Sun Tracking Solar Panel Array For Arctic Applications
Final Report

By: Brandon Ewan, Ashhal Shamsi, Zayd Saeed

Final Report for ECE 445, Senior Design, Fall 2020
TA: Sowjanya Akshintala

09 December 2020
Project No. 34

Abstract

With the world facing the effects of climate change the need for renewable energy solutions in every climate is necessary to limit the effects of climate change into the future. One way of doing this is to bring renewable energy production to as many regions and climates as possible. One such climate is the arctic. This project intends to bring solar energy production to the arctic through a solar panel array that tracks the sun and can withstand the harsh temperatures in the arctic environment.

Table of Contents

1. Introduction

1.1 Problem Statement and Solution Overview

With the world facing the effects of climate change one way to reduce the world's greenhouse gas emissions is to increase the use of renewable energy production. In recent years the use of renewable energy has increased in the United States. Currently 17.5% of the United State’s energy usage comes from renewable sources with 1.8% coming from solar energy [1]. For the world to lower its carbon emissions renewable energy sources like solar need to reach as many places as possible. To get solar energy production to as many places as possible means putting solar panel arrays in the harshest of environments such as the arctic. Putting solar panels in the arctic comes with its challenges though. The main issues being the cold and the amount of time that the sun is out being lower than other places in the world. For example in the American Southwest the sun is shining for a majority of the year while in the arctic the sun will not shine for days or weeks at a time. In the United States there is already some solar energy production in the arctic regions of Alaska. Most current solar panels are used for power generation in remote areas off the grid and for heating [2]. In arctic regions like Alaska where year-round sunlight is not available the solar panels need to extract as much solar energy as possible while also being able to withstand the arctic temperatures.

The goal is to create a solar panel array to bring more solar energy production to the arctic. This will be done by making an array that has dual axis tracking meaning that the panels can autonomously track the sun across the sky from East to West as well as tracking the Sun’s location above the southern horizon. This design will also need to be able to withstand the arctic temperatures of the arctic. This will be done by heating the essential components such as the battery and the motors so they can still operate at the low temperatures.

1.2 High Level Requirements

- The system must be able to withstand “Arctic” temperatures as low as -35∘C.
- The system must be powered at all times, either from the battery source or the solar panels.
- The system must be at least 15% more efficient than a fixed solar panel array in terms of energy production.

2.Design

This design for an arctic solar panel array has four main components that are essential to successful operation: the power unit, the control unit, the movement unit, and the temperature control unit. The power unit ensures that a constant 5V is supplied to all of the components. The control unit includes the microcontroller that calculates the Sun's position and signals which relays should be switched on or off. The movement unit positions the solar panel array to the correct position that was calculated by the control unit. The temperature control unit monitors the ambient temperature and will maintain an optimal operating temperature. This block diagram differs slightly from the original block diagram due to the locking relay being removed and locking mechanism being moved to using the motors' internal locking capabilities rather than using an external mechanism.

2.1 Block Diagram

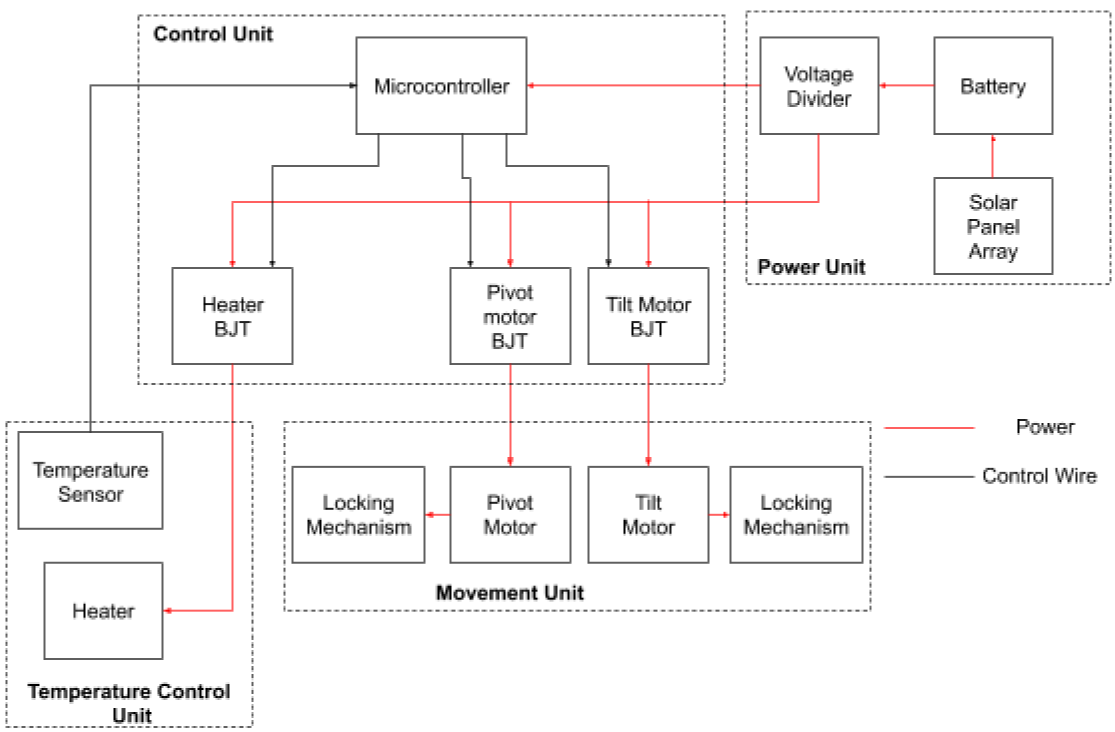

Figure 1. Sun Tracking Solar Panel Block Diagram (Final)

2.2 Power Unit

The power unit is the essential component that is required to supply power to the overall system and interface with the solar panel array

2.2.1 Voltage Divider Design

For the power unit to function properly it needed to take the 18V input from the battery and divide it into 5V and 12V. The final design contained two 5V outputs rather than a 12V. The initial idea for the voltage dividers involved something with a constant voltage drop across it such as a diode. An example of the simulated circuit design is shown in figure 2. However, the voltage was not constant with these diodes. This resulted in the output voltage varying depending on the load which was undesirable as we needed a constant voltage out the output. This issue warranted a redesign of the voltage divider circuit.

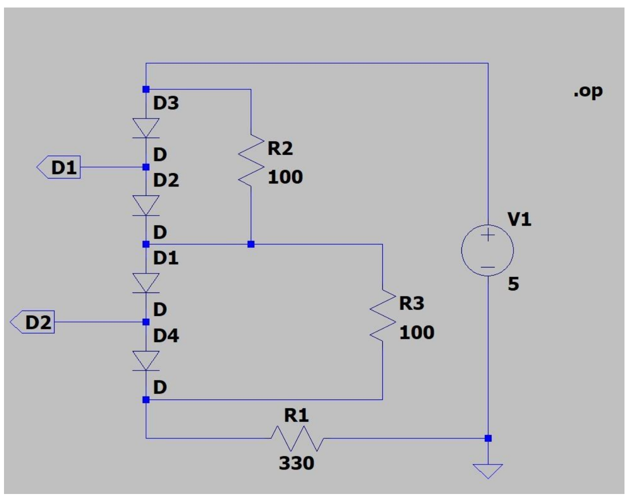

Figure 2. Diode Idea for Voltage Divider Simulation Schematic

The next approach was to use a standard resistor voltage divider using Eq.1 and Eq. 2 to get the desired resistor values for each divider. The resistors for the 12V divider were changed to be the same as the 5V divider when the motors for the project were changed from a 12V motor to a 5V motor.

12V divider resistor calculation $$18\frac{R_1}{R_1+R_2} = 12,\ R_1 = 2.2k\Omega,\ R_2 = 1.2k\Omega \qquad \text{Eq.1}$$

5V divider resistor calculation $$18\frac{R_1}{R_1+R_2} = 5,\ R_1 = 2.2k\Omega,\ R_2 = 5.7k\Omega \qquad \text{Eq.2}$$

After finding the resistor values for the dividers and running some simulations of this voltage divider, we realized that when the output to the dividers was connected to a load it would change the current through the divider and the load. This current change would lead to a variance in the voltage which would be an undesirable behavior because the design requires a constant voltage. To fix this problem we implemented a voltage following op-amp circuit to the outputs of each divider which would result in the voltage remaining constant. The simulation of this circuit as shown in figure 3, verified this result with the voltage being constant at the output even with an applied load.

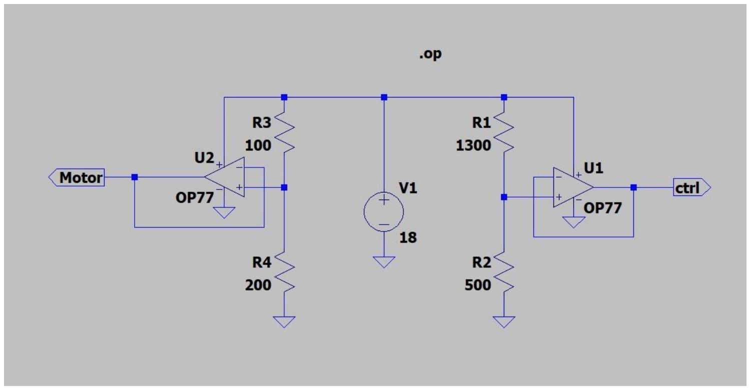

Figure 3. Op-Amp voltage Divider Simulation Schematic

The op-amp design was chosen as the design that would be used on the final PCB because it would output a constant voltage of 5V and was not dependent on the current draw of the rest of the circuit. For the final PCB only 5V dividers were needed which resulted in the 12V divider being replaced by a second 5V divider.

The constant 5V output was verified in the final circuit with and without a load attached to the voltage divider. Without a load the voltage divider had an output of 5.1V and with an attached load the voltage divider had an output of 5.1V. This result shows that the output voltage would remain constant even when under load. The difference between the predicted output of 5V and the actual output of 5.1V is a difference of 2% which falls within our specification of $\pm 5\%$. This discrepancy is likely caused by the tolerances of other parts of the circuit such as the resistors used in the divider not being exactly the listed value. This discrepancy could also be caused by some non ideal behaviors in the op-amp.

2.2.2 Battery Design

Our original idea for the battery was to use a lithium-ion or lead acid battery that was rechargeable and could still operate in the low temperatures of the arctic. The problem with these types of batteries is that they are about $300 which is well outside our budget for this project. We then looked at using rechargeable 9V batteries instead. These also led to a similar issue where they would be too expensive to use given the budgetary constraints of this project. We eventually settled on using standard 9V batteries to power all of the components. This resulted in them not being rechargeable which meant the solar panels couldn't also be used to power the system.

The verification process of the battery used a resistive circuit to draw the specified 100mA for 5 hours. Measurements of the battery voltage were taken every hour to ensure that the battery remained within the specification of 18V $\pm 5\%$. Table 1 shows the results of this test. This test shows that the battery can still output a voltage within our specified tolerance but as the battery drains the voltage lowers to a point that can be outside our specification. An interesting result from this test was that the battery only output 17.4V to start rather than the expected 18V. This may be due to the battery not making a good enough connection to the circuit which could result in the voltage difference. Whenever we would connect a battery to our circuit for testing the battery was always at or slightly above the specified 18V.

Hour	Voltage
0	17.4V
1	17.52V
2	17.32V
3	17.24V
4	17.18V
5	17.08

Table 1. Battery verification test results

2.2.3 Solar Panel Array Design

The solar panel array had to be designed in a way so that it was easy to move on the platform so it could follow the sun's movement throughout the day. Initially the solar panel array was going to also charge the battery and power the system during the day. As described in the battery design section this wasn't possible. This resulted in the solar panels only being connected to a multimeter for testing purposes. The solar panels also needed to be able to output 10V at 150mA and each individual panel could only output 5V at 100mA. To meet the design specifications two panels were wired in series and were then wired in parallel to another set of panel wired in series. This configuration results in a maximum output of 10V at 200mA. A diagram of this wiring configuration is shown below in figure 4.

This design was tested on a sunny day with minimal cloud cover and the array output 11.02V at 157.9mA. The current falls within our specification of 150-200mA, however the voltage output does not fall within our specification of 8-9V. The voltage being higher is a surprising result considering the quality of the solar panels that were used. This result also means that we are able to get more energy out of the solar panel array than we initially thought. This means that even though this block was not within our desired tolerances it actually exceeded them which means this array can be even more efficient than initially thought.

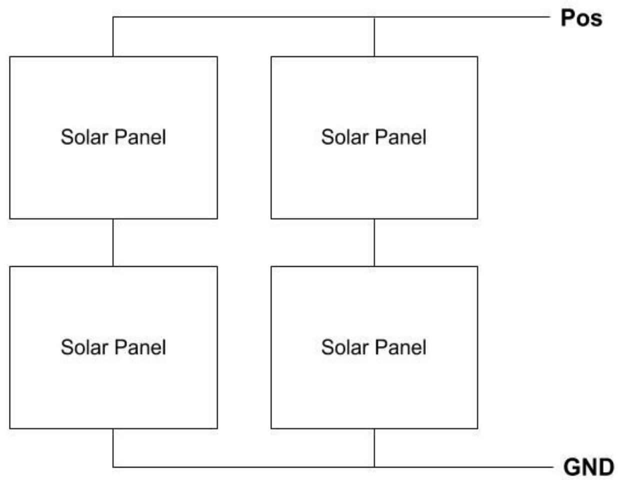

Figure 4. Solar panel array wiring diagram

2.3 Control Unit

The control unit encopasses the microcontroller and the relays that are used to control the motors and the heater. The control unit outputs the correct position to the motors as well as power to the motors and the heater.

2.3.1 Microcontroller

The Microcontroller we chose to use was a Tiva C-Series from Ti that allowed us to work with temporary pins which we could later solder on. This Microcontroller allowed us to take the input from teh temperature sensor as a n analog reading, and output voltage for the switch on the BJTs for the motors using fine increments to control the movement throughout the day and the year as a result.

2.3.2 Relay Design

After researching using relays we discovered that they may be complex to implement and will likely put us over budget. This resulted in us looking into other ways to make a relay that behaves as a controllable switch. This eventually led us to trying to use transistors as controllable switches. At first we tried using a MOSFET as the controllable switch. We attempted a few different orientations and types of MOSFETs to try and get the desired functionality. One of the circuits that we tried is shown in figure 5. Of the circuits that we tested through simulations none of them resulted in the exact functionality that we were looking for. The main issue with the MOSFET circuits was that we could not get them to have the correct switching behavior that was required. Most of them seemed to not pass enough current through them so the power through the applied load was not high enough for the motors.

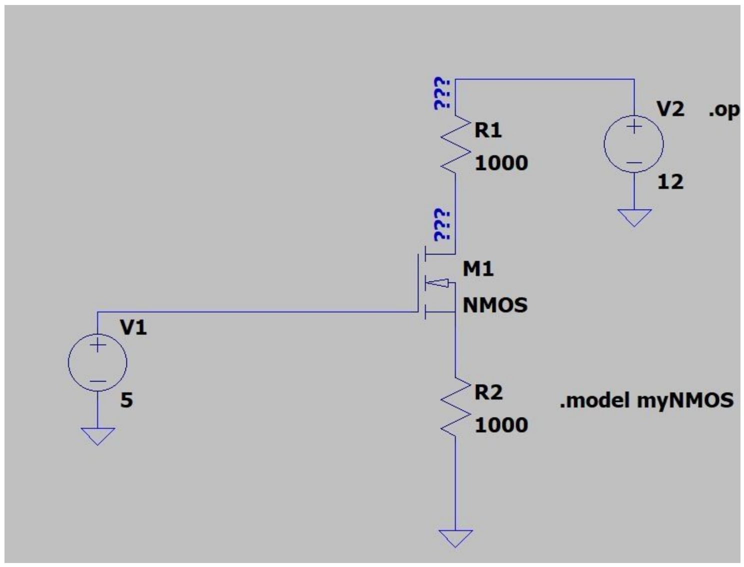

Figure 5. MOSFET Relay Idea Simulation Schematic

After failing to find a design using a MOSFET we began to look at different designs using BJTs. Immediately the BJT designs showed much more promise as they exhibited the correct switching behavior when the 5V signal was applied. After some refinement we achieved the exact switching behavior that was required and the BJT designs were able to pass through a more reliable amount of power which would be more than enough for our needs. One of these refinements is adding a diode across the load. This diode protects the circuit from any back EMFs from the motor when it turns on or off. A simulation of the final design is shown in figure 6.

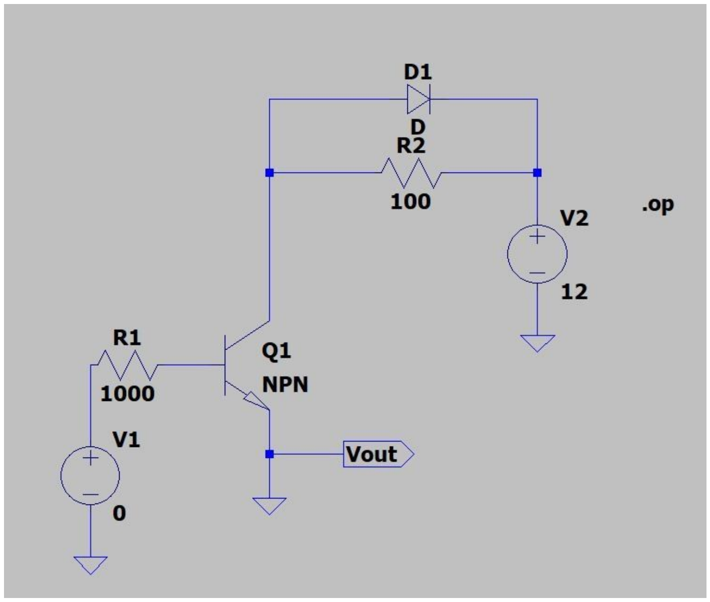

Figure 6. BJT Relay Simulation Schematic

The BJT design with the diode that protects from stray voltages created by the motor is used in the final PCB. The load resistor from the simulation schematic is replaced by the motor leads. This switching relay design was made modular so it could be used for the components that need to have a controlled switch. These components include the three motors and the heater. The original design also had a fourth relay module for a locking mechanism that would lock the motors in place. The locking mechanism relay was eventually removed as it was not needed.

2.4 Movement Unit

The movement unit contains the motors needed to move the array to the correct position. This position is given to the movement unit by the microcontroller. Once in the proper position, the locking mechanism engages, and the unit shuts down while it waits for another signal.

2.4.1 Pivot Motor

The Pivot Motor is used roughly once every hour throughout the day to change the pivot of the solar panel array. The position of the pivot motor is calculated using the azimuth angle of the sun. The azimuth angle determines where the sun is positioned in the sky from East to West. The position is calculated using Eq. 3 and Eq. 4.

$$\delta = 23.45sin(\frac{360}{365}(n-81)) \qquad \text{Eq. 3}$$

$$\phi_s = arcsin(\frac{cos(\delta)sin(H)}{cos(\beta)}) \quad \text{Eq. 4}$$

In these equations δ represents the solar declination angle. The solar declination angle is the relationship between the tilt of the Earth's axis and the sun's position [5]. This angle depends on the day of the year given by n which can range from 1 to 365. For Eq. 4 H is the hour angle which is given by 15 degrees multiplied by the number of hours before or after noon. This is due to the sun's position changing due to the rotation of the earth which is about 15 degrees per hour. A model of the azimuth angle at locations in the arctic environment of Alaska is shown in figure 7.

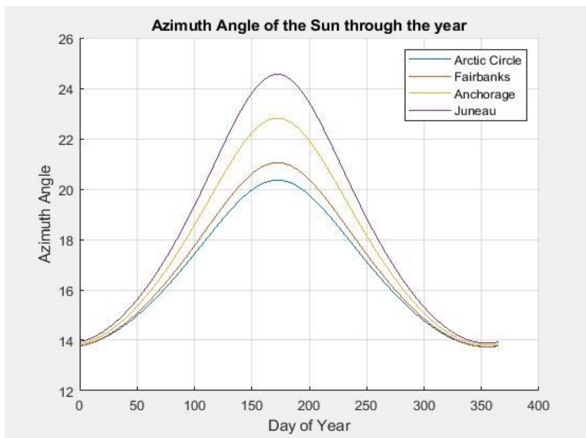

Figure 7. Azimuth angle throughout the year

When testing the movement of the pivot motor we noticed that it would start in a position that was less than 2 degrees off from the calculated position. This error in the movement would result in it increasing throughout the day reaching an error more than 2 degrees which is outside our specified tolerance of 2 degrees. This error was likely caused by friction within the motor or within the structure that moves. This could have been fixed with a more complicated system that had PID control; however, in our testing we found that PID would have added an extra point of potential inconsistency since PID works by oscillating the target back and forth with the error so assuming we were a little bit off more power would have been drained from the battery. Our estimations with using a small increment for the motors worked enough where we only had an error of 2 degrees.

```
double pivot(double m, double H1, double L1){ // this is what is called to get the pivot angle
  double sigma = declinAngle(m);
  double beta = altitude(m, L1);
  double lambda = arcsin(cos(sigma)*sin(H1) / cos(beta));
  double cosH = cos(H);
  double tanS = tan(sigma);
  double tanL = tan(L);
  if (cosH >= (tanS/tanL))
    return lambda;
  return pi + lambda;
}
```

Figure 8: Implementation of the Pivot angle

2.4.2 Tilt Motor

The tilt motor moves the solar panel array to match the vertical position of the sun in the sky. Unlike the pivot motor, the tilt motor only needs to move once per day because the vertical position of the sun in the sky only changes once per day. The sun's vertical position in the sky is again dependent on the solar declination angle from Eq. 3. The sun's vertical position in the sky is also dependent on what latitude the solar panels are at. The equation for the tilt angle is given in Eq. 5. A model of the tilt angle of the solar panel array at the altitudes of locations in Alaska is given in figure 10.

$$Tilt\ Angle = Latitude - \delta \qquad \text{Eq. 5}$$

When testing the movement of the solar panel array we found that the tilt angle was within our tolerance of ± 2 degrees. This accuracy was due to the tilt motor only moving once per day and the tilt angle moves a small amount each day while the pivot motor has to move across its full range of motion every day.

```
double tilt(double m, double L1){ // this is what will be called for the
  double beta = altitude(L1, m);
  double tilt1 = (90 - beta)*torad;
  return tilt1;
}
```

Figure 9: Implementation of of the Tilt Angle

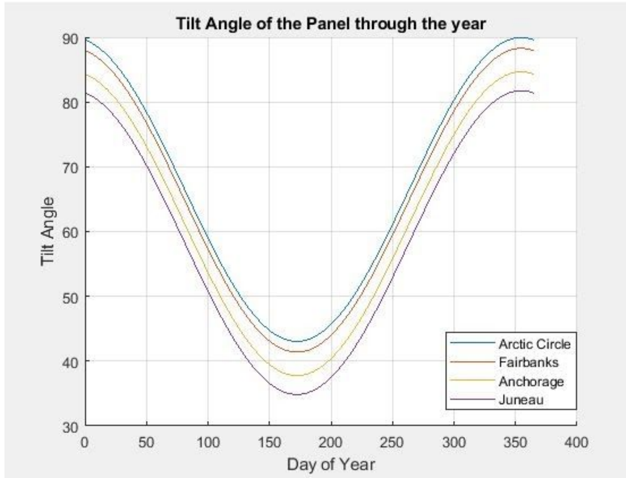

Figure 10. Tilt angle throughout the year

2.4.3 Locking Mechanism

Originally we planned on having a Locking Mechanism that was separate from our motors. This locking mechanism was intended to keep the motor in position until it was time for the array to move again. While designing the system we realized that when powered off the motors have an inherent locking behavior. Due to this behavior when the motors are not needed to move the solar panel array they are powered off and the motors lock in place until they are powered on for the array to move to its new position. This new locking mechanism was also better because we didn't have another point of potential failure as there was no separate device to lock the solar panel array in place.

2.5 Temperature Control Unit

The temperature control unit monitors the ambient air temperature and will regulate the temperature of the system to keep it near an optimal operating temperature.

2.5.1 Temperature Sensor

This Sensor provides an analog value based on the ambient temperature of the enclosure that houses the PCB, battery and microcontroller. The temperature sensor is incorporated onto the PCB in the top corner so it is not close to other electronics that may affect the temperature reading. The temperature sensor specifies that it needs 1mA of current into it for it to function properly. This 1mA is created using a set of resistors in parallel that when the 18V from the battery is applied 1mA of current goes into the temperature sensor. The temperature sensor also has a lead that goes into an analog input of the microcontroller so the ambient temperature can be read and the heater turned on if needed.

To verify that the temperature sensor was within our specifications we had to ensure that the signal going into the microcontroller was constant. To do this we connected the sensor to the microcontroller and continuously requested a value from the sensor. During the continuous data requests the sensor did not have a break where it did not report a value so the temperature sensor worked within our specifications.

2.5.2 Heater

Due to this system being designed for arctic environments we had to ensure that in the cold temperature of the arctic the system could still operate. The heating was accomplished by a small heating pad as it has a large surface area which means it can more efficiently regulate the temperature inside the enclosure. The heater is used when the temperature sensor sends a value to the microcontroller that translates the temperature to being below a certain threshold. For our purposes we set the temperature to 10ºC so that the temperature stabilized to that. The temperature was set to 10ºC because the freezer that we tested in could only reach -18ºC. This resulted in the temperature being stabilized to 10ºC when the system was put in the freezer. For a comparison we also tested the system without the heater to see how it behaved. The results of our freezer tests are shown below in figure 11. From these results we can determine if our heater worked as intended. While we could not find a way to reach the -35ºC that was within our specification requirements we were able to test it to determine that the temperature would remain stable at or above a temperature that would keep the system running.

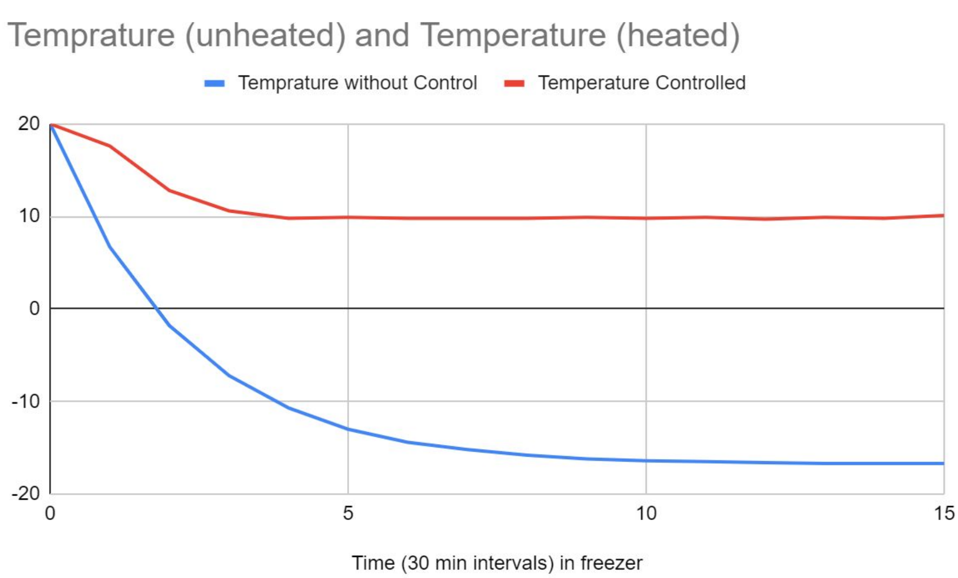

Figure 11. Temperature of enclosure with and without the heater

2.6 Schematics and PCB

All of the above components combine to make the PCB that Is Designed for this project. we designed the PCB with modularity in mind so if something happens to a component such as a transistor failure it can be easily replaced and the rest of the circuit can still behave as intended if something fails. We also designed the PCB with a few extra holes for resistors so a resistor value can easily be changed or extra resistors added to get the desired resistance. These extra resistor holes have proven useful as we had to change the resistance for the 5V signals to the BJT relays. The PCB circuit schematic is shown in figure 12 and the PCB schematic is shown in figure 13.

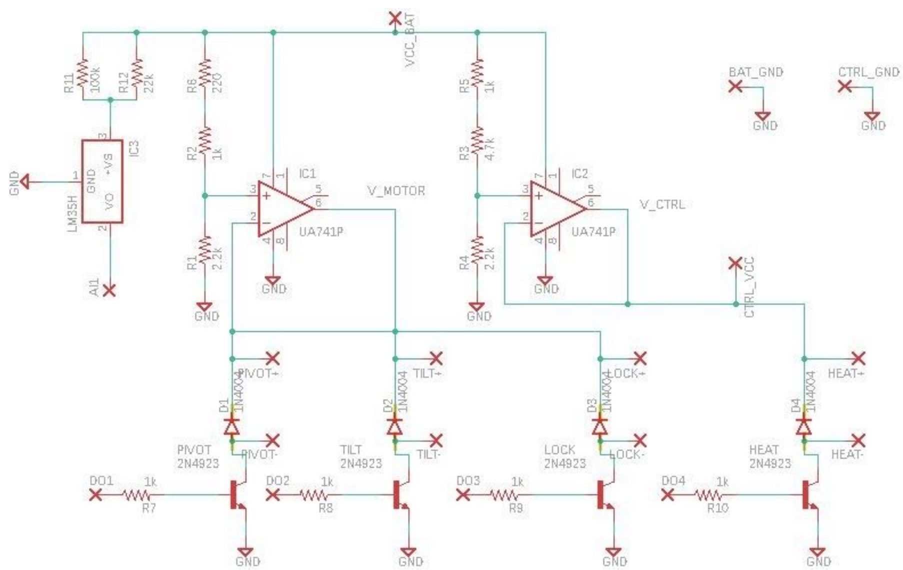

Figure 12. PCB Circuit Schematic

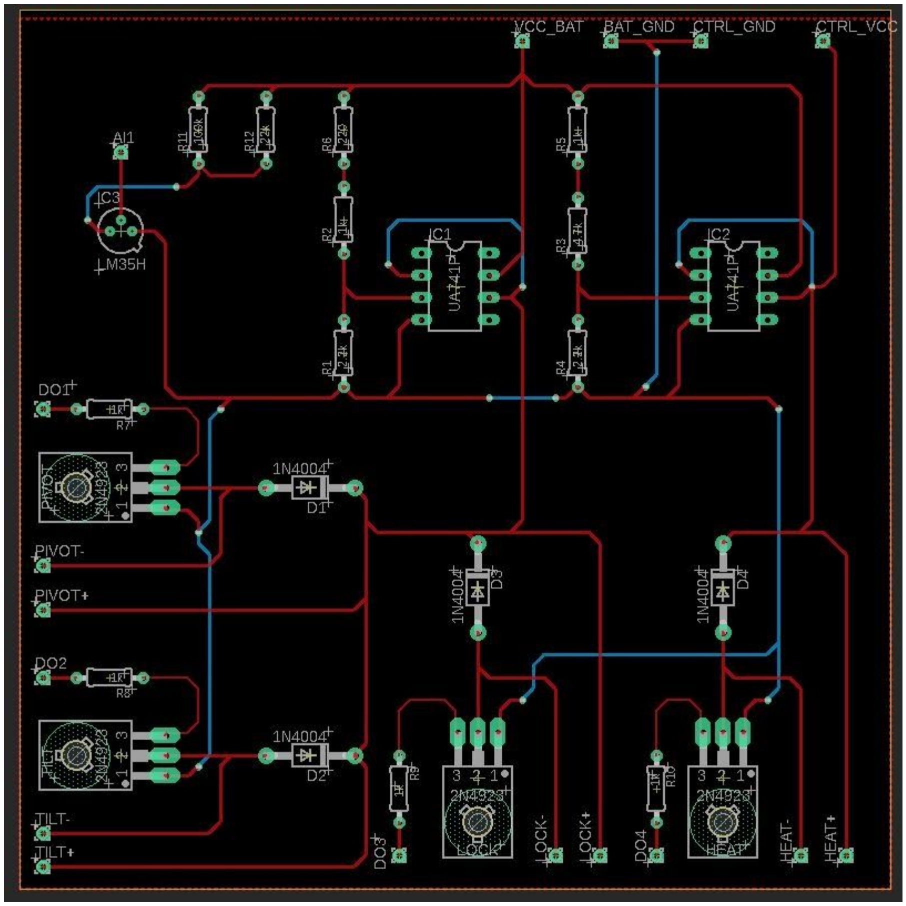

Figure 13. PCB Schematic

2.7 Costs

2.7.1 Materials Cost

Part	Vendor	Quantity	Unit Cost	Total Cost
EK-TM4C123GXL Microcontroller	Digi-key	1	$15.59	$15.59
Sunnytech .5W 5V small solar panel	Amazon	4	$6.99	$27.96
2N5191G BJT	Digi-key	6	$0.67	$4.02
1N4001 Diode	Digi-key	4	$0.02	$0.08
9 Volt batteries	Amazon	8	$1.49	$11.99
PCB	PCBWay	1	$3.10	$3.10
LM135H Temperature Sensor	Digi-key	1	$16.04	$16.04
COM-11288 Heating Pad	Digi-key	1	$3.95	$3.95
µA741CP Op-Amp	Digi-Key	3	$0.49	$1.47
Fiberglass Insulation	Menards	1	$5.89	$5.89
			Total	$90.09

Table 2. Materials Costs

2.7.2 Labor and Total Cost

The labor cost is calculated using a three person team making an hourly wage of $30 per hour at 10 hours per week for an 8 week period. The cost is calculated as follows:

$30/[hr/person] * 10[hr/week] * 8[weeks] * 3[people] = $7,200

To calculate the total cost the cost of labor was added to the cost of materials. This calculation is shown as follows:

$7,200 + $90.09 = $7,290.09

3. Conclusions

3.1 Implementation Summary

In section 2 we outlined every single component of our final product that we were able to construct and put together. Our PCB with our temperature sensor, voltage divider, and relays were connected to the inductive heater and microcontroller, which would be sending signals to turn the heater on and off, and to move the motors as need be. In our tolerance analysis, we determined the amount of power that needed to be sent to the motors in order to move them a certain amount. Additionally we needed to determine how close to the critical temperature any of the components began to lose functionality and to adjust the heater activation accordingly. Finally, after setting up the entire structure we tested it in the freezer at -18℃ to determine whether it would survive, as well as setting it outside throughout the day to determine how much improvement our design over the original and found that we had a minimum of 5% more efficiency, which has a much greater impact with higher grade solar panels

3.2 Power Analysis

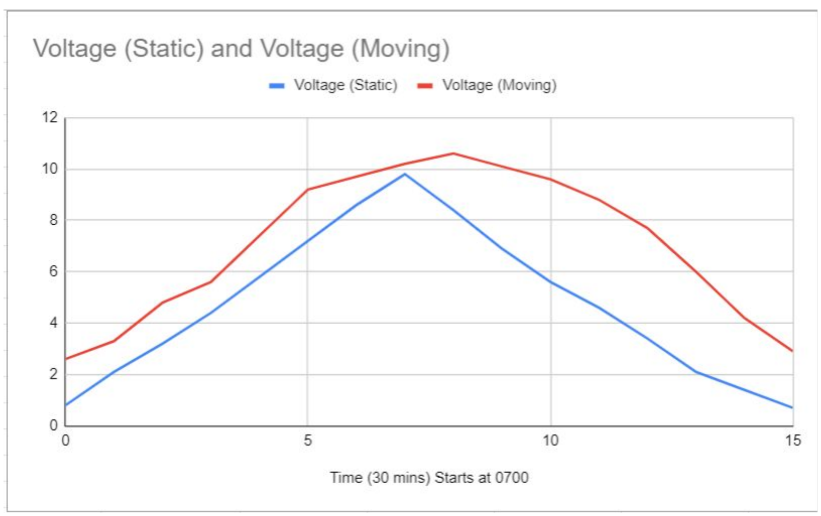

Figure 14. Comparison of output voltage when stationary and moving

We measured the voltage output of the solar panels from around 7 am to around 2:30 pm on consecutive days. The first day we tested it using a regular solar panel to see the output and on the second day we used our design with the moving solar panel. While the weather conditions of both days were slightly different, as reflected in the figure above, there still seemed to be a regular peak at around 10:30-11 am which is expected given the winter-like conditions currently. However, we seemed to find a much bigger difference in the output voltage of the two solar panel designs after this peak than before it, with the peak actually having the smallest difference in output voltage, with only a 4% difference. Because the graph of the static solar panels was relatively linear on both sides of the peak, averaging out the moving solar panel's graph before and after the peak and running a normal-line percentage difference test seemed to be most appropriate. We ended up with around a 15% efficiency increase before the peak and almost a 30% voltage difference after the peak, on average. While these numbers are this large primarily due to the small output voltage, this value would be significantly more normalized when using a higher grade solar panel with a much larger output voltage. Regardless, we managed to reach, and even exceed, our expectations for the efficiency increase with our design compared to a standard solar panel structure.

3.3 Unknowns and Uncertainties

Despite Covid, we were able to get a relatively working structure. Unfortunately, regardless of the pandemic, there was one issue that was difficult to overcome: our structure was meant to withstand the arctic environment, and there was really no plausible way to simulate said environment with the resources we had. Firstly was our temperature regulation. While we did test the condition of our structure in a freezer with an ambient temperature of -18℃ and it did not dip below 10℃, the actual temperature of the arctic can reach -35℃, not accounting for windchill, and we are unsure how exactly our design would fare in that environment. The other issue is the solar panel efficiency. While we did see an improvement in power output from the solar panel when we tested tracking versus no tracking, there were several differences since we did tests on separate days which would have different weather conditions and sun exposure. Even more important is how this efficiency would change when you account for the arctic environment with only around 6 months of sunlight and ranging conditions of Alaska. If we had more resources, we could try to simulate the environment as best as possible, but ultimately it seems unfeasible to exactly replicate it.

3.4 Future Work and Improvements

This project is a proof of concept for what is achievable in an environment with more harsh climates that do not have as much solar energy throughout the day and as a consequence each year. Our goal was set out to improve upon these conditions to try and create a system where renewable energy could exist. While we were able to successfully build a prototype that could be implemented, the size and calculations would have to be scaled up to be able to create a usable amount of power. More efficient means of gathering the energy, which means better solar panels and more efficient rechargeable batteries. To improve upon this design a layer of insulation has to be placed in the middle to two layers of the supporting structure so that it cannot interact with anything else alleviating the impact insulation has on the environment and people. We were unable to do this because we would not have had access to the internals as a result. If this device were to be improved and deployed, we would see an increase in the usage of renewable energy in these regions that are hard pressed to have them because of their harsh environments.

3.5 Ethics and Safety

While there are not many safety and ethical hazards associated with our project, there are certainly some notable ones. Firstly, our design utilizes 9 V Lithium-ion batteries, which are usually safe but can result in potentially dangerous behavior. A larger issue is battery failure or even an explosion as our design is for use in significantly colder temperatures. To avoid this possibility, we have a heater that regulates the temperature of the entire product.

A similar issue regarding the rechargeable battery is the potential for overcharge, resulting in an exothermic reaction. For this reason, we ensure that the battery does not charge beyond 8.5 V, to allow for a comfortable buffer in an emergency.

While our design is relatively small, we are going to attempt to make it as sturdy as possible by maintaining the majority of the weight at the bottom of the product. In practice, however, our design is going to be used in a much colder environment with high-speed winds, which may result in the structure falling over and injuring people and potentially animals. To remedy this, we plan to embed the assembly in the ground, anchoring itself deep to prevent falling over while also using some of that underground heat to regulate temperatures.

While we are investing all resources to avoid accidents, the IEEE code of ethics category that best applies to our design would be II.9: “to avoid injuring others, their property, reputation, or employment by false or malicious actions, rumors or any other verbal or physical abuses” [4], which is ensuring that our design prevents infliction of any form of harm on any other individual through a lack of structural integrity, which we believe that our prevention practices align with I: “To uphold the highest standards of integrity, responsible behavior, and ethical conduct in professional activities” [4]. There are, without a doubt, risks undertaken in the process of designing such technology, but with the benefits far outweighing the risks, we find it to be a worthwhile endeavor.

References

[1] “Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA),” 27-Feb-2020. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=427. [Accessed: 06-Oct-2020].

[2]“U.S. Energy Information Administration - EIA - Independent Statistics and Analysis,” *Alaska - State Energy Profile Analysis - U.S. Energy Information Administration (EIA)*. [Online]. Available: https://www.eia.gov/state/analysis.php?sid=AK. [Accessed: 06-Oct-2020].

[3]“10.16_SolarTrackingSystems_blog,” *Solar News*, 29-Aug-2018. [Online]. Available: https://news.energysage.com/solar-trackers-everything-need-know/10-16_solartrackingsystems_blog-2/. [Accessed: 06-Oct-2020].

[4]“IEEE Code of Ethics,” *IEEE*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 06-Oct-2020].

[5]G. M. Masters, *Renewable and efficient electric power systems*. Hoboken, NJ: IEEE press, 2013.

Appendix

A. Requirements and Verification Tables

Table 3. Requirements and Verification for the Battery

Requirement	Verification
The battery must supply >500mAH of charge at 18V +/-5%	A. Connect a fully charged battery to the system B. Discharge battery at 100mA for 5 hours C. Use a voltmeter to ensure the voltage remains within the 18V threshold

Table 4. Requirements and Verification for the Voltage Divider

Requirement	Verification
1. Provides 5V +/- 5% and 12V +/- 5% from an 18V source with currents from 0-150mA	1. Connect the input to an 18V source and draw 150mA 2. Using a voltmeter measure the two outputs to ensure the output voltages are within 5% of 5V or 12V

Table 5. Requirements and Verification for the Solar Panel Array

Requirement	Verification
Outputs 150mA - 200mA between 8V and 9V in full sunlight. (100,000 lux)	A. Place the solar panel array in 100,000 lux light. B. Measure the open circuit voltage with a voltmeter ensuring the voltage is under 9V C. Terminate the solar panel with a load that ensures a voltage drop of 8V D. Ensure the current through the load is above 150mA using an ammeter

Table 6. Requirements and Verification for the Microcontroller

Requirement	Verification
1. The microcontroller must accurately calculate the sun's position in the sky 2. The microcontroller must be able to run at -35°C	1. A. Verify that the tilt angle value calculated matches the value calculated by the equation: $Tilt\ Angle\ =\ 90° - \beta$ B. Verify that the calculated azimuth angle matches the angle given by the equation: $\phi_s\ =\ arcsin(\frac{cos(\delta)sin(H)}{cos(\beta)})$ 2. A. Set the microcontroller in a freezer or a cooler that has a temperature of -35°C B. Use verification steps from 1. To determine functionality.

Table 7. Requirements and Verification for the Heater Relay

Requirement	Verification
When the enable signal is on 18V +/-0.25V power is passed through to the heating element	A. Set the enable signal from the microcontroller to 5V B.Using a multimeter ensure that the output voltage is 18V +/-0.25V

Table 8. Requirements and Verification for the Lock Relay

Requirement	Verification
When the enable signal is on 12V +/-0.25V power is passed through to the locking mechanism	A. Set the enable signal from the microcontroller to 5V B.Using a multimeter ensure that the output voltage is 12V +/-0.25V

Table 9. Requirements and Verification for the Pivot Motor Relay

Requirement	Verification
When the enable signal is on 12V +/-0.25V power is passed through to the pivot motor	A. Set the enable signal from the microcontroller to 5V B.Using a multimeter ensure that the output voltage is 12V +/-0.25V

Table 10. Requirements and Verification for the Tilt Motor Relay

Requirement	Verification
When the enable signal is on 12V +/-0.25V power is passed through to the tilt motor	A. Set the enable signal from the microcontroller to 5V B.Using a multimeter ensure that the output voltage is 12V +/-0.25V

Table 11. Requirements and Verification for the Locking Mechanism

Requirement	Verification
The locking mechanism should lock within 2 +/- 0.5 seconds of the motors moving to a new position.	A. Move the motors to a position +/- 10° from the current position B. Start a timer to timer once the motors stop moving C. Stop the timer when the locking mechanism closes and ensure time does not exceed 2.5 seconds

Table 12. Requirements and Verification for the Pivot Motor

Requirement	Verification
1. The pivot motor will move the array to within +/- 2°	A. Send a pivot position to the motor from the microcontroller B. Using a protractor measure the angle of the motor position and ensure that the angle is within 2° of the angle given by the microcontroller

Table 13. Requirements and Verification for the Tilt Motor

Requirement	Verification
The tilt motor will move to be within +/-2° of the tilt angle given by the microcontroller.	A. Send a pivot position to the motor from the microcontroller B. Using a protractor measure the angle of the motor position and ensure that the angle is within 2° of the angle given by the microcontroller

Table 14. Requirements and Verification for the Temperature Sensor

Requirement	Verification
A continuous feedback loop exists between the temperature sensor and microcontroller that enables the heating unit once the sensor detects that the temperature dips below 0℃	The microcontroller constantly polls the temperature sensor to detect a temperature dip. Once it starts approaching 0℃ the heater turns on to prevent the temperature from actually dropping below 0℃

Table 15. Requirements and Verification for the Heater

Requirement	Verification
When the outside air temperature is below 0℃, the heater must keep the control enclosure and motors at or above 0℃	A. Set the system in a freezer that is below 0℃ for 5 hours B. Measure the temperature of the motors and the control enclosure to ensure the temperature is at or above 0℃