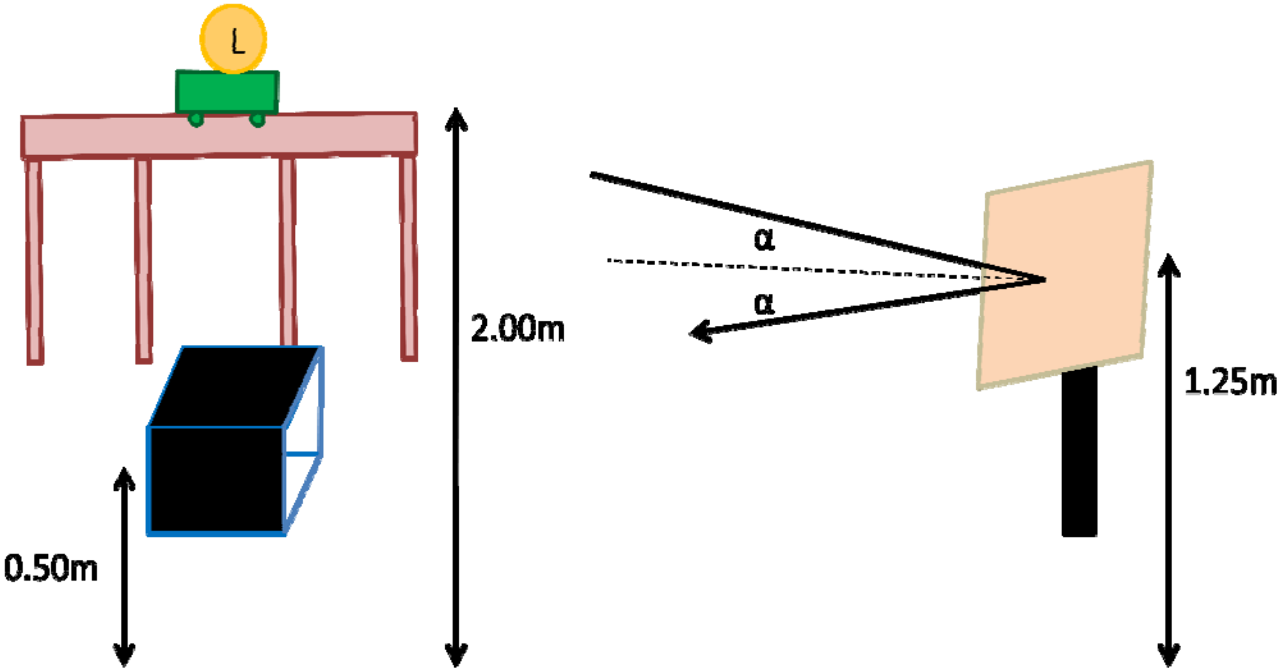


Appendix H: LED Solar Sensor Circuit Diagram



[21]

Appendix I: Preliminary Test Diagram



Appendix J: Detailed Analysis

Heat Transfer Analysis

The 400 watt metal-halide light bulb emits a power, P_{light}, of 110 Photo synthetically Active Radiation (PAR) watts and is attached to a reflector that is approximately 0.6 meters in diameter. The footprint area of the light, A_{fprint}, was measured to be 3.08m^2 at a distance of five meters from the light. A mirror with an area, A_{mirror}, of 0.25m^2 will receive power, P, of 8.9 PAR watts as shown in Eq. 1:

$$P = P_{light} * \frac{A_{mirror}}{A_{fprint}} \qquad \text{(Eq. 1)}$$

The energy emitted by the mirror, $E_{reflected}$, can be then calculated by Eq. 2 below:

$$E_{reflected} = \alpha_{mirror} * A_{mirror} * P \qquad \text{(Eq. 2)}$$

where the reflectivity of the mirror, α_{mirror}, is 0.94, and is the specification of the mirror obtained by our team. This yields energy reflected, $E_{reflected}$, as 2.1 PAR watts. Finally, we needed to calculate the energy that would be transferred into the insulated box. One side of the box will be Plexiglas with a tranmissivity, β,of 0.92. The energy gained inside the box, E_{gain}, will then be 1.9 PAR watts as described by Eq. 3:

$$E_{gain} = \beta * E_{reflected} \qquad \text{(Eq. 3)}$$

Finally, to calculate the heat transfer into the insulated box we must assume an ideal situation in which the area of the reflector is equal to the face of the target box. We must calculate the mass of the air contained by the box and use this value to determine the temperature change. The box will be 0.5m x 0.5m x 0.125m for a volume, V, of 0.03125m^3. The density of air, ρ, approximated at an ambient temperature, T_0, of 293 Kelvin, is 1.2 kg/m^3. The mass of the air, m, must be substituted from Eq. 4 into Eq. 5 below, considering a specific heat of air, c, to be 1005 J/kg*K:

$$m = \rho * V \qquad \text{(Eq. 4)}$$

$$E_{gain} * t = Q = m * c * (T - T_0) \qquad \text{(Eq. 5)}$$

The heat transfer, Q, will occur over the time of testing, t, of thirty minutes, such that the final temperature will be approximately 385 K, for a temperature change of approximately 92 K assuming perfect tracking during the entire test and no losses.

Detailed Torque and Gear Analysis

We must first calculate the angular speed at which the motor will turn in our test, ω. We will do this by using Eq. 6, where θ is the angle moved by the reflector, which is 2.199115 radians. This is divided by the time taken in the test, 1800 seconds, and then converted to RPM. This gives us a value of 0.011667 RPM for the speed the reflector must rotate. Because a 10:1 gear is used between the motor and the gear, the speed the motor must rotate will be 10 times that of the reflector, or 0.11667 RPM.

$$\omega = \frac{\theta}{1800} \cdot \frac{60}{2\pi} \qquad \text{(Eq. 6)}$$

In order to determine how hard it will be to rotate our reflector, the torque required to rotate the reflector must be calculated. To do this, we must first calculate the moment of inertia of the reflector and its attachments. We will do this by using Eq. 7, where I_{total} is the total moment of inertia for the turning reflector, I_r is the moment of inertia of the reflector itself, and I_{pole} is the moment of inertia of the pole the reflector is on.

$$I_{total} = I_r + I_{pole} \qquad \text{(Eq. 7)}$$

The moment of inertia must be calculated for both the pole and reflector individually, and are done so by using Eq. 8and 9. In Eq. 8, m_{pole} is the mass of the pole the reflector is attached to of 9.087 kg, $r_1$is the inner radius of the reflector pole of 0.0712 m, and r_2 is the outer radius of the reflector pole of 0.0762 m. In Eq. 9, m_r is the mass of the reflector of 4.55 kg, h is the height of the reflector of 0.5 m, and w is the width of the reflector of 0.5 m. This yields a moment of inertia of the reflector of 0.18958 kg·m^2 and a moment of inertia of the pole of 0.0493 kg·m^2. Summing these two together gives us a total moment of inertia of 0.239 kg·m^2.

$$I_{pole} = \frac{1}{2} m_{pole}(r_1^2 + r_2^2) \qquad \text{(Eq. 8)}$$

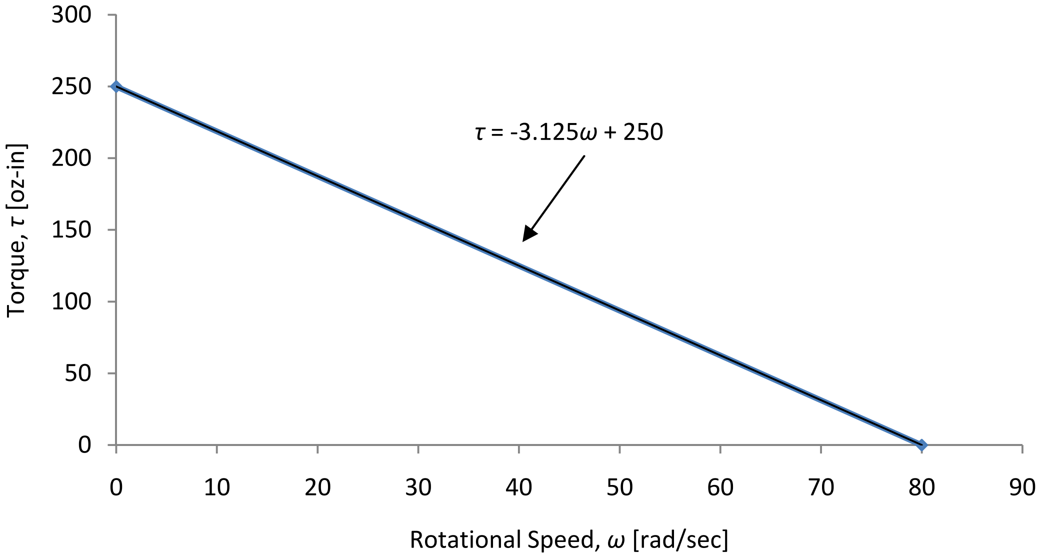
$$I_r = \frac{m_r(h^2+w^2)}{12} \qquad \text{(Eq. 9)}$$

The torque required to move the reflector, τ, is then calculated using Eq. 10. θ_{inc} is the smallest increment angle that the motor will move, which is 0.00175 radians. With the found values for the moment of inertia and the angular, we determine our torque value to be 1.443 oz-in. We must ensure that our motor will be able to output at least this amount of torque at the angular speed we will be using in our test.

$$\tau = \frac{\frac{1}{2} I_{total}\omega^2}{\theta_{inc}} \qquad \text{(Eq. 10)}$$

We selected a Pololu motor for our reflector system that we feel will work in our testing procedures. To verify that the motor we selected will operate under the conditions we wish to run at, we must look at the torque curve for our motor. The motor has a stall torque of 250 oz-in and a free-run angular velocity of 80 RPM [22]. We use these values to create a torque curve for the motor as shown in Fig. J.1. We must find the maximum torque that the motor can output at the speed we wish to run our test at. Using the angular speed of the motor calculated before and the equation of the motor torque curve, we can determine the maximum torque the motor can output before it stalls. Plugging in our value of 0.11667 RPM gives a stall torque of 249.6354 oz-in. This value is much higher than the torque we require of 1.443 oz-in. This ensures that our motor will be able to rotate our reflector for our testing purposes.

Fig. J.1: Torque Curve of Selected Pololu Motor



Appendix K: Fabrication Plan

Below is the procedure to manufacture and assemble the prototype and test set-up.

Manufacturing Overview for Prototype

Select a part to manufacture. Check which sub-component the part is listed under and use the tools listed for that sub-component. Acquire the needed tools/machines and the part drawling. Follow the manufacture steps listed for the part. Repeat until the correct quantity of each part is manufactured.

Table K.1: Tools and Machines

Sub-component	Tools
L - Beams	Band Saw, Drill Press, 1/4" drill bit
Support Shafts	Band Saw, Pipe Clamp, Drill Press, 1/4" drill bit
Sheet Metal	Mill, Band Saw, 1/4" drill bit, #4 drill bit, M3 tap
Gears	Drill Press, 3/4" drill bit
Reflector	Glass Cutter, T-Square

Table K.2: Part List and Quantity

L-Beams	**Quantity**
L Middle	2
L Middle2	2
L Cross	3
L Short	2
L Frame	2
L Bracket	4

Support Shafts	**Quantity**
Base Pole	2
Bracket Pole	1
Sensor Pole	1
Inner Pole	1

Sheet Metal	**Quantity**
Bracket	2
Bar	2
Motor Mount	1

Gears	**Quantity**
Sensor Gear	1
Motor Gear	1
Reflector Gear	1

Reflector	**Quantity**
Mirror	1

Fasteners	**Quantity**
Bolt # 1	10
Bolt # 2	7
Bolt # 3	36
Bolt #4	2
Nut	55
Set Screws	3
Motor screws	4

Bearings	**Quantity**
Thrust Bearing	2
Thrust Bearing Washer	4
Angular Bearing	2

Table K.3: Speed Rate Table

Material	**Machine**	**Speed (FPM)**
Steel	Mill	100
	Band saw	50-100
	Drill Press	110
Aluminum	Mill	165
	Band Saw	275-325
	Drill Press	250

To find the speed in RPM, use the speeds listed in table and the equation below.

$$\left(\frac{12\times(Speed)}{\pi\times(Tool\ Diameter)}\right)\div(\#\ of\ tool\ cutting\ edges) = \text{RPM}$$

Manufacturing Steps and Drawings for Prototype

L- Beams: Always cut the beam to the proper length before drilling the holes.

Fig. K.1: Dimensions of L Cross

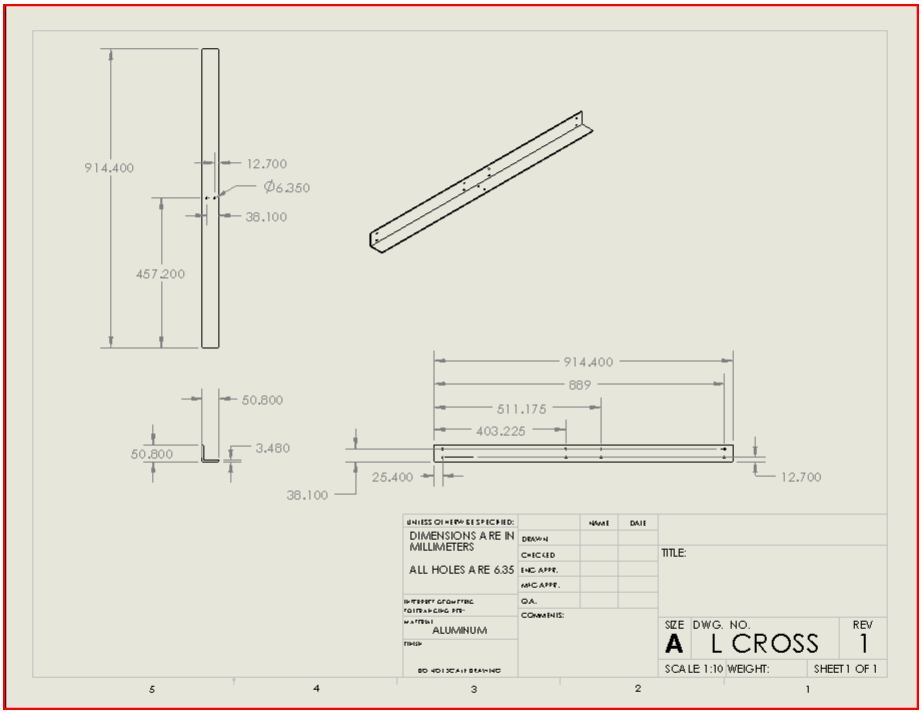


Fig. K.2: Dimensions of L middle

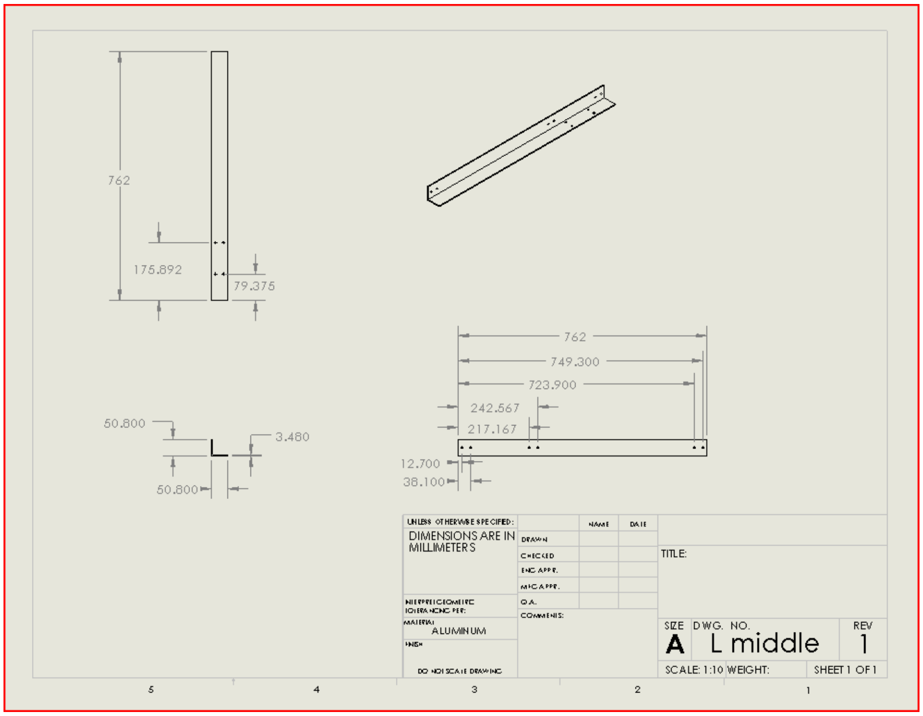


Fig. K.3: Dimensions of L middle2

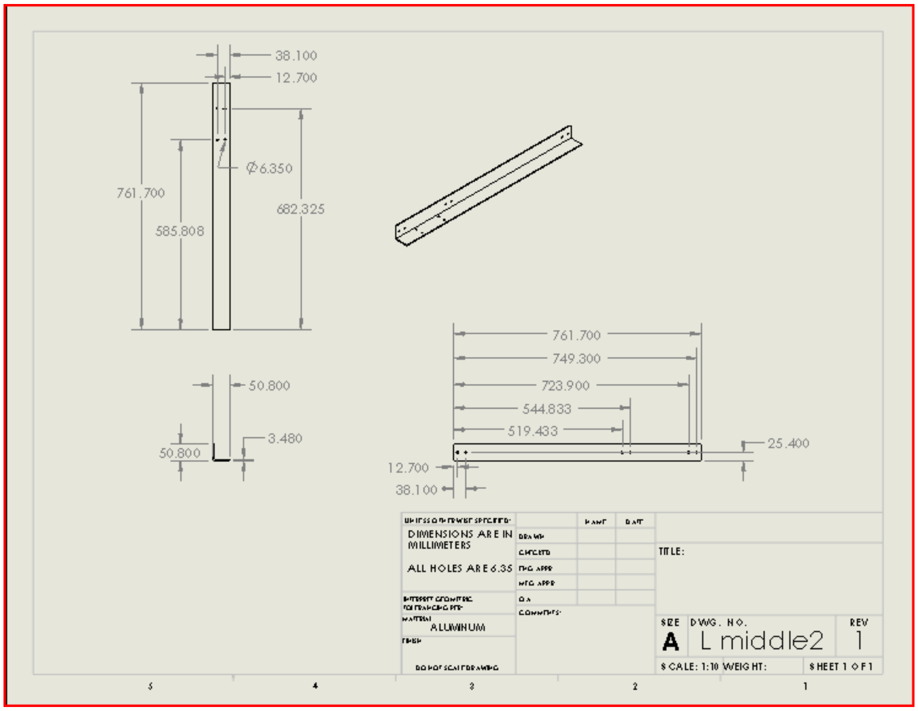


Fig. K.4: Dimensions of “L Short”

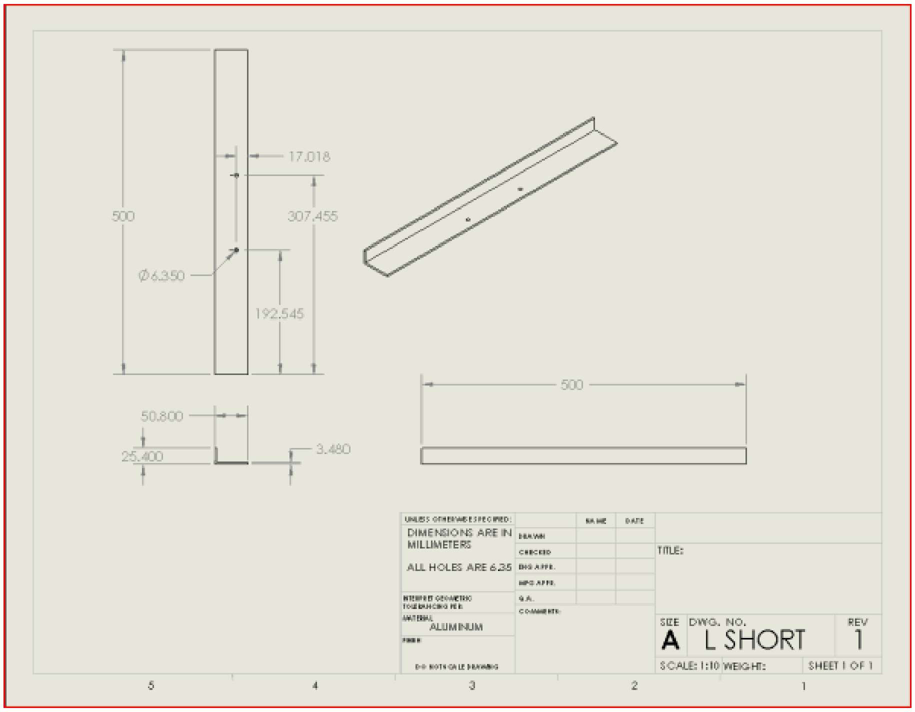


Fig. K.5: Dimensions of L Bracket

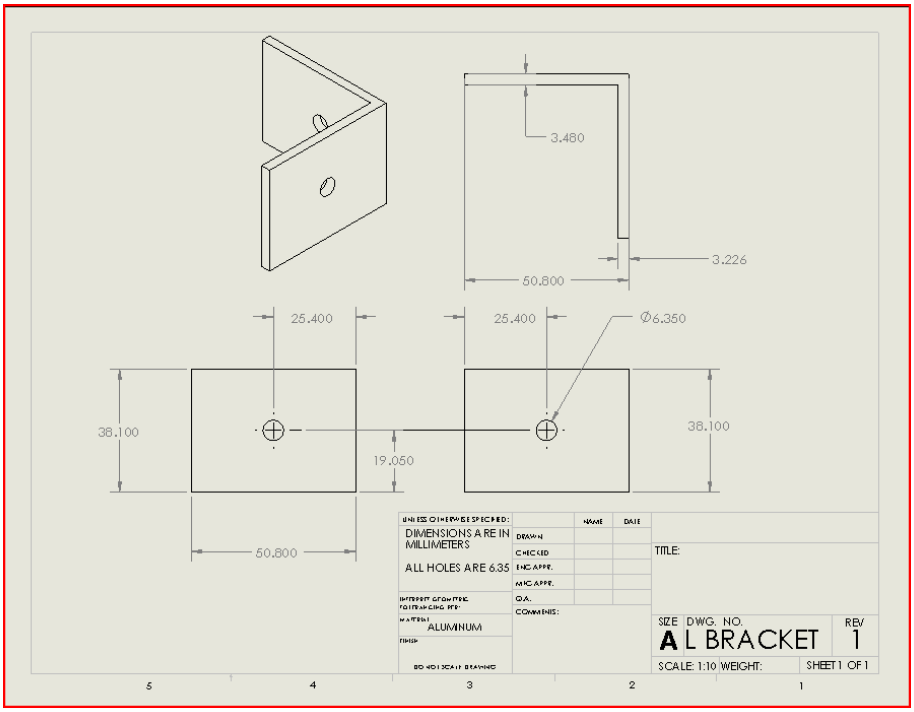
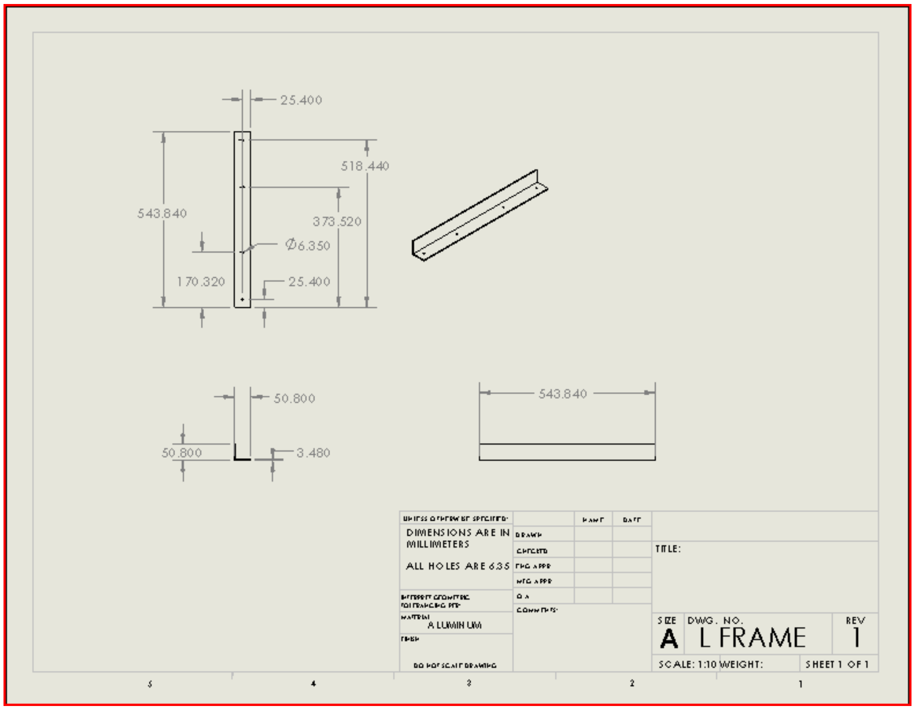


Fig. K.6: Dimensions of L Frame



Support Shafts: Always cut the pole to the proper length before drilling the holes.

Fig. K.7: Dimensions of Base Pole

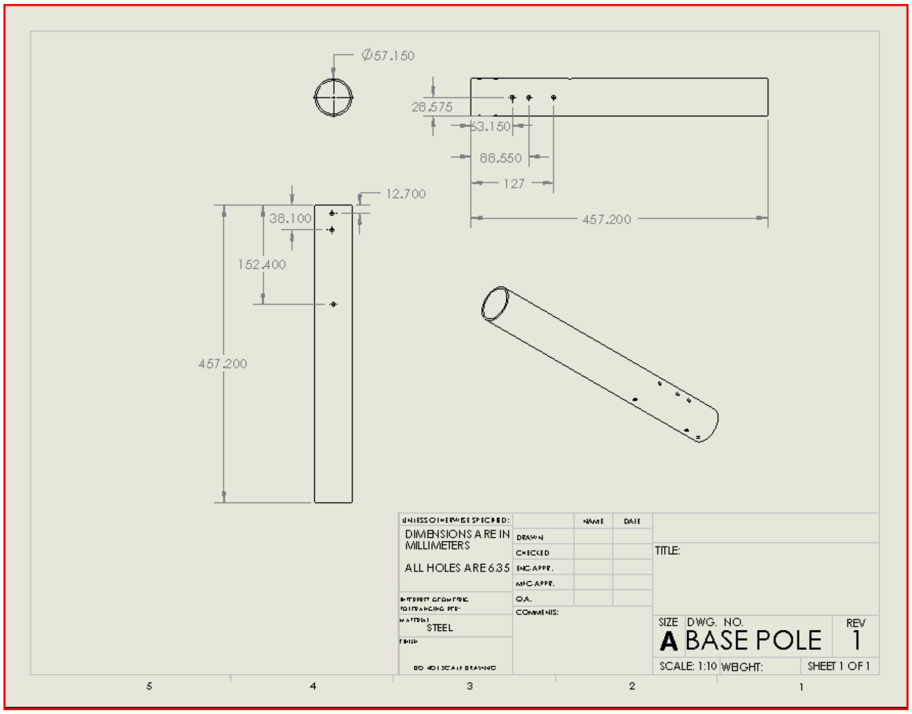


Fig. K.8: Dimensions of Bracket Pole

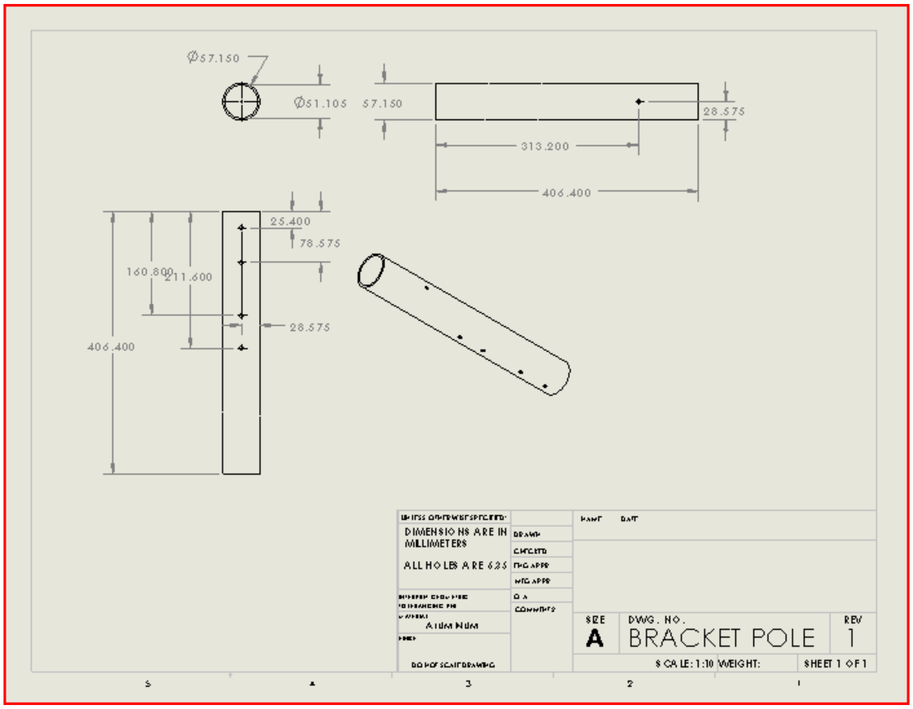


Fig. K.9: Dimensions of Inner Pole

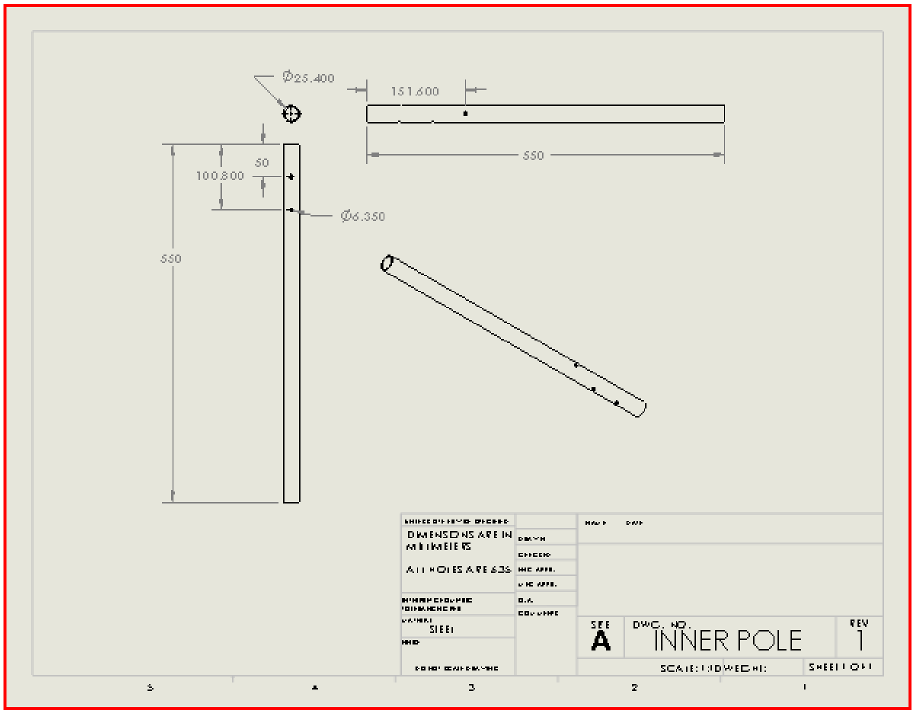
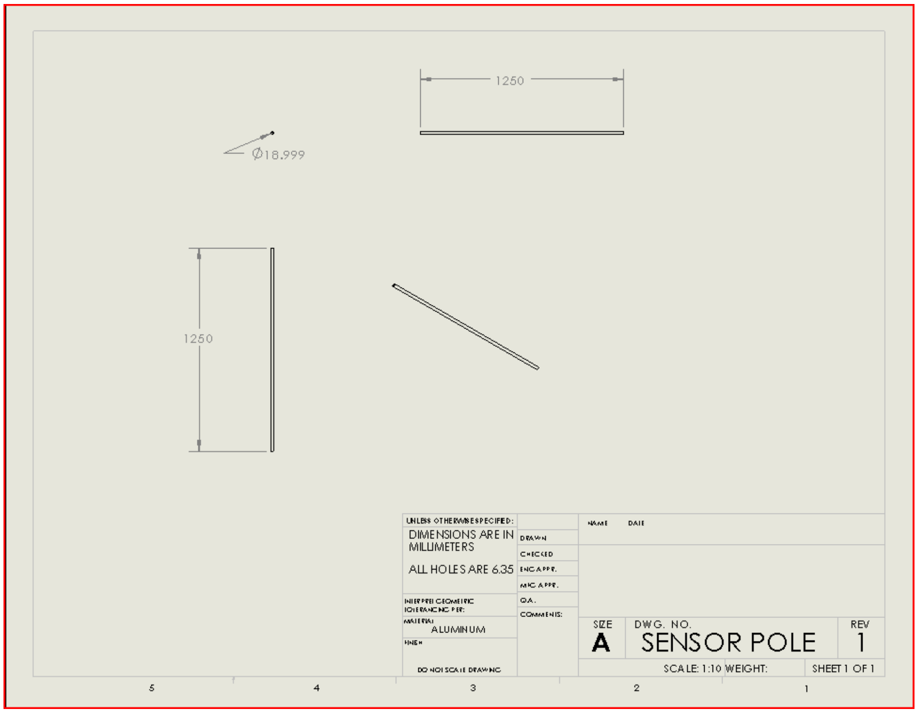


Fig. K.10: Dimensions of Sensor Pole



Sheet Metal: Mill the semi-circle and drill the holes before cutting the Square chunk of sheet metal into its proper shape. Mill the Motor mount to its correct dimensions and then tap the screw holes

Fig. K.11: Dimensions of Bracket

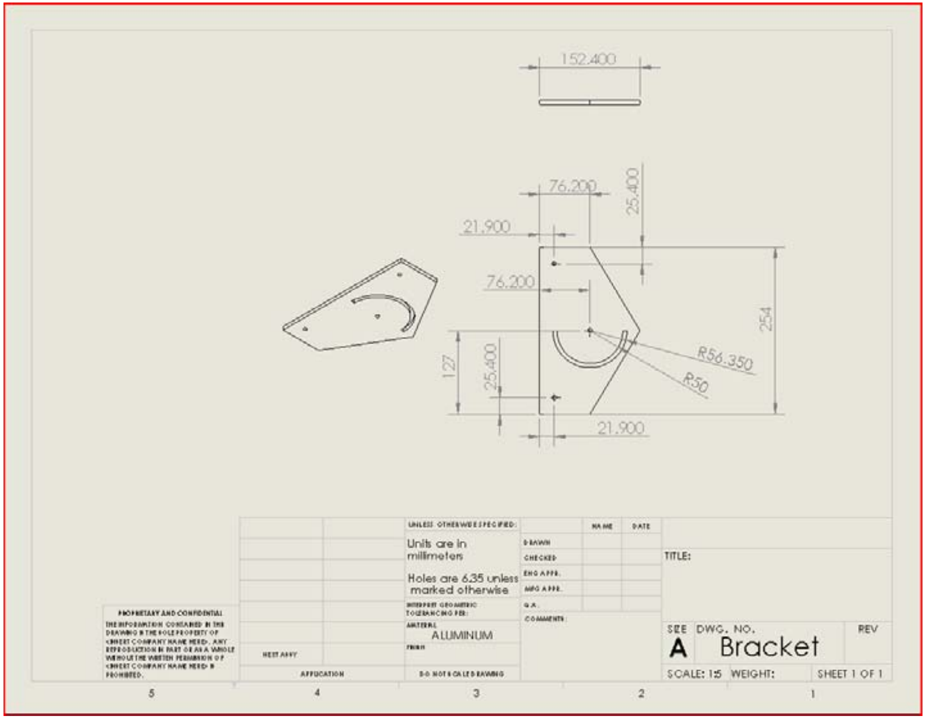


Fig. K.12: Dimensions of Bar

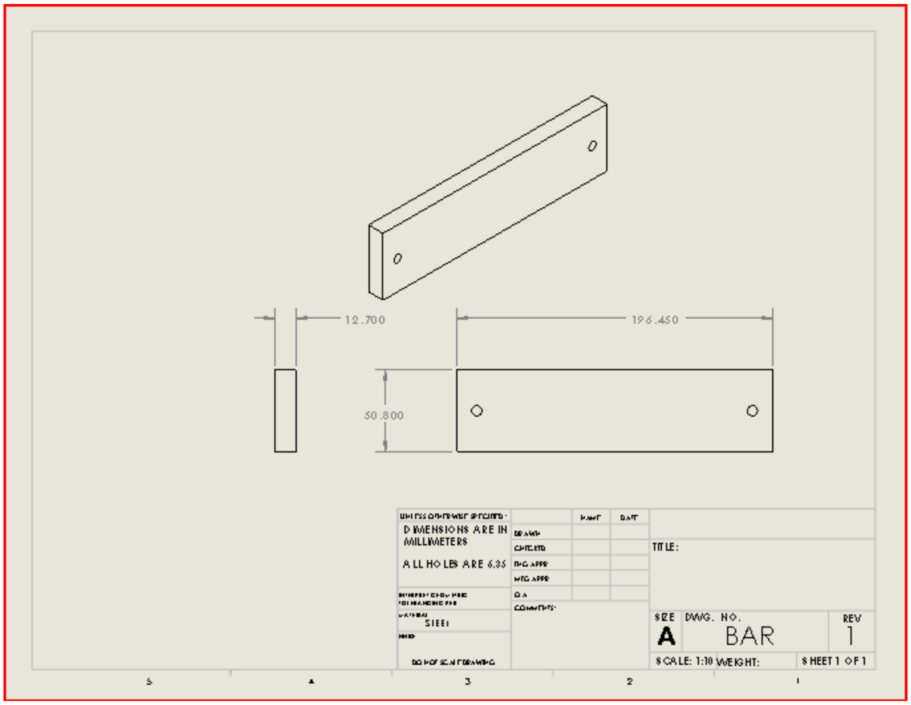
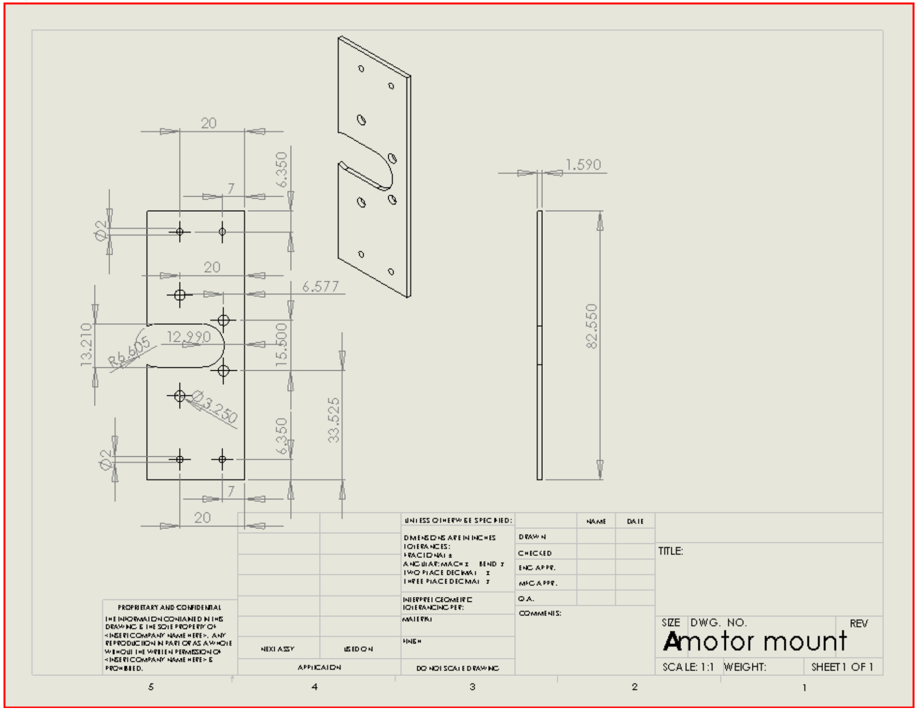
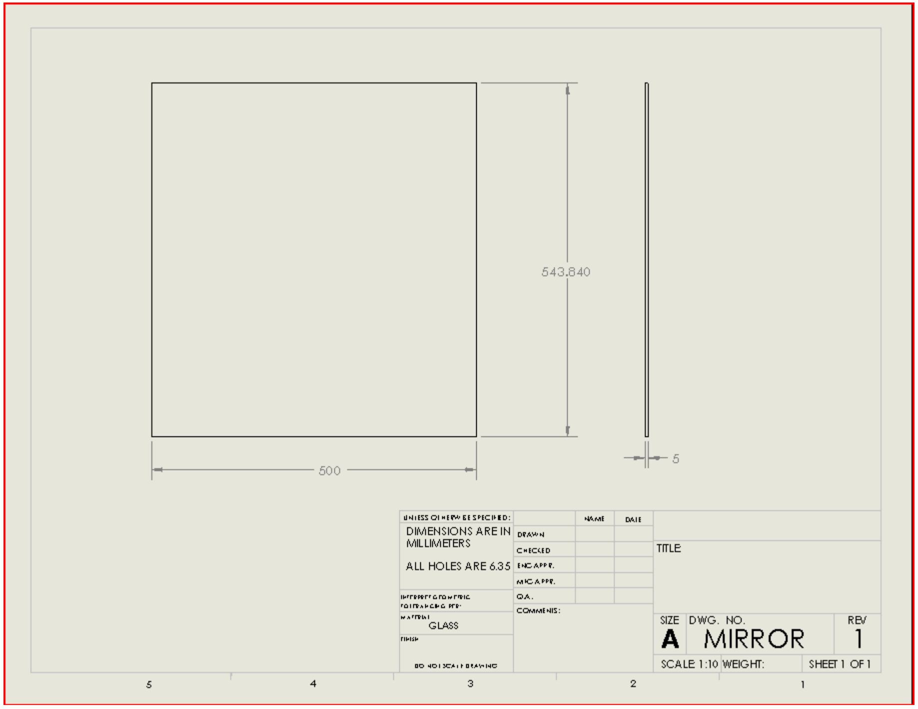


Fig. K.13: Dimensions of Motor Mount

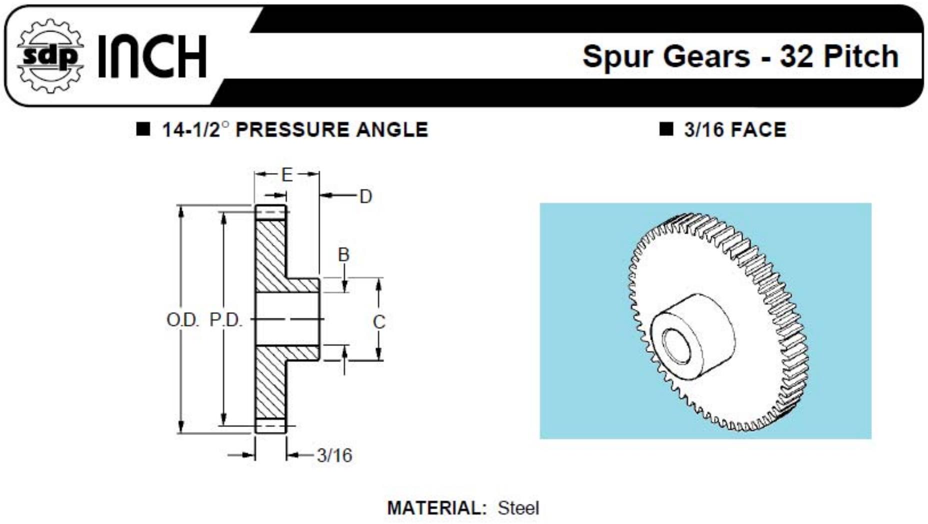


Reflector: Outline where the mirror will need to be cut with a soft felt tip marker. Use a glass cutter to scratch along the line. Place a pencil beneath the glass along the line where it is to cut. Using the pencil as a pivot, carefully break the glass along the line. Only do one side at a time.

Fig. K.14: Dimensions of Mirror

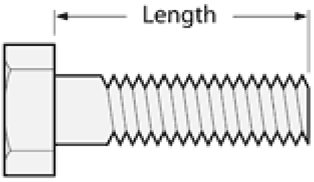


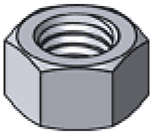
Gears: Drill the correct bore size into the gear. Then drill a small hole through the gear hub. Tap the small hole for the set screw.



Part Name	No. of Teeth	P.D.	O.D.	B Bore (Stock)	B Bore (Drilled)	E Length	C Hub Dia.	D Hub Proj.
Sensor Gear	80	2.5	2.562	3/8	.75	9/16	1-1/8	3/8
Motor Gear	16	0.5	.562	3/16	.2362	1/2	13/32	5/16
Reflector Gear	160	5.0	5.062	3/8	.75	11/16	1-3/8	1/2

Fasteners: nuts, bolts, and set screws



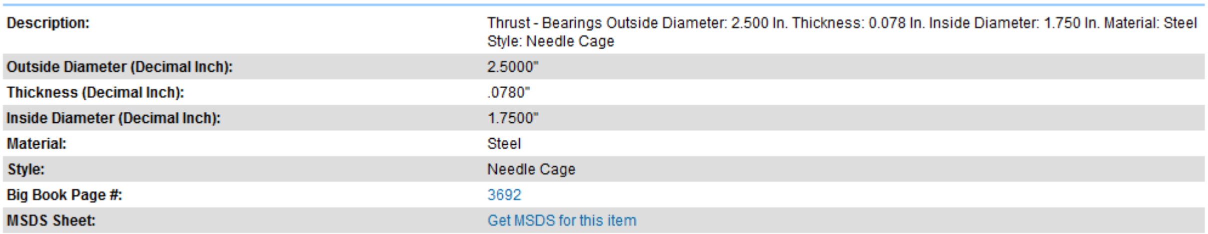


Part Name	Diameter (inch)	Length (inch)
Bolt #1	1/4	3
Bolt #2	1/4	2-1/2
Bolt #3	1/4	3/4
Bolt#4	1/4	4
Nut	1/4	---
Set screw	.079	.1807
Motor Screw	.079	.3

Bearings: Stock

Thrust Bearing

MSC #: 03380995



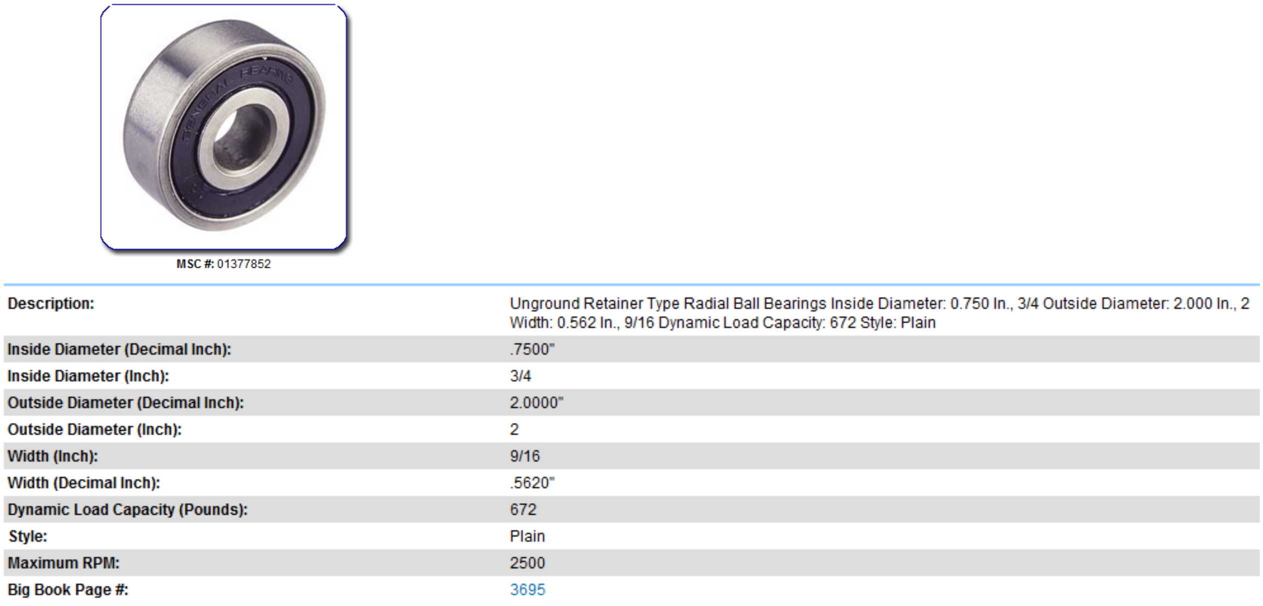
Description:	Thrust - Bearings Outside Diameter: 2.500 In. Thickness: 0.078 In. Inside Diameter: 1.750 In. Material: Steel Style: Needle Cage
Outside Diameter (Decimal Inch):	2.5000"
Thickness (Decimal Inch):	.0780"
Inside Diameter (Decimal Inch):	1.7500"
Material:	Steel
Style:	Needle Cage
Big Book Page #:	3692
MSDS Sheet:	Get MSDS for this item

Thrust bearing washer

MSC #: 03381175

Description:	Thrust - Bearings Outside Diameter: 2.490 In. Thickness: 0.032 In. Inside Diameter: 1.750 In. Material: Steel Style: Flat Race
Outside Diameter (Decimal Inch):	2.4900"
Thickness (Decimal Inch):	.0320"
Inside Diameter (Decimal Inch):	1.7500"
Material:	Steel
Style:	Flat Race
Big Book Page #:	3692
MSDS Sheet:	Get MSDS for this item

Angular Bearing



MSC #: 01377852

Description:	Unground Retainer Type Radial Ball Bearings Inside Diameter: 0.750 In., 3/4 Outside Diameter: 2.000 In., 2 Width: 0.562 In., 9/16 Dynamic Load Capacity: 672 Style: Plain
Inside Diameter (Decimal Inch):	.7500"
Inside Diameter (Inch):	3/4
Outside Diameter (Decimal Inch):	2.0000"
Outside Diameter (Inch):	2
Width (Inch):	9/16
Width (Decimal Inch):	.5620"
Dynamic Load Capacity (Pounds):	672
Style:	Plain
Maximum RPM:	2500
Big Book Page #:	3695

Manufacturing Overview for Test Set-up

The track, car and insulated box must all be fabricated for the test set-up. The track requires two sub-components: the tracking and the base. The car is made up of six wheels, six axles and a support. The box is made of Styrofoam and Plexiglas.

As outlined in Table I.1 below, all wood, Styrofoam and Plexiglas will be cut to size using a hack saw. The 2x4s used for the actual track will have ¼" holes drilled for dowel rods. The metal axles will require a band saw for cutting. The support for the car will need ¼" holes drilled for the axles.

Table K.4: Manufacturing Plan for Test Set-up

Component	Tools
2x4 Wood	Hack Saw, Clamp Drill Press, 1/4" drill, Clamp
Screw	Power Drill
Plastic Axle	Hack Saw
Wheels	N/A
400W Metal Halide Bulb	N/A
Light Reflector	N/A
Wheels	N/A
Axles, Connector	Band Saw, Clamp
Support	Hack Saw, Clamp Drill Press, ¼" drill, Clamp
Styrofoam	Hack Saw, Clamp
PlexiGlas	Hack Saw, Clamp

Fig. K.15: Dimensions for Base Connector, 2x4

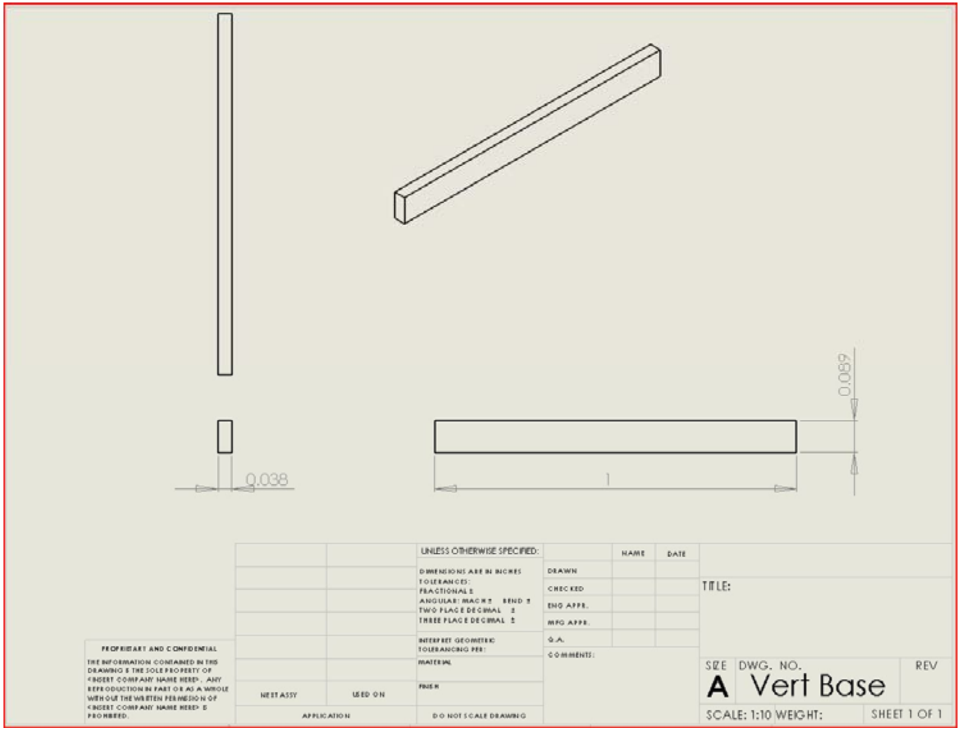


Fig. K.16: Dimensions for Base Support #1, 2x4

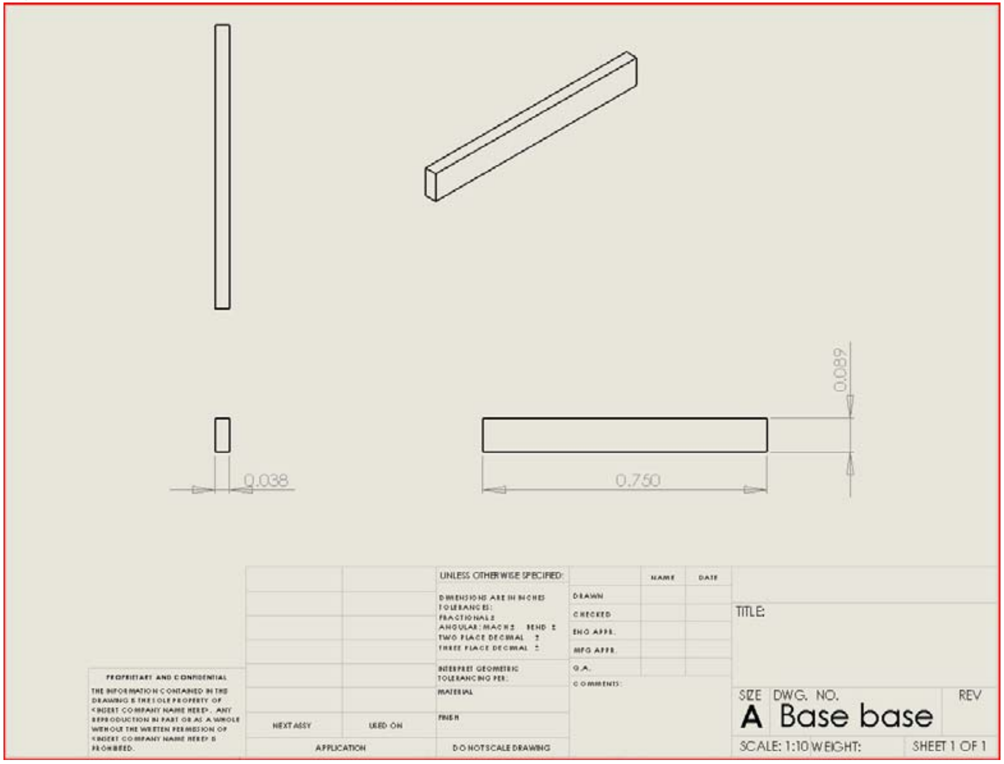


Fig. K.17: Dimensions for Base Support #2, 2x4

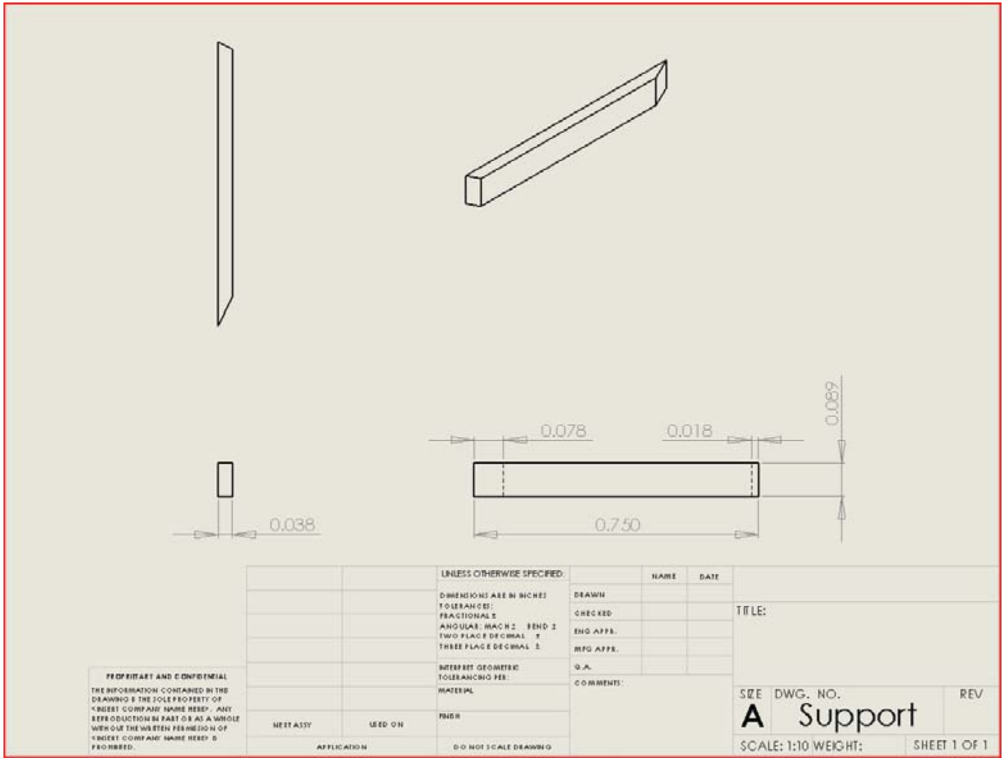


Fig. K.18: Dimensions for Track, 2x4

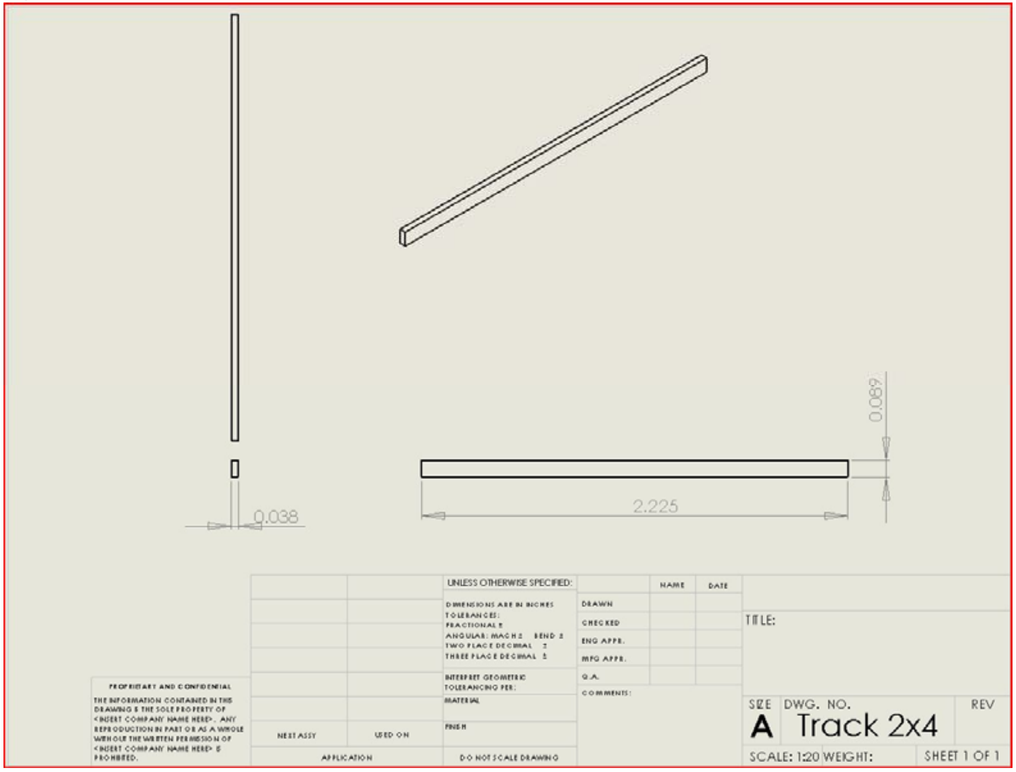


Fig. K.19: Dimensions for Car Support

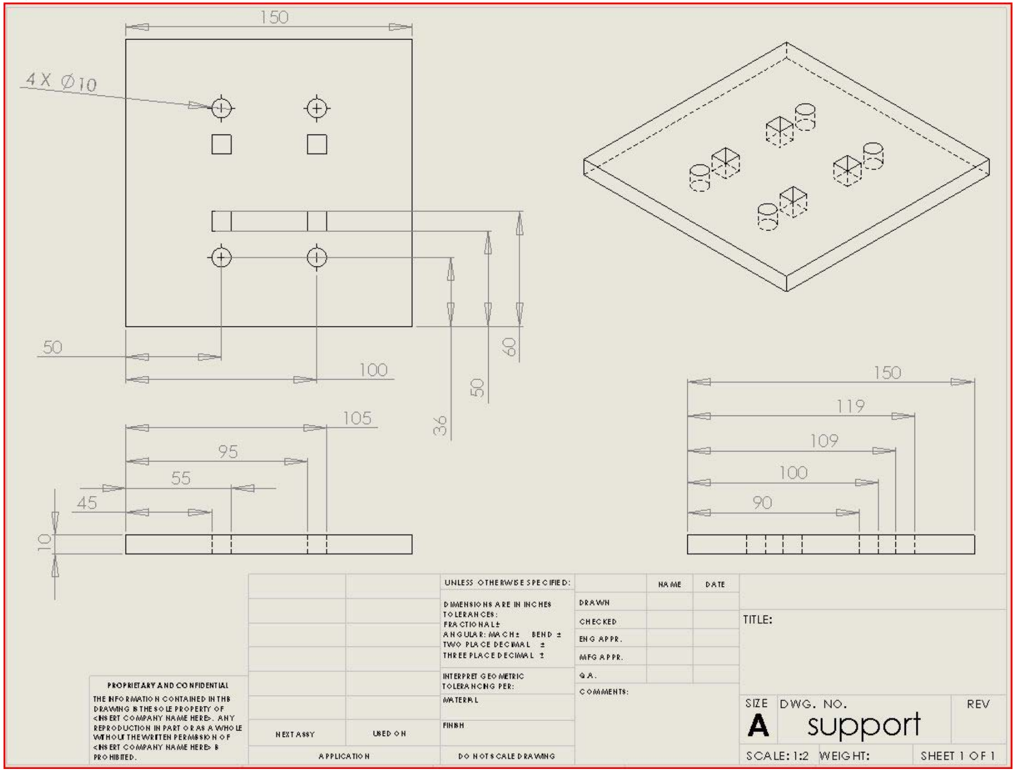


Fig. K.20: Dimensions for Wheel

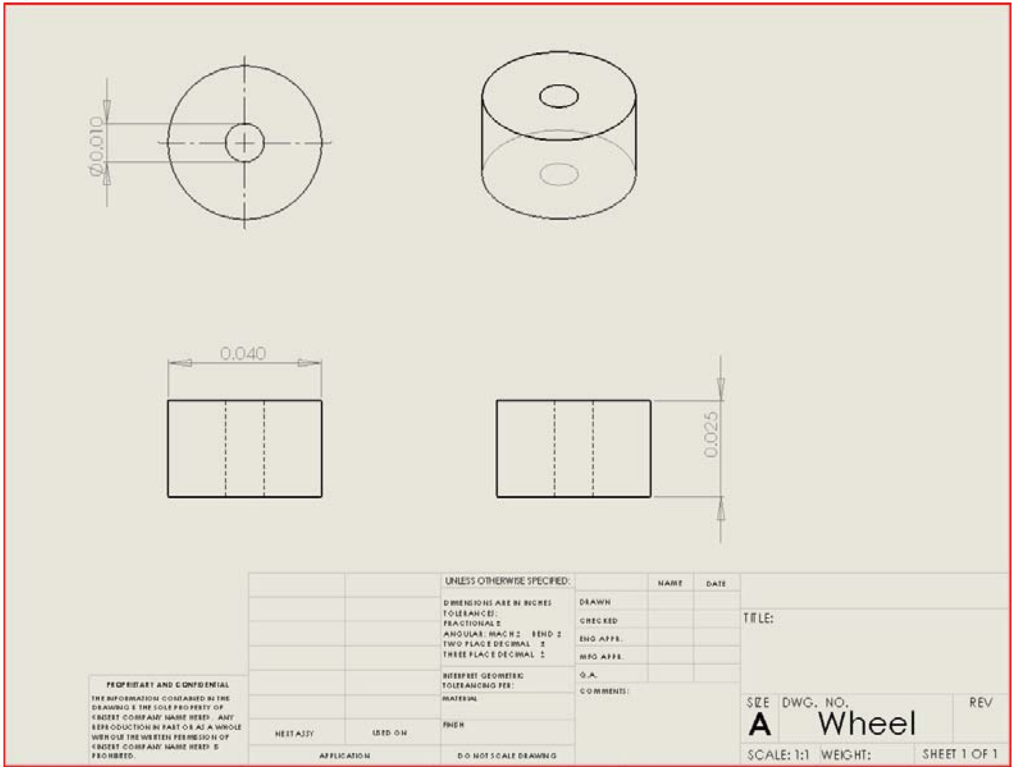


Fig. K.21: Dimensions for Long Axle

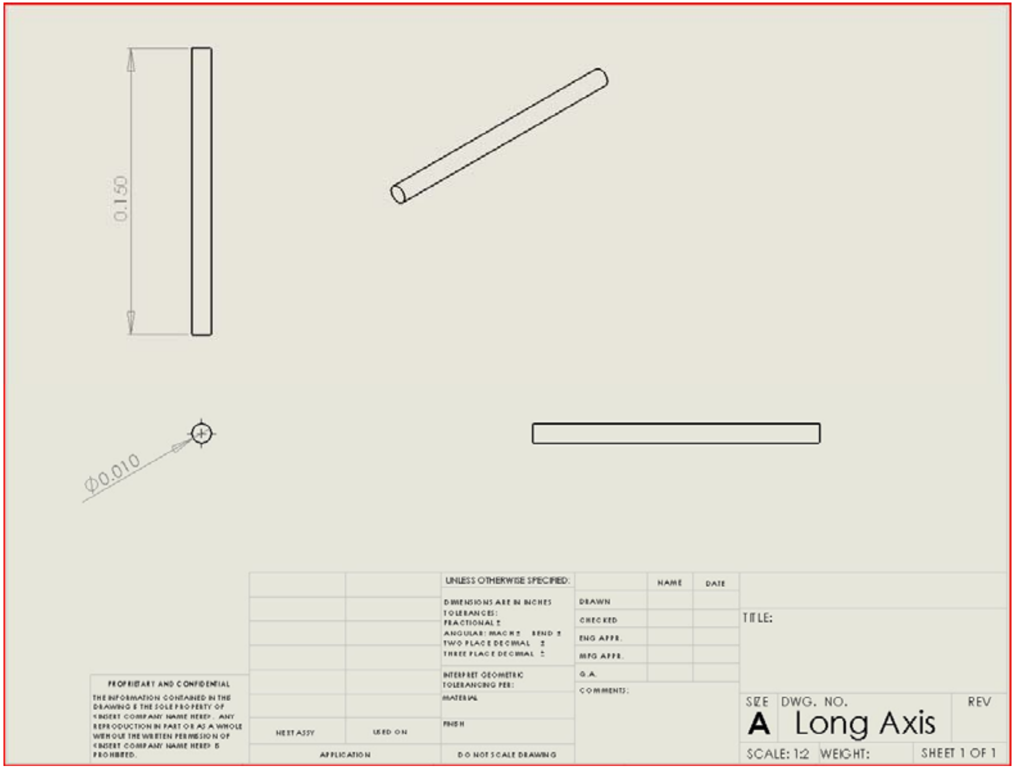


Fig. K.22: Dimensions for Short Axle

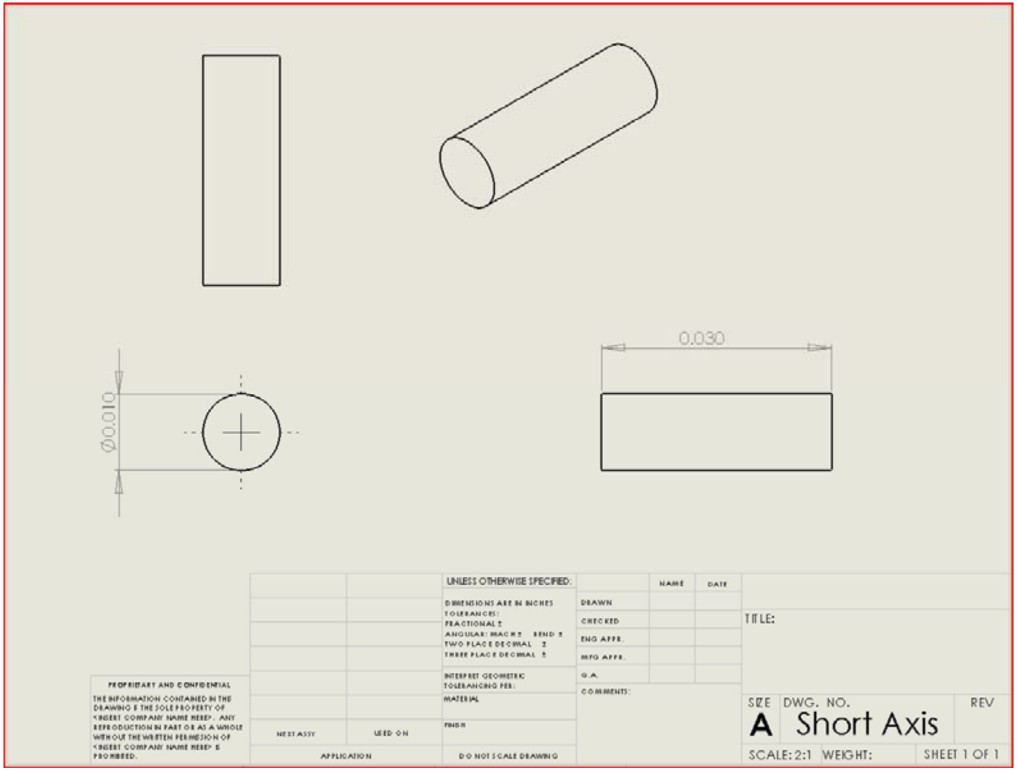


Fig. K.23: Dimensions for Axle / Support Connector

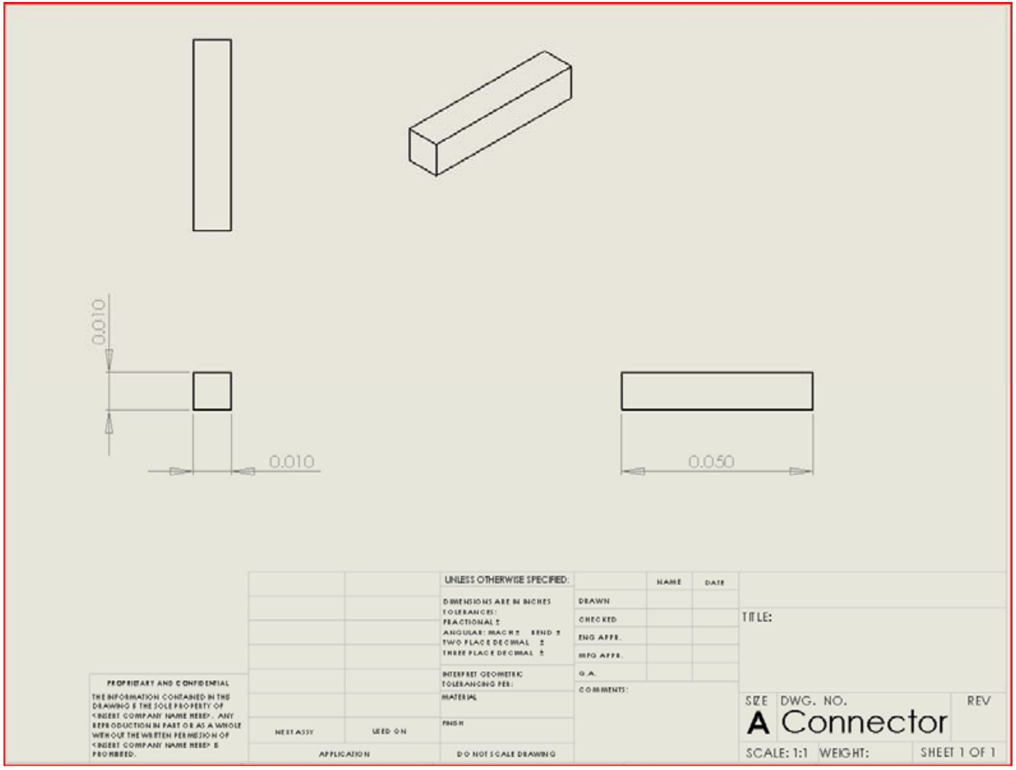


Fig. K.24: Dimensions for Plexiglas Side of Box

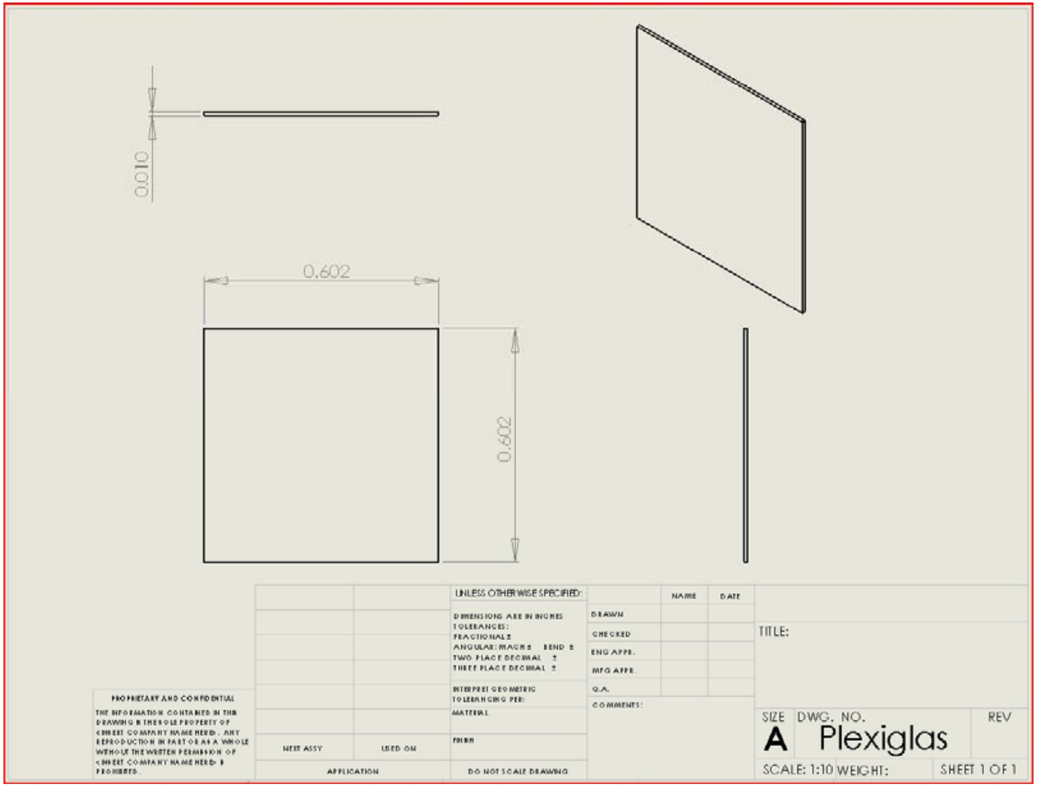


Fig. K.25: Dimensions for Back of Box

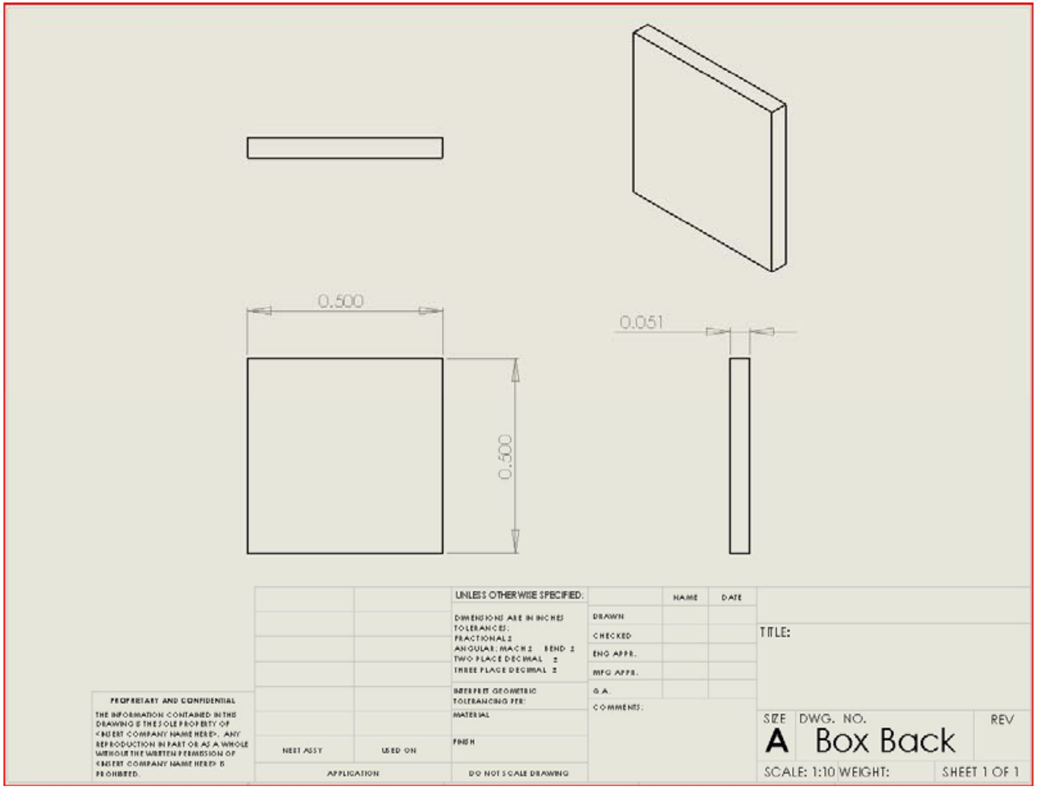


Fig. K.26: Dimensions for Sides of Box

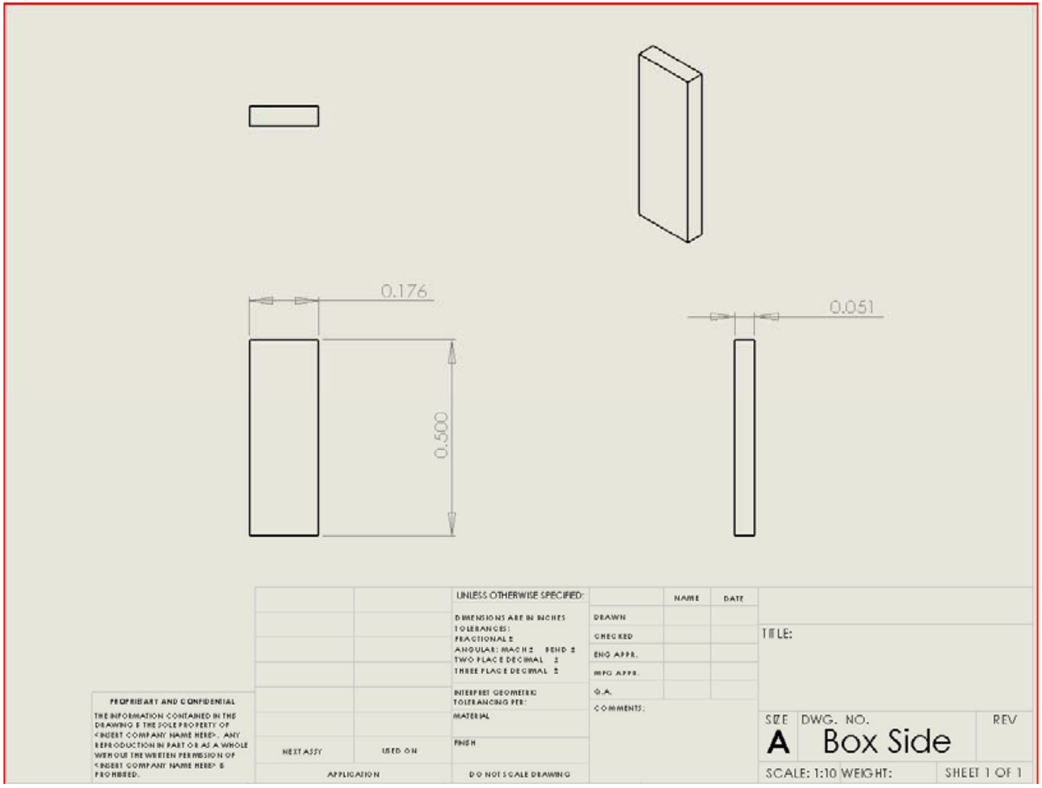
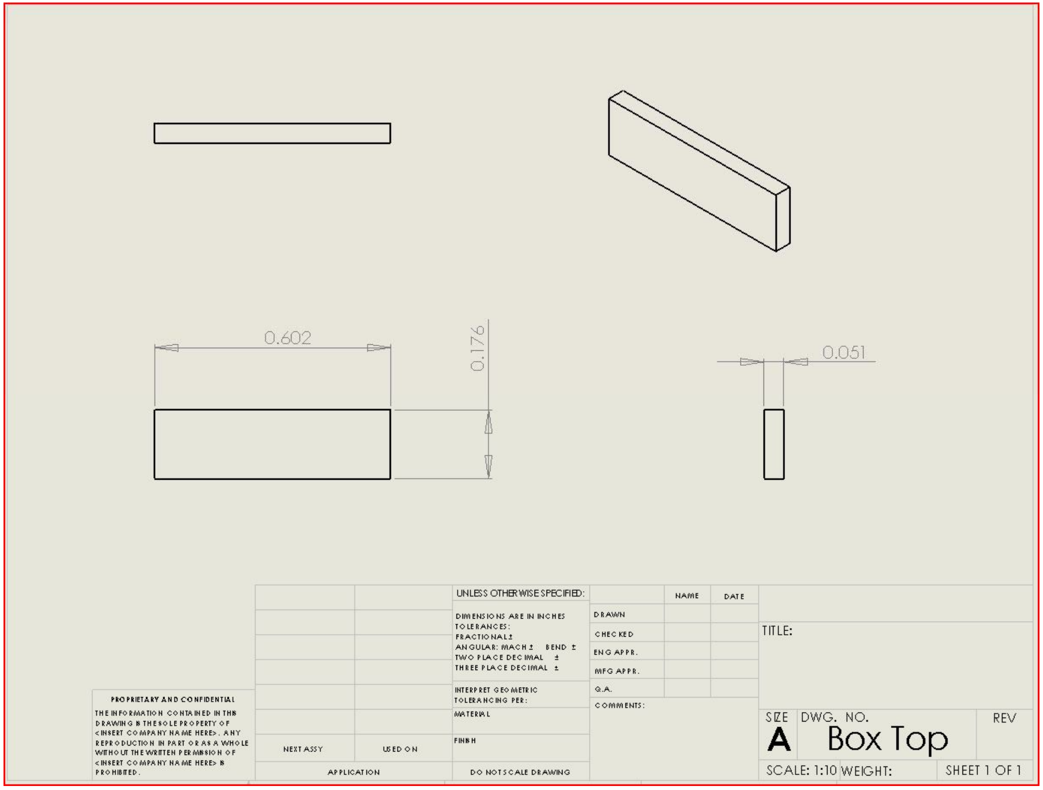


Fig. K.27: Dimensions for Top / Bottom of Box



Appendix L: Assembly Overview

Assembly Overview of Prototype

Base Assembly

Step 1)

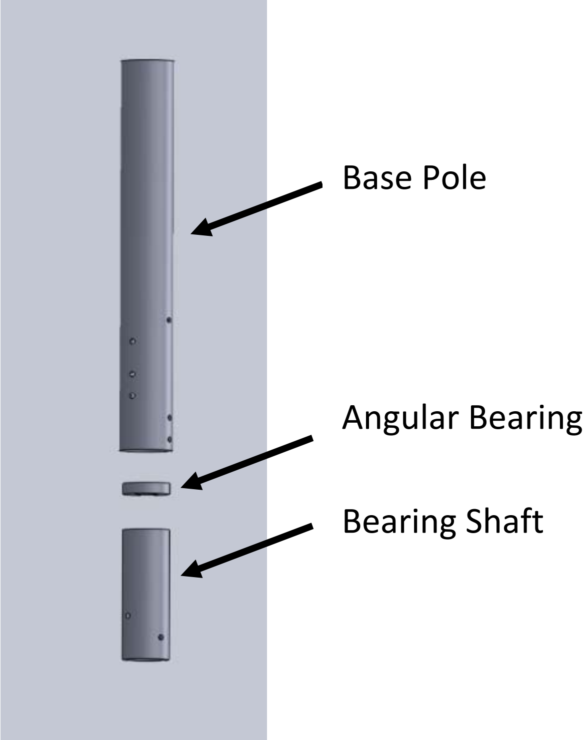
Parts Needed: Base Pole – 1
Angular Bearing – 1
Bearing Shaft – 1

Procedure:

a) Orient the base pole so that the holes are close to the bottom.

b) Align the 3 parts so that the Bearing Shaft and Angular bearing can be inserted into the Base Pole.

c) Insert the Angular Bearing and then the Bearing shaft through the bottom of the Base pole

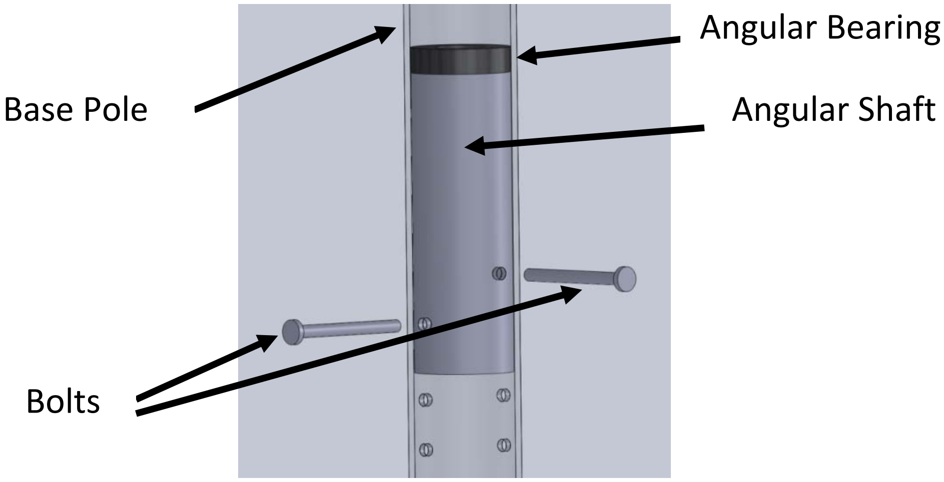


Step 2)

Parts Needed: Bolt #2 – 2
Nut – 2

Procedure:

a) Insert the two bolts into the uppermost holes of the base pole so that they align with the holes in the Bearing Shaft
b) Tighten the nuts

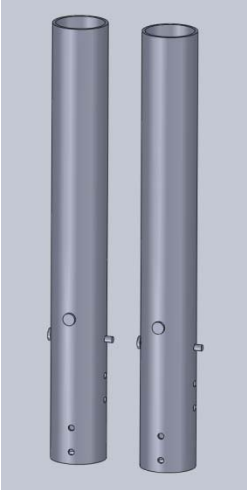


Step 3)

Parts Needed: Base Pole – 1
Angular Bearing – 1
Bearing Shaft – 1
Bolt #2 – 2
Nut – 2

Procedure:

a) Repeat steps 1 and 2 so that there are now two base poles an angular bearing and angular shaft inside

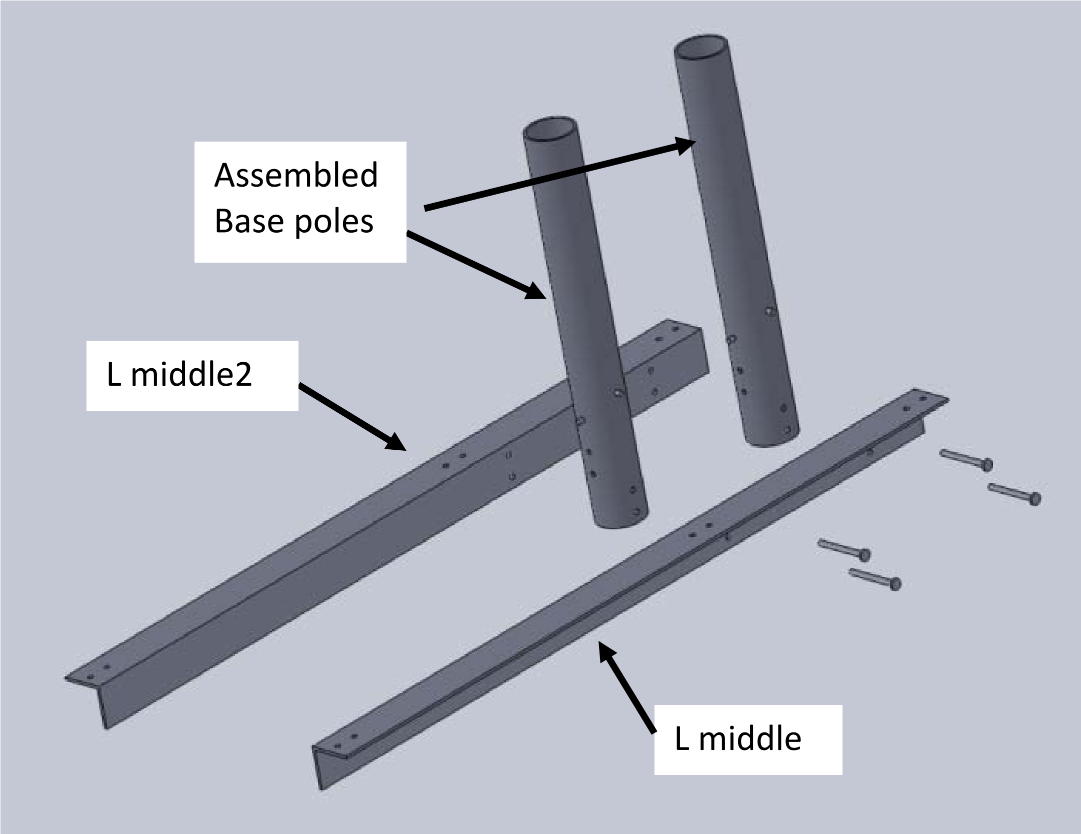


Step 4)

Parts Needed:	L middle – 1
	L middle2 – 1
	Bolt #1 – 4
	Nut - 4

Procedure:

a) Orient the L-beams so that they form an upside down L with the 6 holes facing upward.
b) Align the lowest 2 holes on the base pole with the holes on the face of the L-Beams.
c) Tighten nuts

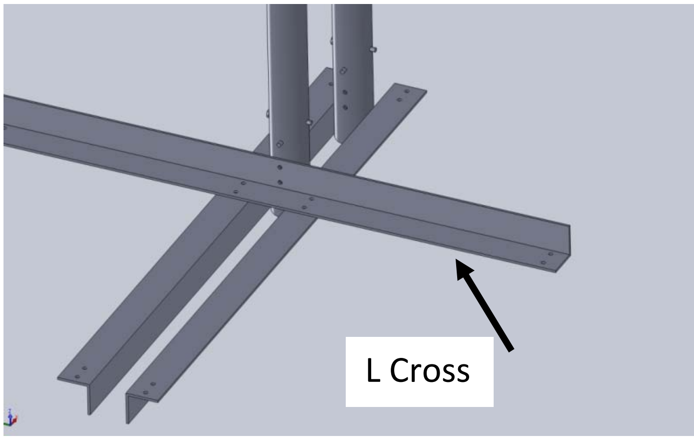


Step 5)

Parts Needed:	L cross – 1 Bolt #3 – 4 Nut - 4

Procedure:

a) Orient the L cross beam so that it forms an L pointing away from the base pole.
b) Align the holes on the L cross beam with the L middle beams and the base pole.
c) Insert bolts and tighten the nuts

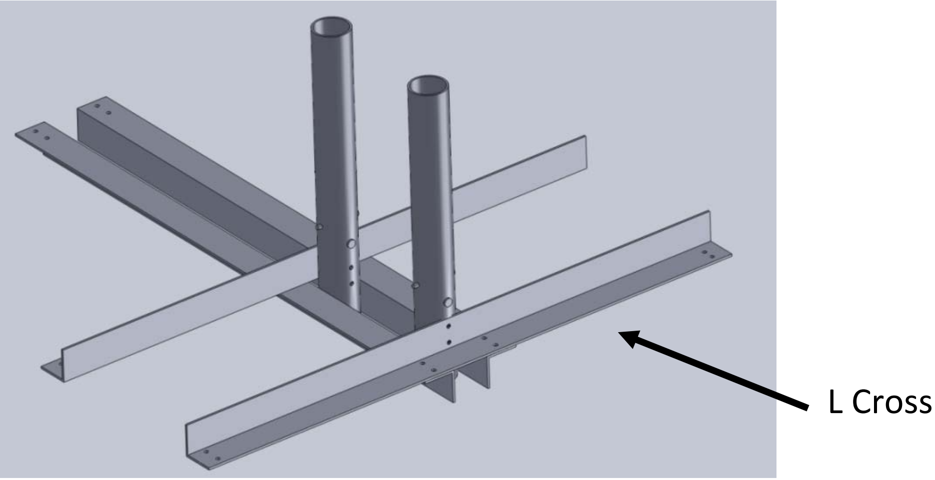


Step 6)

Parts Needed:	L cross – 1 Bolt #3 – 4 Nut - 4

Procedure:

a) Orient the L cross beam so that it forms an L pointing away from the base pole.
b) Align the holes on the L cross beam with the L middle beams and the base pole.
c) Insert bolts and tighten the nuts

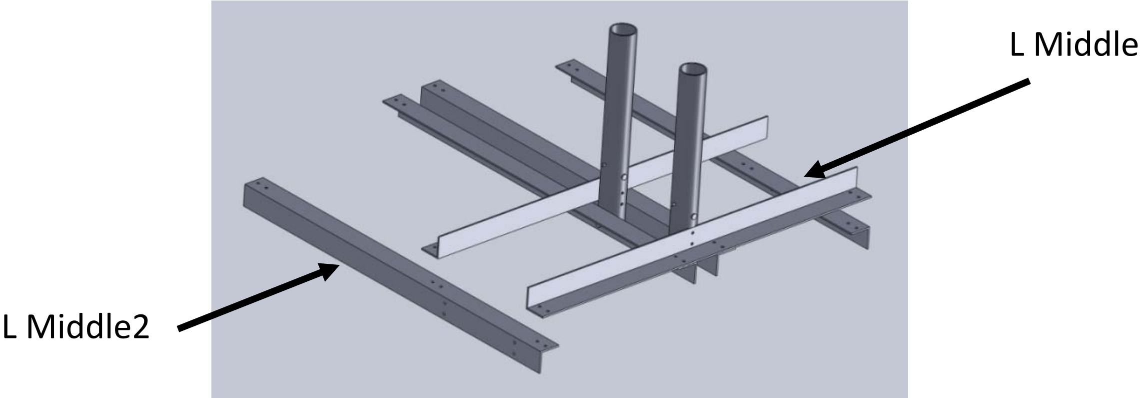


Step 7)

Parts Needed: L middle – 1
L middle2 -1
Bolt #3 – 4
Nut - 4

Procedure:

a) Orient the L middle beams so that they form an upside down L pointing toward the center of the structure
b) Align the holes on the L cross beams with the L middle beams.
c) Insert bolts and tighten the nuts

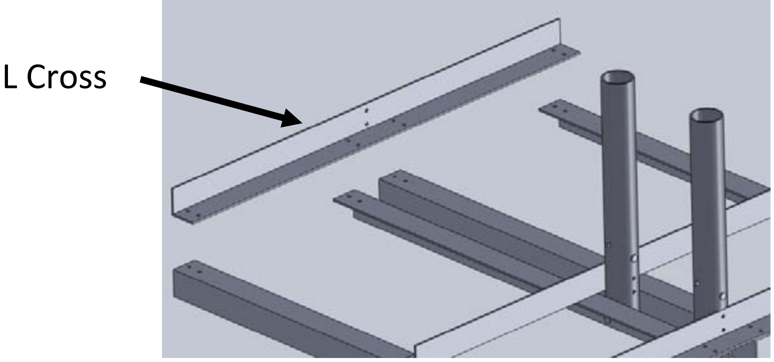


Step 8)

Parts Needed: L Cross – 1
Bolt #3 – 4
Nut - 4

Procedure:

a) Orient the L cross beam so it forms an L pointing toward the center of the structure
b) Align the holes on the L cross beams with the L middle beams.
c) Insert bolts and tighten the nuts

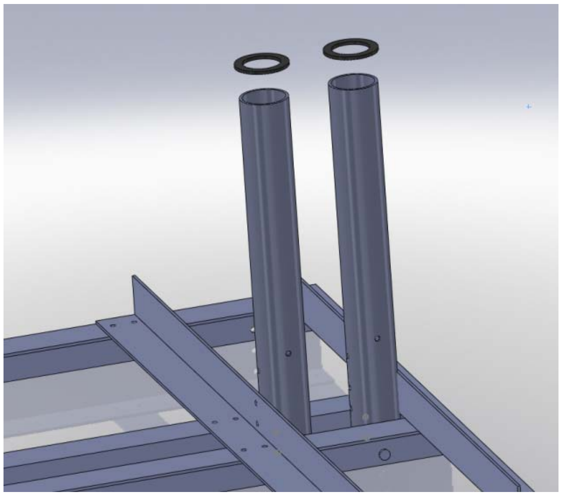


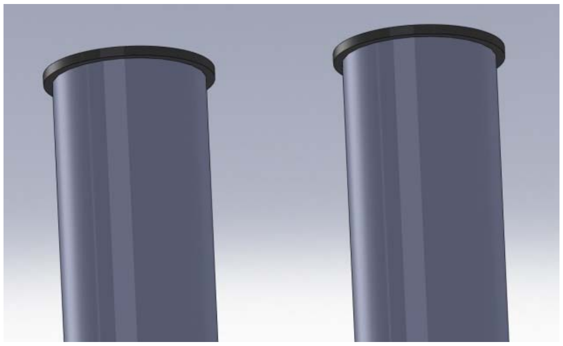
Step 9)

Parts Needed: Thrust Bearing – 2

Procedure:

a) Alight the thrust washers above the base poles
b) Weld along the bottom surface of the washers so that they are attached to the base poles



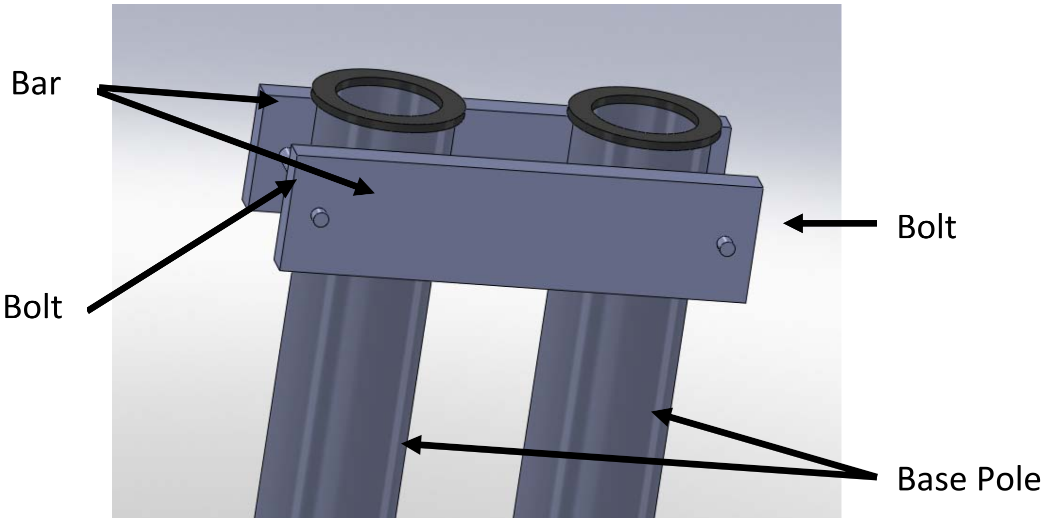


Step 10)

Parts Needed: Bar – 2
Bolt #4 – 2
Nut - 2

Procedure:

a) Position the bars so that they rest against both of the base poles
b) Align the holes and insert two #4 bolts
c) Tighten the nuts until there is a snug fit so that the bars do not slide down the poles.

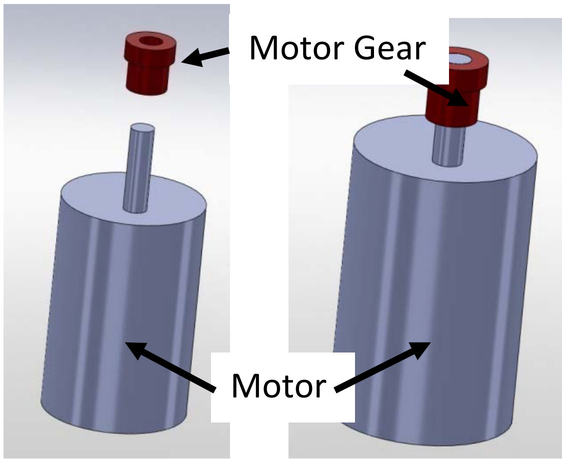


Step 11)

Parts Needed: Motor – 1
Motor gear – 1
Set Screw – 2

Procedure:

a) Align the motor shaft and the motor gear
b) Insert the gear on the shaft until it is flush on the top
c) Tighten set screw into the gear hub

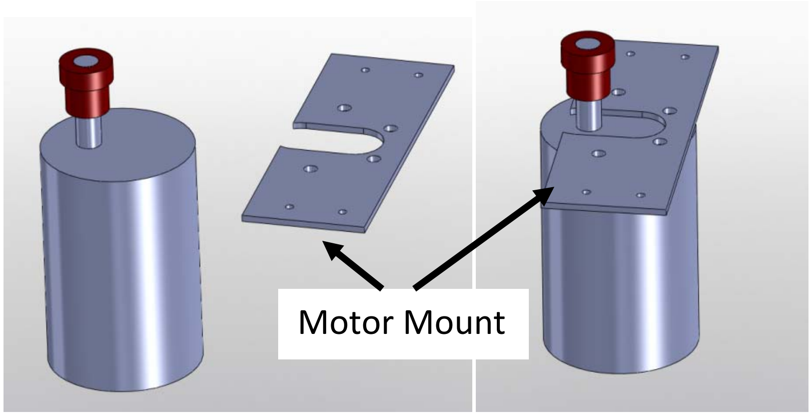


Step 12)

Parts Needed: Motor mount – 2
Motor screws – 4

Procedure:

a) Position the Motor mount so it can slide around the motor shaft
b) Align the holes of on the motor and on the mount.
c) Insert four motor screws (there are taped holes in the motor not shown in the CAD drawling)

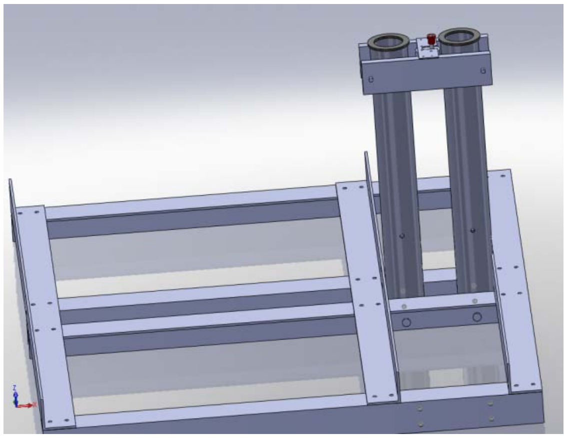


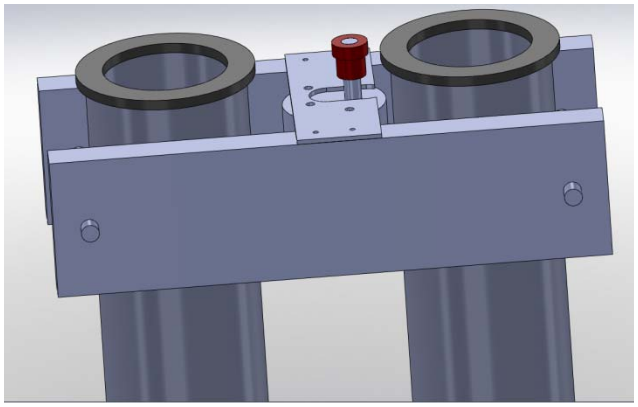
Step 13)

Parts Needed:	Motor mount assembly
	Motor screws – 4

Procedure:

a) Position the Motor mount so it rests on the bars and is flush on each side
b) Align the holes of on the motor mount and on the bars.
c) Insert four motor screws



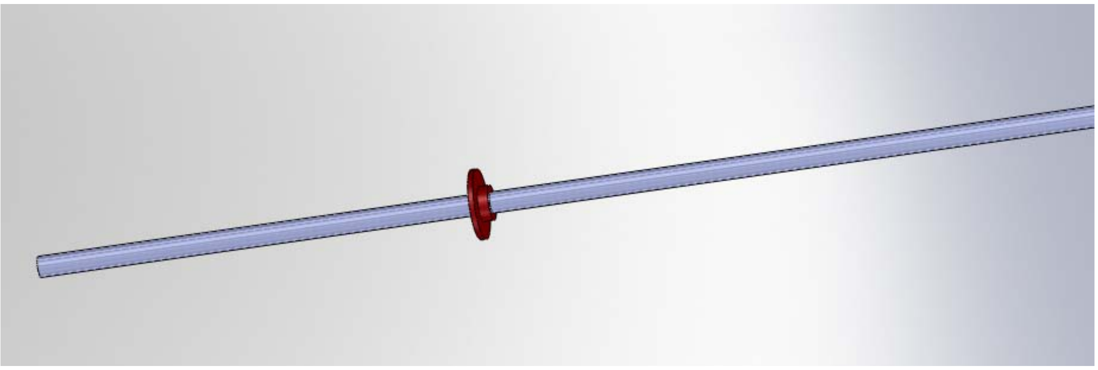


Step 14)

Parts Needed:	Sensor Pole – 1
	Sensor Gear – 1
	Set Screw – 1

Procedure:

a) Slide the sensor gear onto the sensor pole until is is about 300 mm from the end.
b) Insert the set screw into the gear hub

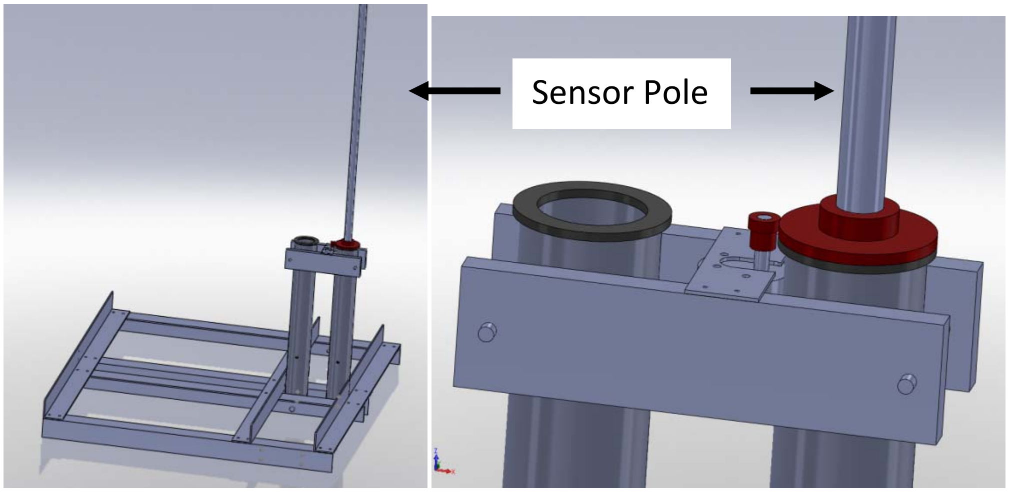


Step 15)

Parts Needed:	Sensor Pole asembly Base assembly

Procedure:

a) Slide the sensor pole into the rear Base pole until the gear rests on the thrust bearing
b) Make sure the sensor gear has ligned up with the motor gear



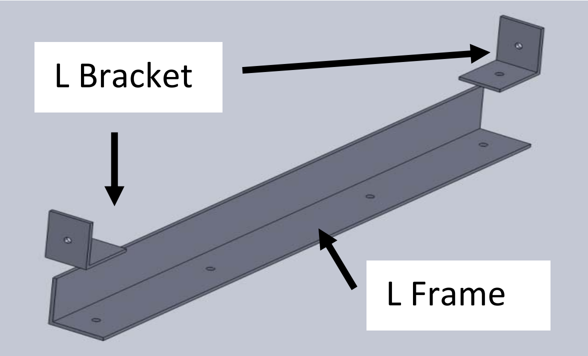
Reflector Assembly

Step 1)

Parts Needed:	L Bracket – 4 L Frame – 2 Bolt #3 – 4 Nut – 4

Procedure:

a) Align the L bracket holes with the outside holes on the L-Frame so that the L Bracket makes the shape on an L pointed twoard the interior.
b) Insert 2 bolts and tighten the nuts
c) Repeat steps a and b on second L Frame part

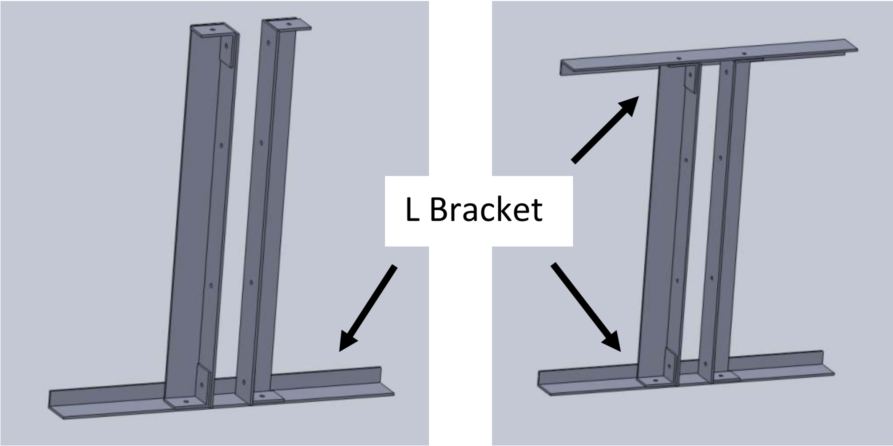


Step 2)

Parts Needed:	L Short – 2 Bolt #3 – 4 Nut – 4

Procedure:

a) Align the L Short beams so that the short side is parallel with the face of the L frame that does not have any holes. Have the L frame beams make the L shape twoard the outside of the assembly
b) Insert 2 bolts and tighten the nuts
c) Repeat with second L shot beam on the opposite end of the L frame

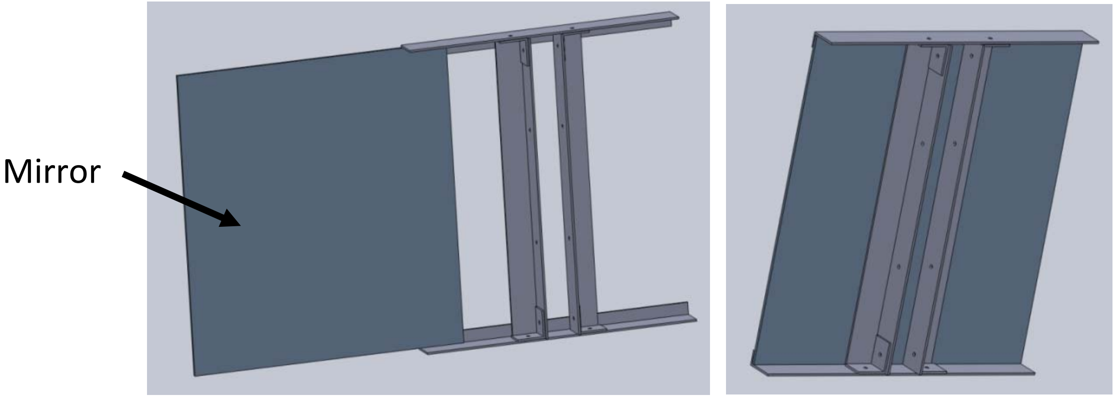


Step 3)

Parts Needed:	Mirror – 1

Procedure:

a) Align the mirror so that the reflective side faces the away from the assembly and is parallel to the L frame beams.
b) Insert the mirror along the L short beams until it is flush on each side



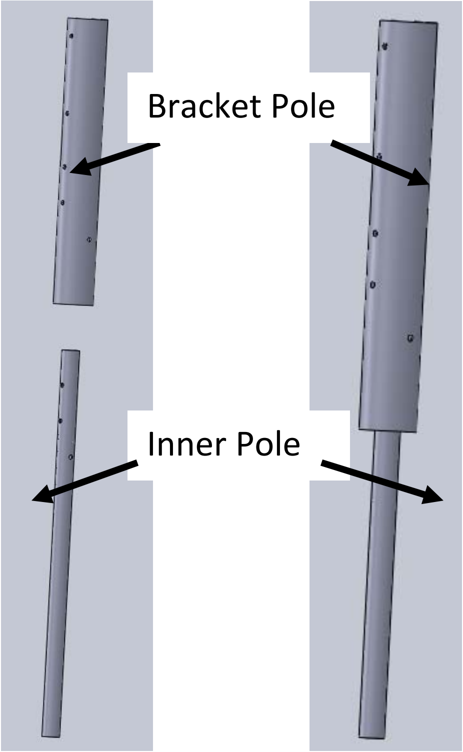
Bracket Assembly

Step 1)

Parts Needed:
Bracket Pole – 1
Inner Pole – 1
Bolt #1 – 3
Nut – 3

Procedure:

a) Align the Inner pole and the braket pole so that the inner pole can be inseted.
b) Insert 3 bolts into the 3 lowest holes of the braket pole and tighten the nuts.

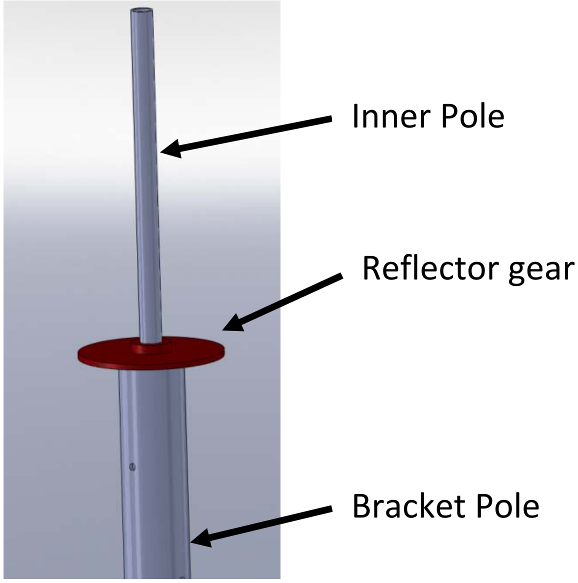


Step 2)

Parts Needed: Reflector Gear – 1
Set Screw – 1

Procedure:

a) Align the Inner pole and the reflector gear.
b) Insert the sensor pole and lower the gear until it rests on the rim of the bracket pole.
c) Insert the set screw into the gear hub

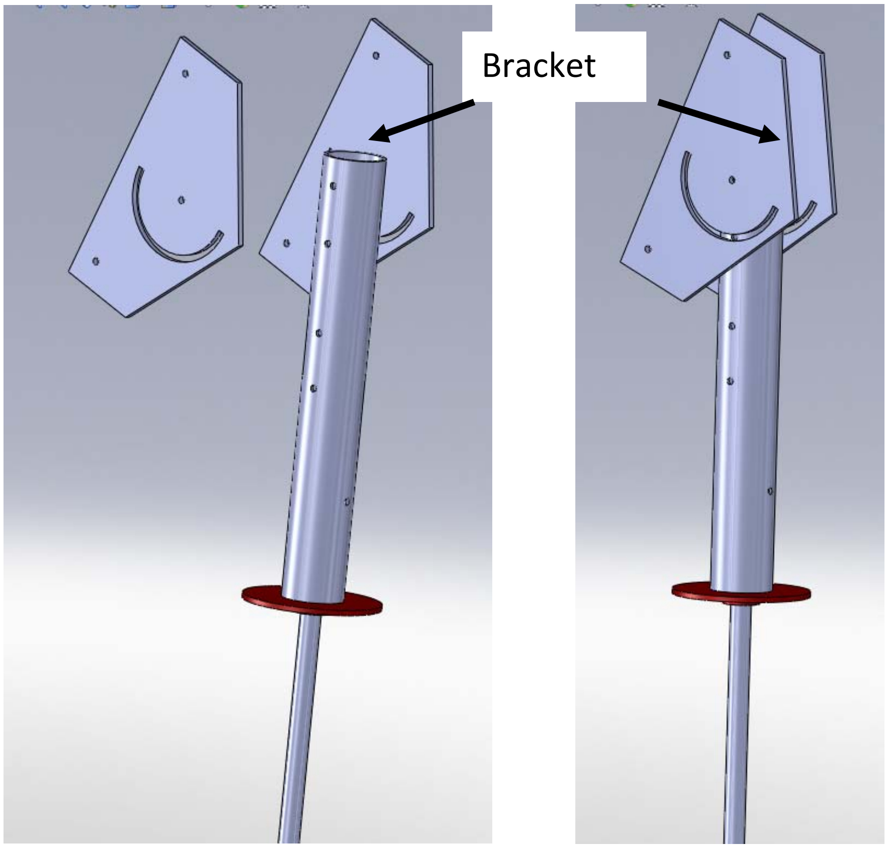


Step 3)

Parts Needed: Braket – 2
Bolt # 4 – 2
Nut – 2

Procedure:

a) Align middle hole on the bracket with the top hole on the braket pole.
b) Insert a bolt through both brackets and the braket pole.
c) Insert the second bolt through the semi-circle slots and the hole second from the top on the bracket pole



Final Assembly

Step 1)

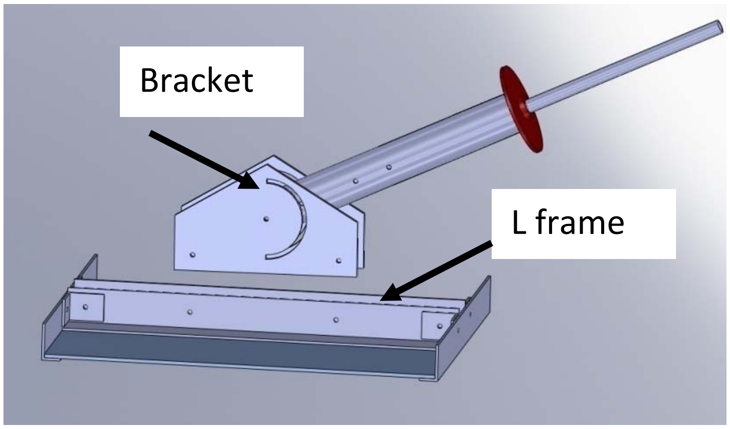
Parts Needed:	Braket Assembly
	Reflector Assembly
	Bolt # 3 – 4
	Nut – 4

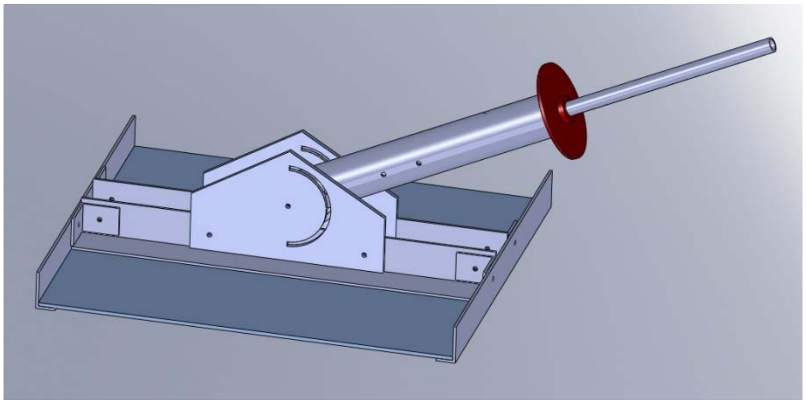
Procedure:

a) Align the holes on the braket with the holes on the L frame beams. The L frame beams should be inside of the bracket.

b) Insert bolts the brackets and the frame

c) Tighten nuts



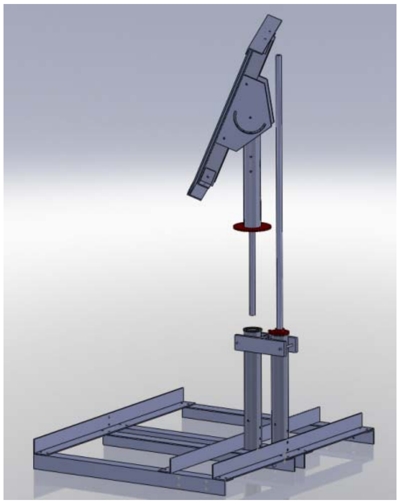


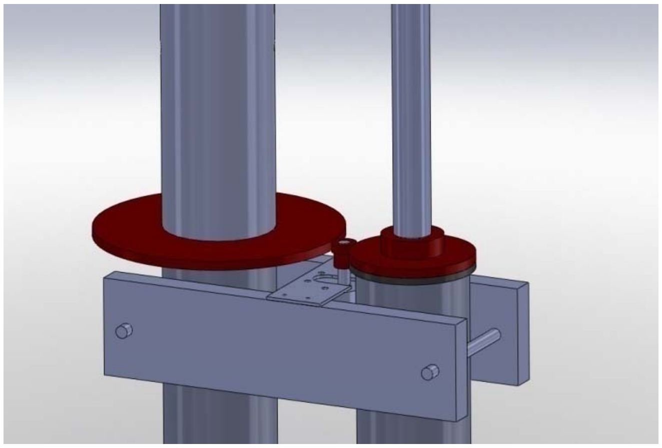
Step 2)

Parts Needed:	Braket Assembly Reflector Assembly Bolt # 3 – 4 Nut – 4

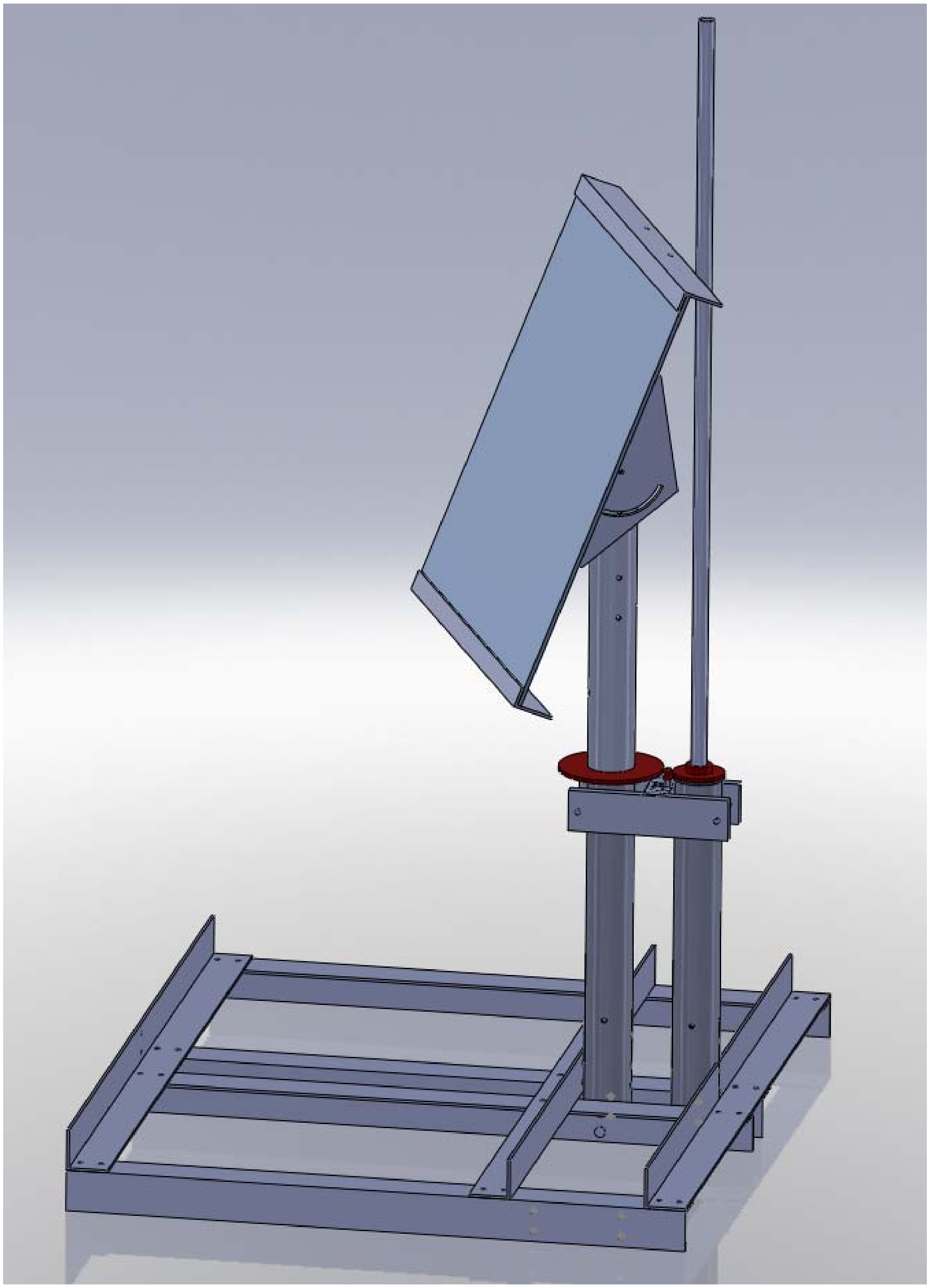
Procedure:

a) Align the inner pole on the bracket assembly with the front base pole.
b) Insert the the inner pole until the reflector gear rests on the thrust bearing.
c) Make sure that the gears are aligned.





Final Assembly



Assembly Overview for Test Set-up

The track assembly will be constructed separately from the car since they are separate entities. The following outlines the methods used to assemble the track, the car, and the insulated box.

Procedure (See Figures L.1 –L.12 below for visual direction):

1) Create Track
    a. Create Base
        i. Screw Base Connector into Base Support #1
        ii. Screw (2) Base Support #2s into the Base Connector and Base Support
        iii. Repeat until 9 Bases have been created
    b. Create Tracking above Base
        i. Screw Track into the top of a Base Connector at center of Track
        ii. Repeat until 7 track parts have been created
        iii. Screw each part together at an angle of 154.28 degrees
        iv. Screw a Base to each end of the Track
2) Create Car
    a. Attach (6) Wheels onto the (4) Long Axles and (2) Short Axles
    b. Attach the (4) Connectors to the (2) Short Axles
    c. Attach the (4) Connectors and (4) Long Axles to the Support
3) Create Box
    a. Attach the (2) Sides of Box to the Bottom of Box with epoxy
    b. Attach the Back of Box to the Bottom of Box and Sides of Box using epoxy
    c. Attach the Top of Box to the Sides of Box and Back of Box using epoxy
    d. Attach the Plexiglas to the assembly using epoxy

Fig. L.1: Step 1a

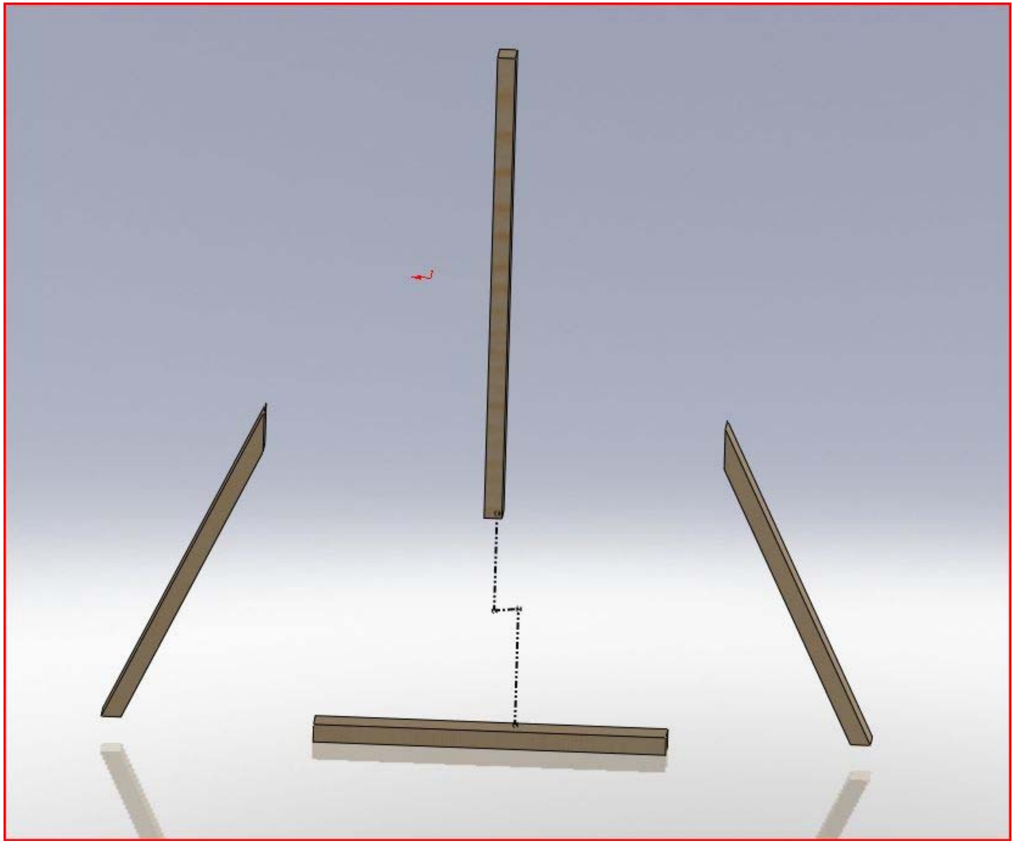


Fig. L.2: Step 1b

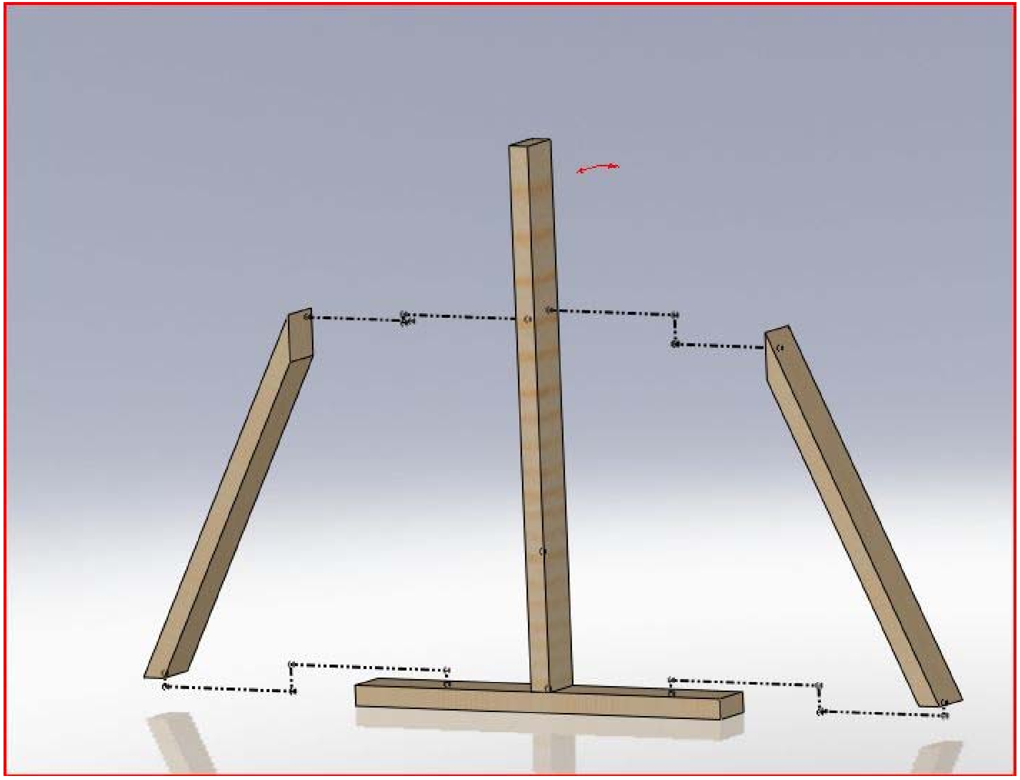


Fig. L.3: Step 2a

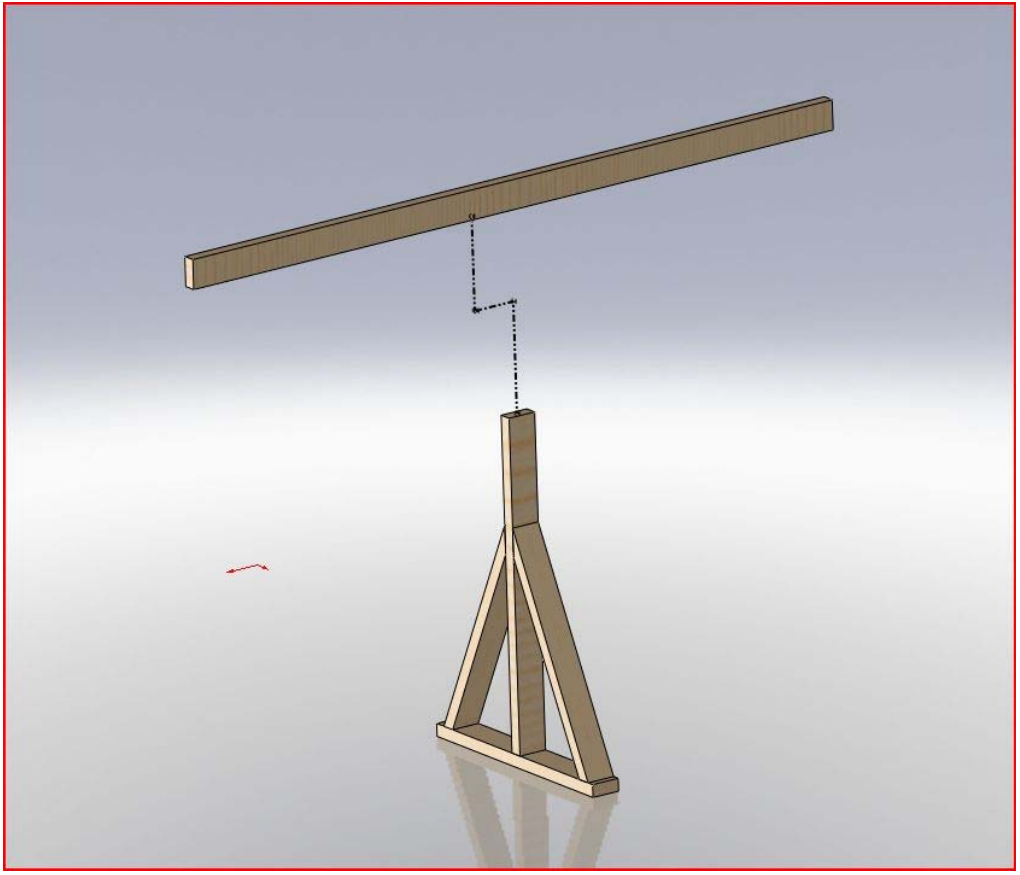


Fig. L.4: Step 2c

Fig. L.5: Step 2d

Fig. L.6: Step 3a

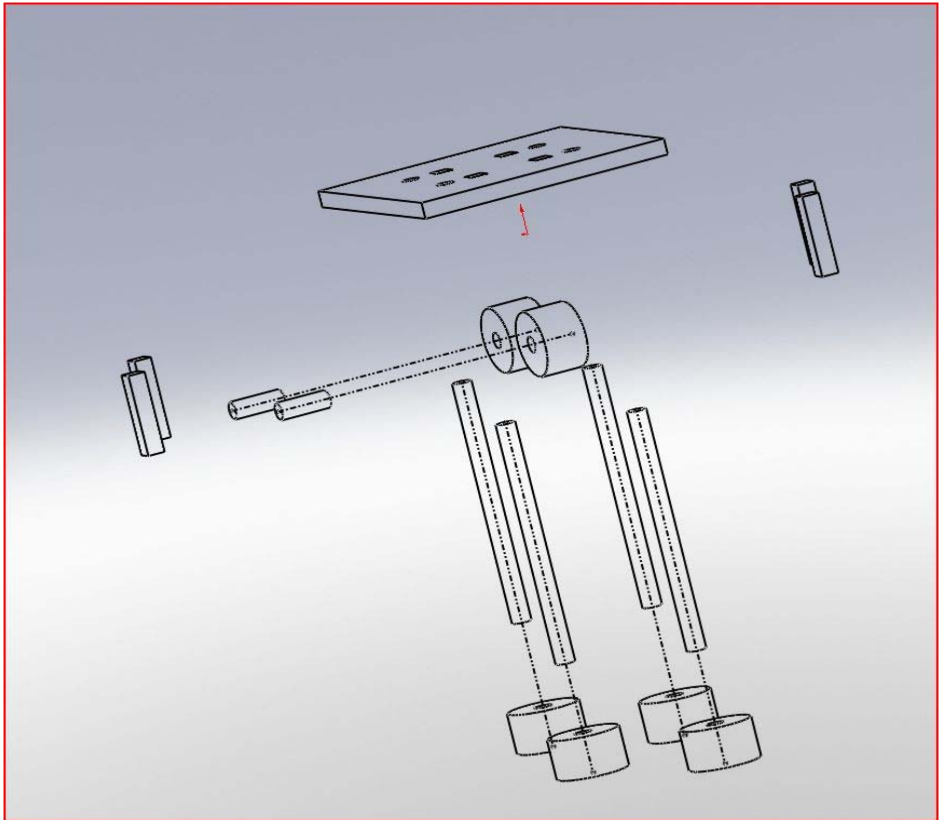


Fig. L.7: Step 3b

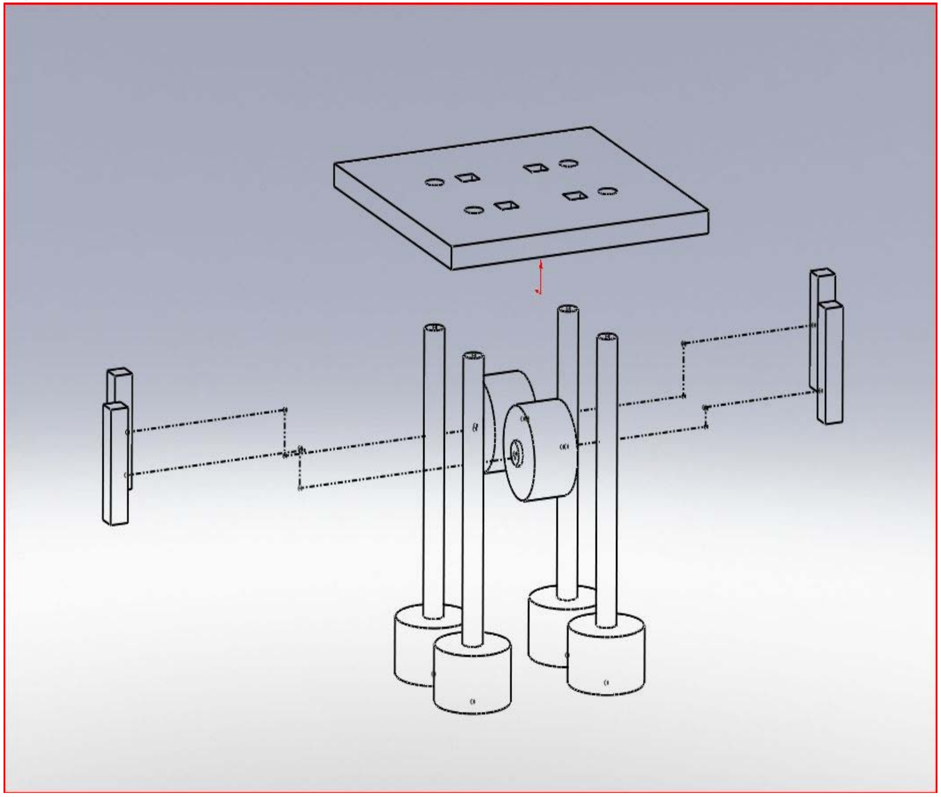


Fig. L.8: Step 3c

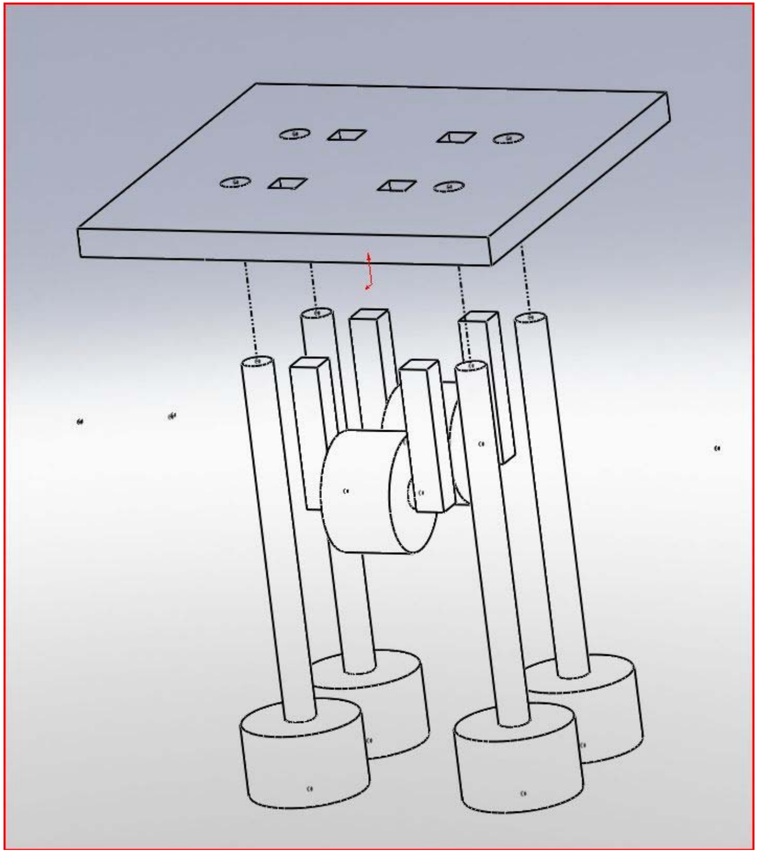


Fig. L.9: Step 4a

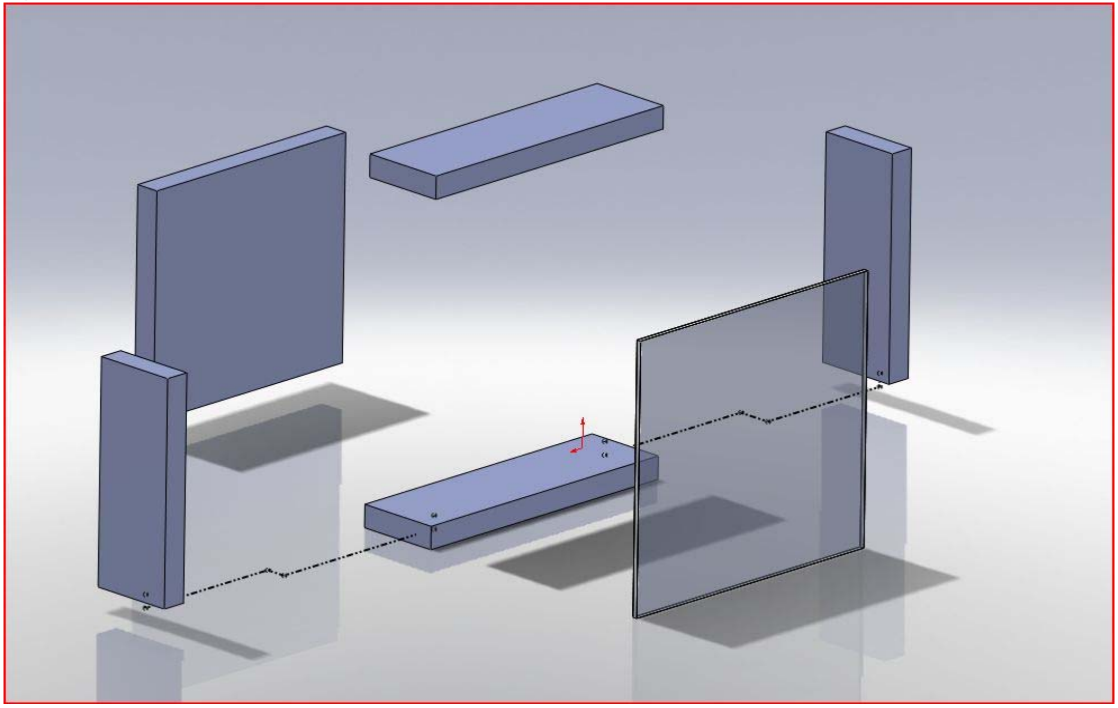


Fig. L.10: Step 4b

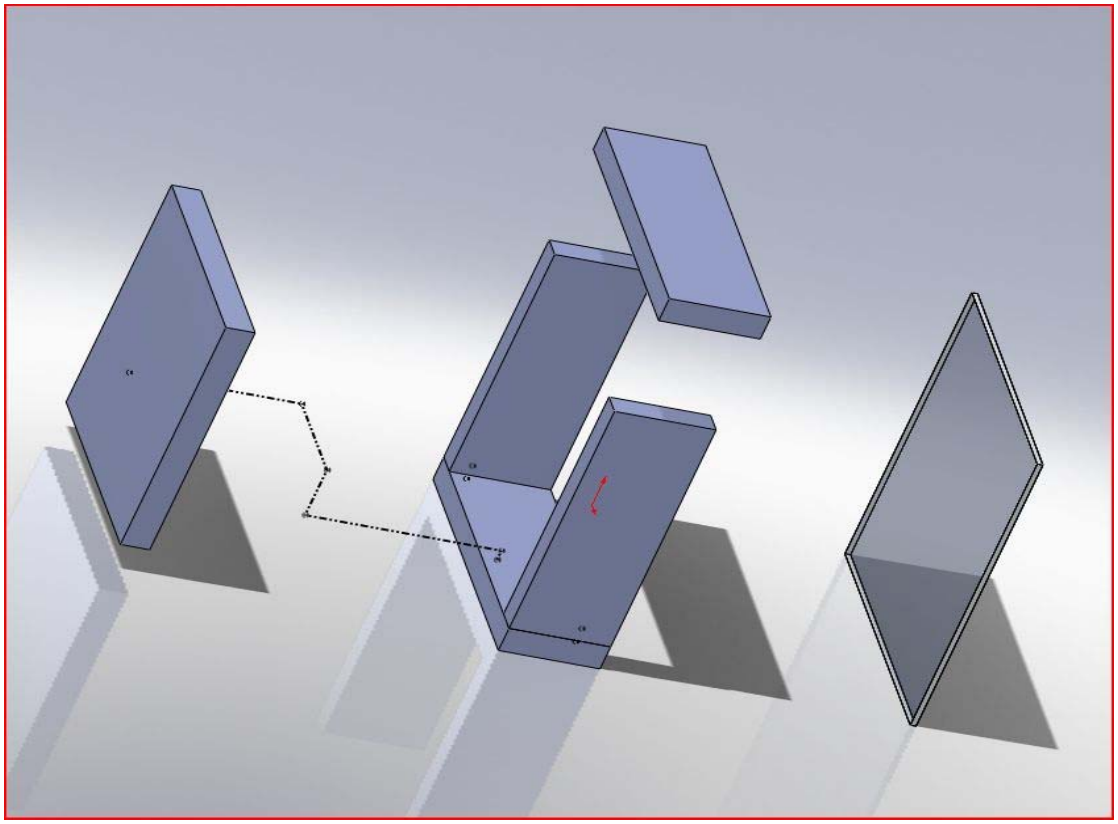


Fig. L.11: Step 4c

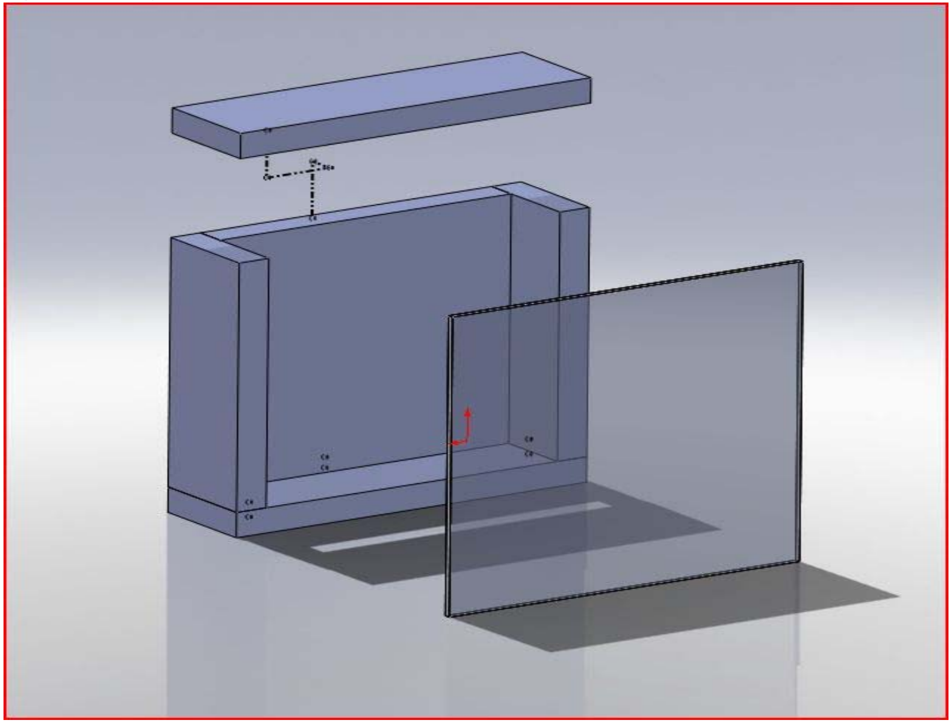
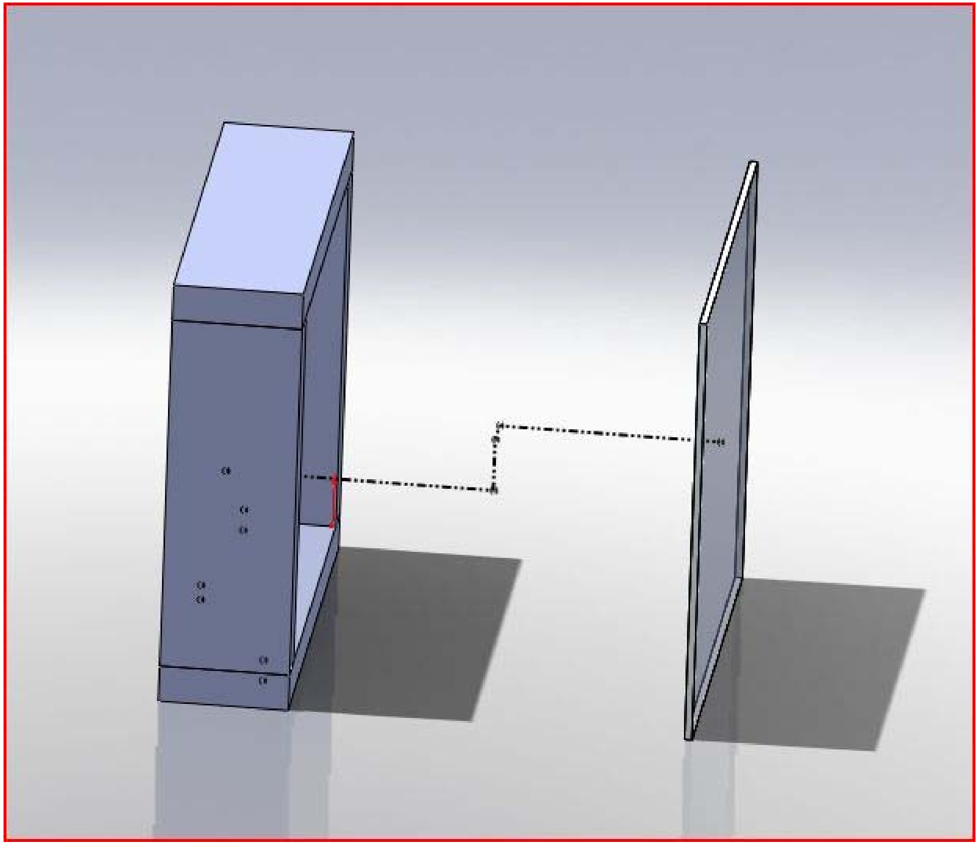


Fig. L.12: Step 4d



Appendix M: Final Design Drawings.

These are components that will be on the final Design but were not made for the prototype.

Fig. M.1: Final Sensor Pole

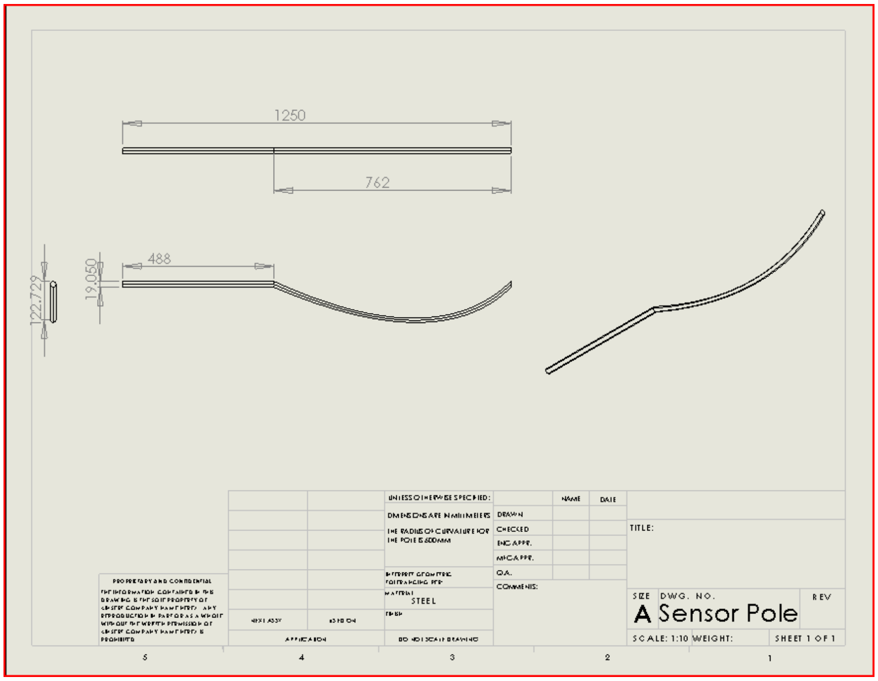


Fig. M.2: Final Reflector Backing

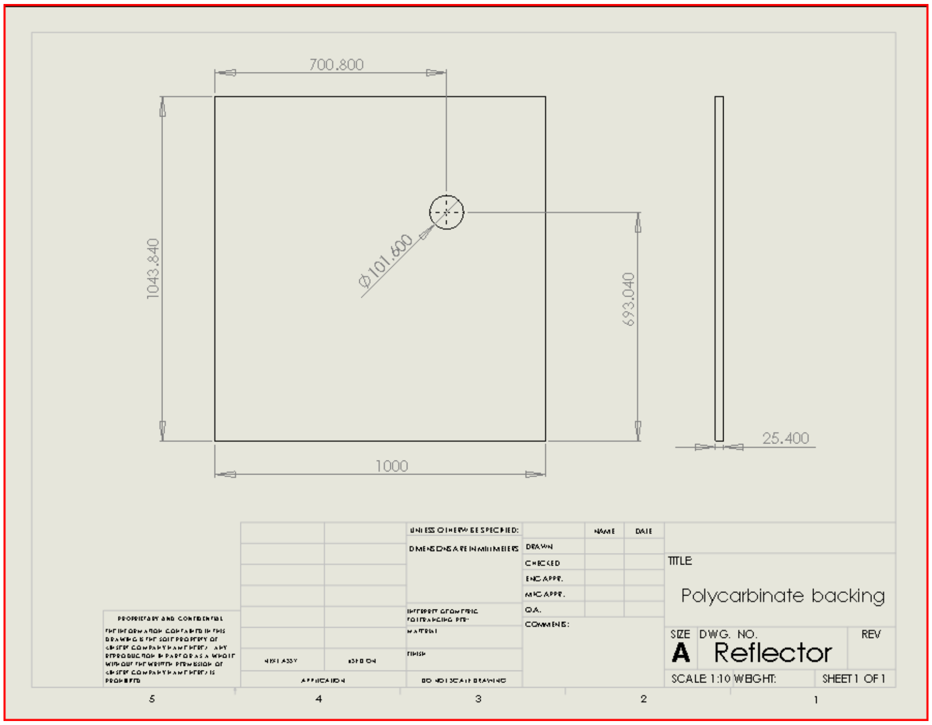


Fig. M.3: Gear Case Top

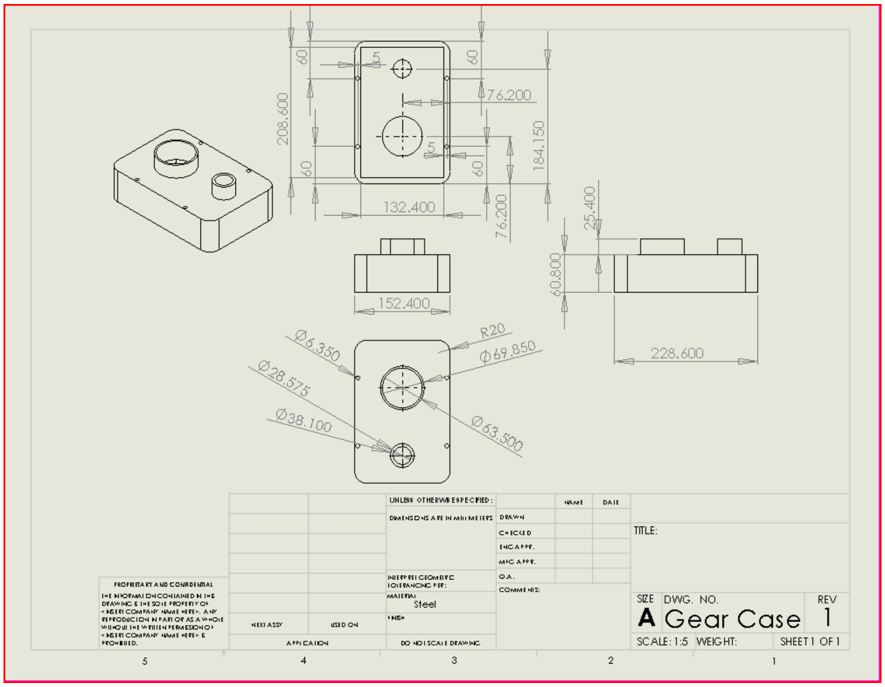
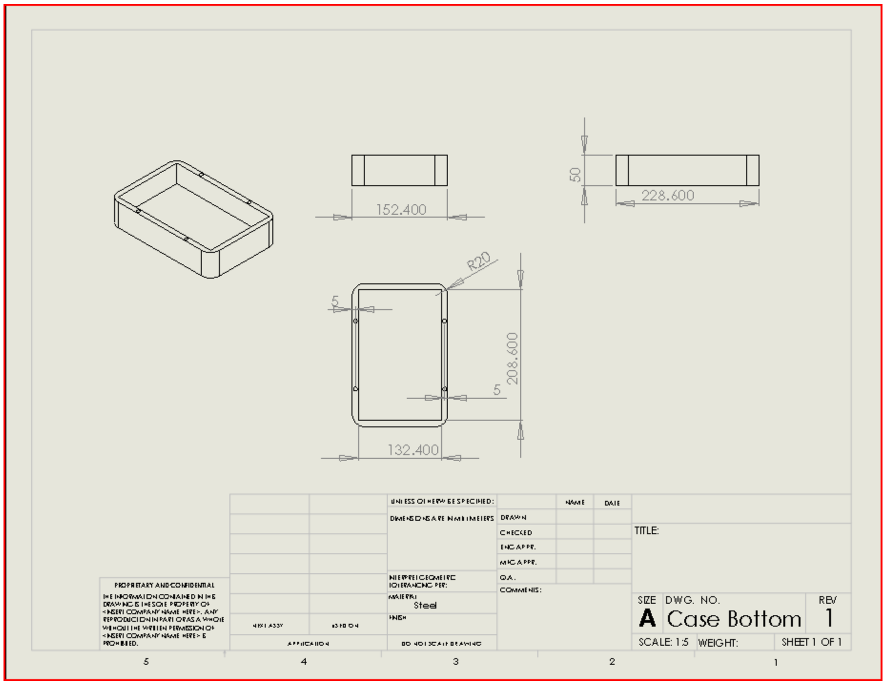


Fig. M.4: Gear Case Bottom



Bios

Cathryn Fageros was born in Houston, TX, lived several years in the Tampa, FL, moved again to Ann Arbor, MI, and currently resides in the quaint village of Manchester, MI with her family and several dogs. She enjoys creative tinkering, strenuous workouts, and long walks on the beach. She dislikes grubs, goose bumps, and over frosted cupcakes. Cathryn is studying musicology as her sequence, and has a profound appreciation for music and its ability to inspire the masses (pictured at left at the Detroit Electronic Music Festival (D.E.M.F)). From a young age Cathryn was interested in sustainable design, building her first solar oven at age 9. When she arrived at the University of Michigan, she became a member of the women's rowing team and naturally made the decision to major in Mechanical Engineering to pursue her love of designing and building things. Cathryn currently works weekends at the Blue Leprechaun on South University and is having loads of fun studying the behavioral and social interactions of intoxicated persons.

My name is **Justin Hummel** and I'm a farm boy from the small town of Imlay City, MI. I grew up Bailing hay and driving tractors so it's only fitting that this summer I start my career with John Deere. I will be part of their engineering development program where I will rotate through 3 different jobs for six months each before I am permanently placed. My love for building and designing sweet lego creations and tree forts during my childhood pointed me in the direction of mechanical engineering. By shear fate I landed here at the University of Michigan rather than CMU where all my high school friends ended up. I've attempted to make the most of my college experience and it has led me to a six week engineering program in Germany last summer where I studied at the technical university of Berlin. Another huge part of my college experience has been my commitment to the Pi Kappa Phi Fraternity where I served on the Executive Council as the Risk manager and now currently I fill a more demanding role as the president. I'm also obsessed with sports so I participate in Intramural volleyball, softball, soccer, flag football, track, wrestling, inter-tube water polo, broomball, and the swim meet. That's me in a nut shell. I also work nights as the Flash as shown in my picture

Christopher Bence was born in southeast Michigan. He has lived in a couple southeast Michigan cities including Grosse Pointe and Farmington Hills before coming to Ann Arbor. He is a big fan of most sports including, unfortunately, the infamous Detroit Lions. His interests in renewable energy and sustainability led him to this specific project, and he is currently pursuing an Energy Concentration with the University of Michigan.

My name is **Paul Smith** and I hail from Rochester Hills, Michigan. I was born out east in New Haven, Connecticut and have moved around a bit in my life but have been in Michigan a majority of my life, enough to call it my home. I developed an interest in mechanical engineering through my father and grandfather, both having a strong interest in the auto industry with my grandfather working for various companies his whole life. This fascination with building things and being hands on caused me to strive to be a mechanical engineer, and the University of Michigan seemed like the perfect place to start after high school. I also have an interest in German and I am pursuing a minor in German studies, which I hope will one day allow me the opportunity to travel to Germany whether it is on my own or with a company I work for. I will be graduating in April and hope to begin a career soon thereafter. I also have a very deep interest in music and love to play guitar in my free time, which does not come very often as a ME student. I have a life-long dream of one day performing in front of millions of people, whether it is on the music stage with a band or giving a demonstration of a new device or product I helped to create.