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Investigating Potential Improvements to Enhance the Performance of a Solar Thermal Collection System: Design of the Dual Axis Tracking System

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INVESTIGATING POTENTIAL IMPROVEMENTS TO ENHANCE THE PERFORMANCE OF A SOLAR THERMAL COLLECTION SYSTEM

Design of the Dual Axis Tracking System

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ABSTRACT

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ADVISOR: David Hodgson

Due to the current energy crisis, there are a large number of opportunities in the applications of renewable energy technologies. Specifically, my partner and I have explored those associated with a solar thermal collection dish. The sun, being a virtually limitless supply of energy, ought to be used to its fullest potential. This technology is designed to do just that. Using a concave reflective surface, the sun's thermal energy is concentrated to a central location where it is then collected by a working fluid. This type of approach achieves very high temperatures and maximizes the effectiveness of the thermal energy collection process.

In order for the dish to efficiently capture the sun's thermal energy, a motorized solar tracking system first needed be implemented. Using photovoltaic sensors, one linear actuator, and one small gear-head motor, I was able to create a dual-axis system capable of tracking the sun's movement in a smooth, controlled manner. The supporting structure itself is constructed from T-Slotted framing materials and rests atop a rolling cart for mobility. All phases of constructing and calibrating the system were completed by March 16th, 2012. Further system improvements and data collection exercises are now being explored by faculty and students.

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Introduction

Background:

Energy is becoming a much more valuable commodity as time goes on. Mankind has confirmed that fossil fuels are a limited resource, meaning that the only way to support life as we know it is to explore other options. Since this realization, man has begun to branch out technologically in an effort to capture energy from renewable sources such as the wind, moving bodies of water, and the sun. These technological advancements have progressed a great deal since they first became popular in the mid-20th century.[1] That being said, each of these fields still have a long way to go before the human race can consider itself a sustainable species. Each of the technological devices which are employed for these purposes can be made more effective and more spatially efficient.

Due to the frequently discussed energy crisis, there is great opportunity in the applications of these technologies. For the scope of this project, we would like to investigate specifically the capabilities of solar thermal collection. The sun, being a virtually endless supply of energy, must be used to its fullest potential. Solar thermal energy can be used for numerous heating applications, and it can also produce electricity if a Stirling engine is employed.

There are several different types of solar thermal collection systems, categorized based on their geometries. Flat plates, evacuated tubes, parabolic troughs, and parabolic dishes are the four most common. Each physical design has its own set of advantages and disadvantages. For instance, parabolic geometries are able to focus the sun's energy from a large area to a smaller focal point. This produces a much greater collection temperature and heat flux, improving the performance of the device. However, a drawback of the parabolic system is that the collection device must be continually aimed toward the sun. Depending on the collector geometry, either a single or dual axis tracking system is required. This greatly increases to the costs associated with

[1] Kalogirou, 238-239

the collection process. Therefore, the technology is only used when the performance of the device can outweigh the financial requirements. There is obviously a large amount of interest in perfecting this tracking function and reducing these costs.

Tracking can be categorized into two main groups, closed-loop and open-loop. Closed-loop refers to a system in which feedback is used to control the movement of the device. This is normally provided by photo-electric sensors which measure their alignment with the primary light source; the sun. By communicating with one or two motion producing devices, the sensors can accurately keep the collection device pointed at the sun. The second type, known as open-loop, does not require any feedback. This type of system uses a geometric algorithm to predict the sun’s location throughout the course of a day. It only requires the latitude, date, and time of day to be input into the software. Both systems are capable of achieving great accuracy and are used an equal amount in modern applications.

For this project, we have decided to investigate the performance of a solar thermal collector dish. With this technology, there are still many improvements which can be made. Using a concave reflecting surface, the sun’s energy is concentrated to a central location where it is then collected by a working fluid. This type of approach maximizes the collection of thermal resource by achieving high levels of heat flux at the focal point. As previously mentioned, this type of collection geometry requires a tracking system. In order for the technology to correctly reflect the sun’s energy to that central point, the collection device must be capable of traversing the sky on two axes. Geometric precision and two slow-acting motors will produce the required movement.

Project Motivation:

In today’s market, there are a large number of opportunities pertaining to the applications of renewable energy technologies. Specifically, we would like to explore those associated with a solar thermal collection dish.

One of the large issues with this technology is the losses which are associated with the collection element. After the thermal energy is reflected from the surface of the dish and transferred into the element, convective currents in the surrounding air are able to extract a significant amount of the heat. Our goal is to address this concern by enclosing the element within an evacuated glass tube. This solution will eliminate these losses, allowing only minor amounts of thermal radiation to escape. Once completely assembled, the system will be tested on the roof of the Peter Irving Wold Center throughout the Winter 2012 term to obtain data and reach meaningful conclusions.

Our testing process will provide us with the data necessary to formulate conclusions as to the performance of the design. The thermal energy collection will be evaluated and compared to that of traditional systems in order to determine the overall impact of implementing the evacuated collection unit. In specific, we will measure the thermal output power that each design is able to achieve. By engineering and constructing a unique system, it will be possible to acquire unique research data. If our improved design shows promise, we will then report these findings in an effort to progress the field of solar thermal energy. At the very least, this project will contribute to an emerging field of renewable energy. In addition, this device will be donated to Union College's Mechanical Engineering Department following the completion of the project, where it may be used for further research and teaching purposes.

Final Design

After a lengthy analysis, I have been able to fully design a dual axis tracking system which will be used in tandem with the thermal collection system. A three dimensional model of the system, excluding the linear actuator and rotational drive mechanisms, is shown in Figure 1. A fully dimensioned drawing of the system can be found in Appendix A: Dimensioned Drawing.

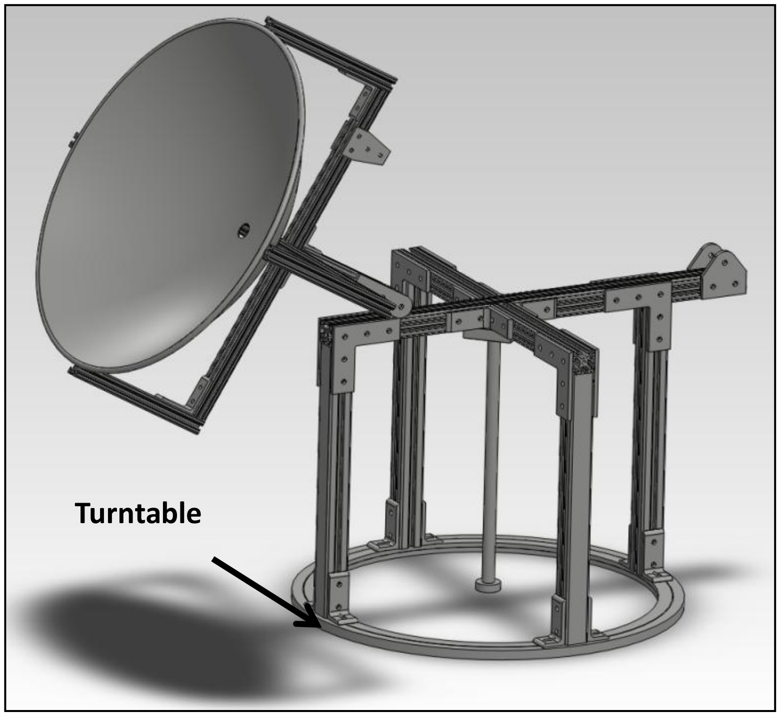

Figure 1: SolidWorks model of the tracking system

As shown above, the final design which I have created is composed primarily of 80/20 structural framing, which will be purchased through McMaster Carr. There are four vertical legs supporting the system, all of which are to be fastened to a free rotating 24” ring-style turntable. The rotational components will all be located within the ring and implemented as to drive the ¾” steel shaft in the center. The specific components include one small Pololu 131:1 gear head motor, two timing belt pulleys, and an L-series timing belt. By resting the structure on top of the turntable and anchoring the drive shaft with a ball bearing, the motor and gear system will be able to remain in place while the structure itself is free to rotate. The goal of the gear train system is to

step the motor down and produce slower speeds with higher torque, both being favorable characteristics to the tracking system. Attaching one 0.64” pulley to the motor and another 4.58” pulley to the drive shaft, we will achieve a speed of 11.11 rpm and an output torque of 1.296 kg-m. This gear train has been chosen to produce the required motion as described in the analysis section.

To achieve the desired elevation changes, a linear actuator will be installed just behind the dish, fastened to the long horizontal bar of the structure and to the upper half of the dish bracket. Each end will be secured using a pivot mount, allowing the device to push and pull the dish as needed to obtain the necessary angle. The linear actuator selected for this task is a Pololu 12V, 20:1 device with a 12” stroke. The locations of the pivot points have been selected for this specific piece of equipment as to enable the angle of elevation to change from 0.01° to 76.7° from the horizon. As previously described, the required range is 0-73°. The location of the linear actuator and pivot locations are displayed in Figure 2.

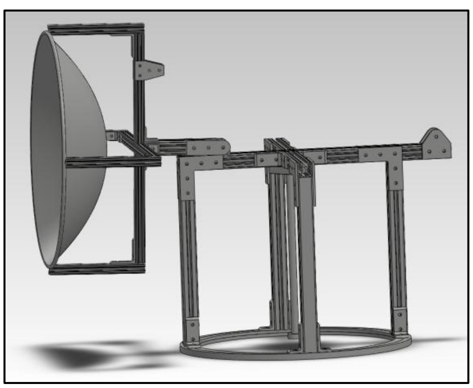

Figure 2: Linear Actuator Fully Open

Figure 3: Linear Actuator Fully Closed

Each of the motors used in this design include feedback components so that their movements can be tracked throughout the course of the day. The gear head motor employs an encoder, while the linear actuator comes with a built-in potentiometer. These simple devices will allow us to map each component’s performance at all times without having to physically watch the system. It will be extremely helpful in diagnosing potential causes of poor performance.

The bracket which has been designed to hold the dish also has several key components. The bracket uses four 80/20 arms to encompass the collector and contact the small lip around its edges. Each of these arms has a reach of 9.8 inches, as to allow for the thermal collection system to be installed through the central hole in the dish with ease. This subsystem includes the collection element and the connecting length of insulated tubing. One or two small tube clamps may be used to secure these components to the dish bracket. The arms of this bracket are also notched at the points where they will contact the dish. This small indentation will be coated with aerosol rubber spray so they will not damage the aluminum surface. The four arms will each be fitted with a screw-in latch mechanism which will cover the lip of the dish and pinch it against the notched 80/20 frame. This will secure the dish in all three dimensions and allow for the structure to be accurately positioned towards the sun.

Attached to the uppermost arm of the dish bracket will be the solar tracking sensor. Using an 80/20 90° angle bracket, the sensor will be positioned perpendicular to the plane on which the dish is located. The sensor element will detect the position of the sun and send feedback to the electronic controller. As the controller receives this information, it will output a corresponding signal to a dual motor driver. In turn, the driver will supply the two motors the necessary power, achieving the motion necessary to aim the device directly towards the source of light. The dual axis sensor chosen for this task is that sold by Heliotrack and the motor driver is from Dimension Engineering. Pictures and drawings of some of the more important tracking system components can be found in Appendix C.

The entire tracking structure, once constructed, will be secured atop a polypropylene cart to allow for easy transport. Since this system is just a prototype, many adjustments might need to be made to perfect its design and functionality. The cart will enable us to bring everything in and out of the lab where these changes can be made easily. When it is positioned on the roof, the wheels will be locked and the base of the cart will be weighted down to eliminate any chances of

the cart moving or tipping over. In its entirety, this design should produce the desired tracking movements allowing us to focus on the testing of several thermal collection elements.

Analyses

Required Positioning:

Before doing any real design phase of the project, I first needed to know just how much of the sky the tracking system would need to cover in the course of a day. To determine the vertical and horizontal ranges, I investigated the day of the year on which the sun made the largest movements; the summer solstice (June 21st).

Using an online calculator[2], I was able to determine the sun's highest point in the sky on this day, also known as the angle of elevation. I was also able to determine the angle from due north where the sun was positioned throughout the day, or the azimuth angle. Based on Union College's latitude (42˚ 48:45 N), the day of the year (6/21), and the time of day (varying), I found that the tracking system would have to produce an elevation range of 0 - 73˚ from the horizon and an azimuth range of 58 - 302˚ from due north. I checked these values with another online source just to be sure of their accuracy[3], and found that the two varied by less than a thousandth of a degree.

Elevation Change:

The next object of analysis was making sure that the geometry of the structure allowed the linear actuator to achieve all desired angles. Picking one with a 12" stroke and knowing the fully-closed length, I was able to break the system triangles and use simple geometric laws to determine the maximum and minimum angles that could be produced. By adjusting the distance

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[2] "NOAA Solar Position Calculator." *NOAA.gov*.
[3] "Calculation of Sun Position, Sunrise and Sunset."

between pivot points, I was able to use the Pololu device to obtain an elevation (α) range of from 0.01° to 76.7° from the horizontal. This was found using a horizontal distance between pivot points (x) of 22", a bracket extension from the base pivot (a) of 6.5" and a vertical height of the uppermost pivot (b) of 8". See Figure 3 for a drawing of these parameters.

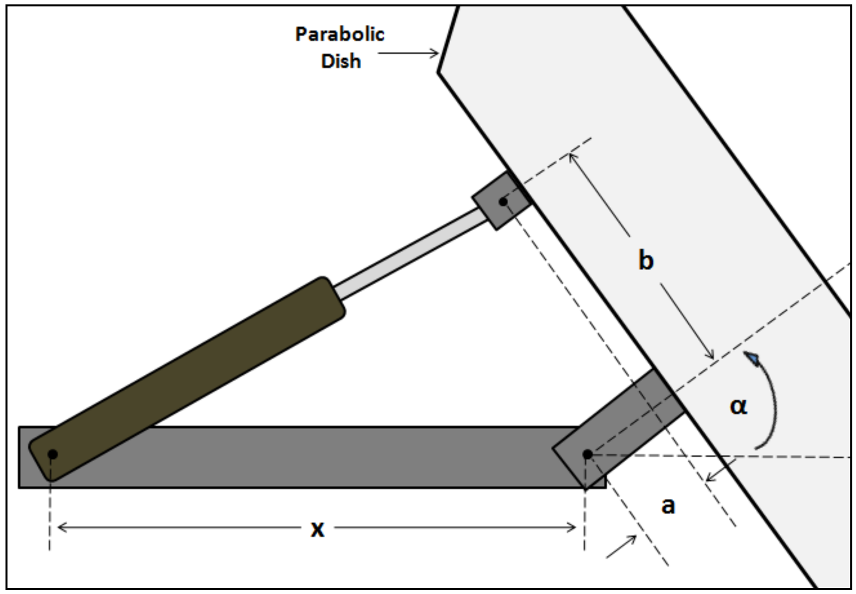

Figure 4: Pivot Locations and Produced Angle of Elevation (α)

This range exceeds the necessary maximum while eliminating any chance of the dish contacting the base structure and causing unwanted damage. Since the sun will be changing vertical position at an extremely slow rate, the speed at which the actuator needs to move was not an issue. The rated speed of 0.5 in/s is certainly more than is required.

Rotational Motion:

I then investigated the motion of the gear train and motor controlling the opposite axis. The motor, also a Pololu component, was selected to allow for lower speeds and higher torque. It was also chosen to allow for complete 360˚ clockwise and counter-clockwise motion. The two gears were then selected to step the motor down even more in speed, producing even greater

levels of torque. Selecting a small pulley for the motor and another larger pulley for the drive shaft, I obtained a gear ratio (R) of 7.2 with,

$$R = \frac{N_{out}}{N_{in}} \qquad \text{(Eq. 1)}$$

Using this ratio, the output torque and angular velocity were determined with,

$$R = \frac{\tau_{out}}{\tau_{in}} = \frac{\omega_{in}}{\omega_{out}} \qquad \text{(Eq. 2)}$$

Table 1 below displays the input and output parameters that were considered in these calculations.

Table 1: Input and Output Parameters from the Selected Gear Train

	Input	**Output**
Gear Size	0.64 inches	4.58 inches
Number of Teeth (N)	10	72
Torque (τ)	0.18 kg-m	1.296 kg-m
Angular Velocity (ω)	80 rpm	11.11 rpm

The torque output was needed for an additional analysis of wind force, while the output velocity was needed to determine if this specific gear train would be able to keep up with the sun's movement throughout the day. Knowing that the sun would be moving over a maximum azimuth range of 244˚ in about 12 hours, I chose to find what this speed would be if it were moving this distance in 6 hours. Even using this extreme exaggeration, the dish would only have to move at a rate of 0.0019 rpm to keep up with the sun. This shows that the motor and gear train that was selected will have no problem in this application.

Wind Force:

Wind force was one a major concern that needed to be addressed before deciding on any specific components of the tracking system. Since the collection device will eventually be

spending a great deal of time on the roof, all aspects of the support structure must be able to withstand significant gusts of wind. While the aluminum frame itself was not much of a concern in this regard, the two motion producing devices each needed to be investigated. Both the linear actuator and a small rotary motor, needed to be sized accordingly in order to supply the necessary power to overcome such forces.

The linear actuator that was desired had a dynamic load rating of 50 kg. We were able to determine the maximum air speed which the device would be able to oppose,

$$F_D = .5 C_D A \rho V^2 \qquad \text{(Eq. 3)}$$

where F_D is the drag force produced by the wind, C_D is the drag coefficient associated with a dish geometry, A is the frontal area of the dish, ρ is the density of the air, and V is the air speed. This maximum velocity was found to be 28.51 m/s (63.78 mph). If the wind exceeds this value, this linear actuator will not be able to move, however the device is rated to withstand up to 227 kg without failure. So, gusts over 60.75 m/s (135.9 mph) will have to be experienced in order for the supporting structure of the linear actuator to break. Since we will be testing this solar thermal system the majority of the time in calm conditions, the lesser value of 28.51 m/s will most likely never be exceeded and the power rating of this linear actuator will be sufficient.

Likewise for the motor and gear train chosen, a maximum output torque of 1.296 kg-m was determined. From this value, we were able to determine what wind speed this component could handle using,

$$\tau = .5 C_D A \rho V^2 r \qquad \text{(Eq. 4)}$$

with the same variable as above except for τ being the torque and r being the radius of the dish. From this we found that the maximum wind speed that the system would be able to withstand is 8.31 m/s (18.59 mph). Again, since we are planning to test in times of nice weather, these drive components should have more than enough power for the application.

Funding

Pricing all components and materials for the solar thermal collection system, we had estimated a total project cost of $2,365.96. This amount includes costs for everything mentioned in the "Final Design" section above as well as that which Kevin Quillinan will require to construct the thermal collection system. Over the first term, we requested funding from the boards of the Student Research Grant as well as the Presidential Green Grant; $1,000 and $2,000 respectively. Thankfully, both grants were approved for the full amounts, providing us with more than enough funding to complete the project.

During the second term of the project, we purchased almost all of the necessary materials and components to fabricate the system. In total, we spent $2,230.66. While this was less than our previous estimate, we did not have the time to complete all aspects of the project (see "Furthering the Project"). For a more detailed breakdown of the project parts and purchases, refer to Appendix B: Project Costs.

Implementing the Design

Fabrication & Assembly:

After some initial purchases from McMaster Carr and Pololu, I could begin the fabrication phase of the project. Since the structural design was made up of all metal components, I used a number of metal-working tools to do this. T-slot framing materials were cut to their proper lengths using a miter saw with a carbide blade. This took a fair amount of time since the lengths needed to be exactly right in order for the assembly to go smoothly. Each piece was also taken to a wire-wheel and hand filed to remove any sharp edges. Once the materials were machined, the base frame was assembled using corresponding fasteners and brackets. Next, the same process was performed to create the frame which holds the dish in place. This upper assembly was then attached to the base frame using an aluminum pivot joint which was designed for the T-slot material.

After the two assemblies were joined, I then attached them to the turntable. This required drilling out four equally spaced holes in the inner ring of the device, and then drilling and tapping the ends of the four legs of the base frame. Long stainless steel screws were then used to secure the legs to the turntable. Next, I attached the mounts for the linear actuator to the top of the base frame and the uppermost strut of the dish frame. The bottom pivot mount was the one that came with the actuator while the top two were ordered T-slot brackets which needed to be machined to accomodate the stroke arm. Also, as previously mentioned in “Analyses”, the distances between the dish frame pivot and the two pivot mounts for the actuator were critical. By placing them at just the right locations, the fully-closed and fully-open actuator positions are capable of achieving the necessary elevation range. The linear actuator was then mounted and this elevation range was tested using a 12 V power supply. Figure 5 displays how the upper and lower frameworks were assembled and connected, as well as mounted to the turntable.

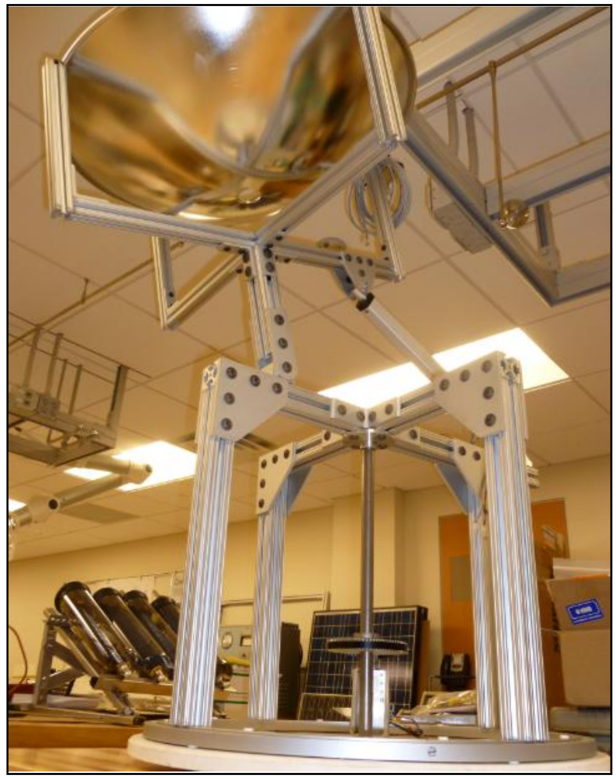

Figure 5: Assembled T-slot Framework

The next task was to machine the dish frame arms to accept the round edges of the dish. This process was very tedious, utilizing a plunge router which was fixed to a table. With a ¼ inch radius rounded bit, each arm could be run over the router at just the right depth to apply the curvature to their ends. After this was completed, the central holes in the ends were then tapped to accept larger T-slot fasteners and the corresponding tabs. This design allowed the dish to be put in place and then secured by tightening the tabs onto the edges of the dish. Both the ends of the T-slot framing as well as the tabs were coated with liquid rubber to ensure that the dish would not be scratched or damaged when it was put in place.

Following the mounting of the dish, I focused on finishing the base. Since all of the rotational components needed to be located in the center of the base frame, the structure required some type of bottom board on which the turntable would rest. For this piece, I was able to find some ¾ inch PVC board which could be cut to size. Again utilizing the plunge router, I created a

jig which allowed me to cut a large circle out of the board and also apply a bevel to the edge. The diameter of the circle was designed to be just larger than that of the turntable. Next, I drilled five holes in the outer ring of the turntable, centered the structure on the PVC board, and fastened it down. By countersinking the five holes, the flat head screws were made flush with the top of the ring, eliminating any chance of them interfering with the overhanging base legs. As a final touch, I purchased five small rubber feet and fastened them to the bottom of the PVC board. The finished base is shown in below in Figure 6.

Figure 6: PVC Base Board Mounting

In order to mount the rotational components on the board, I first needed to design several key components. Specifically, I created a motor mount which would keep the gearhead motor upright and a flange which would attach the drive shaft to the bottom of the tracking structure. Also, I had the PVC board counter-bored to accept a ball bearing, the drive shaft cut to length, and the two timing belt pulleys bored out to accept the drive shaft and motor shaft. After the Union College machine shop finished all of these pieces, I mounted the motor and assembled the rotational drive design. Unfortunately, when I tested the system, I found that the timing belt kept slipping on the pulleys instead of rotating the structure. This was primarily due to the motor mount design, as it would flex under the pressure from the belt and decrease the desired tension between the two pulleys. To address this issue, I created a second design in which the mount had stronger supports, thus eliminating the flexibility. Also, this design was given fastener slots

instead of clearance holes, allowing me to put the motor in place and then tighten it down quickly to preserve the tension. Additionally, I bought a longer timing belt in hopes that the geometry would contact more teeth on the smaller pulley. Figure 7 is a photograph showing all of these rotational components. And lastly, I designed a sensor mount which attaches the solar sensor to the uppermost arm of the dish frame, keeping it in line with the direction which the dish faces. Refer to "Appendix D: Detailed Drawings" to view the parts which were designed and machined.

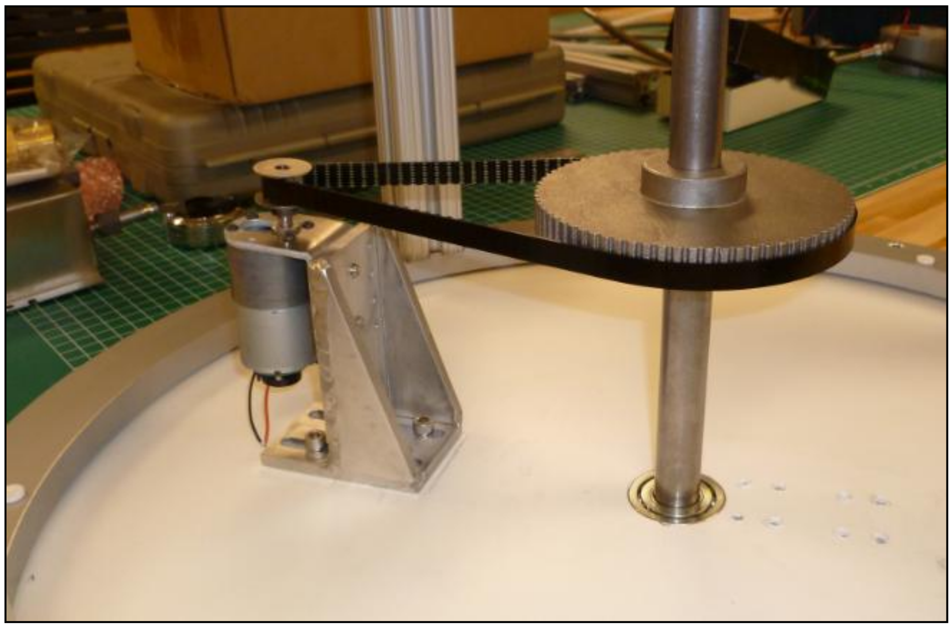

Figure 7: Assembled Rotation System

This concluded the fabrication and assembly phase of the project. All in all, it took roughly three weeks of work to complete the design. It was a very interesting process in which I gained a great deal of understanding of metal work. Also, it was extremely rewarding seeing the hard work of the first term pay off as the design came to life, as shown in Figure 8.

Figure 8: Completely Assembled Tracking Structure

Configuring the Electronics

After completing the physical structure, the electrical devices then needed to be configured in a manner which would allow the system to be moved outdoors for programming. Thankfully, we were able to use a small room which looks out at the roof of the Peter Irving Wold Center; a perfect “control room”. I relocated a computer and power supply to the room, making it a more convenient programming location.

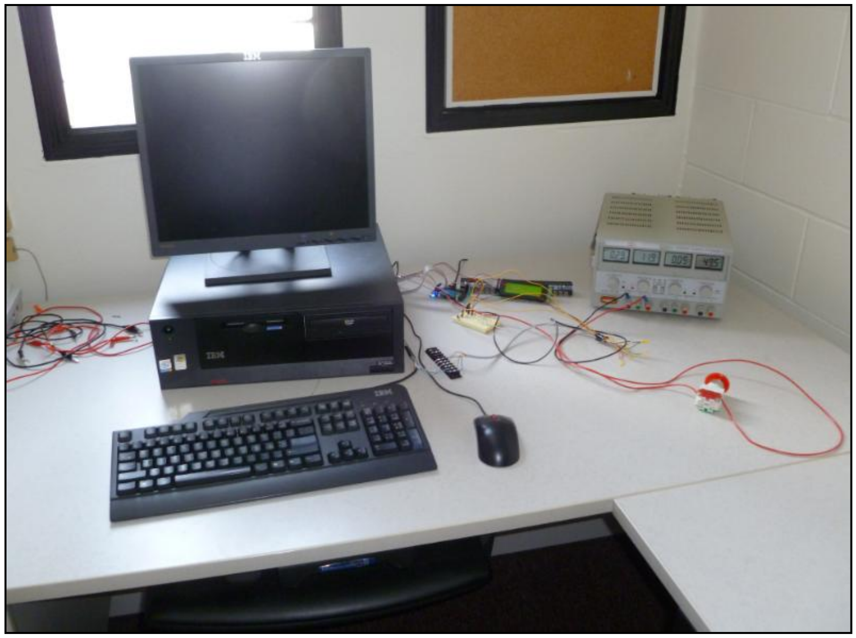

Figure 9: Control Room Setup

After some consideration, we decided it would be easiest to keep the controller inside, out of the elements, and nearby the programming station. In order to do this however, we needed to extend the cords of the gearhead motor, linear actuator, and sensor to come in through a small opening in the wall to reach the controller. To do this, we used "quick wire connections" joining additional lengths and allowing us to connect and disconnect the components with ease. Also, the solar sensor required that we employ several 475 Ω resistors to act as voltage dividers. A representative diagram for this wiring setup is shown in Figure 10, and Figure 11 displays the specific wiring required for the sensor alone.

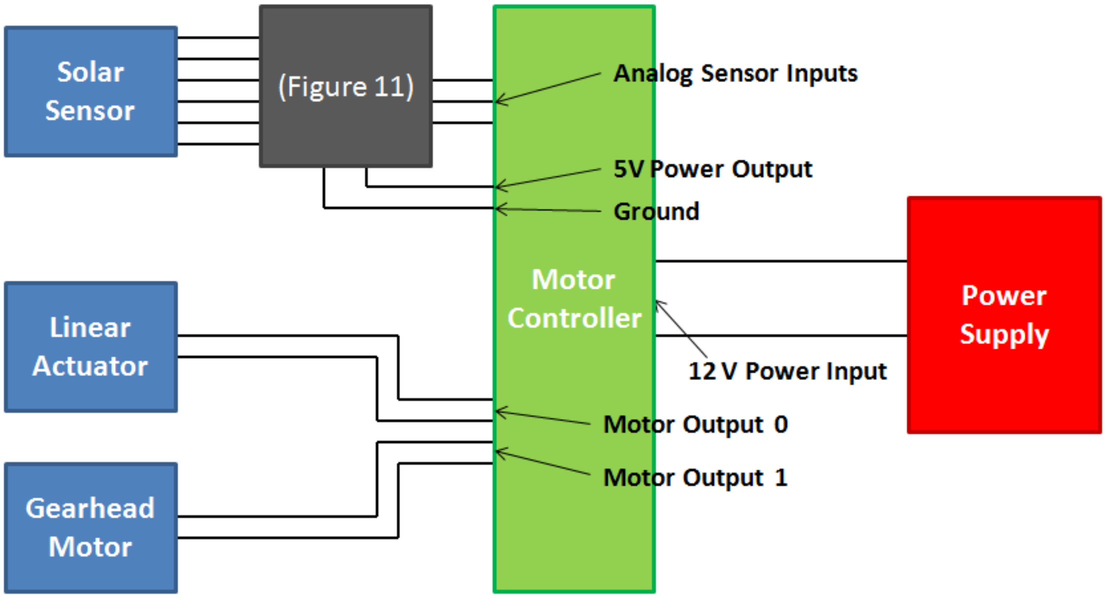

Figure 10: Wiring Setup for the Control Room

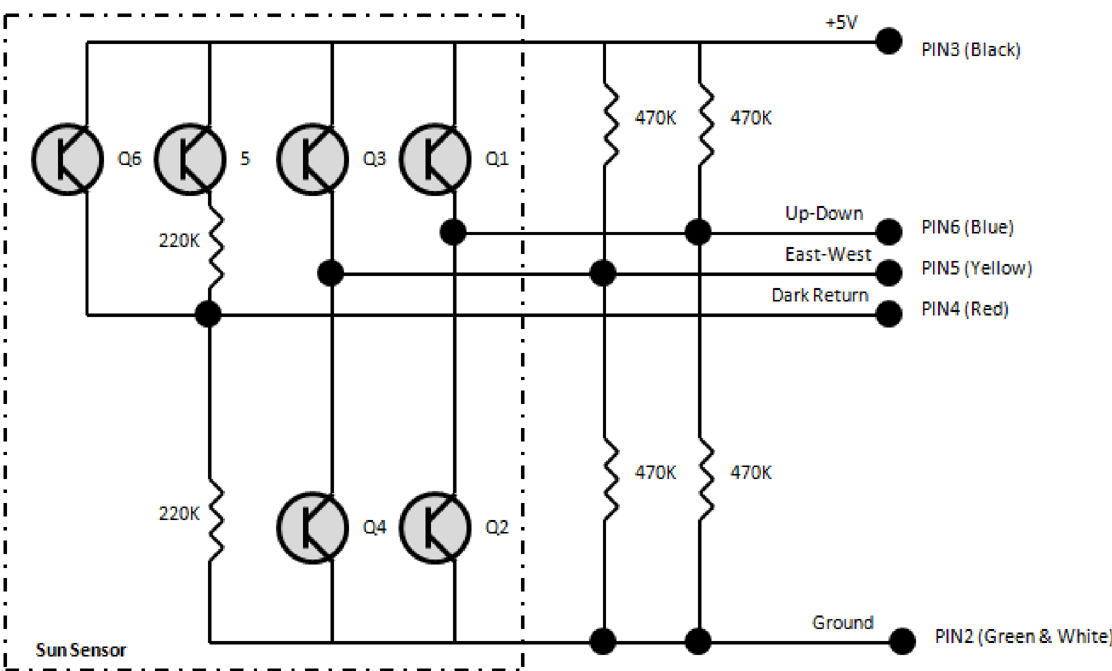

Figure 11: Wiring Diagram for the Solar Sensor

The sun sensor was initially difficult to work with because of the poorly labeled wiring diagram that was supplied by the vendor. However, using the one shown in Figure 11, the sensor

does function well. The only stipulation is that a large light source is needed for testing purposes. At one point I was attempting to work with a bright LED flashlight, and the sensor did not obtain very helpful data in the form of voltage differences. All in all, configuring the electronics took roughly five weeks of the second term.

Programming

Programming and debugging the motor controller was the final step in obtaining a functional tracking system. To do so, we first downloaded the necessary utilities and drivers from Pololu's online resource library. The specific integrated development environment (IDE) recommended by this company was Atmel's AVR Studio 4. Using this interface, we were able to create a script which takes in the analog readings from the sensor and outputs corresponding motor speeds to the two motors, adjusting the structure's position until the dish is aligned with the sun. In addition, we programmed the controller to display certain digital images on an external display for the benefit of the user.

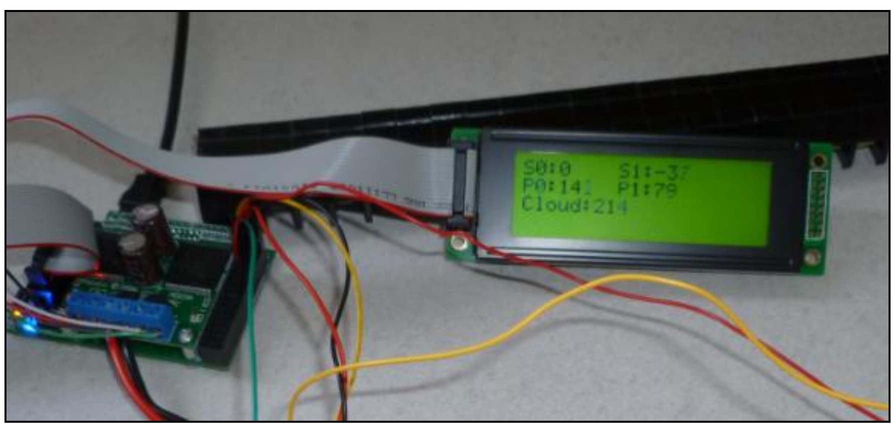

Figure 12: External Display

```
   #include <pololu/orangutan.h>
   unsigned long prevMillis = 0;
   int main()
   {
     set_analog_mode(MODE_8_BIT);    // 8-bit analog-to-digital conversions
5  while (1)
   {
     start_analog_conversion(2);  // start initial conversion of cloudy sensor
     while (analog_is_converting())
     { }
    int mSpeed0=0;
10   int mSpeed1=0;
     int Cloud=0;
     int pot=0;
     Cloud=analog_conversion_result(); //get cloudy result
     if (abs(Cloud)> 50)
15   { // enter the while loop
       start_analog_conversion(0);
       while (analog_is_converting())
       {
        }
20     pot = analog_conversion_result();  // get result    // determine the trimpot position
               lcd_goto_xy(0,1);
               print("P0:");
               print_long(pot);
               print("    ");
25             mSpeed0 = pot*2-256;  // turn pot reading into number between -256 and 255
               if(mSpeed0 == -256)
                   mSpeed0 = -255; // -256 is out of range
               if(mSpeed0 == 256)
                   mSpeed0 = 255; // 256 is out of range
30             if(abs(mSpeed0)<=30)
                   mSpeed0 = 0; // eliminates insignificant motion

       start_analog_conversion(1);
       while (analog_is_converting())
       {
35      }
        pot = analog_conversion_result();  // get result    // determine the trimpot position
                lcd_goto_xy(8,1);
                print("P1:");
                print_long(pot);
40              print("    ");
                mSpeed1= pot*.75-96;  // turn pot reading into number between -256 and 255
                if(mSpeed1== -256)
                    mSpeed1 = -255; // -256 is out of range
                if(mSpeed1 == 256)
45                  mSpeed1 = 255; // 256 is out of range
                if(abs(mSpeed1)<=30)
                    mSpeed1 = 0; // eliminates insignificant motion
            set_motors(mSpeed0, mSpeed1);
            lcd_goto_xy(0,0);
50          print("S0:");
            print_long(mSpeed0);
            print("    ");
            lcd_goto_xy(8,0);
            print("S1:");
55          print_long(mSpeed1);
            print("    ");
            }
            lcd_goto_xy(0,2);
            print("Cloud:");
60          print_long(Cloud);
            print("    ");
            if (Cloud <100)
            print("  Overcast");
            else
            print("            ");
65      }
   }
```

Figure 13: AVR Studio 4 Script for Solar Tracking Capabilities

Figure 13 displays the actual script which is capable of tracking the sun's movement throughout the course of a day. Line by line, the script does the following:

<u>Lines 1-3:</u> Loads the necessary file library for the Pololu controller

Line 4: Sets the analog mode to an 8-bit conversion

Line 5: Enters the while loop to continually take in the inputs and output the commands

Line 6: Begins the initial conversion of the analog reading

Line 7-8: Tells the controller to wait until the controller is done reading the input

Lines 9-12: Sets variables as integers; "mSpeed0" is the motor speed for the linear actuator, "mSpeed1" is the motor speed for the gearhead motor, "Cloud" is the dark return sensor input, and "pot" is input readings from the East-West/Up-Down sensors

Line 13: Obtains the dark return sensor input

Line 14: Tells the controller that if that input is too low, then it should not continue tracking

Lines 15-20: Reads the input from port 0 and sets the "pot" for the Up-Down movement

Lines 21-24: Prints the "pot" reading for port 0 on the external display as "P0"

Lines 25-29: Sets the motor speed variable of the linear actuator based on the port 0 reading

Lines 30-31: Prohibits the linear actuator from making very small insignificant changes

Lines 31-36: Reads the input from port 1 an sets the "pot" for the East-West movement

Lines 37-40: Prints the "pot" reading for port 1 on the external display as "P1"

Lines 41-45: Sets the motor speed variable of the gearhead motor based on the port 1 reading

Lines 46-47: Prohibits the gearhead motor from making very small insignificant changes

Line 48: Sets the motor speeds based on the two variable values

Lines 49-57: Prints the motor speeds on the external display as "S0" and "S1" respectively

Lines 58-65: Prints "Overcast" on the external display if the dark sensor input is too low and the tracking function has been temporarily disabled

Lines 66-67: Exit the while loops

To program the controller, it first needs to be hooked up to a 12V power supply. Then, using a USB connector, the controller needs to be linked with the computer and the programming button on the controller must be held down until a beep sounds and a yellow LED lights up. This

indicates that the controller has entered the programming mode. With the desired programming script open, the user must build the script by hitting F7 or clicking the "Build Active Configuration" button on the top toolbar. If there are any issues with the script, the program will notify the user at the bottom of the screen in terms of errors and warnings. Next, the user needs to connect the controller by hitting the "Connect to the Selected AVR Programmer" button at the top of the screen. In the "Programming" box, the script must be located on the computer and selected. Lastly, the user needs to click the "Program" button in the box and the controller will sync with AVR Studio. After turning the controller off and then back on, it should be ready for action.

Debugging the script was a process in itself. Using Pololu example scripts, we continually built upon our one single script until the tracking system was performing all necessary functions. This required quite a bit of time playing around with motor speeds and input values. For example, one issue we faced was with the output voltage being supplied to the gearhead motor. If too great a voltage was supplied to it, the timing belt would slip and/or the structure would go too fast to align itself precisely with the sun. If too little voltage was supplied, the motor would not have enough power to turn the structure due to resistance caused by wires and hoses. By adjusting this motor speed several times, we eventually discovered a perfect medium in which the gearhead motor effectively tracked the sun. Similarly, we also needed to vary the input value at which the controller would recognize that it was overcast outside, temporarily disabling the tracking function of the system.

The programming and debugging phase of the project took roughly three weeks to complete. I would say that this portion was equally, if not more-so, enjoyable than the fabrication and assembly stage. It was absolutely incredible to see the system come to life after a full 20+ weeks of work. The finished system, with the thermal collection loop also implemented, is shown in Figures 14 and 15. The true goal of the dual axis tracking system, to effectively reflect the sun's thermal energy to a central focal point of the dish, is shown in Figure 16.

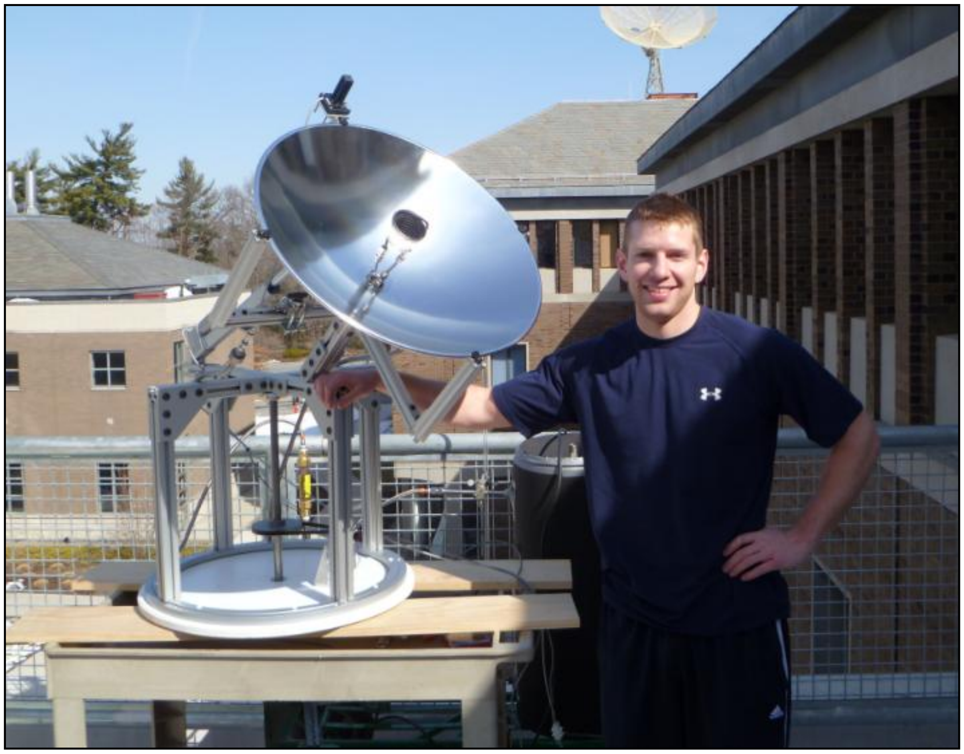

Figure 14: Complete Solar Thermal Dish Collection System

Figure 15: Functioning System as Monitored from the Control Room

Figure 16: Solar Thermal Receiver in the Focal Point of the Dish

Furthering the Project

If I were to continue this project, there are certainly some ways to improve the system's capabilities. First and foremost, I would extend the power cables to a length that would allow us to mount the collection system on top of the newly constructed scaffolding on the roof. This would raise the system up above the atrium roof, extending the slim window of opportunity that we had to work with this term. Only about 6-8 hours of sunlight hit the lower portion during the day. To implement this, however, I would first need to weather-proof all of the electrical components on the system as well as their external connections.

Another improvement I would like to make is that which utilizes the feedback elements of the gearhead motor and linear actuator. This term, we found that the encoder on the gearhead motor output a signal which was much too fast for the motor controller to interpret. To fix this issue, we could purchase a relatively inexpensive encoder interface device which would be capable of taking in the rapid signals and outputting usable data. Having this feedback data along with that of the potentiometer, we would be able to plot and analyze the tracking system's movements throughout the course of a day. It would then be possible to form factual conclusions regarding the performance of the machine.

I would also like to improve the rotational drive system. Although it does function as is, it could be made more robust by implementing a timing belt tensioner. This would certainly decrease the potential of the belt slipping off of the pulleys and allow us to increase the motor speed if so desired. Also, I believe that the turntable could be better lubricated to minimize the level of resistance that the rotational components are forced to overcome.

Lastly, if my partner Kevin Quillinan and I each had a few more weeks, we would definitely like to obtain an evacuated solar thermal receiver. This would allow us to compare data sets with other, more basic receiver types to determine how much the device can improve the system. Analyzing the cost effectiveness of the receiver in different climates would be even more

ideal, as the convection heat losses would certainly increase in colder environments. This research would be a very interesting addendum to the project as is.

Conclusions

Overall, I believe this project was a true success. Although Kevin and I weren't able to obtain much experimental data due to various circumstances, we are able to say that we designed and built a fully functional solar thermal dish collection system. In the upcoming months we will be presenting our progress at the 2012 Steinmetz Symposium and possibly also at the ASME International Conference on Energy Sustainability. Kevin and I are both excited that we have accomplished this much in just two terms, and we look forward to the possibility of continuing our efforts to obtain meaningful data and conclusions.

Acknowledgements

We would like to express our gratitude to the following people and organizations. Without their support this project would not have been possible. Thank you!

Prof. Hodgson & Prof. Wilk,

the Union College Boards of the Green Grant & Student Research Grant,

and to Paul, Jim, and the other helping hands at the Union College Machine Shop

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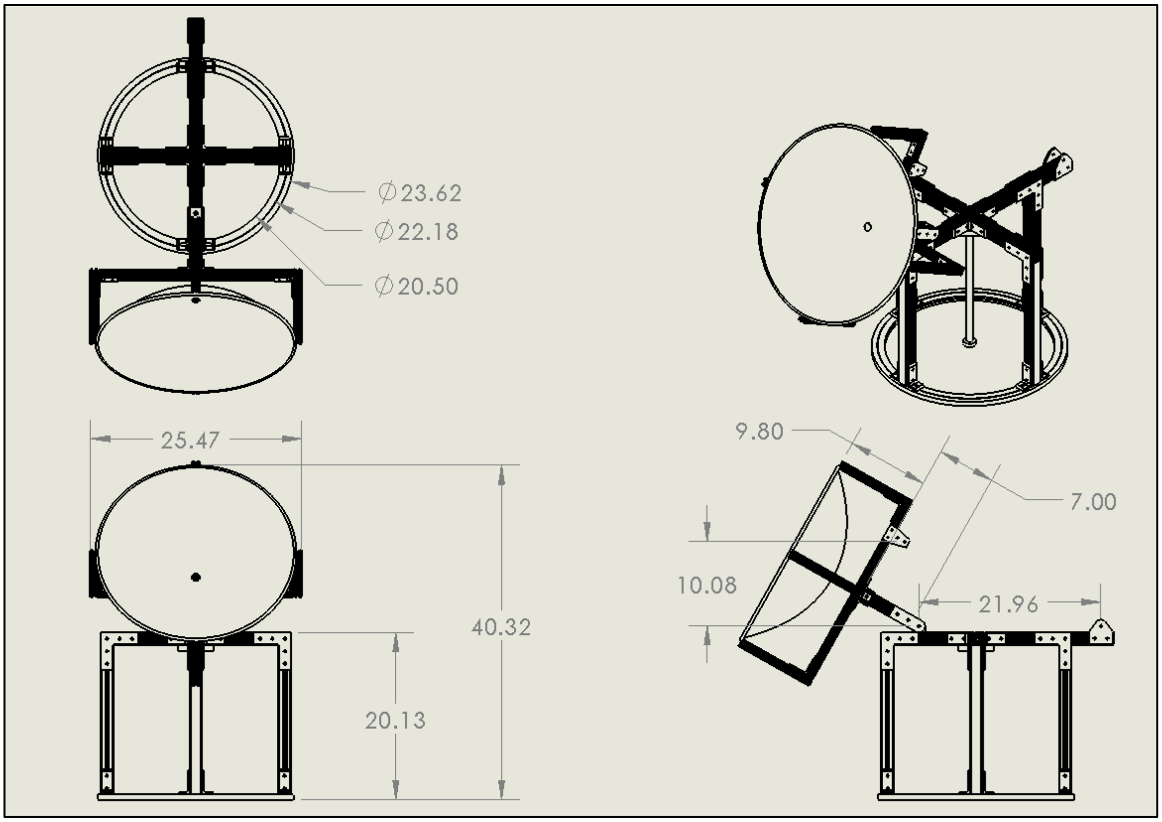
Appendices

Appendix A: Dimensioned Drawing
Appendix B: Project Costs
Appendix C: Tracking Components
Appendix D: Detailed Drawings

Appendix A: Dimensioned Drawing



Appendix B: Project Costs

Table 1: Anticipated Bill of Materials

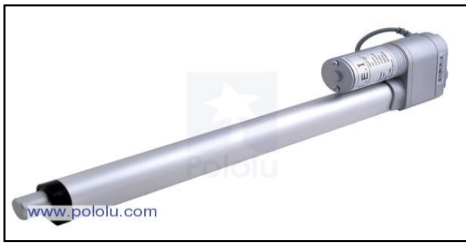
Item	**Vendor**	**Unit Price**	**Qty.**	**Total Cost**
Tracking System				
Linear Actuator	Pololu	$109.95	1	$109.95
Gear-Head Motor	Pololu	$39.95	1	$39.95
Controller	Dimension Engineering	$79.99	1	$79.99
Sensor	Heliotrack	$65.00	1	$65.00
T-Slotted Framing (1-1/2" Sq. x 8')	McMaster Carr	$60.13	1	$60.13
T-Slotted Framing (1" Sq. x 6')	McMaster Carr	$19.79	1	$19.79
T-Slotted Framing (1-1/2") Inside 90° Bracket	McMaster Carr	$4.89	12	$58.68
T-Slotted Framing (1-1/2") Side 90° Bracket	McMaster Carr	$5.10	8	$40.80
T-Slotted Framing (1-1/2") Pivot Mount	McMaster Carr	$6.59	2	$13.18
T-Slotted Framing (1") 90° Inside Bracket	McMaster Carr	$4.56	8	$36.48
T-Slotted Framing (1") Pivot Mount Base	McMaster Carr	$6.59	2	$13.18
T-Slotted Framing (1") Pivot Mount	McMaster Carr	$6.59	2	$13.18
Dish Latch	McMaster Carr	$1.89	4	$7.56
Aerosol Rubber Coating (11oz)	McMaster Carr	$9.91	1	$9.91
Structural Flange	McMaster Carr	$8.00	1	$8.00
Drive Shaft (.75")	McMaster Carr	$21.96	1	$21.96
Timing Belt Pully (0.637" OD)	McMaster Carr	$7.40	1	$7.40
Timing Belt Pully (4.584" OD)	McMaster Carr	$41.17	1	$41.17
Ball Bearing	McMaster Carr	$6.28	1	$6.28
Timing Belt (3/8" Width)	McMaster Carr	$4.20	1	$4.20
Ring-Style Turn Table	McMaster Carr	$247.16	1	$247.16
Polypropylene Cart	McMaster Carr	$201.32	1	$201.32
Thermal Collection System				
Aluminum Dish	Scientifics Online	$70.00	1	$70.00
Insulation	McMaster Carr	$14.52	1	$14.52
SS Tubing	McMaster Carr	$37.45	1	$37.45
Rubber Tubing (ft)	McMaster Carr	$2.79	50	$139.50
Heat Exchanger	McMaster Carr	$207.67	1	$207.67
BBQ paint	Sears	$7.14	1	$7.14
Pump 1/40 HP	PEX Supply	$130.00	1	$130.00
15 Gallon Tank	McMaster Carr	$92.47	1	$92.47
Pipe Insulation	McMaster Carr	$50.00	1	$50.00
Type K Thermocouple probes	Omega Engineering	$27.00	5	$135.00
100 Ft Roll Type K Thermocouple extension wire	Omega Engineering	$89.00	1	$89.00
2 Flow Meters	McMaster Carr	$216.34	1	$216.34
5- ¼ inch Ball Valves	McMaster Carr	$41.60	1	$41.60
Safety Glasses (Welding)	McMaster Carr	$30.00	1	$30.00
TOTAL				**$2,365.96**

Table 2: Project Purchases

Month	Vendor	Description	Amount	*Purchased By*
Dec.	McMaster	Tracking System	$784.36	*RDW*
Dec.	Pololu	Motors & Controller	$350.65	*DH*
Dec.	Heliotrack	Sun Senor	$77.00	*DH*
Dec.	Hardware Stores	Misc.	$89.90	*EL*
Jan. 6	McMaster	SS Tubing	$165.51	*RDW*
Jan. 18	McMaster	Tank & Flow Meter	$237.20	*RDW*
Jan.	PEX Supply	Pumps	$142.00	*RDW*
Jan. 31	McMaster	SS Fittings, etc.	$368.14	*RDW*
Jan.	Pololu	Replacement Wire	$15.90	*EL*
		Total Amount Spent	**$2,230.66**	
		Remaining Funds	**$769.34**	

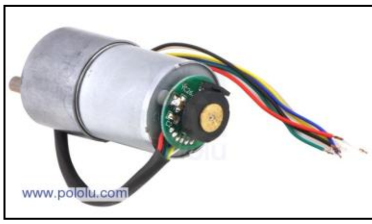
<u>Appendix C:</u> Tracking Components

Pololu Linear Actuator and Potentiometer:



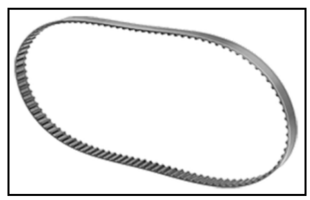
http://www.pololu.com/catalog/product/2313

Pololu Gearmotor and Encoder:



http://www.pololu.com/catalog/product/1447

McMaster Carr Timing Belt and Pulleys:



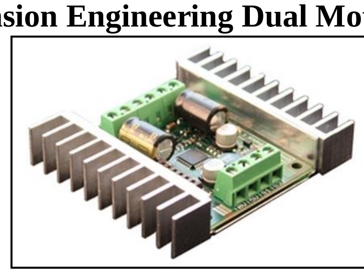
http://www.mcmaster.com/#

Item #'s: 6495K733 6495K711 1679K29

Heliotrack Solar Sensor:

http://heliotrack.com/Products.html

Dimension Engineering Dual Motor Driver:



http://dimensionengineering.com/Sabertooth2X12.htm

<u>Appendix D:</u> Detailed Drawings

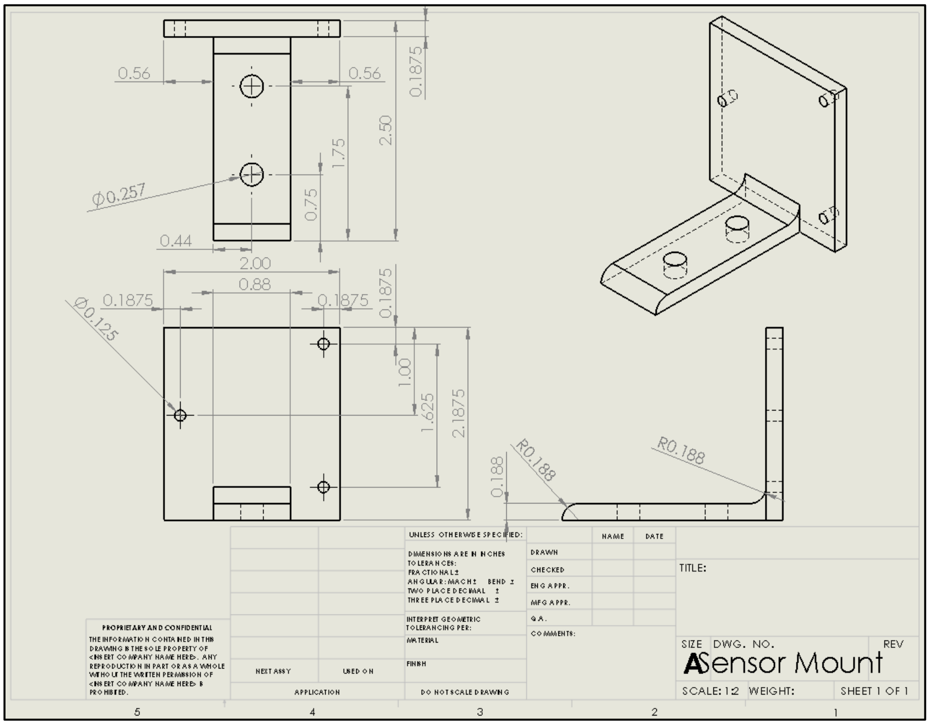


Figure 1: Sensor Mount

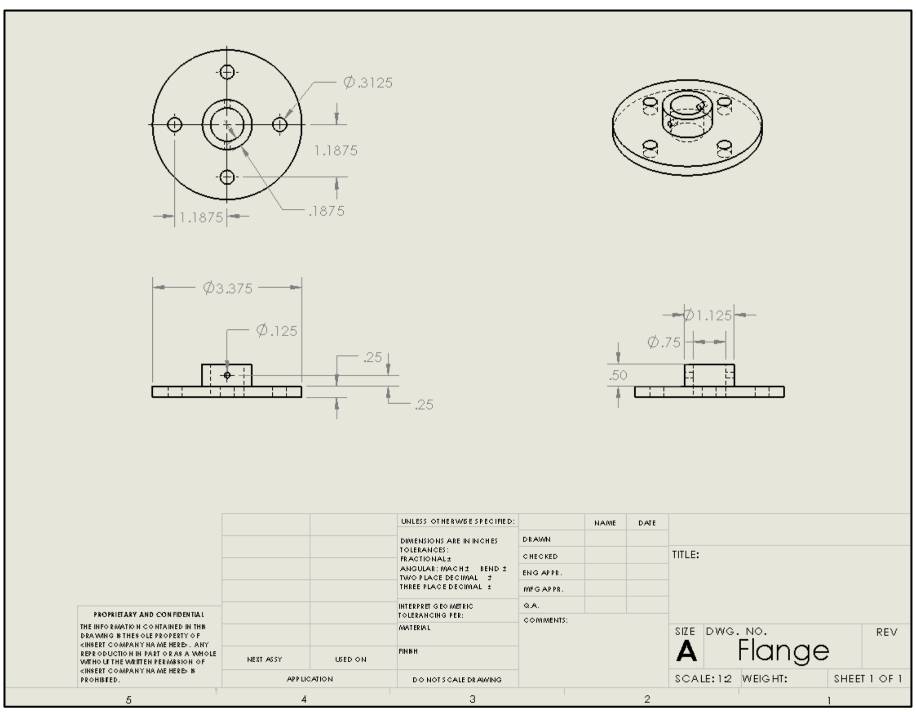


Figure 2: Flange for Drive Shaft

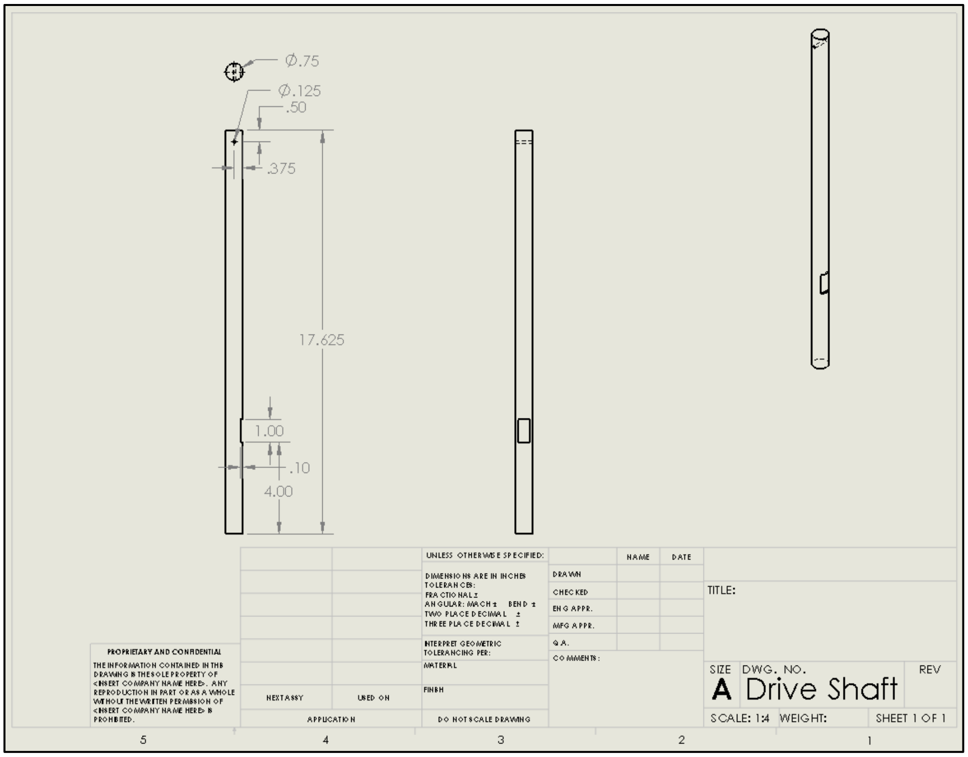


Figure 3: Drive Shaft

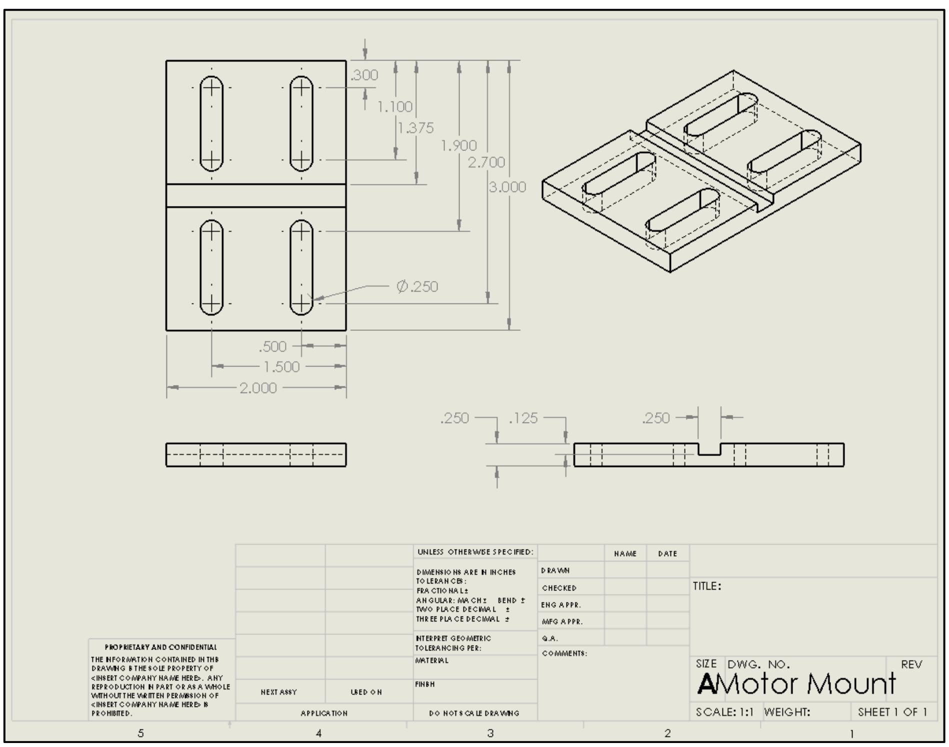


Figure 4: Slotted Base of Motor Mount

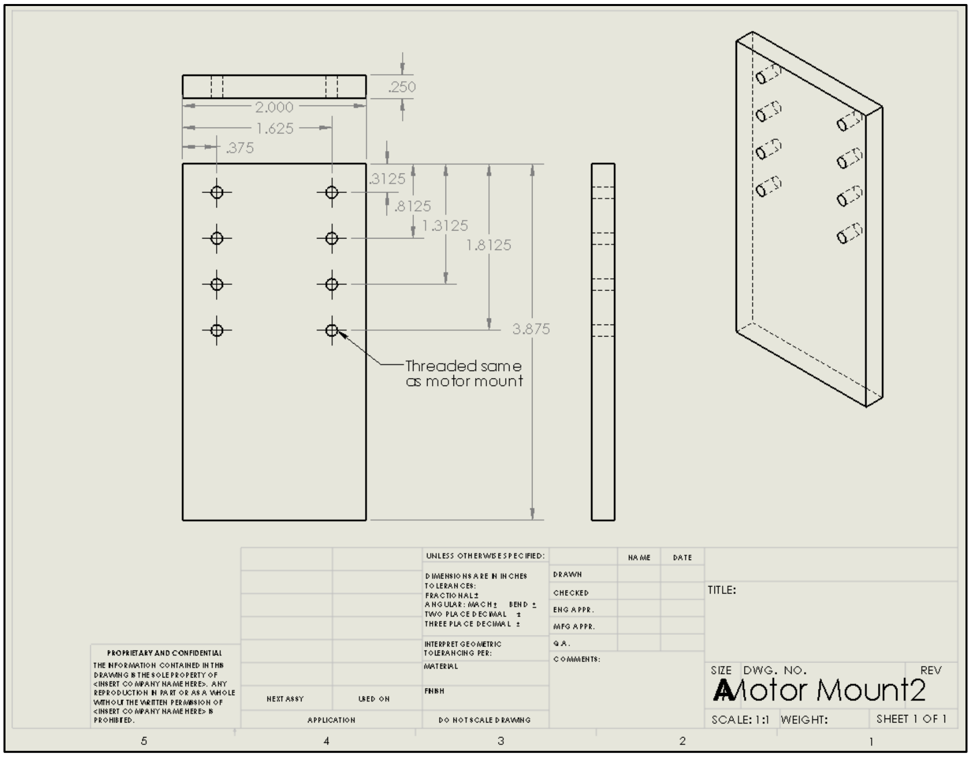


Figure 5: Vertical Plate of Motor Mount

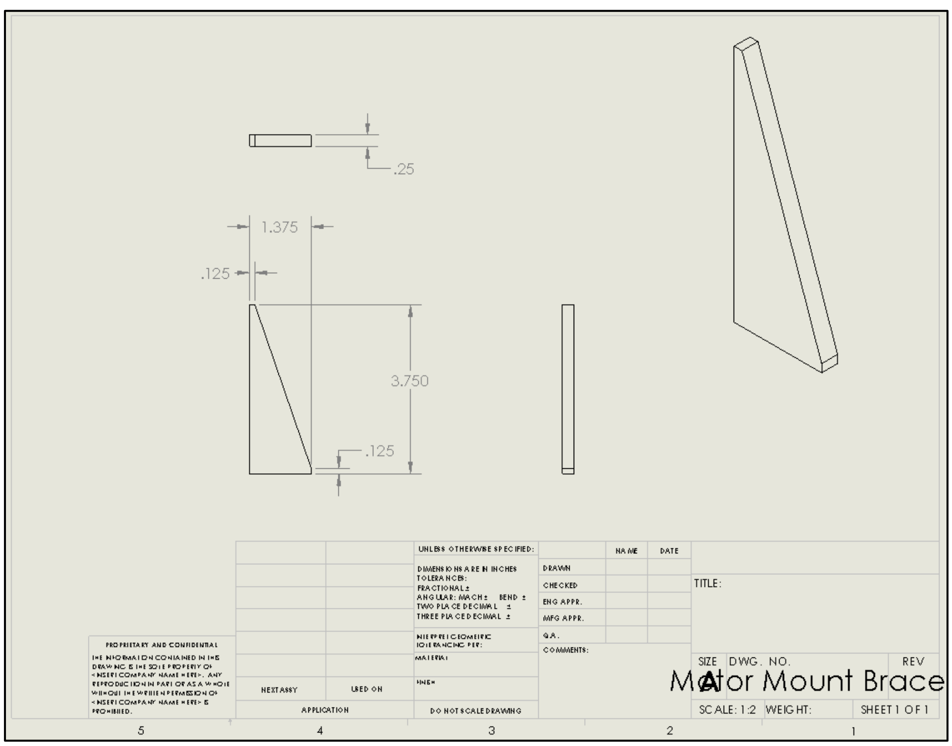


Figure 6: Support Brace for Motor Mount

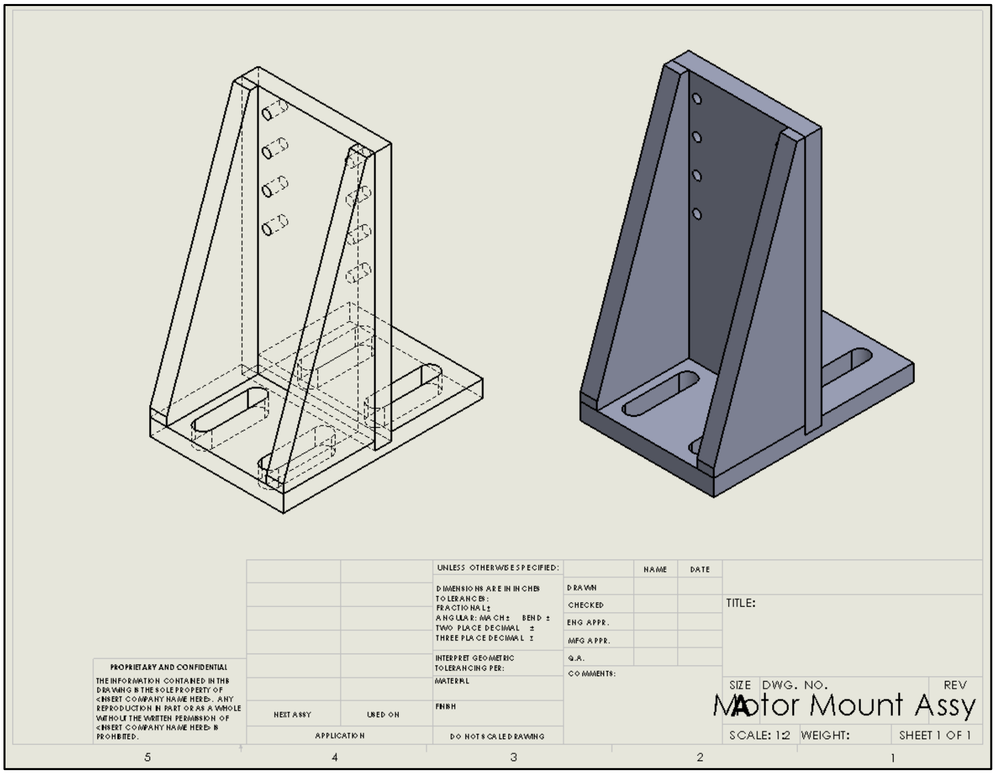


Figure 7: Assembled Motor Mount