Single Axis Solar Panel Tracking Mount Using Stepper Motor and Accelerometer Positional Control

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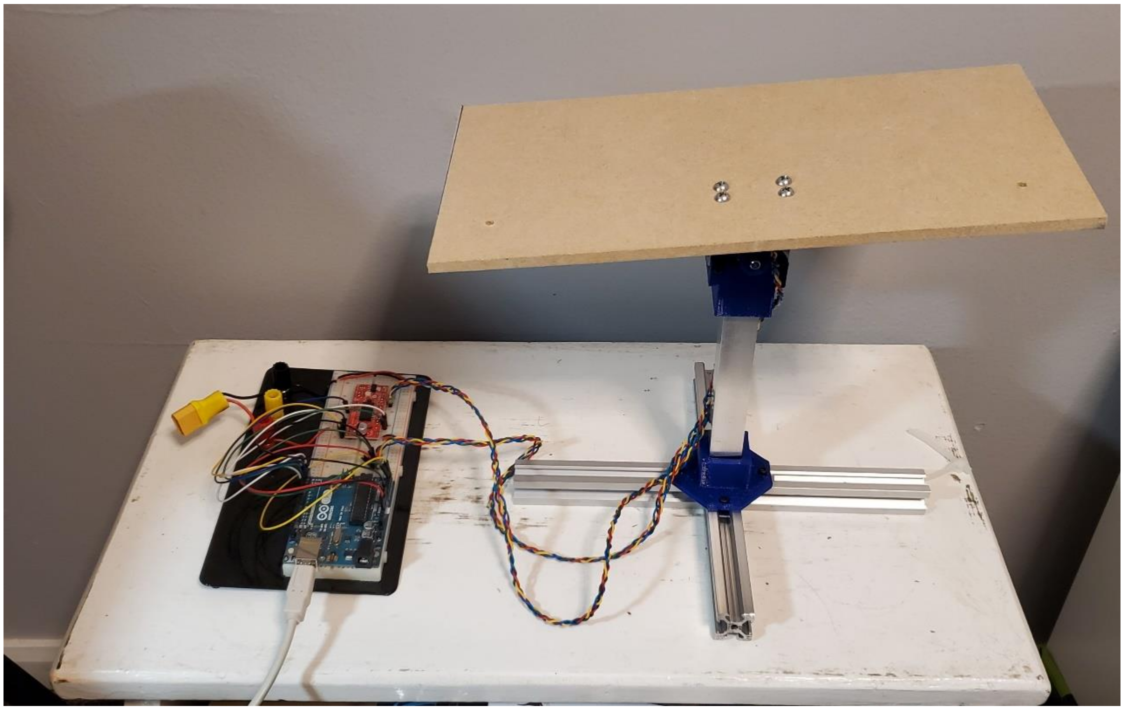

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

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San Luis Obispo

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Chapter 1: Abstract

Optimal solar panel systems rotate to track the sun, as solar panels operate at their maximum potential when the panel plane is completely normal to the sun’s rays. These tracking systems often using two axes of movement. This project is to design a system that will allow a solar panel to track the sun using only one rotational axis, which saves energy and uses fewer parts. The system tracks the entire range of the sun's motion and has positional feedback to allow control of the solar panel's angle. The position of the tracking system is controllable via an external computer. The goal of this project is to construct a solar tracking device that accurately tracks the sun in order to maximize the energy output of the solar panel.

1.1: Introduction

I selected the project based on its focus on control systems and mechatronics, with some components of digital signal processing and power electronics. The project mainly revolves around motor control and the interpretation of digital control signals. It is somewhat related to a separate senior project in which the algorithm for maximizing the power output of a single axis tracking solar panel is developed. The project will experiment with solar tracking algorithms to optimize solar energy output in a manner similar to the research done in [7] and [10]. This project focuses on building the hardware systems that will be controlled by this algorithm.

While single axis solar panels are not a new development and are a well established part of the solar industry, the goal of this project is to build a single axis solar tracker for laboratory use, in order to optimize and test solar tracking algorithm. The project will include an exploration of the PID control systems (as demonstrated in [11]) and microcontroller processes (as demonstrated in [5], [9], [12]) previously used by other researchers to control solar panel trackers. Through top-down design of the solar tracking device, the hope is to explore unique methods for actuating the solar panel and controlling position, which may be more efficient or more accurate than other systems.

The project mainly encompasses class material from control systems classes such as EE302, as well as embedded computing for the microcontroller and signal processing (CPE329). There will also be electronics design tasks utilizing material from EE409. The motor control aspects of the project will be related to motor and power classes such as EE255/295. The project will require additional knowledge and techniques not covered by course material such as PCB design, CAD, and solar power simulation.

Please note that due to the COVID-19 pandemic, all classes were moved to an online format in Spring 2020 and the project hardware from Fall and Spring 2019 became inaccessible. The project shifted from a full scale prototype to a miniature model that focused on the positional control electronics and lacked many of the previous mechanical requirements.

1.2: Customer Needs, Requirements, and Specifications

Customer Needs Assessment

The customer specified that the solar panel tracking system must be single axis. There are a wide variety of solar panel makes and models the end user may mount to the tracker, therefore the device must have mounting options and a weight capacity suitable for most types of solar panels. The customer also requested a -90° to 90° range of rotation to fully track the sun's movement in order to track the sun from sunrise to sunset.

Requirements and Specifications

The tracking module would ideally have a -90° to 90° range of movement in order to track the sun's full range of movement throughout the day. Also, tracking the sun, by definition, requires that the device rotates the solar panel fast enough to keep up with the sun's movement. Since this project does not encompass the control system and tracking algorithm, it must be able to communicate with an external device to control its movement. While the goal of the project is to create a tracking system that consumes as little power as possible, there should be a benchmark of 10% relative to the solar panel's maximum power output. For the tracker to achieve a net gain in power output, its power consumption must be small compared to the increase in efficiency it causes. The solar panel tracker must be able to function for long periods outdoors, requiring a certain degree of water and dust resistance as has been researched in [4]. Table 1 below describes each engineering specification and which marketing requirement each one fulfills.

Table 1. Single Axis Solar Panel Tracker Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1	-90° to 90° range of movement	This is the range of movement for the tracker to face the sun from sunrise to sunset.
1	Rotates at a speed adequate to track the sun	Solar tracking requires the device to move at the same angular rate as the sun.
2	Includes a computer-compatible digital input port	Control of the tracking module is done by another team via a separate device.
3	Tracker power consumption must be under 10% of the solar panel's power output	Power consumption must be very low for a tracking system to achieve a net gain in power output.
4	Meets IP65 dust/water resistance tests	This is an adequate level of protection for typical outdoor use
5	30kg weight capacity	This is an upper estimate for standard size solar panels plus mounting hardware

Marketing Requirements

1. Capable of tracking the sun throughout the day
2. Can be controlled by a separate external system
3. Low power consumption
4. Suitable for functioning outdoors
5. Can carry a wide variety of different solar panels

The requirements and specifications table format derives from [1], Chapter 3.

Table 2. Single Axis Solar Panel Tracker Deliverables

Delivery Date	Deliverable Description
2/14/20	Design Review
3/6/20	EE 461 demo
3/6/20	EE 461 report
5/18/20	EE 462 demo
5/22/20	ABET Sr. Project Analysis
5/27/20	Sr. Project Expo Poster
5/22/20	EE 462 Report

Table 2 above lists the due dates of each written deliverable required for the project. A more specific project schedule is included in the Project Planning section.

1.3: Functional Decomposition

Table 3. Single Axis Solar Panel Tracker Inputs and Outputs

Module	Single Axis Solar Tracker
Inputs	Digital Control Signal: Data from external computer or microcontroller Mains Power: 120V AC, 60Hz outlet power Current Position Data: Measurement of the tracker’s angular position
Outputs	Angular Position: Solar panel positioned at the angle specified by the input instructions (-90°-90°)
Functionality	The solar tracker rotates such that the attached solar panel faces the angular position specified by the external control signal.

Table 3 above describes the inputs, outputs, and general functions of the solar panel tracker system. The function of the system is to point the solar panel in the angular direction matching the instruction given by the input control signal. The device takes in a digital control signal from another device which indicates the position the solar tracker should be facing. The device also requires a power source, which will be from a standard 120V wall socket. The system additionally takes a measurement of its current position as an input which it uses for feedback control. The output of the system is the solar panel’s physical position, facing the angle specified by the digital control signal input. The inputs and outputs are illustrated in the Level 0 block diagram in Figure 1 below.

Level 0 Block Diagram

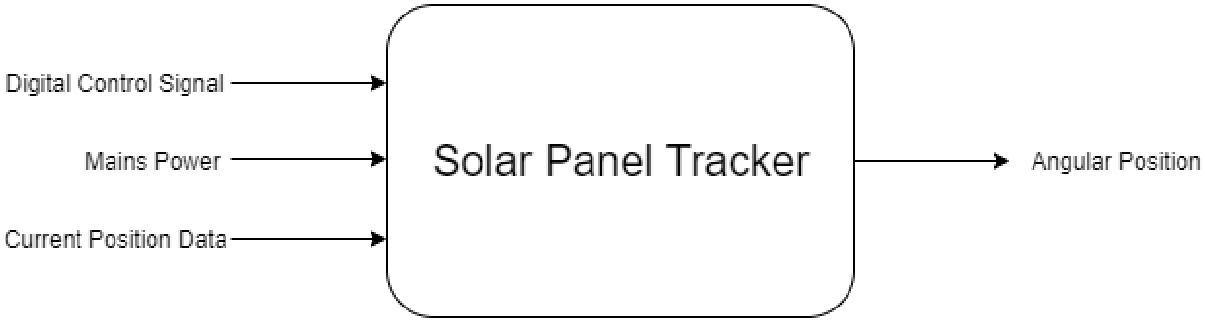


Figure 1: Single Axis Solar Tracker Level 0 Block Diagram

Level 1 Block Diagram

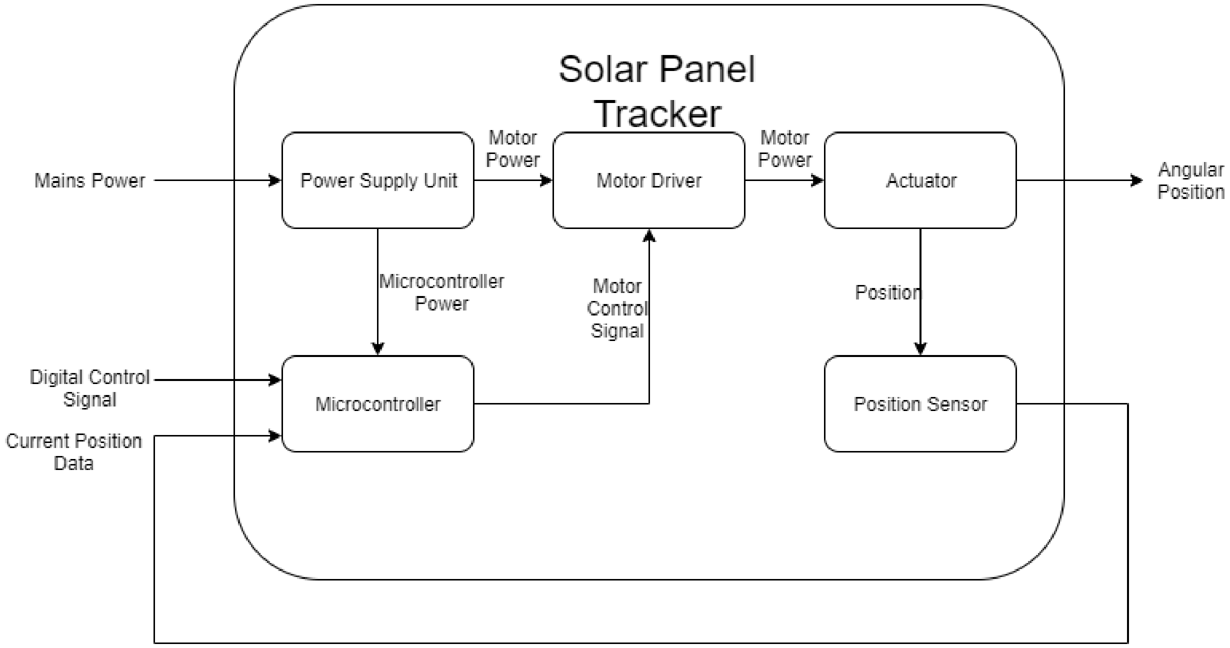


Figure 2: Single Axis Solar Tracker Level 1 Block Diagram

Figure 2 above is a Level 1 block diagram which illustrates the flow of data and power between the individual subsystems of the device. A power supply unit steps down the input AC power to low voltage DC power usable by the microcontroller and motor driver. The microcontroller takes the digital control signal and current position data and uses positional feedback to determine how the actuator must move in order to reach the desired position. It sends the according signals to the motor driver, which in turn sends power to the actuator to rotate the solar panel. A position sensor reads the current position of the solar panel and sends the position data to the microcontroller.

1.4: Project Planning

Gantt Chart

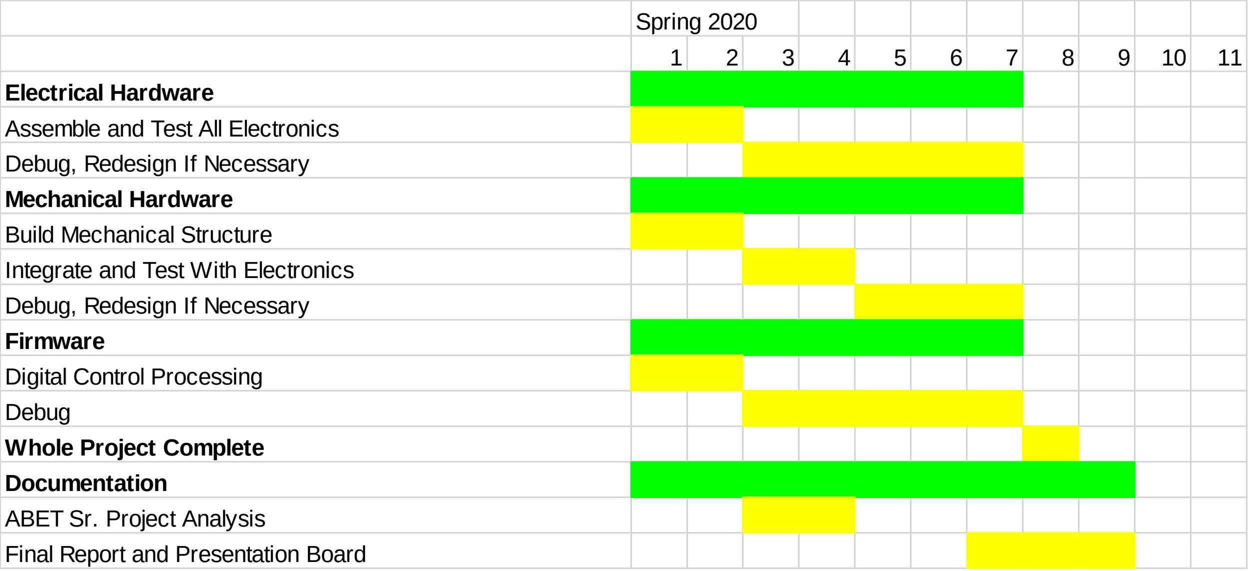
Table 4. Gantt Chart (Fall 2019)

	Fall 2019											
	1	2	3	4	5	6	7	8	9	10	11	12
Project Plan	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Abstract V1	🟨											
Requirements and Specifications		🟨	🟨									
Block Diagram				🟨								
Literature Search		🟨	🟨	🟨	🟨							
Gantt Chart						🟨						
Cost Estimates						🟨						
ABET Sr. Project Analysis							🟨					
Requirements and Specifications V2+Intro								🟨				
Report V1	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨				
Advisor Feedback Due					🟨					🟨		
Report V2											🟨	

Table 5. Gantt Chart (Winter 2020)

	Winter 2020										
	1	2	3	4	5	6	7	8	9	10	11
Electrical Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Design Actuator Driver Module, Purchase Components	🟨	🟨	🟨								
Assemble Actuator Driver Module				🟨	🟨	🟨					
Test, Debug, and Revise Actuator Driver Module							🟨	🟨	🟨	🟨	
Design Power Supply, Purchase Components	🟨	🟨	🟨								
Assemble Power Supply				🟨	🟨	🟨					
Test, Debug, and Revise Power Supply							🟨	🟨	🟨	🟨	
Design Signal Processing Module, Purchase Components	🟨	🟨	🟨								
Assemble Signal Processing Module				🟨	🟨	🟨					
Test, Debug, and Revise Signal Processing Module							🟨	🟨	🟨	🟨	
Assemble and Test All Electronics											
Debug, Redesign If Necessary											
Mechanical Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Select Critical Components	🟨	🟨									
CAD Assembly, Purchase Parts			🟨	🟨	🟨	🟨					
Build Mechanical Structure							🟨	🟨	🟨	🟨	🟨
Integrate and Test With Electronics											
Debug, Redesign If Necessary											
Firmware										🟩	🟩
Digital Control Processing										🟨	🟨
Debug											
Whole Project Complete											
Documentation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Design Review						🟨					
Interim Report and Demo									🟨	🟨	

Table 6. Gantt Chart (Spring 2020)



	Spring 2020										
	1	2	3	4	5	6	7	8	9	10	11
Electrical Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Assemble and Test All Electronics	🟨	🟨									
Debug, Redesign If Necessary			🟨	🟨	🟨	🟨	🟨				
Mechanical Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Build Mechanical Structure	🟨	🟨									
Integrate and Test With Electronics			🟨	🟨							
Debug, Redesign If Necessary					🟨	🟨	🟨				
Firmware	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Digital Control Processing	🟨	🟨									
Debug			🟨	🟨	🟨	🟨	🟨				
Whole Project Complete								🟨			
Documentation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
ABET Sr. Project Analysis			🟨	🟨							
Final Report and Presentation Board							🟨	🟨	🟨		

Tables 4-6 above are the Gantt charts for each quarter of this project. Fall 2019 consists of planning and preparation tasks, which are complete as of the writing of this report. Winter 2020 will consist mostly of electronic design, assembly, and testing for the microcontroller, motor driver, and power supply. The mechanical design and construction of the frame and drive system will begin during this quarter, but at less of a priority than the electrical components. In Spring 2020, the electronics should be complete but additional time is allotted for troubleshooting. The mechanical parts should be finished in the beginning of this quarter, and the mechanical and electronic systems will be integrated and tested together. The firmware will be finished in the beginning of the quarter and the whole system will undergo testing and troubleshooting. The whole device should be functional by Week 7 of Spring quarter. The end of the quarter will consist of finishing the final report and the presentation board.

Cost Estimates

Table 7. Cost Estimates

Item	Cost (USD)	Explanations/Notes
Actuator	50	An upper average for medium sized gearmotors
Electronic Components	100	Microprocessor, ICs, passive components
PCB Manufacturing	40	For two boards plus shipping, multiple revisions
Structural Materials	200	Aluminum extrusions and brackets
Fasteners	30	Moderate number of screws and nuts
Mechanical Components	100	Gears, shafts, bearings, etc.
Labor	2250	150 hours, $15/hour
Total	2770	

Table 7 above enumerates the costs of the parts and materials needed to construct the solar tracker. The actuator is currently undetermined and may be a DC gearmotor, linear actuator, or brushless motor; $50 is allotted for the cost of this actuator since this is an average cost for medium sized motors. The electronics such as the microprocessor, power supply, and discrete components should total under $100, and the PCB manufacturing will likely be under $40 (This is a high estimate due to shipping and multiple revisions). Various mechanical parts are required such as aluminum extrusion for the frame, and gears, shafts, and bearings for the drive system. The project has approximately $1000 additional funding for aluminum extrusions and frame parts, but the actual cost of these parts will likely be well under this value, approximately $200.

Chapter 2: System Design and Construction

2.1: Mechanical Structure

The experimental setup required a frame with appropriate dimensions and strength to carry a 2073x1072mm industry standard solar panel. The frame therefore must be 1m high from base to rotational axis ideally with 10-20cm additional clearance. The frame was composed mainly out of standard 3030 aluminum T-slot extrusion due to its strength and ease of construction. Plates to attach the extrusion beams together were also bought off the shelf, and hardware to mount bearings were machined from aluminum. A 1/2 inch diameter steel D-shaft was the axis of rotation on which the panel would be mounted. The shaft was inserted through a pair of flange bearings mounted to aluminum plates, which were in turn mounted to the vertical frame T-slot extrusions. An ANSI 25 72 tooth sprocket was attached to the D-shaft. The intention was for this sprocket to be driven via chain by a smaller sprocket attached to the motor output shaft to add gear reduction. This stage of the mechanical design is illustrated in Figure 3, the Solidworks assembly for the frame and axis of rotation.

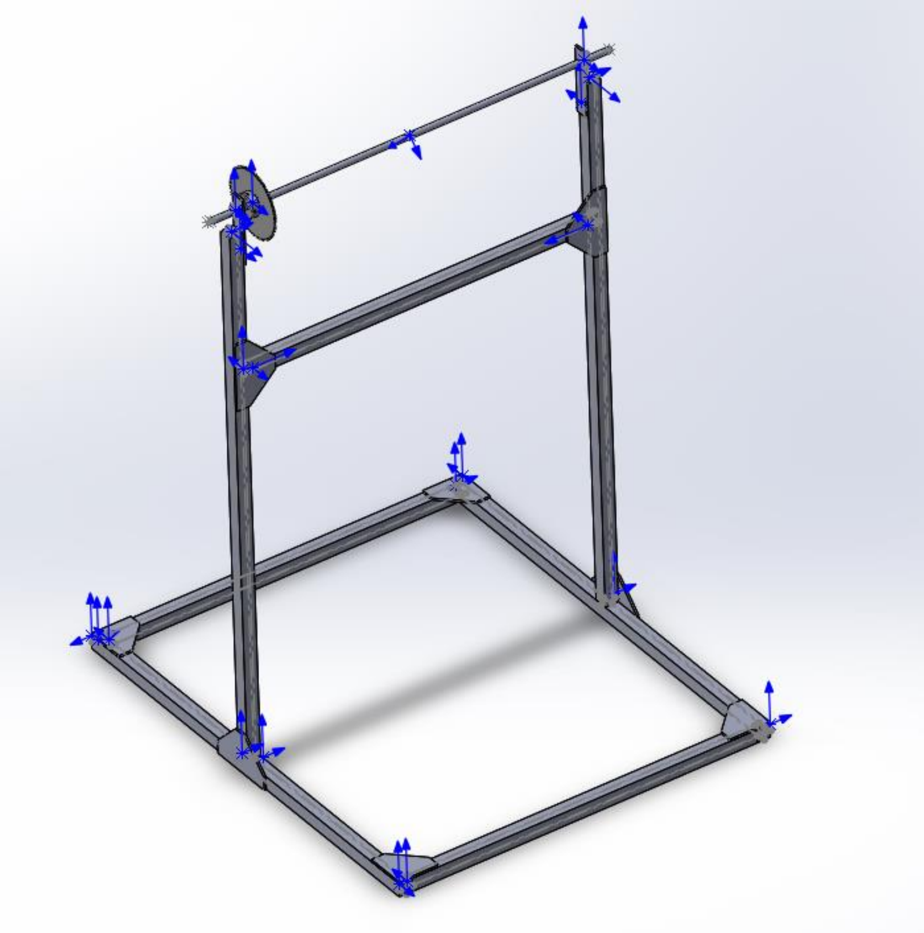


Figure 3: CAD Model of Extruded Aluminum Frame

Due to circumstances preventing further work on the full size frame, a smaller prototype model was constructed in order to test the positional control system. The model did not require the structural strength or size to carry a solar panel. This version was constructed out of smaller 2020 size T-slot extrusions, 3/4 inch aluminum square tubing, and 3D printed brackets. A 3D printed hub connected an MDF board (to model the solar panel) and an accelerometer to the shaft of a stepper motor.

2.2: Stepper Motor and Motor Driver

For the original full scale solar panel tracker, the motor requirements were that it provide enough torque to rotate the solar panel and was capable of speeds fast enough to track the sun. Low speeds later became desirable for safety reasons and to minimize strain on the solar panel and frame. A NEMA 23 size 100:1 geared stepper motor was selected due to its high gear ratio, which increased its torque and reduced its speed. With a 1Nm holding torque before the gearbox [13], it would have a 100Nm holding torque with the gearbox, and 514Nm torque after the 14 to 72 tooth chain reduction. The solar panel would be mounted on a 10cm distance from the shaft according to the mechanical design, and the solar panel weighs 25.4kg [6], for a necessary torque of 24.9Nm. The geared motor torque far exceeds the torque required. While the gearing does improve the motor's low speed capability, there is no minimum speed requirement for a stepper motor, which makes them ideal for low speed, high precision applications. The stepper motor has a 1.8 degree step angle, which when divided by the 100:1 gear ratio and the 14 to 72 tooth chain reduction, becomes 0.0035 degrees, which is an extreme level of precision for this application. A smaller step angle means the device can make smaller adjustments towards its target angle.

When the project shifted to a small scale model, torque was no longer a concern as the device did not need to carry the load of a real solar panel. A smaller, ungeared NEMA 17 stepper motor was chosen. The step angle of this stepper motor is 1.8 degrees according to the datasheet [14], which is inadequately precise for the purposes of a solar panel tracker. However, the step angle of a stepper motor can be divided into a higher resolution using microstepping, a control method that allows for divisions of the step angle by 2, 4, or 8 depending on the driver.

The stepper motor must be controlled using a stepper motor driver board. The requirements for the driver in this project were that it could run at 12V and that it had 1/8 microstepping. 12V is the standard motor voltage for solar panel trackers, as it allows the user to easily power the device using batteries. The microstepping requirement is so that the motor step angle can be subdivided into more precise steps. The selected stepper driver module was the Sparkfun Easydriver, which fulfills both of these criteria as per the specifications in the datasheet [15]. Given the 1.8 degree step angle of the motor, the stepper motor driver can divide the step angle by 8, for a microstep angle of 0.225 degrees. This allows for fine sub-degree adjustments.

The stepper motor driver board has two main control pins that take digital signals from the microcontroller: The DIR pin which determines which direction the motor rotates, and the STEP pin which tells the driver to make one step of the motor on the rising edge of the input signal. There is an additional ENABLE pin that can be used to turn the motor control on or off, and two pins (MS1 and MS2) that are used to select different subdivisions of microstepping. For the purposes of this project, the ENABLE pin was always set low to enable motor movement (this pin has active low logic), and both MS pins were set high to select 1/8 microstepping. The driver board has VCC and GND connections for the motor power, and four output pins to connect to the leads of a bipolar stepper motor. This setup is identical to the one detailed in the reference guide [16].

2.3: Accelerometer Angle Measurement

The accelerometer is a device that measures the acceleration in one direction. If the device is at rest, it can be used as an inclinometer by measuring the acceleration due to gravity. In this project, an accelerometer was attached to the output shaft of the solar panel mount to measure the angle of the solar panel. The accelerometer is mounted in a direction where the Y-axis is parallel to the motor output shaft, and the X and Z axes are perpendicular to it, as illustrated in Figure 3. The advantage of an accelerometer for this application instead of a potentiometer commonly used in solar panel tracking mounts is that an angle measurement through an accelerometer is taken relative to the Earth's gravitational acceleration, while a potentiometer measures the angle of the solar panel relative to the frame. Since the accelerometer measures the angle relative to true level, the measured angle is not dependent on the angle of the frame due to uneven ground, while the potentiometer measured angle would cease to be accurate if the frame is not level with the true horizontal. Note that the accelerometer comes with drawbacks, the most problematic being that the gravitational angle measurement is only accurate if the device is stationary and not accelerating, in which case the device cannot distinguish between these accelerations and gravitational acceleration.

The accelerometer used in this project was the MMA8452Q Triple Axis Accelerometer Breakout from Sparkfun. The MMA8452Q (detailed in the datasheet [17]) is a commonly used accelerometer IC, the breakout board includes supporting components and pads to connect to other devices. The device is well documented and this project utilizes libraries written by Sparkfun to easily read data from it as utilized in the reference guide [18]. The accelerometer is powered by a 3.3V source, and communicates with a microcontroller through I2C. It includes an SDA and SCL pin for the I2C data protocol. Due to the orientation the accelerometer is mounted to the motor output shaft, the Z axis is used as the measurement direction. To measure an angle, the accelerometer measures the current acceleration in Gs using the function “getCalculatedZ()” in the library. This returns a value that ranges from -1 to 1 given that there are no non-gravitational accelerations. The measured angle is the inverse sine of this value. The control loop for this project measures and calculates this value each cycle in order to determine the current angle of the solar panel.

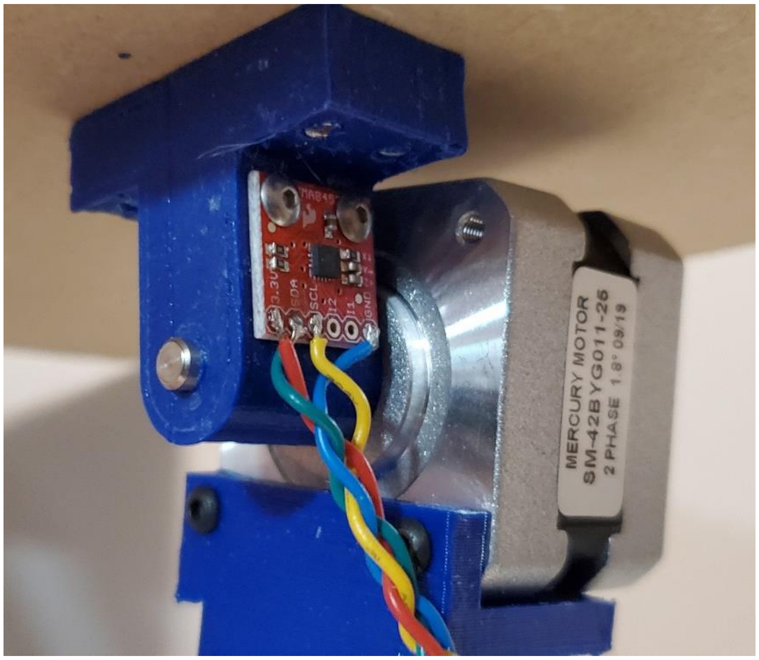


Figure 3: Accelerometer Mounting Position on Motor Output Shaft

2.4: Microcontroller and Feedback Control

In order to utilize the libraries written for the accelerometer, the program was to be written in Arduino. The microcontroller must have connections for I2C to interface with the accelerometer, as well as a 3.3V power source. The microcontroller also requires five digital output pins to control the stepper motor driver. Processing requirements are fairly low, as the peripheral components are not dependent on high signal speeds, and the control loop runs at a low rate. For prototyping convenience, a small form factor board with breadboard compatible header pins was desirable. For these constraints, the Teensy 4.0 was chosen. It has the required data pins and is designed to be small and breadboard compatible. Its processing speed far exceeds that required for this project, but that is not a problem. Information about this microcontroller is detailed in the datasheet [19].

The Teensy 4.0 was replaced partway through the project with an Arduino UNO microcontroller. This was due to a communication port problem with the host computer, which caused it to stop being compatible with the Teensy board. While an inconvenient deviation, it does confirm that the program has low processing requirements and is unaffected by the type of microcontroller used, provided that it has enough digital I/O pins and supports I2C.

The program first initializes the I/O and I2C pins, as well as the serial connection to the host computer. The stepper driver is enabled and set to 1/8 microstepping. The main loop begins, and the program prompts the user on the host computer to input a desired target angle value. Integer and float values are accepted, the program informs the user and re-prompts if the input is out of range (-90 to 90) or is a non-number. Once a valid setpoint is given, the secondary control loop begins, which begins with a calculation of the current angle using the accelerometer as detailed in section 2.3. The current angle is subtracted from the setpoint angle to find the error value, or how far the motor must turn to reach the setpoint angle. The error value is divided by 0.225 (the 1/8 microstep angle of the stepper motor) to find the number of motor steps required to reach the setpoint angle. The DIR pin on the stepper driver is set based on the sign of the error value, and the calculated number of pulses is sent to the STP pin of the motor driver to move the motor by the calculated position. In order to achieve higher accuracy, this loop is iterated multiple times. Between loops, the program pauses for one second, which allows the mechanical hardware to settle and stop vibrating before taking the next acceleration measurement. This eliminates the issue of vibrations causing inaccurate acceleration readings. The conditions of the loop cause the loop to repeat until the measured angle is within 0.25 degrees of the setpoint or the loop has been iterated 10 times (to prevent an infinite loops). Once this loop has finished iterating, the main loop prompts the user to input another angle value.

Chapter 3: System Performance

3.1: Performance Testing

The primary performance metric was the device's accuracy, in terms of positioning the solar panel as close as possible to the user input target angle. A series of tests was conducted to determine the accuracy of the device. The first experiment tests medium distance angle change intervals, stepping in increments of 10 degrees and measuring each position. This test was repeated three times.

Table 8. Medium Increment Positioning Test

Target Angle	Measured Angle		
	Trial 1	Trial 2	Trial 3
0	0.1	0.2	-0.1
10	9.8	10.2	10.3
20	20.1	19.8	20
30	30.1	30.3	29.8
40	39.8	40	40.2
50	50.1	49.8	50.2
60	59.7	60	59.9
70	70.7	70.4	70.6
80	83	81.3	82.1
90	90	89.9	89.4

The result of the medium increment test indicate that the device is capable of an accuracy of +/- 0.2 degrees from the target angle up until the 70 degree test. In the tests 70 degrees and after, the angle deviates multiple degrees from the target angle. In the 70 and 80 degree tests, the resulting angles are up to 3 degrees too high. Note that the 90 degree test remains at or below 90 degrees because the frame physically restrains it from moving past this angle. The mathematically likely reason for this problem is that the angle calculation relies on taking the inverse sine of the acceleration. This means that as the panel becomes closer to vertical and the acceleration approaches 1, smaller changes in the input of the inverse sine function result in larger changes to the output. This causes the calculations to lose precision, especially given the limited number of digits produced by the accelerometer. While the device is technically capable of positioning from -90 to 90 degrees, the range for optimum accuracy is -70 to 70 degrees.

The second test measured the solar panel tracker's ability to make small adjustments accurately. The test was run in the same manner as the medium distance test, except the angle was incremented by 1 degree for each data point. This test more accurately represents the solar panel tracker's end use, as throughout the day a solar tracker only moves in very small increments at a time.

Table 9. Small Increment Positioning Test

Target Angle	Measured Angle		
	Trial 1	Trial 2	Trial 3
0	0.1	0.2	-0.1
1	1	1.2	0.9
2	1.9	2.1	2.2
3	3.2	2.9	3
4	4	4.2	3.8
5	5.1	5.2	5.1
6	5.9	6	5.8
7	7.3	6.8	7.1
8	8.1	8.1	7.8
9	9	9.2	9.1
10	10.3	10.1	9.8

The results of the small increment test show that the positional control is almost as accurate as the motor hardware allows when making small changes to the angle. The error is almost always up to +/- 0.2 degrees. These values are what were expected, given that the smallest adjustment the motor can make is 0.225 degrees. This means the device is incapable of adjustments smaller than 0.225 degrees. It is likely that a geared stepper motor or one built with smaller steps would be able to achieve higher accuracy.

3.2: Expense Tracking

Table 10 below enumerates the costs of the hardware components purchased for the development and construction of the project. The hardware cost ($271.42) was far below the initial estimated cost of $520. The initial calculations slightly overestimated the cost of the mechanical and structural components. The cost of the motor and electronics were further overestimated, the main difference being that the original estimate anticipated PCB manufacturing and higher power components. The mechanical hardware was constructed at full scale, while the electronics were purchased after the project switched to a small scale model. The small scale model did not require a separate power supply unit as the original estimations anticipated. Since weight capacity ceased to be a problem, a much smaller and less expensive motor and motor driver were used, which cut down costs considerably.

Table 10. Expenses (Actual)

Item	Cost (USD)	Quantity	Extended Cost (USD)
½ Inch Diameter D-Shaft, 36 Inch	24.62	1	24.62
ANSI 25 Roller Chain Sprocket, 14T	11.54	1	11.54
ANSI 25 Roller Chain Sprocket, 72T	45.08	1	45.08
ANSI 25 Roller Chain, 3 Feet	15.42	1	15.42
ANSI 25 Roller Chain Link	1.00	1	1.00
½ Inch Set Screw Shaft Collar	1.68	2	3.36
½ Inch Flange Bearing	7.30	2	14.60
M5x10 Screws, 100 Pack	5.95	1	5.95
M5 Hammer Nuts, 100 Pack	13.95	1	13.95
3030 90 Degree T Joining Plate	2.45	4	9.80
3030 90 Degree Bracket	3.45	4	13.8
3030 Aluminum Extrusion, 2000mm	16.95	2	33.90
Teensy 4.0	19.95	1	19.95
Breadboard	9.95	1	9.95
XT60 Connector	1.50	1	1.50
Jumper Wires M/M	2.25	1	2.25
Jumper Wires M/F	1.95	1	1.95
Jumper Wires F/F	1.95	1	1.95
Stepper Motor	15.95	1	15.95
EasyDriver Stepper Motor Driver	14.95	1	14.95
Sparkfun Accelerometer Breakout	9.95	1	9.95
Total			**271.42**

Chapter 4: Conclusion

4.1: Accomplishments

The final version of the device mostly fulfilled the purpose of the project. Many mechanical goals of the project such as carrying capability had to be completely abandoned, as the full size prototype could not be constructed and a smaller model was substituted. Regarding the engineering specifications, the model fulfilled the requirements for speed, movement range, and accepting inputs from an external computer. Water/dust ratings, power consumption, and carrying capacity became non-issues. While it was not an original numerical engineering specification, accuracy became a main focus for the device. The model offers accuracy within +/- 0.2 degrees, which is considered to be accurate enough for solar panel trackers. The method of positional control utilized for this project, while needing some improvements, has potential as a low cost and low computing power method for controlling solar panel trackers at low speeds and high precision.

4.2: Improvement Opportunities

The accuracy of the device's positional control would benefit greatly from using a geared stepper motor. Gearing down the stepper motor would effectively divide the step angle further, allowing for adjustments of very small fractions of a degree. In addition, the gearing would reduce the vibration of the panel, reducing the necessary pause time between control loop iterations. Another potential area of improvement is the accelerometer. As discussed in section 4, the accuracy of the acceleration measurement is limited by the resolution of the accelerometer as the acceleration approaches 1G. One simple solution would be to use an accelerometer with a higher bit resolution. Another option would be to utilize the 3 axis accelerometer by retaking the measurement with the X-axis accelerometer if the Z-axis accelerometer reads a steep enough angle. When the Z-axis acceleration is high, the X-axis acceleration is low, and vice versa. This way, the acceleration measurement would always be in the most accurate range for whichever accelerometer is in use.

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Appendices

Appendix A. Source Code

```
//Code for stepper motor and accelerometer based positional control for solar
panel tracker
//Ezra Pramono
//June 9, 2020

#include <Wire.h>                  // Must include Wire library for I2C
#include "SparkFun_MMA8452Q.h"     // Click here to get the library:
http://librarymanager/All#SparkFun_MMA8452Q
#include <math.h>

MMA8452Q accel;                    // create instance of the MMA8452 class

 //Declare pin functions on Microcontroller
#define stp 2
#define dir 3
#define MS1 4
#define MS2 5
#define EN  6

//Declare variables for functions
int x;
char inputBuffer[16];
float setpoint;
float acceleration;
float currentAngle;
float error;
int stepCount;
int cycles;


void setup() {
  pinMode(stp, OUTPUT);
  pinMode(dir, OUTPUT);
  pinMode(MS1, OUTPUT);
  pinMode(MS2, OUTPUT);
  pinMode(EN, OUTPUT);

  Serial.begin(9600); //Open Serial connection for debugging
  Serial.println("Enter Angle in Range -90 to 90");

  Wire.begin();

  if (accel.begin() == false) {
    Serial.println("Not Connected. Please check connections and read the
hookup guide.");
    while (1);
  }

  digitalWrite(MS1, HIGH); //Pull MS1, and MS2 high to set logic to 1/8th
microstep resolution
  digitalWrite(MS2, HIGH);
```

```
  digitalWrite(EN, LOW); //Pull enable pin low to allow motor control

}

void loop() {
  // put your main code here, to run repeatedly:

  while(Serial.available()){

      Serial.readBytes(inputBuffer, sizeof(inputBuffer)); //read serial
input, convert to numerical value
      float userInput = atoi(inputBuffer);
      memset(inputBuffer, 0, sizeof(inputBuffer));

      error = 1; //initialize reference value to avoid an error in loop later
      cycles = 0;

      if (userInput <= 90 && userInput >= -90) { //make sure input is within
bounds
        setpoint = userInput; //record input as setpoint

        Serial.print("setpoint ");
        Serial.println(setpoint);

        while ((error > 0.25 or error < -0.25) && cycles < 10) { //loop until
adequately close to setpoint or reaches 10 cycles
          acceleration = accel.getCalculatedZ(); //read Z axis acceleration
from accelerometer
          if (acceleration < -1) { //Avoid inverse cosine error
            acceleration = -1;
          }
          else if (acceleration > 1) {
            acceleration = 1;
          }
          Serial.print("acceleration ");
          Serial.println(acceleration);
          currentAngle = asin(acceleration)*57.2958; //take inverse sine of
acceleration, convert from radians to degrees
          Serial.print("current angle ");
          Serial.println(currentAngle);
          error = setpoint-currentAngle; //find error value from current
angle to setpoint
          Serial.print("error ");
          Serial.println(error);
          Serial.println();

          stepCount = abs(error)/0.225; //calculate number of steps required
to reach setpoint

          if (error > 0) {
            digitalWrite(dir, HIGH); //Pull direction pin low to move
counterclockwise (towards positive angle)
          }

          else if (error < 0) {
            digitalWrite(dir, LOW); //Pull direction pin low to move
clockwise (towards negative angle)
```

```
          }

          for(x= 0; x<stepCount; x++)  //send pulses equal to stepCount
          {
            digitalWrite(stp,HIGH); //Trigger one step
            delay(5);
            digitalWrite(stp,LOW); //Pull step pin low so it can be triggered
again
            delay(5);
          }

          cycles += 1;
          delay(1000);
        }
        Serial.println("Finished");
      }

      else {
        Serial.println("Input out of bounds");
      }
  }
}
```

Appendix B. ABET Senior Project Analysis

• 1. Summary of Functional Requirements

Optimal solar panel systems rotate to track the sun, as solar panels operate at their maximum potential when the panel plane is completely normal to the sun's rays. These tracking systems often using two axes of movement. This project is to design a system that will allow a solar panel to track the sun using only one rotational axis, which saves energy and uses fewer parts. The system tracks the entire range of the sun's motion and has positional feedback to allow control of the solar panel's angle. The position of the tracking system is controllable via an external computer. The goal of this project is to construct a solar tracking device that accurately tracks the sun in order to maximize the energy output of the solar panel.

• 2. Primary Constraints

The tracking module would ideally have a -90° to 90° range of movement in order to track the sun's full range of movement throughout the day. Also, tracking the sun, by definition, requires that the device rotates the solar panel fast enough to keep up with the sun's movement. Since this project does not encompass the control system and tracking algorithm, it must be able to communicate with an external device to control its movement. While the goal of the project is to create a tracking system that consumes as little power as possible, there should be a benchmark of 10% relative to the solar panel's maximum power output. For the tracker to achieve a net gain in power output, its power consumption must be small compared to the increase in efficiency it causes.

• 3. Economic

The production and maintenance of this product will require human labor, thus providing jobs to many. If the final product utilizes the same 3030 extruded aluminum frame as the prototype, labor hours are minimal and does not require complex or high skill tasks such as welding. The structure consists of extrusions and brackets that are screwed and bolted together, which can easily be assembled by the end user.

People may invest in this product in the hopes of making a return on the increase in solar power output they provide. In addition, the device improves the energy output of solar panels, allowing solar farms to generate more profit. The implementation of this product would increase the yield of a solar energy plant, thus producing more profit for the user and making solar power more desirable. The device is likely to reduce the use of fossil fuels, as it would cause an increase in solar energy yield by approximately 25-30%. The project earns money for the manufacturer and investors dependent on how many units are sold, and earns money for the end user by increasing the yield of solar power production.

Costs accrue through the project's lifecycle as the device requires repairs and maintenance. This includes parts and materials as well as human labor costs to maintain and fix the devices. The mechanical parts are relatively standard and most are off-the-shelf, which should make replacement and maintenance economical. The electronics consist of several off-the-shelf modules, which makes it simple to swap out parts. Benefits accrue as the device increases solar panel module output. By improving solar module efficiency, the product increases the total energy yield of solar farms over time.

The estimated cost of the project is $2770 (See Cost Analysis, page 8), which includes electronic parts, structural and mechanical materials, and human labor. In addition to consumables, the project also requires the use of electrical and mechanical shop tools and equipment. This includes oscilloscopes, power supplies, and soldering tools used to test and assemble electronic systems, as well as the cutting and machining tools used to construct mechanical components and the frame. The true cost was $2521.42, due to the electronics being simplified and less expensive than anticipated in the original plans. However, this change was partly due to the downscaling of the final product to a miniature model.

• 4. If manufactured on a commercial basis:
The cost of hardware was $271.42. This cost could be brought down to $200 if the materials are bought wholesale in bulk, and the electronics production is optimized. Manufacturing labor is estimated to be approximately $150, assuming $15/hour wages and 10 hours of assembly per product. The manufacturing cost is estimated to be about $350. An estimated 10000 units are to be sold each year, depending on the capacity of the manufacturer. If the sale price is $600 for a profit of $250, the estimated annual profit is $2.5 million.

The cost for the end user to operate the device is dependent almost entirely on repair and maintenance. For the purpose of this calculation, the required maintenance is regular lubrication and inspection, and occasional repair of wiring and replacement of gears, sprockets or bearings. If inspection and lubrication labor costs $20 per hour and is half an hour per device per month, and an annual gearbox replacement is $50, the annual maintenance cost is $570.

• 5. Environmental
The environmental impact of this project is mostly positive, as it increases solar power yield by approximately 30%, and reduces the amount of land required for solar farming. The one downside is that if this product encourages the construction of more solar power plants, more land is required. Depending on where this occurs, companies may unfortunately overrun natural environments to build these solar farms. However, this effect is offset by the fact that tracking solar panels are more efficient than an equivalent sized static solar panel, decreasing the amount of solar panels needed for the same energy output. An additional environmental consideration is the E-waste produced at the end of life of the electronic components. This is addressed in the Sustainability section. By increasing the yield of solar power, the hope is that a larger percentage of the world's power generation comes from solar compared to nonrenewable sources. By making solar energy a more appealing option than oil and coal, the use of oil and coal will be reduced thus reducing the emission of greenhouse gases.

• 6. Manufacturability

The manufacturing supply chain requires the use of off-the-shelf components, and the supply of these products may become unstable. This is an issue that would be resolved with planning and inventory management. The electronics would ideally be consolidated into a single board, which simplifies manufacturing since there are fewer boards to produce. The electronics are mostly surface mount ICs and passive components, with some through-hole mounts for connectors and larger components. All the electronics can be produced using standard existing PCB technologies. Since the physical structure is constructed out of bolted together extrusions and brackets, manufacturing consists of the production of these base components and their assembly. Most of the base components such as the aluminum extrusion would be bought from a third party supplier, only requiring custom manufacturing for motor mounts, bearing blocks, and other items unique to this product. Assembly would be very simple, as there is no welding or other expensive processes that need to be done.

• 7. Sustainability

When the system requires repairs and maintenance, the solar module under repair will be out of commission, decreasing energy yield and disrupting the power flow of the plant. However, due to the mostly off-the-shelf components, replacement parts are easy to find, and since the electronics are mostly modular, it would be easy to swap out individual modules. Maintaining this device will likely require the replacement of electronic components. Ideally, damaged electronic components are to be recycled, but E-waste infrastructure is not always available. The parts most likely to incur wear are the stepper motor, gears, and bearings. Recycling for gears and other mechanical components is already commonplace. Motors must go to E-waste, but consist of copper windings and magnets that are easily separated and recycled. Adding a second axis of tracking would increase yield further, but has other drawbacks such as increasing space required and drawing more energy to power itself. Adding a second axis would also double many of the current parts required: a second motor, accelerometer, and motor driver.

• 8. Ethical

The main IEEE ethical code this project fulfills is “1) to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment;”

The use of the product is ethical as it promotes the use of renewable energy. This benefits the safety and welfare of the public through its benefits for the environment. The product strives to comply with sustainable design practices by increasing the use of solar energy in opposition to nonrenewable energy sources.

The product also fulfills the ethical code “5) to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems; “

The intention of the project is to clearly state how the product will affect humanity in the ecological and economic manners outlined in previous sections. A large effort will be made to publicize all projected effects on the environment and on jobs and investment, both positive and negative.

The project must also fulfill the ethical code “3) to be honest and realistic in stating claims or estimates based on available data; “

The project will involve the presentation of data to show how much of a benefit it provides, and it is important that the results are presented in an honest manner regardless of whether the data is beneficial to the claims of the project. For example, the data for the energy yield must be presented accurately and nondeceptively.

- **9. Health and Safety**

The manufacturing and maintenance of this product may be an inherent danger due to the tools and processes required. For example, the product has moving parts such as the actuator that may be a pinch hazard to the operator. The device moves a large and heavy solar panel that presents a collision hazard. Precautions must be taken in order to produce and maintain the devices safely. While the voltages and currents used in the product are relatively low, they still pose a potential electrocution hazard to those operating it or performing maintenance. Basic electrical safety measures, such as ensuring power is off before handling, must be followed by the operators of this device.

- **10. Social and Political**

If this project succeeds in making solar power more productive and more desirable, energy companies will invest less in fossil fuels in favor of solar energy. This may lead to backlash from parties supporting the interests of fossil fuel production. Such a decline in fossil fuel usage would threaten the jobs and livelihoods of those working in the fossil fuel industry, which includes many low and middle class workers. In addition, there would be inequities among companies planning to utilize the product. Since implementing solar tracking on a large scale requires substantial overhead, struggling solar companies would be at a disadvantage against the ones that can afford to install the system.

- **11. Development**

The mechanical portion of this project required a large amount of CAD design before the construction of the physical product, to ensure dimensions were all valid. The mechanical CAD design was done in Solidworks, and it was good practice in designing with imported part files. The design also required some mechanical calculations for the torque required to actuate the solar panel. Such mechanical engineering tasks were not done often in electrical engineering classes, so they were an interesting interdisciplinary exercise. The challenges in the electrical portion were mostly related to the positional control loop, and the characteristics of the stepper motor and accelerometer. A large part of the troubleshooting involved trying to get accurate measurements out of the accelerometer. Some of the issues were that it did not provide accurate measurements if it was in the process of a movement, so the program had to pause to stabilize the measurement. This was particularly an issue with the stepping motions of the stepper motor, as it introduced frequent changes in acceleration. The project would go more smoothly provided more experience with stepper motor controls and the use of accelerometers.