

Development of a Low-Cost Pyranometer

From: The Solar Sailors

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Executive Summary

Our team has developed a cost effective pyranometer, the PV Matey, to assist our sponsor. Kilowatts for Humanity is a nonprofit that electrifies communities in developing countries. Their solar stations provide services such as refrigeration, device charging, and offline servers to residents that can be experiencing electricity for the first time. To ensure that the fixed rooftop panels continue to provide quality power, a pyranometer is mounted alongside them. This device measures the solar energy absorbed by a plane in W/m^2 . The data provided by a pyranometer helps to monitor variations between the power absorbed by the panels and the energy that they produce. Atypical variations indicate that the panels require maintenance or cleaning. The PV Matey is small, fairly accurate, and is an affordable solution to help our sponsor continue their mission of providing renewable energy to communities in need.

Background

We are the Solar Sailors. We have been tasked with creating a low-cost pyranometer that can take in the solar irradiance from the Sun, and measure how much power a solar panel would receive from this sunlight. The device outputs power in watts per meter squared, which would visually show how much power the solar panel would be getting. This is used to help the organization know if their solar panel is generating the proper amount of energy, and if it needs to be maintained or cleaned.

Most commercial pyranometers on the market today can range from \$200 to \$1000. They also tend to come with many features that are not always needed in certain locations, making the costly pyranometer less useful. KiloWatts for Humanity is a non-profit organization that aims to generate power to power-insufficient countries. They partnered with the University of Idaho to create a more affordable pyranometer that works better for their needs and will help other countries regulate their power.

Problem Definition

We are required to produce a prototype that will output an analog signal from 4 to 20 mA corresponding linearly to 0 - 2,000 W/m². Our design choices are centered around creating a prototype that is affordable, accurate, and reproducible. As a result, Kilowatts for Humanity is receiving a parts list, build instructions, circuit schematics, PCB and case design files, completed prototypes, and any remaining spare parts from our project. Table 1 shows our sponsor's requirements for this project.

Sponsor Requirements	
Analog Output	0-5V or 4-20 mA
Price range	\$20 - \$80
Accuracy	Less than 15% error
Field of View	180°
Environment	Outdoor Setting
Operating Ambient Temperature	10 – 50 °C
Reproducible	Can be calibrated in mass

Table 1: Sponsor Requirements

Project Plan

We divided everyone into a set role for the course of the project. Adriana Oliveira oversaw contact with our client, Steve Szablya, and sent out the weekly updates to the team, client, and instructor. Lukas Vermeulen was the budget keeper. He documented all the purchases made in our project and kept an organized list of the materials bought. He also oversaw ordering the parts and would pick up the items as well. Brady Jerome was the meeting organizer and schedule planner. He oversaw sending reminders to keep up with the tasks that needed to be done and generate a workable schedule to

organize when the team could meet. He also created and managed the Wikipage with the data and information about the project. Finally, Nickolas Borek was the document keeper. He ran the portfolio and held all our documents in one place for us to use later and to hand in to our instructor.

We kept track of our progress and important dates using a Gantt Chart which was updated as the semesters progressed. We stayed mostly on schedule, but occasionally fell behind when we needed to order a new part or ran into unexpected problems with our design. Despite various setbacks and having busy schedules, we were able to produce a functional prototype.

Concepts Considered

Sensor Selection

A sensor that produces an analog signal in response to sunlight is key to creating a pyranometer. There are several sensor types capable of meeting these requirements including photodiodes, phototransistors, thermopiles, and thermistors. As we pursued a sensor, we looked for factors such as price, field of view, and accessibility. A deciding factor not mentioned in our sponsor's requirements is spectral response. Based on functionality, our sensor needed to accept the same wavelengths as a solar panel, from 380 to 750 nm wavelengths.

Microcontroller Selection

For this project, we wanted a microcontroller that was small, affordable, and easy to interact with. We found two microcontrollers that met these three criteria: the Arduino Nano Every and the Adafruit QT Py.

The Arduino Nano Every came out in June of 2019. It utilizes the ATmega4809 32-bit processor and can be used on a breadboard or directly soldered to a printed circuit board using its castellated pads. It runs on 5 V power from the USB or 6-21 V

when powered externally. It also has 48 kB of flash memory, 6 kB of SRAM, and 256 Bytes of EEPROM memory. This microcontroller fits the criteria for this project. It is decently small at 15x45 mm, costs \$9.30 per unit, and uses Arduino IDE as its integrated design environment. There are endless forums and community support for Arduino IDE, which is one of the reasons we considered this microcontroller.

The Arduino Nano Every has thirty pins to be utilized: five power pins, nine analog pins, and sixteen digital pins. It interfaces with Arduino IDE using a USB port, but can be configured to run without being connected to the computer by a USB cable. The Arduino Nano Every can output digital signals and pulse width modulation but does not have a true analog output like a DAC (Digital-to-Analog Converter). Figure 1 shows an image of the Arduino Nano Every. A link to the Arduino Nano Every can be found in the Concepts Considered Section of the Appendix. Figure 2 shows the pinout for the Arduino Nano Every.



Figure 1: Arduino Nano Every

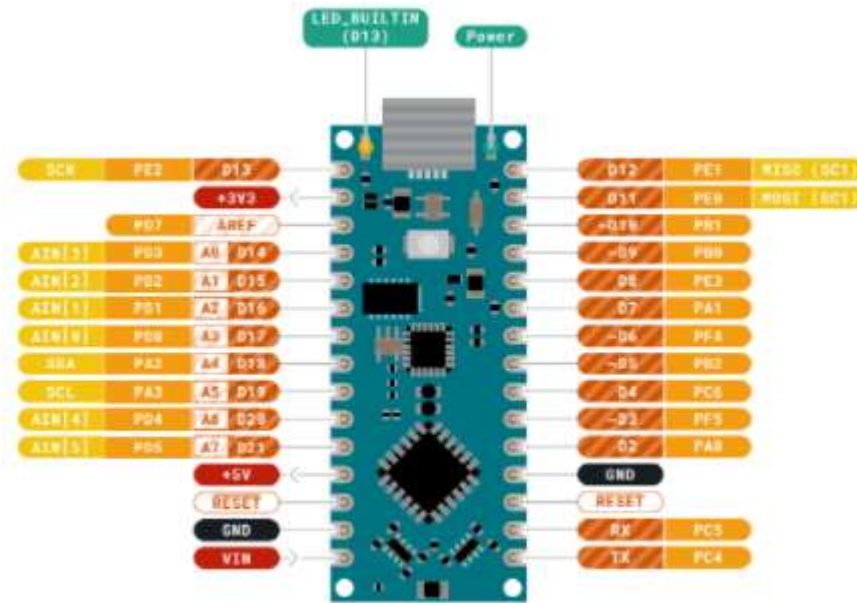


Figure 2: Arduino Nano Every Pinout

The other microcontroller considered for this project is the Adafruit QT Py. The Adafruit QT Py came out in September of 2020. The QT Py utilizes the ATSAM21E18 32-bit processor and can also be used on a breadboard or directly soldered to a printed circuit board using its castellated pads. It runs on 5 V power from the USB or 5 V when powered externally using the 5 V pin. It also has 256KB of flash memory and 32KB of RAM; there is also a spot on the bottom of the QT Py to add 2MB of extra flash memory. This microcontroller fit the criteria for this project. It is incredibly small at 23.5x17.5 mm, costs \$6.00 per unit, and can be used with Arduino IDE as well as CircuitPython, which is a variation of Python coding.

The Adafruit QT Py has fourteen pins to be utilized. The QT Py has three power pins. Many of the other pins can be analog or digital pins, depending on their configuration. It can output digital signals, pulse width modulation, capacitive touch which can be used in audio circuits, and has a true analog output using the DAC on pin A0. A link to the Adafruit QT Py can be found in the Concepts Considered Section of the Appendix. Figure 3 shows an image of the Adafruit QT Py. Figure 4 shows the pinout for the Adafruit QT Py.

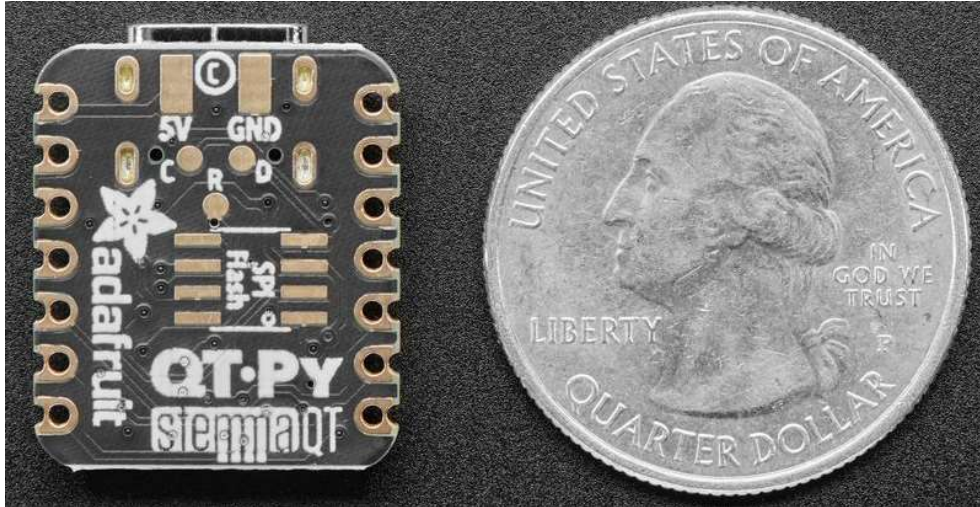


Figure 3: Adafruit QT Py

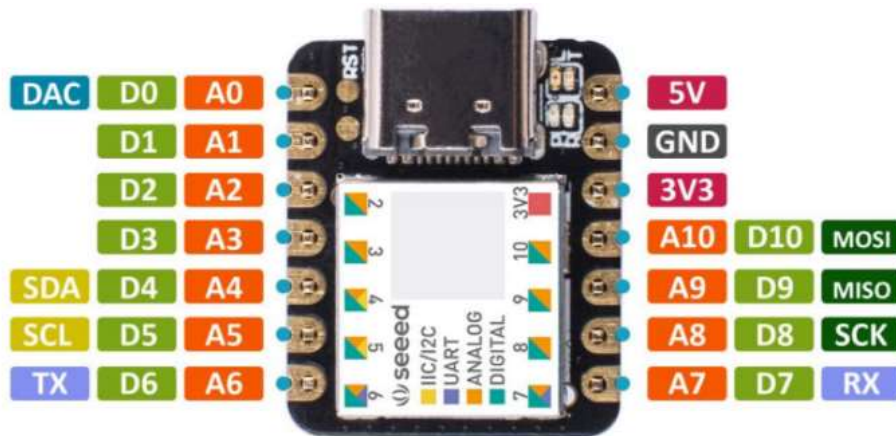


Figure 4: Adafruit QT Py Pinout

Light Intensity Filter

The filter in the device is used to filter out intensities of light. The idea for a filter came from an article about a similar project that a different group ran. This group realized that their sensor could not read all the intensities of light, so they needed a filter to “step down” the light intensity. A link to this article is in the Appendix under “Low-Cost Pyranometer Article” in Concepts Considered. We investigated price per sheet, area of the filter, and obtainability.

Sensor Protection

A sensor requires an opening in the case to receive sunlight. A clear covering that will let light through uninterrupted while protecting our circuitry from the elements is needed. Options that meet these requirements for the covering include glass or acrylic disks or domes. Factors that we considered in making this selection include durability and cost.

Concept Selection

Sensor Selection

Each member of the team oversaw researching a sensor type. We filtered results for our sensors based on requirements such as price, field of view, and spectral response. The top five products that were in stock and fit this description were entered into a shared excel document. As a team, we went over each sensor suggestion until a final sensor was selected. Table 2 shows which sensors we investigated and their qualities.

	Brand/model	\$ per one unit	\$ per ten units	Viewing angle (degrees)	Temperature restraints	Measured wavelength	Output range, if given	Packaging	Link	
Photodiodes (Brady)	Option 1	SFH 2701	\$0.84	\$6.50	120°	-40°C ~ 85°C	400 nm to 1050 nm	15V (max)	2-SMD, No Lead	https://www.digikey.com
	Option 2	TEMD7000X01CT-ND	\$0.99	\$7.70	120°	-40°C ~ 100°C	430 nm to 1100 nm	60V (max)	0805 (2012 Metric)	https://www.digikey.com
	Option 3	VEMD2020X01CT-ND	\$0.89	\$6.93	30°	-40°C ~ 100°C	750nm to 1050nm	60V (max)	2-SMD, Gull Wing	https://www.digikey.com
	Option 4	VEMD2023SLX01CT-ND	\$0.91	\$7.11	70°	-40°C ~ 100°C	750nm to 1050nm	60V (max)	2-SMD	https://www.digikey.com
	Option 5	BPW21R	\$12.32	\$111.60	50°	-40°C ~ 125°C	about 400 nm to 700 nm	10V	Leaded	https://www.newark.com
Notes:	For a few of my prices, they list either the total cost of 10 units, or the cost per unit if purchasing 10 units. I wasn't fully sure what to write for that, so I did the price for purchasing all 10 units									
Phototransistors (Adriana)	Option 1	SFH 3310	\$1.03	\$6.35	150°	-40°C ~ 100°C (TA)	350 to 970 nm (Max sensitivity 570nm)	5.5V	Through hole	https://www.digikey.com
	Option 2	SFH 3710-Z series	\$0.94	\$7.29	120°	-40°C ~ 85°C (TA)	350 to 950 (Max sensitivity 570nm)	5.5V	Surface mount	https://www.digikey.com
	Option 3	SFH 3410-Z series	\$1.18	\$9.57	120°	-40°C ~ 100°C (TA)	350 to 970 nm (Max sensitivity 570nm)	5.5V	3-SMD, Gull Wing	https://www.digikey.com
	Option 4	SFH 3410-2/3-Z series	\$1.31	\$10.68	120°	-40°C ~ 100°C (TA)	351 to 970 nm (Max sensitivity 570nm)	5.5V	3-SMD, Gull Wing	https://www.digikey.com
	Option 5	APS3227SP1C-P22	\$0.72	\$5.58	120°	-40°C ~ 85°C	390 to 700 nm (Max sensitivity 580nm)	60V	Surface mount	https://www.digikey.com
Notes:	I used the digikey website to filter only photosensors that can accept 550-580nm wavelengths to be in the center of the spectrum that we need (visible light: 380 to 740nm). Option 3 and 4 are very similar.									
Thermopiles (Lukas)	Option 1	G-TPCO-031	\$8.64	\$7.09	110 degrees	-20 to 85 C	8 to 14 um	5+-1.3 mV		https://www.newark.com
	Option 2	ZTP-135SR	\$5.91	\$3.73	80 to 90 degrees	-20 to 100 C	5 to 17 um	N/a		https://www.newark.com
	Option 3	SMTIR9901	\$13.02	\$12.18	Variable	-20 to 100 C	5.5 um high pass	N/a		https://www.newark.com
	Option 4	G-TPMO-101	\$16.71	\$136.40	50 degrees	-20 to 85 C	5.5 um high pass	N/a		https://www.digikey.com
	Option 5	G-TPCO-033	\$?	\$?	88 degrees	-20 to 85 C	5.5 um high pass	7+-2.1 mv		https://www.te.com
Notes:										
Thermistors (Nick)	Option 1	AMETHERM SL32 2R025	\$1.28	\$12.80	360°					
	Option 2									
	Option 3									
	Option 4									
	Option 5									

Table 2: Sensor Comparison

Our team selected the SFH 3310 phototransistor for this prototype. It was an affordable option with a pack of ten running at \$0.64 per sensor. It also has a viewing angle of 150°. This was slightly smaller than the 180° field of view that we were looking

for. We sacrificed the extra 30° for a sensor that was affordable and had the right spectral response. Our sensor detects 350–970 nm wavelengths, which is well within the range of a solar panel. The data sheet for the SFH 3310 is available in the appendix.

Microcontroller Selection

To decide between the Arduino Nano Every and the Adafruit QT Py, we performed a side-by-side, quantitative analysis of the two microcontrollers. Table 3 shows the two microcontrollers and their desired qualities.

	Adafruit QT py	Arduino Nano Every
Cost (\$)	\$6.00	\$9.30
Output (Type, Bits)	DAC and PWM, 10-bit	PWM, 8-bit
Output Magnitude	5 V	5 V
Size (mm)	23.5x17.5	18x45
Input Resolution	12-bit	10-bit
Memory	256 KB	48 KB
RAM	32 KB	6 KB (SRAM)
Clock Speed	48 MHz	20 MHz

Table 3: Microcontroller Comparison

From this table, we determined that the Adafruit QT Py would be a better microcontroller for our project. It is cheaper, smaller, more accurate, faster, and more versatile than the Arduino Nano Every. The best quality of the QT Py is the true analog output from the DAC. The DAC eliminates the need for a low-pass filter to transform the digital PWM signal into an analog voltage. By eliminating the low-pass filter, we decrease the overall cost and size of the product.

Teflon Filter Testing

The sensor itself only works properly up to 1000 lux. However, the Sun can give off a maximum of 120,000 lux. Because of this, we needed another alternative to reduce

the amount of incoming light intensity. After reading about a similar project, we found that Teflon would make a good attenuator of sunlight. After obtaining the Teflon, we then performed an attenuation test on the filter to discover how much light the Teflon attenuates. Through our tests, we found that our Teflon sheet attenuated 73.8% of incoming light. Then, using various equations, we calculated that our prototype would need at least four sheets to attenuate the 120,000 lux from the Sun to under 1000 lux for our device.

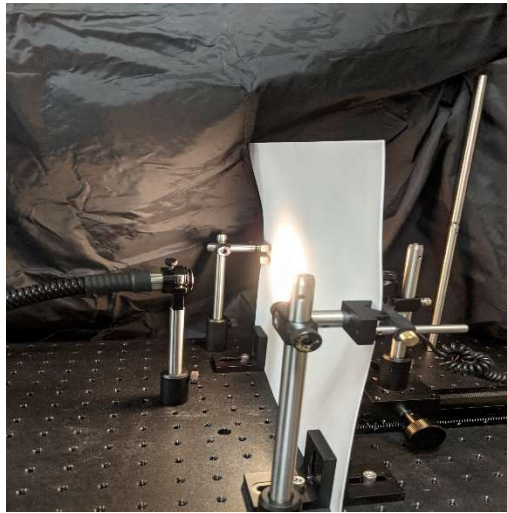


Figure 5: Teflon Attenuation Testing

Sensor Protection

We selected a 1/8th inch thick clear acrylic disk with a diameter of 2 inches as a cover to our sensor. Acrylic is more affordable than glass and is less likely to crack. A disk shape is also cheaper and easier to source than a dome. The acrylic should last at least ten years before yellowing and will provide continuous protection from water and dust.

System Architecture

Conceptual Design- Circuit

The circuit consists of a diode, the sensor, resistors, an op amp, and the microcontroller. The diode is connected between the power source and the rest of the circuit, with the anode towards the power source. This is done to properly power the QT Py using the 5 V pin. The phototransistor's collector (short leg) and "V+" leg of the op amp is also connected to the cathode of the diode.

The phototransistor produces a current based on the light hitting the sensor. The QT Py cannot directly read current, so a resistor is placed in series with the phototransistor and the QT Py measures the voltage across the resistor. The resistor voltage is proportional to the current produced by the phototransistor through Ohm's law.

The QT Py uses first-order linear regression to convert the resistor voltage to the equivalent irradiance in W/m^2 . This process is discussed in the Calibration section. The irradiance value lies on a range of 0-2,000 W/m^2 . After the QT Py calculates the irradiance value from the resistor voltage, the irradiance value from 0-2,000 W/m^2 is multiplied by 1023/2000. This converts the irradiance to a value that the digital-to-analog converter (DAC) can output since the range of the QT Py's DAC, found on pin A0, is 0-1023. The new value, V_{out} , from 0-1023, that corresponding to 0-2,000 W/m^2 is sent to the DAC with the command,

"analogWrite(A0, V_out);"

Then the voltage-to-current converter converts the output voltage from the DAC to the equivalent current. The 1.6 Ω resistor represents the equivalent resistance of 100 feet of wire to the data logger. The output current ranges from 4-18 mA. Figure 6 shows the circuit schematic for the design.

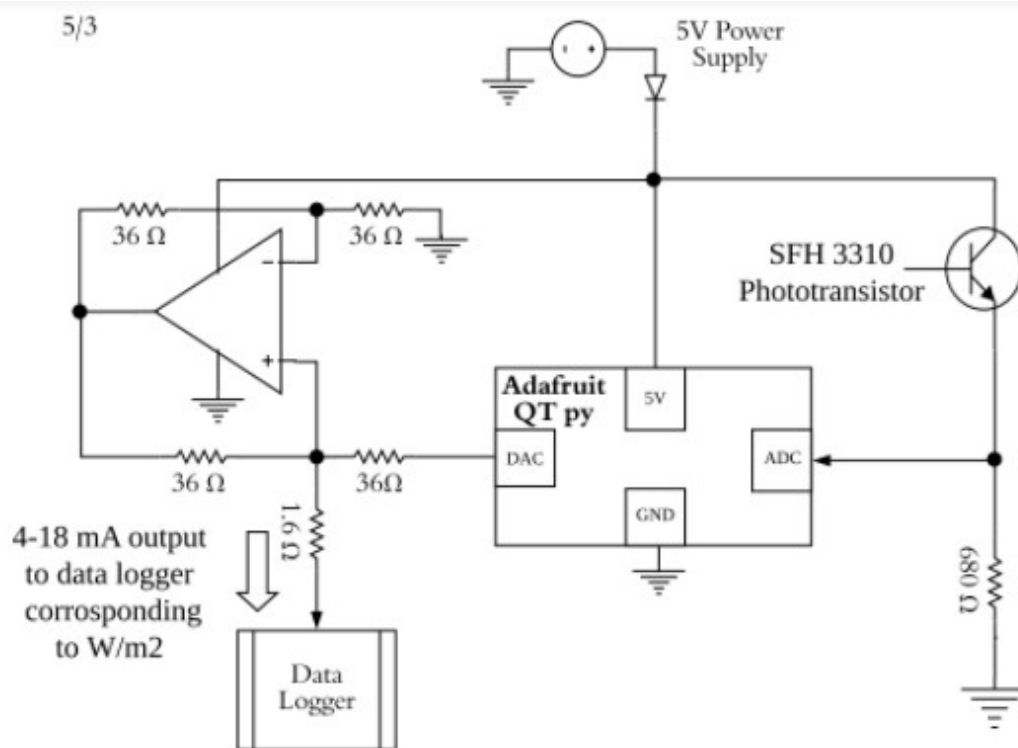


Figure 6: Circuit Schematic

Phototransistor Sensor- BJT

The sensor is a phototransistor, which is a light sensitive BJT. Various sensors were considered, but the phototransistor was selected because of its viewing angle, through-hole design, and wavelength range. This sensor meets the requirements for the range of a solar panel, which was the goal with the sensor. The output of the sensor is a current output, which is then outputted to the microcontroller.



Figure 7: SFH 3310 Phototransistor

Microcontroller- Adafruit QT PY

The product uses the Adafruit QT Py to control the circuit. The circuit is powered by a 5 V signal from a wall outlet power jack. The QT Py reads the voltage across the 680 Ω resistor which is proportional to the current produced by the phototransistor. The QT Py measures the voltage with a 3.22 mV resolution. The high resolution ensures that the QT Py will accurately read changes in the voltage.

Then the QT Py uses first-order linear regression to calculate the equivalent irradiance measured by the phototransistor. For more information on this process, see the Calibration section. Once the irradiance is calculated, the QT Py outputs a proportional voltage from the DAC using the process described in the Conceptual Design section.

Filter- Teflon Specifications

The filter is made from Teflon and is a 1-millimeter-thick sheet that can be cut to fit the design of the device. Teflon can be used to attenuate light intensity, which was useful in our design. It is placed over the top of the phototransistor and used to bring the light intensity below 1000 lux.

Voltage-to-Current Converter

The voltage-to-current, also known as the Howland Current Converter, converts the voltage output from the QT Py's DAC into the equivalent current output using Kirchhoff's Current Law and Ohm's Law. Figure 8 shows the circuit diagram for the Howland Current Converter.

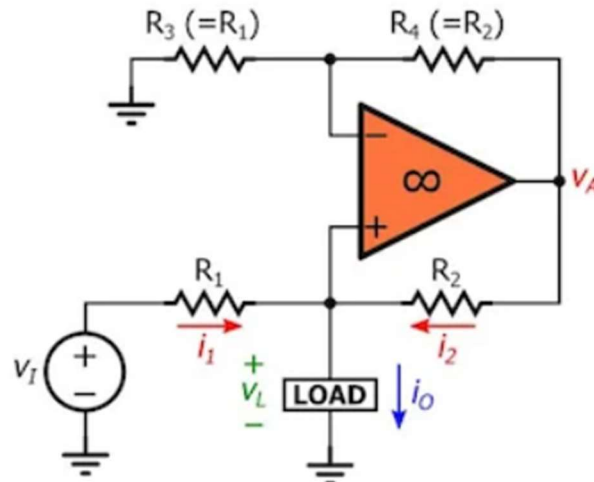


Figure 8: Howland Current Converter Circuit Diagram

There are six main equations in this circuit:

$$\text{Equation 1: } I_0 = I_1 + I_2 = \frac{V_1 - V_L}{R_1} + \frac{V_A - V_L}{R_2}$$

$$\text{Equation 2: } V_A = V_L \left(1 + \frac{R_4}{R_3}\right)$$

$$\text{Equation 3: } I_0 = AV_1 - \frac{V_L}{R_0}$$

$$\text{Equation 4: } A = \frac{1}{R_1}$$

$$\text{Equation 5: } R_0 = \frac{R_2}{\frac{R_2}{R_1} - \frac{R_4}{R_3}}$$

$$\text{Equation 6: } \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

Equation 1 illustrates KCL at the V_+ terminal of the Op Amp. Equation 2 illustrates the non-inverting amplifier equation for the output voltage. Equation 3 is found by substituting Equation 2 into Equation 1. Equation 4 shows the gain of the Op Amp. Equation 5 shows the output resistance of the circuit seen from the load. Equation 6 illustrates the balanced-bridge condition which makes I_0 independent of the voltage across the load.

The output current is a function of the resistors R_1 , R_2 , R_3 , and R_4 . From Equation 6, we see that the resistors must be as equal as possible for this circuit to operate properly. To accomplish this, resistors with a 1% tolerance are used in the circuit. Using LT Spice simulations, we determined the value of the resistors needed to get a 4-20 mA

current output was $36\ \Omega$. Figures 9 and 10 show the circuit simulated in LT Spice and its results.

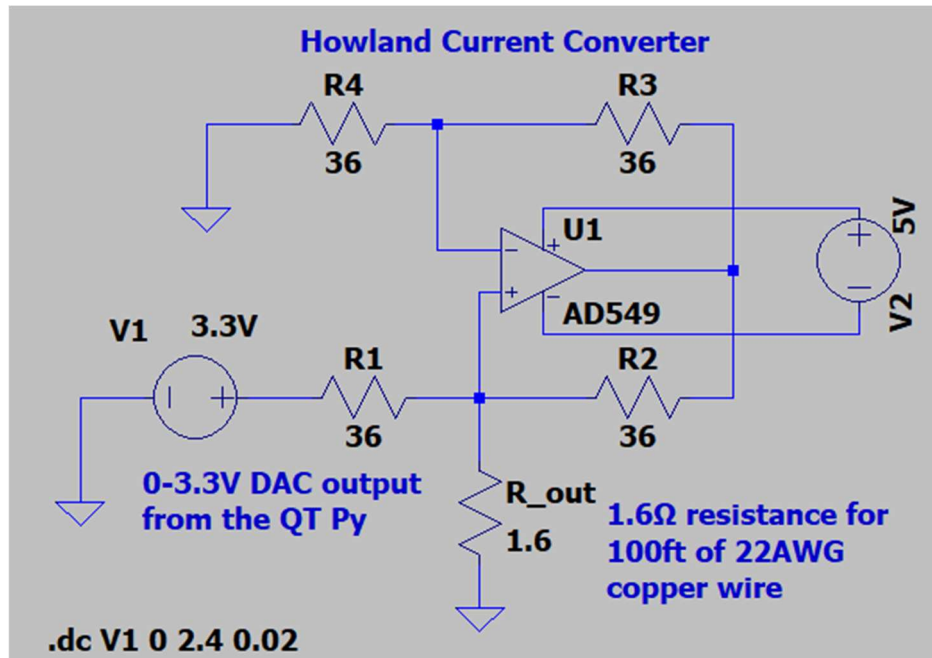


Figure 9: Our version of the Howland Current Converter Circuit in LT Spice

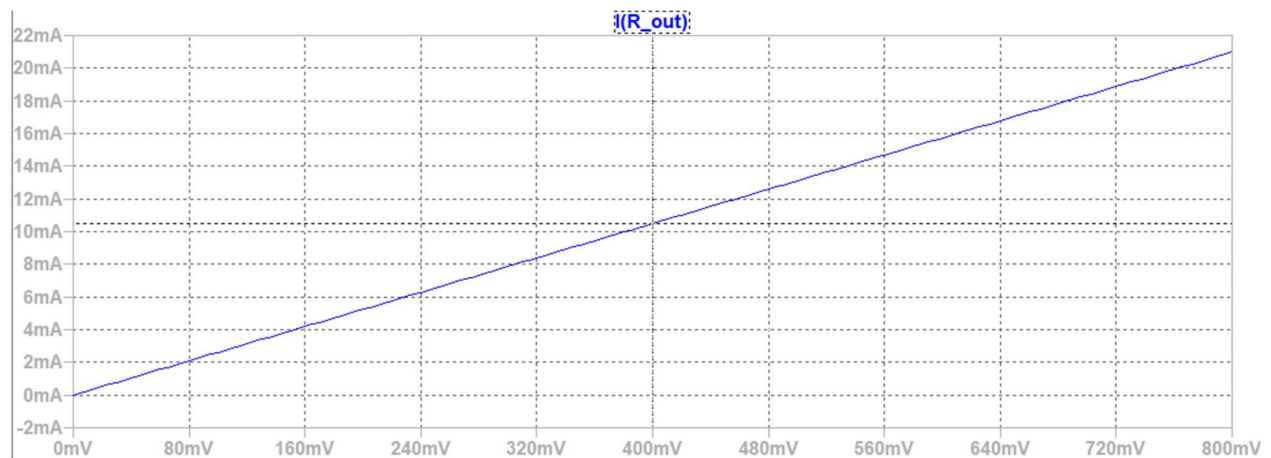


Figure 10: Howland Current Converter Simulation Results

From Figure 10, to output 4 mA, we need to output ~ 155 mV from the DAC and to output 20 mA, the DAC must output ~ 760 mV. Since the Howland Current Converter highly depends on the ideality of the components in the circuit, we tested it on a bread board to try to replicate the simulation results.

After testing the circuit, we found that our simulations were not entirely accurate. We found that we needed to output ~ 800 mV from the DAC for a 4 mA current output

and 3.3 V from the DAC for a 18 mA current output. We were unable to achieve the desired range of 4-20 mA using this circuit. This error could be caused by the non-ideality of the components or a slight mismatch in resistor values. Despite being unable to reach our desired range, our output range of 4-18 mA will work fine for this product. 4-18 mA corresponds to 0-1800 W/m^2 which is higher than any irradiance value that would be measured. This means our product can output the equivalent current based on any input the sensor might receive.

Sensor Calibration Testing

Calibration testing required the circuit to be powered by a USB to USBC connection and not the 5 V pin. We calibrated our prototype based on the irradiance output from the MP-100: Pyranometer Integral Sensor.



Figure 11: The MP-100: Pyranometer Integral Sensor

The following equation is a linear calibration curve representing the relationship between the prototype's output (mV) and the calibrated Pyranometer's irradiance (W/m^2).

$$\text{Calibrated output}(W/m^2) = (M * PV \text{ Matey}(mV) - B) * F$$

$M = \text{Slope}$

$B = Y \text{ intercept}$

$F = \text{Variance Factor}$

To create this curve, we compared the outputs of both sensors in a controlled environment. We set up the Fiber Lite DC-950 as an adjustable light source as seen in figure 12.



Figure 12: Fiber Lite DC-950

We closely mounted the PV Matey and a calibrated Pyranometer equidistant from the light source as seen in figure 13.

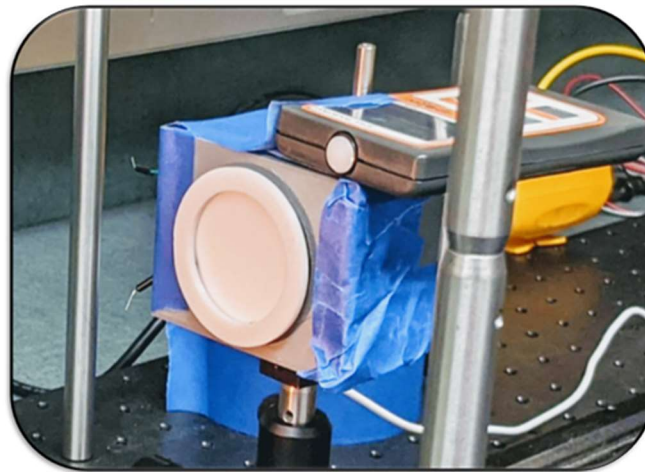


Figure 13: Mounted sensors

By incrementally increasing the intensity of the light source and recording the analog output of the PV Matey (mV) and the calibrated Pyranometer (W/m^2) we created a graph of their relationship as seen in figure 14. The linear trendline equation from this graph is the calibration curve function.

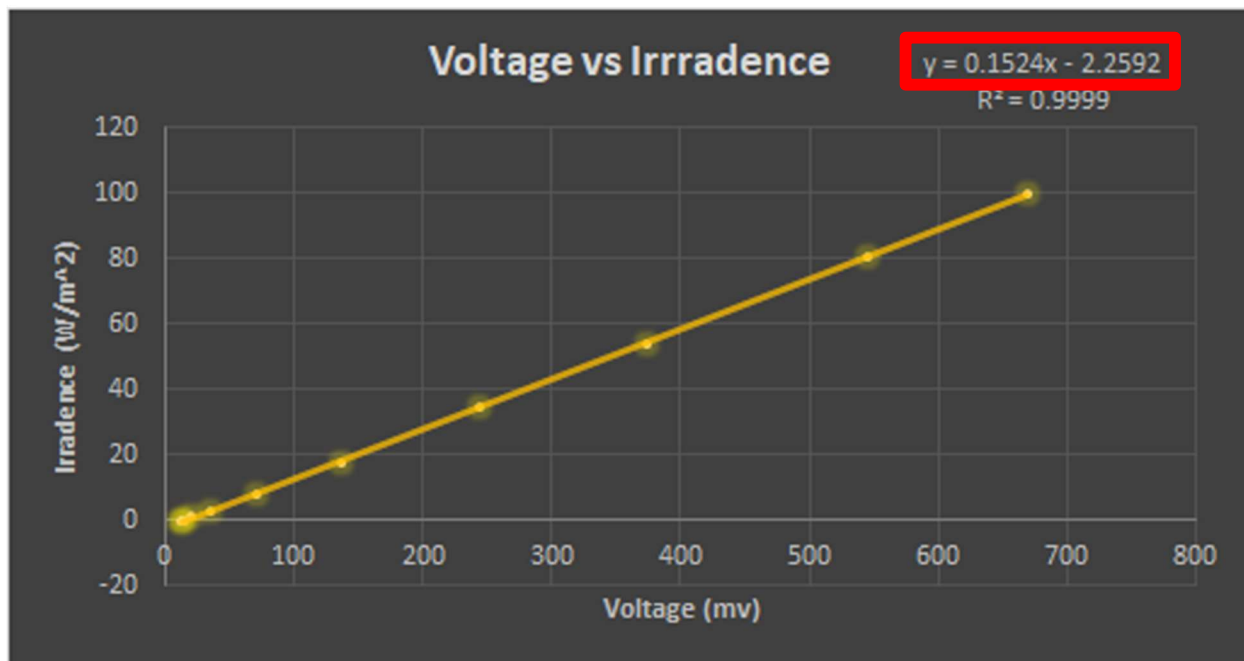


Figure 14: Calibration curve

The graph below shows a disparity between the data from the calibration curve (W/m^2) and the output from a commercial pyranometer (W/m^2) without a variance factor.

$$y = 0.1524x - 2.2592$$

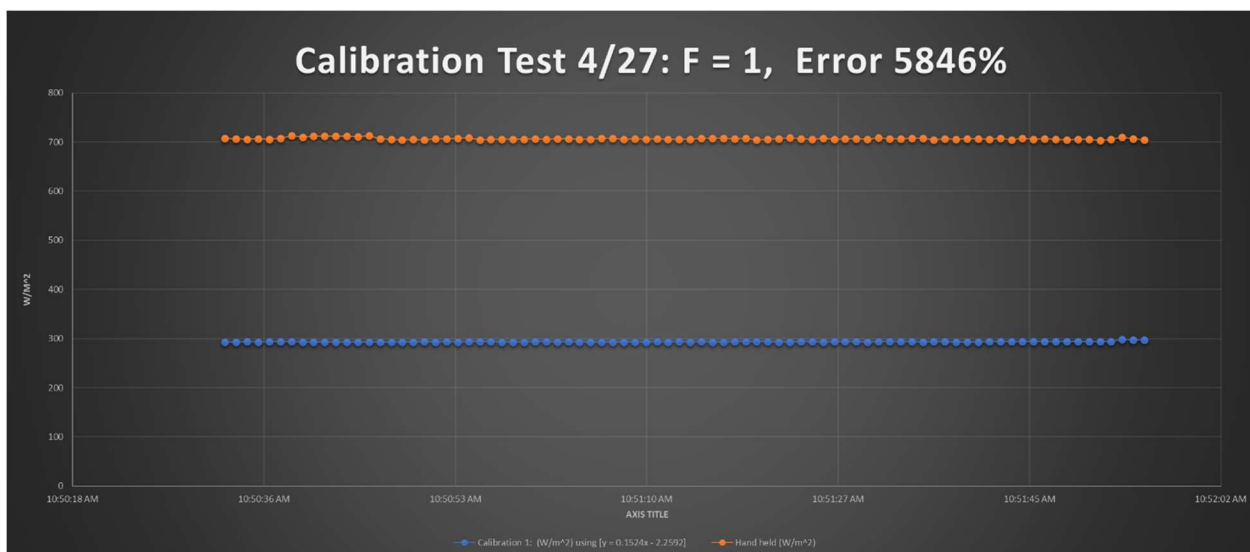


Figure 15: Calibration testing without a Variance Factor

To fine tune our output, we multiplied this curve by a variance factor shown below.

$$F = \frac{\text{Commercial Pyranometer } \left(\frac{W}{m^2}\right)}{\text{PV Matey (mV)}} = 2.4076$$

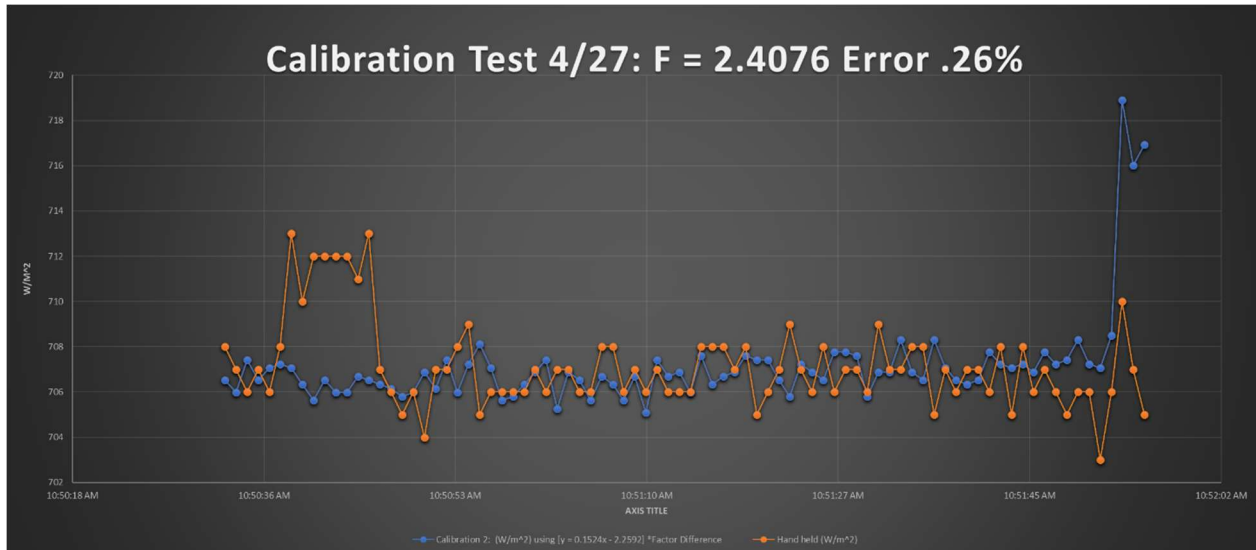


Figure 16: Calibration Testing with a Variance Factor

As seen in figure 16, the error after adding the variance factor drops to 0.26% compared to the massive error in figure 15. This exceeds our project requirement for have a 15% or lower error in values. Using the variance factor was needed to drop the error down. As such, it will need to be used in the future as well. Overall, we are very satisfied with our results with the calibration tests.

Case

Manufacturing

Based on the responses from our sponsor we were informed that this design would be a low volume unit roughly 2-8 units produced per year. As such we decided to opt for our case design to be manufactured via fused deposition modeling (FDM) 3D printing. We chose 3D printing over other manufacturing methods for three reason. First to get a tool for injection molding would cost between \$1,000-\$4,000 making it an

unrealistic option to use on such a low production unit. Second due to remote location where these devices are set to be deployed, manufacturing methods that relied on heavy machines i.e., lathe, CNC machine, etc. need to be done off site and then shipped to location adding an additional shipping cost and a delay to receive replacement parts. Finally, any manufacturing method intended to be done on site must be able to run in a low power environment ~400 W or less since the primary power source would be solar power. Based on those restrictions, our team opted for 3D printing because it was able to handle those restrictions. Since it would only cost the operator ~\$1 per case and was able to be done on site since budget kit printers, such as the Ender 3, have a maximum power draw of 360 W. This reduces the down time to get replacement parts and mitigates shipping cost.

Material Selection

Since we opted for our case to be manufactured through 3D printing, we considered four potential materials PLA, PETG, ABS and Carbon fiber. PLA was the easiest material to print with and did not require a fume hood to print indoors; but it had the lowest strength and glass transition temperature about ~60 C which could cause the case to deform on hot days. PETG was a step up from PLA on print difficulty but still manageable for beginners and like PLA it can be safely printed indoors without a fume hood. Furthermore, it is both lighter and stronger than PLA and boasts a higher UV resistance than either PLA or ABS. ABS is stronger than PLA and PETG. Due to its petroleum nature, ABS requires a fume hood to be safely printed indoors. Also, its abundant production for injection molding makes it the cheapest of the bunch. It also has the added caveat of being unstable, leading to a higher rate of deterioration when exposed to outdoor conditions.

Carbon Fiber is the strongest of the materials looked at and has the added benefit of being resistant to weathering. It was also one of the hardest materials to print requiring both a steel hot end and a decent extruder to mitigate the risk of jamming. Furthermore, it also had the highest cost per spool of all the materials looked at. Based on this information we opted to use PETG since it had one of the highest solar resistance while maintaining a relatively low cost and printability. Figure 17 shows the

bill of materials for this project. The link for each component is found in the Component section of the Appendix.

PV Matey Bill of Materials			Manufacturing Plan							Cost	
Part No. or Assy No.	Description	Quantity	Make or Buy?	Source (or Fabrication Location)	Fabrication Technique (if appl.)	Is the Drawing Avail.?	Is the Material Avail.?	Who will lead (Name)?	Target Completion Date	Unit Cost (\$)	Extended Cost (\$)
Full Assy 1											
Subassembly 1	Sunlight Capture	1									
Subassembly 2	Microcontroller	1									
Subassembly 3	Output to Data Logger	1									
Subassembly 4	Case	1									
Subassembly 1	Sunlight Capture	1									
Part 1	SFH 3310 Phototransistor	1	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.86	\$0.86
Part 2	Teflon Sheet*	1	Buy	ePlastics	N/A	No	No	Lukas V.	1-Mar	\$3.08	\$3.08
Part 3	Acrylic Disk	1	Buy	US plastics	N/A	No	No	Lukas V.	1-Mar	\$1.72	\$1.72
Part 4	680 Ω Resistor	1	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.10	\$0.10
Subassembly 2	Microcontroller	1					No				
Part 5	Adafruit QT py	1	Buy	Adafruit	N/A	No	No	Adriana O. and Brady J.	1-Mar	\$6.00	\$6.00
Part 6	1N914 Diode	1	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.10	\$0.10
Part 7	5V, 1A Power Supply	1	Buy	Amazon	N/A	No	No	Lukas V.	1-Mar	\$7.89	\$7.89
Subassembly 3	Output to Data Logger	1					No				
Part 8	36 Ω Resistor	4	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.10	\$0.40
Part 9	Op Amp LM358P	1	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.41	\$0.41
Part 10	22 AWG 3-Conductor Copper Wire	100	Buy	Mouser	N/A	No	No	Lukas V.	1-Mar	\$0.29	\$29.00
Subassembly 4	Case	1									
Part 11	Circuitry Housing*	1	Make	Personal Equipment	3D Print from PETG	Yes	Yes	Nick B.	1-Mar	\$0.20	\$0.20
Part 12	Housing Lid*	1	Make	Personal Equipment	3D Print from PETG	Yes	Yes	Nick B.	1-Mar	\$0.20	\$0.20
Part 13	Acrylic Disk Cap*	1	Make	Personal Equipment	3D Print from PETG	Yes	Yes	Nick B.	1-Mar	\$0.20	\$0.20
Part 14	USB Cord Seal: Upper Piece*	1	Make	Personal Equipment	3D Print from PETG	Yes	Yes	Nick B.	1-Mar	\$0.10	\$0.10
Part 15	USB Cord Seal: Lower Piece*	1	Make	Personal Equipment	3D Print from PETG	Yes	Yes	Nick B.	1-Mar	\$0.10	\$0.10
	Estimate *										
Total BOM Cost										\$	\$0.36

Figure 17: Bill of Materials for the PV Matey Pyranometer

Case Design

To keep the manufacturing cost of the case down, we decided to use an interference fit based design. Furthermore, the added benefit of this design choice was that it made the case innately water and dust resistant by nature, since both pieces must be in direct contact with one another for the interference fit to properly function. To further bolster the case's dust and water resistance, we decided to add a layer of electrical tape around the mating segments that would take part in the interference fit. The electrical tape achieves this by exploiting its rubber like nature, allowing it to expand and fill any voids that would normally allow for water and dust to enter the case.

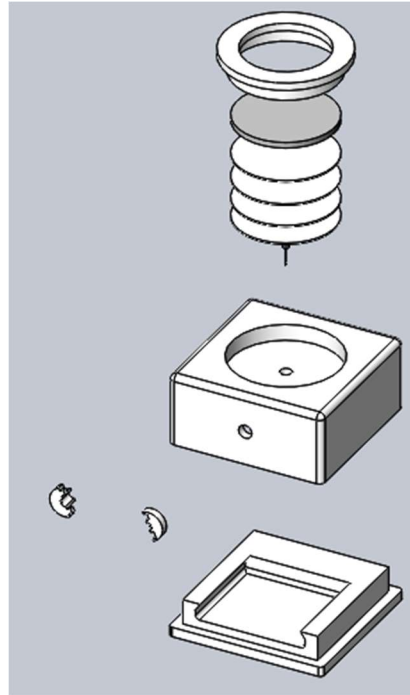


Figure 18: Breakdown of the PV Matey Case

The next consideration that was evaluated was the inherent dimensional inaccuracy of FDM 3D printing technology. Given the low-cost environment that the PV Matey is supposed to operate in, we assumed a worst-case scenario with tolerance of ± 0.4 mm. This tolerance would make it possible to print the case on most kit 3D printers. To make our case design adaptable to any PCB, the case bottom is designed with a slot system in mind. This allows the operator to easily customize the base to meet the needs of any PCB alterations while keeping the cost of the system down.

Design Evaluation

To better improve our prototype, we produced a design failure mode effects analysis (DFMEA) which can be found in the Appendix.

Product Testing Procedures

The Circuit

Tinker Cad simulations were used to verify our sensor's compatibility with a microcontroller. These simulations also improved our understanding of programming and pin placement. Figure 19(a) shows our sensor setup, while figure 19(B) shows a multiple sensor configuration used for testing.

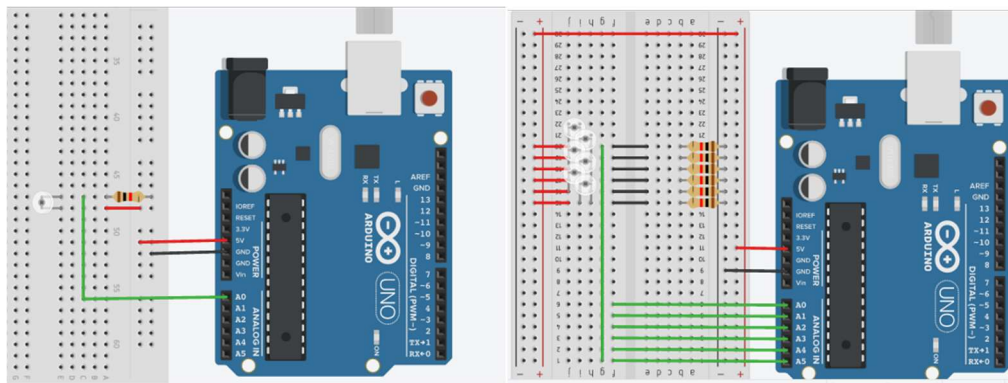


Figure 19: (A) Data collection for one sensor (B) Data collection for six sensors

The Sensor

To better understand the shortcomings of our sensor, we ran a photocurrent test past the range specified in the data sheet. For this test, we used an adjustable light source and lux meter in a dark, controlled environment. Then we compared the output current of our sensor to the lux reading as we increased the intensity of the light source. Figure 20 shows a lux meter mounted to our sensor configuration.

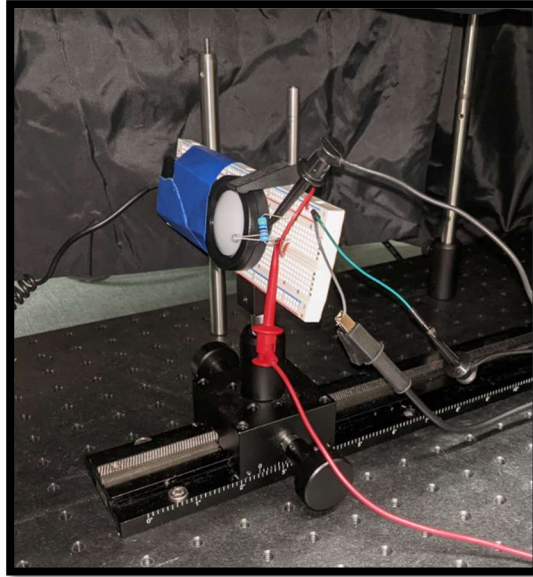


Figure 20: Photocurrent Test

The graph below indicates that at 1000 lux the sensor hits a “saturated” region. Data past this point is no longer linear and loses accuracy. To avoid saturation past this point, filtering is needed. To resolve this problem, we used Teflon sheets to evenly distribute and filter excessive light. See the filtering section above for more information on this attenuator.

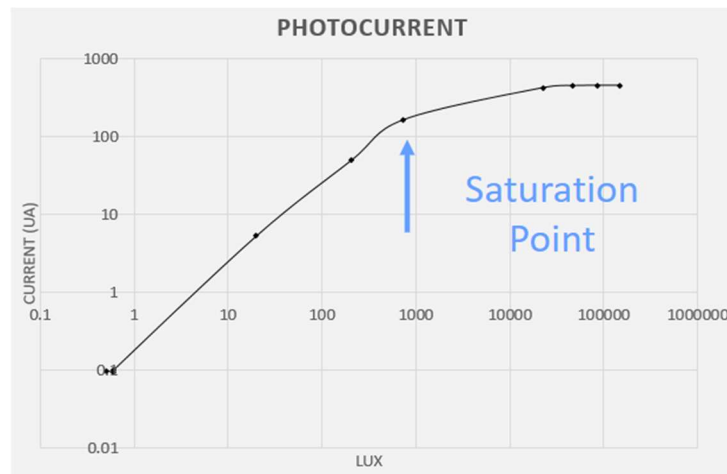


Figure 21: Photocurrent from the SFH-3310

The Case

To ensure that the case would survive a potential drop, we ran a Solidworks simulation. Assuming our device is mounted to a one-story building, we found that a fall

from 10 feet onto a concrete surface would result in a maximum stress of 4.5×10^7 Pascals as seen in figure 22. In Figure 23, a Solidworks displacement test indicates a maximum deformation of 0.748 mm in the case top. Based on these analyses, it is likely that the case would survive a drop with minor permanent deformations.

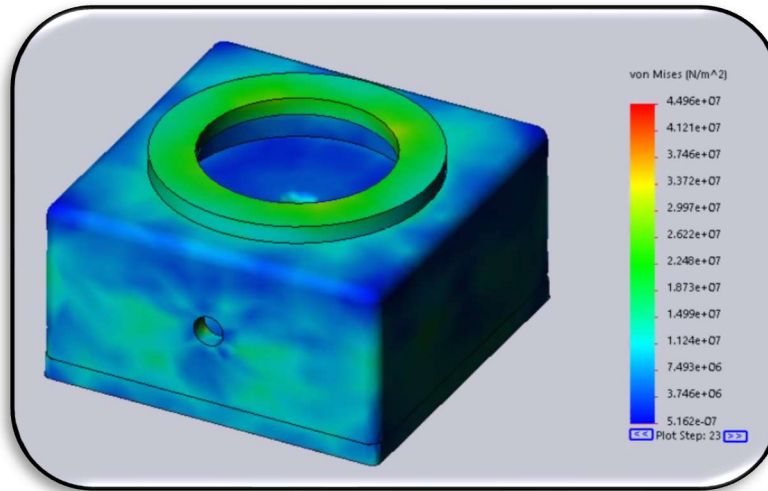


Figure 22: Solidworks Stress Simulation

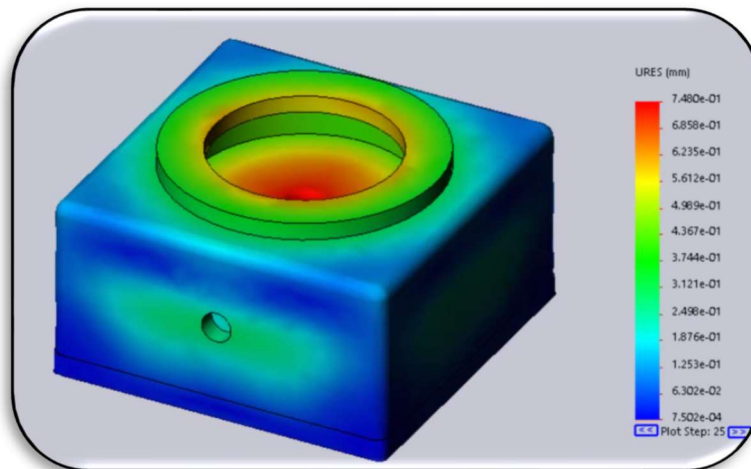


Figure 23: Solidworks Displacement Simulation

To test the water resistance of a sealed cap, we filled the top portion with water. A paper towel was placed under the cap to indicate any potential leaks. After waiting eight hours, the paper towel remained unaffected. Figure 24 show this process. This test indicates that when sealed properly with electrical tape, the cap is water resistant.



Figure 24: Water Resistance Testing

Circuit Assembly

Calibration Circuit

The calibration circuit differs from the full circuit because it does not utilize the voltage-to-current converter. This circuit can be implemented on a bread board using **case_rev1.2** instead of a printed circuit board (PCB), so the user can easily change out components if needed. The PCB from the final circuit assembly can be used if the 5 V pin is not connected to a power source, or if the power source is disconnected.

Calibration Circuit Assembly

1. Connect the collector (short leg) of the phototransistor to the 5 V supply pin of the QT Py.
2. The emitter is connected in series with a 680 Ω resistor and placed into pin A1 of the QT Py.
3. Plug the QT Py to the computer using a USB C cable.

The QT Py reads the voltage across the resistor as the current produced by the phototransistor changes. See the Calibration section for further details on how to properly calibrate the sensor. Figure 25 shows the circuit schematic for the calibration circuit.

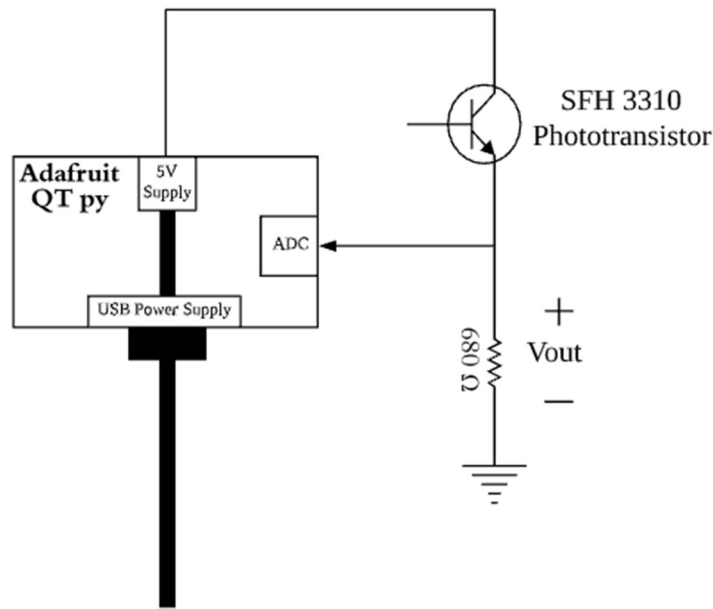


Figure 25: PV Mamey Calibration Circuit

Final Circuit

The final circuit schematic is shown in Figure 6 on page 11 of this document and is implemented on a PCB. The files for the PCB can be downloaded from the Wiki page for this product, which is found in the Appendix. They can be printed by any company that prints PCBs. Figures 26 and 27 show the circuit schematic and PCB layout, which are both designed using Eagle software.

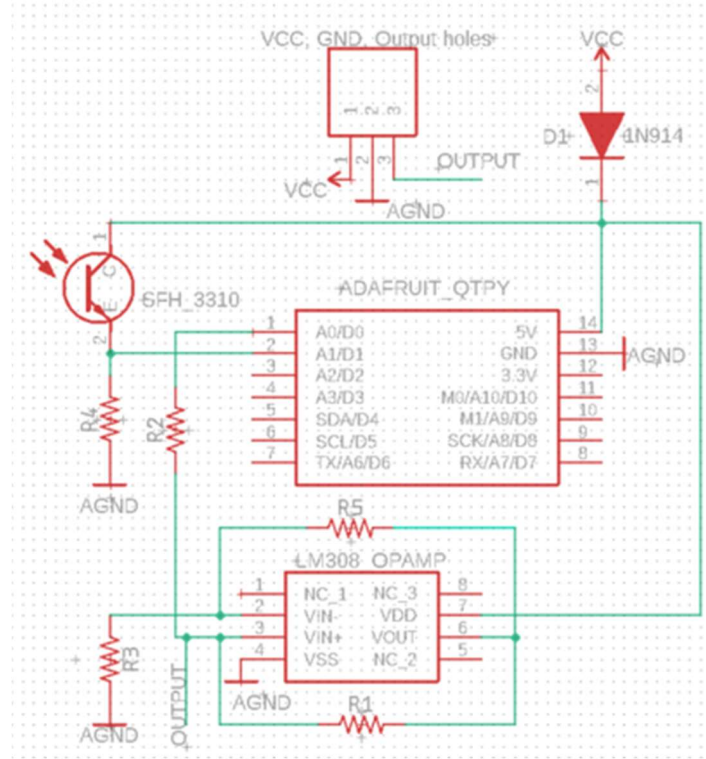


Figure 26: Circuit Schematic

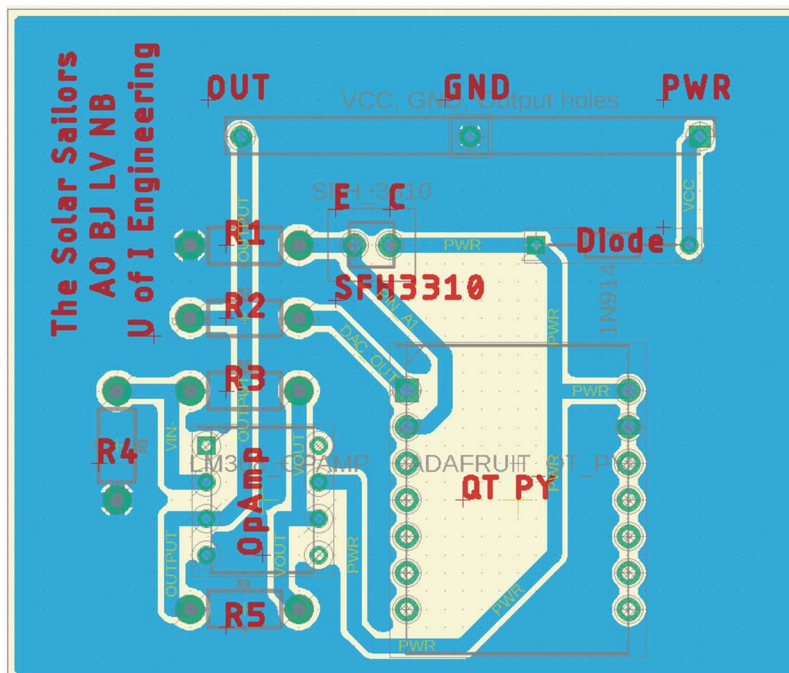


Figure 27: PCB Layout

Figure 27 shows the location for each component on the PCB. The locations of each component are labeled in red lettering on the top of the PCB while the connections between components are on the bottom of the PCB.

Final circuit Assembly

To assemble the circuit on the PCB, follow the instructions listed below.

1. Place the legs of the diode in the holes labeled “Diode”. Place the cathode in the left hole and the anode in the right hole. Figure 28 shows the diagram of a diode.

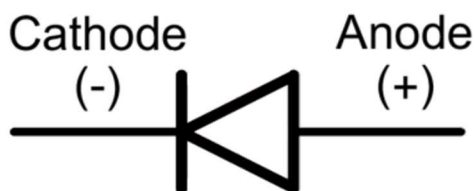


Figure 28: Diagram of a Diode

2. Place the SFH 3310 in the holes labeled “SFH3310”. Place the collector (short leg) in the hole labeled “C” and the emitter in the hole labeled “E”.
3. Place all resistors in their specific holes.
 - a. Place the 680 Ω resistor in the holes labeled “R1”.
 - b. Place four, 36 Ω resistors in the holes labeled “R2”, “R3”, “R4”, and “R5”.
4. Solder the headers that came with the QT Py to the microcontroller. Then place the microcontroller with the soldered headers in the holes labeled “QT Py”. Orient the QT Py with the USB C port facing the phototransistor.
5. Place the Op Amp in the holes labeled “OpAmp”. Orient the Op Amp with the circle in the upper corner towards the label “R4”.
6. Use wire-strippers to strip the outer insulation from the three-conductor cable. Then strip the insulation from the red, black, and white wires.
 - a. Place the red wire in the hole labeled “PWR”.
 - b. Place the black wire in the hole labeled “GND”.
 - c. Place the white wire in the hole labeled “OUT”.
7. Solder all components to the bottom of the PCB.
 - a. See the Appendix for instructions for best soldering techniques. More instructions can be found on the internet, if needed.

8. Repeat the process in step 6 at the other end of the three-conductor wire.
 - a. Place the red wire in the positive hole of the screw terminal power source.
 - b. Place the black wire in the negative hole of the screw terminal power source.
 - c. Place the white wire in the data logger or connect it to a multimeter to measure the current output from the PV Matey.

Figure 29 shows the completed circuit soldered to the PCB.

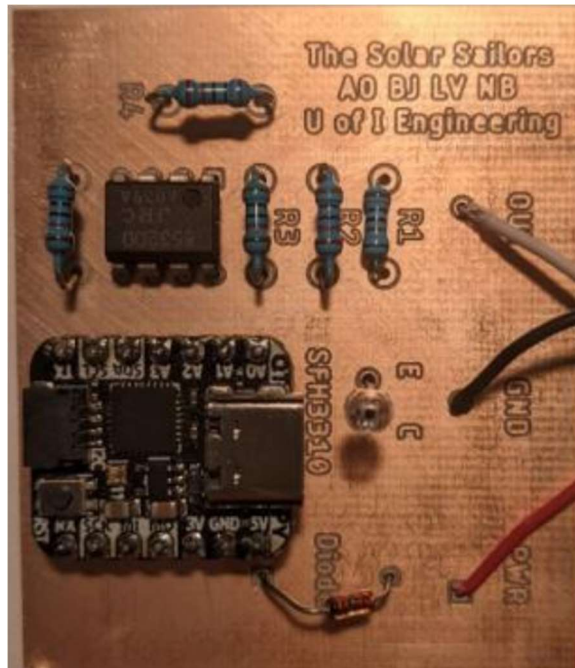


Figure 29: Components attached to the PCB

Future Work

While our prototype does work, there are a few things that could be improved. For this design, we tried to keep the cost to a minimum. If the sponsor wants a more accurate device, one thing to improve would be the sensor. Through our testing, we found that a few sensors had varying values between them. This could be due to the overall cost of the sensor, as well as the viewing angle.

Another thing to investigate would be a professionally printed PCB. Our current copper PCB can eventually lead to corrosion, which should be look at in the future. While our design does work, it is very basic, so this simple design might not work in future updates to this prototype. A professionally printed PCB would offer a lot more in terms of usability and durability.

We would recommend looking into a domed lens on the top of the device. While the flat acrylic disk works just fine, it can cause pooling of liquid on the top of the case. The pooled water could cause data collection errors that would be avoided using a dome. A domed glass or acrylic disk would prevent this pooling but could raise the overall cost of the device. A link for different glass domes can be found in the Recommendations section of the Appendix.

The last recommendation for this product would be to use a different circuit for the current output. Since our circuit is so dependent on the ideality of the components, we recommend using a circuit that is not so sensitive. Another option would be to design a voltage-controlled current source, as seen in Figure 30.

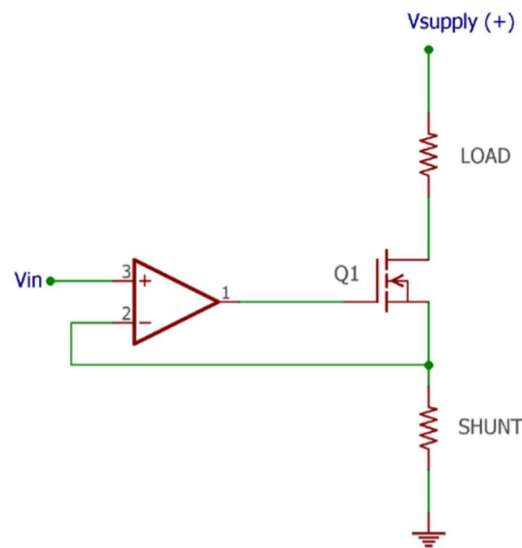


Figure 30: Voltage-Controlled Current Source Circuit Diagram.

We were able to complete preliminary testing on this circuit and measured favorable results. This circuit worked when the voltage input from the wall outlet power jack increased from 5 to 9 V. To keep the QT Py's input power at 5 V, a voltage regulator or voltage divider could be used. Despite our limited success with this circuit, the idea needs to be more developed before it is implemented. See the Improvements section of the Appendix for the link to this circuit.

Appendix

Components

680Ω Resistor (1): <https://www.mouser.com/ProductDetail/Vishay-Dale/CCF07680RGKE36?qs=sGAEpiMZZMtG0KNrPCHnjXeT93wkI59768WqROcKsvM%3D>

Adafruit QT Py (1): <https://www.adafruit.com/product/4600>

3D printing PETG filament (1): https://smile.amazon.com/DURAMIC-3D-Printing-FilamentDimensional/dp/B07TRPQ4MN/ref=sr_1_2_sspa?crd=1FH4OZWBN70YJ&dc_hild=1&keywords=petg+3d+printer+filament&qid=1613577099&sprefix=PETG+3d%2Caps%2C226&sr=8-2-spons&pvc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzME9aOFJGVjZLUesmZW5jcnlwdGVkSWQ9QTA0NTUyODQ3NkRDMzhUT1VDRyZlbnNyeXB0ZWRBZEIkPUeWnjkWMDkzMTdYQkZGQjgzMlVYTjZ3aWRnZXROYW1lPXNwX2F0ZiZlY3Rpb249Y2xPy2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=

Phototransistor SFH 3310 (1): <https://www.mouser.com/ProductDetail/720SFH3310>

*Note: This phototransistor can be changed out for another phototransistor that has the same pinout and footprint. Be sure to check the datasheet for the SFH 3310 phototransistor when looking for a replacement phototransistor.

2" Acrylic Disks (1): <https://www.usplastic.com/catalog/item.aspx?itemid=40805&catid=441>

12"x12" Teflon Sheet (1): <https://www.eplastics.com/PTFENAT0-040X12X12>

36Ω Resistor (4): <https://www.mouser.com/ProductDetail/Vishay-Dale/CCF0736R0GKE36?qs=sGAEpiMZZMsPqMdJzcrNwnPpI93fAKplt%2Fje72JuHDk%3D>

Op Amp LM358P (1): <https://www.mouser.com/ProductDetail/Texas-Instruments/LM358P?qs=X1HXWTtiZ0QtOTT8%252BVnsyw%3D%3D>

*Note: This Op Amp can be changed out for another Op Amp that has the same pinout and footprint. Be sure to check the datasheet for the Op Amp LM358P when looking for a replacement Op Amp.

22 AWG Insulated Copper Wire (29'): <https://www.superbrightleds.com/moreinfo/power-wires-cables/pvc-jacketed-3->

[conductor-22-awg-power-wire-pp-frpvc-gray/1850/4475/](#)

5V, 1A Power Source (1): https://www.amazon.com/inShareplus-Voltage-Transformer-100-240V-Connector/dp/B07GL9YB3Z/ref=sr_1_1_sspa?dchild=1&keywords=5v%2Bpower%2Bsupply&qid=1618527091&sr=8-1-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEyNE9ONjFDN004SDIYJmVuY3J5cHRlZEIkPUeWODEwOTAzVUVGTIRHOEVWFFHJmVuY3J5cHRlZEFkSWQ9QTA2OTAzMzkYRk81S084QIU0MkxaJndpZGdldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGlja1JlZGlyZWNOJmRvTm90TG9nQ2xPy2s9dHJ1ZQ&th=1

1N914 Diode (1): <https://www.mouser.com/ProductDetail/512-1N914T50A>

Concepts Considered

Microcontrollers

Arduino Nano Every: <https://store.arduino.cc/usa/nano-every>

Adafruit QT Py: <https://learn.adafruit.com/adafruit-qt-py>

Low-Cost Pyranometer Article:

<https://drive.google.com/file/d/106akF6K0mFLK4IN4aw6NxlOrWNkQHP13/view?usp=sharing>

Recommendations

Glass Domes:

https://www.aliexpress.com/item/32664743041.html?spm=2114.search0302.3.24.7686674ftBGzql&ws_ab_test=searchweb0_0,searchweb201602_0,searchweb201603_0,ppcSwitch_0&algo_pvid=fa9d9ab3-05c2-4a5a-8154-b581754f76c4&algo_expid=fa9d9ab3-05c2-4a5a-8154-b581754f76c4-3

Voltage-Controlled Current Source: <https://circuitdigest.com/electronic-circuits/voltage-controlled-current-source-circuit-using-op-amp#:~:text=In%20a%20voltage%2Dcontrolled%20current,like%20BJT%2C%20SCR%2C%20etc.>

Sensor

SFH 3310 Phototransistor Datasheet: https://dammedia.osram.info/media/resource/hires/osram-dam-5898517/SFH%203310_EN.pdf

Wiki Page Link

[http://mindworks.shoutwiki.com/wiki/Development of a Low Cost Pyranometer](http://mindworks.shoutwiki.com/wiki/Development_of_a_Low_Cost_Pyranometer)

System _____
 Subsystem _____
 Component _____
 Design Lead _____
 Core Team Solar Sailors

**Potential
 Failure Mode and Effects Analysis
 (Design FMEA)**

Key Date 3/20/2021

FMEA Number _____
 Prepared By Nickolas Borek
 FMEA Date 3/20/2021
 Revision Date 5/4/2021
 Page 1 of _____

Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S e v	Potential Cause(s)/ Mechanism(s) of Failure	P r o b	Current Design Controls	D e t	R P N	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	New Sev	New Occ	New Det	New RPN
Case Top	Links the case cap, case bottom and cable clamp	Fracture	Loss of ability to keep water and dust out	3	Impact	6	NA	2	36	Preform impact test on the Case Top		Added fillets and design verified with Solidworks Sim	3	5	2	30
Case Top	Links the case cap, case bottom and cable clamp	Fracture	Loss of ability to keep water and dust out	3	solar corrosion (0-3) years	4	NA	7	84	Preform solar corrosion analysis on Case Top		Changed case material to PETG	2	3	5	30
Case Top	Links the case cap, case bottom and cable clamp	Fracture	Loss of ability to keep water and dust out	4	solar corrosion (4-10) years	7	NA	7	196	Preform solar corrosion analysis on Case Top		Changed case material to PETG	3	5	5	75
Case Top	Links the case cap, case bottom and cable clamp	Fracture	Loss of ability to keep water and dust out	3	Defect during 3D printing process	5	NA	7	105	Optimize printer g-code		3D print instructions added to the user manual	3	2	7	42
Case Top	Links the case cap, case bottom and cable clamp	Deformation	Inability to open case and loss of strength	4	High temperatures and exposure to chemicals	4	NA	3	48	Find a replacement material for PLA		Changed case material to PETG	4	2	3	24
Case Top	Links the case cap, case bottom and cable clamp	Sealant failure	Inability to keep water and dust out of the case	5	Improper case assembly	5	NA	5	125	Add detailed case assembly instructions to user manual		case assembly instructions added to the user manual	5	3	3	45
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Fracture	Loss of ability to keep water and dust out	4	Impact	5	NA	4	80	Preform impact test on the Case Cap		verified design with Solidworks Simulations	4	3	4	48
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Fracture	Loss of ability to keep water and dust out	3	solar corrosion (0-3) years	4	NA	7	84	Preform solar corrosion analysis on Case Cap		Changed case material to PETG	2	3	5	30
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Fracture	Loss of ability to keep water and dust out	4	solar corrosion (4-10) years	7	NA	7	196	Preform solar corrosion analysis on Case Cap		Changed case material to PETG	3	5	5	75

Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S e v	Potential Cause(s)/ Mechanism(s) of Failure	P r o b	Current Design Controls	D e t	R P N	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	New Sev	New Occ	New Det	New RPN
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Fracture	Loss of ability to keep water and dust out	3	Defect during 3D printing process	5	NA	7	105	Optimize printer g-code		3D print instructions added to the user manual	3	2	7	42
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Deformation	Inability to open case and loss of strength	4	High temperatures and exposure to chemicals	4	NA	3	48	Find a replacement material for PLA		Changed case material to PETG	4	2	3	24
Sensor Cap	Holds the sensor, acrylic, and Teflon sheets	Sealant failure	Inability to keep water and dust out of the case	5	Improper assembly	5	NA	5	125	Add detailed case assembly instructions to user manual		case assembly instructions added to the user manual	5	3	3	45
Case Bottom	Holds the PCB	Fracture	Loss of ability to keep water and dust out	3	Impact	6	NA	2	36	Preform impact test on the Case Bottom		Added fillets and design verified with Solidworks Sim	3	5	2	30
Case Bottom	Holds the PCB	Fracture	Loss of ability to keep water and dust out	3	solar corrosion (0-3) years	3	NA	7	63	Preform solar corrosion analysis on Case Bottom		Changed case material to PETG	2	2	5	20
Case Bottom	Holds the PCB	Fracture	Loss of ability to keep water and dust out	4	solar corrosion (4-10) years	5	NA	7	140	Preform solar corrosion analysis on Case Bottom		Changed case material to PETG	3	4	5	60
Case Bottom	Holds the PCB	Fracture	Loss of ability to keep water and dust out	3	Defect during 3D printing process	6	NA	7	126	Optimize printer g-code		3D print instructions added to the user manual	3	2	7	42
Case Bottom	Holds the PCB	Deformation	Inability to open case and loss of strength	4	High temperatures and exposure to chemicals	4	NA	3	48	Find a replacement material for PLA		Changed case material to PETG	4	2	3	24
Case Bottom	Holds the PCB	Sealant failure	Inability to keep water and dust out of the case	5	Improper case assembly	5	NA	5	125	Add detailed case assembly instructions to user manual		case assembly instructions added to the user manual	5	3	3	45
Cable Clamp	Locks the cable in place and limits cable pullout	Fracture	Loss of ability to keep water and dust out and	3	Impact	6	NA	2	36	Preform impact test on the Cable Clamp		Added fillets and design verified with Solidworks Sim	3	5	2	30
Cable Clamp	Locks the cable in place and limits cable pullout	Fracture	Loss of ability to keep water and dust out	3	solar corrosion (0-3) years	4	NA	7	84	Preform solar corrosion analysis on Cable Clamp		Changed case material to PETG	2	3	5	30

