OUC All-in-One Photovoltaic Sensor

Group 5

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Motivation

In order to be a convincing replacement for traditional fossil-fuel power sources, solar technology needs to be powerful and efficient.

As such, lots of research is done in the manufacturing of new solar panel technology. However, solar farm operators often have limited access to panel level data.

Our goal is to create a device which will give solar farm operators a simple and expandable way of collecting panel level data. It should work on a variety of solar arrays, whether they be small research arrays with a variety of different panels, or a production scale power generation array.

Project Goals and Objectives

Our **primary goal** is to create several prototypes of a photovoltaic sensor applicable in small-to medium-scale solar arrays that determine panel health by monitoring its voltage and amperage.

Our **secondary goal** is to incorporate two supplementary measuring instruments to our original design: a thermocouple capable of tracking panel temperature and a pyranometer that can detect incident light irradiance.

When installed in a solar array, the sensor will collect panel health data which the operator can then use to optimize the longevity and consistency of the array's power generation.

Specifications and Requirements

Engineering Requirements	Priority
32V Rating	High
10A Rating	High
320W Rating (On Terminals)	High
≥ 1 Year Lifespan	Moderate
Under $20 each	Low

Marketing Specifications	Priority
Use MC4 connectors	High
Transfer data to database	High
NEMA 4X or 4R Enclosure	High
Comply with FCC standards	High
Filter out noise	Moderate
Portable	Moderate
Connect between solar panels	Moderate
Reproducible	Moderate
Connections for thermocouple and pyranometer	Low

Demonstrable Specifications	
Voltage Measurement Accuracy	±5%
Current Measurement Accuracy	±5%
Data Transmission	≤ 10s

These specifications are directly from OUC, as the voltage and current are most important in getting accurate panel health readings.

Project Standards

Project Standards: Enclosures

NEMA 250

NEMA 250 provides the standards of ingress protection tests for all of the enclosure types, from Type 1 to Type 13.

For our project, the OUC required a NEMA Type 4X enclosure, which establishes:

- Access to hazardous parts
- Ingress of solid foreign objects (falling dirt)
- Ingress of water (dripping and light splashing)
- Ingress of water (rain, snow and sleet)
- Ingress of solid foreign objects (windblown dust, lint, fibers and flyings)
- Ingress of water (hose-down and splashing water)
- Corrosive agents

Project Standards: Enclosures (ctd.)

IEC 60529

A standard from the International Electrotechnical Commission that establishes a system for classifying levels of protection provided by enclosures. There are different degrees of protection laid out in the standard. The one with which we are concerned is IP66.

This rating offers complete protection of the internal components from anything equal to or larger in size than dust particles.

This rating also offers complete protection against power water jets. This would include any type of power water hose, which could be encountered in the outdoors area on OUC’s property.

Project Standards: Pyranometers

IEC 61724-1:2017

- IEC's assessment of solar irradiance measurement
- Created classifications for pyranometers and their appropriate application
- Defined new methods of upkeep for the devices

Project Standards: Thermocouples

IEC 60584-1:2013

- IEC's internationally-recognized classification system
- Distinguishes each device's material properties

Project Standards: MC4

IEEE 802.15

IEEE 802.15 defines the protocol and compatible interconnection for data communication devices using low-data-rate, low-power, and low-complexity short-range radio frequency (RF) transmissions in a wireless personal area network (WPAN).

Project Standards: Software

Python Enhancement Protocol (PEP) 8 -- Style Guide for Python Code

PEP 8 establishes coding conventions for the Python code comprising the standard library in the main Python distribution.

Project Design Approach

Project Design Implementation

We want to create a simple sensor that provides convenient and accurate data to the Orlando Utilities Commission.

The primary purpose of the device is to collect voltage and current data, but if possible we will also seek to implement temperature and irradiance sensing.

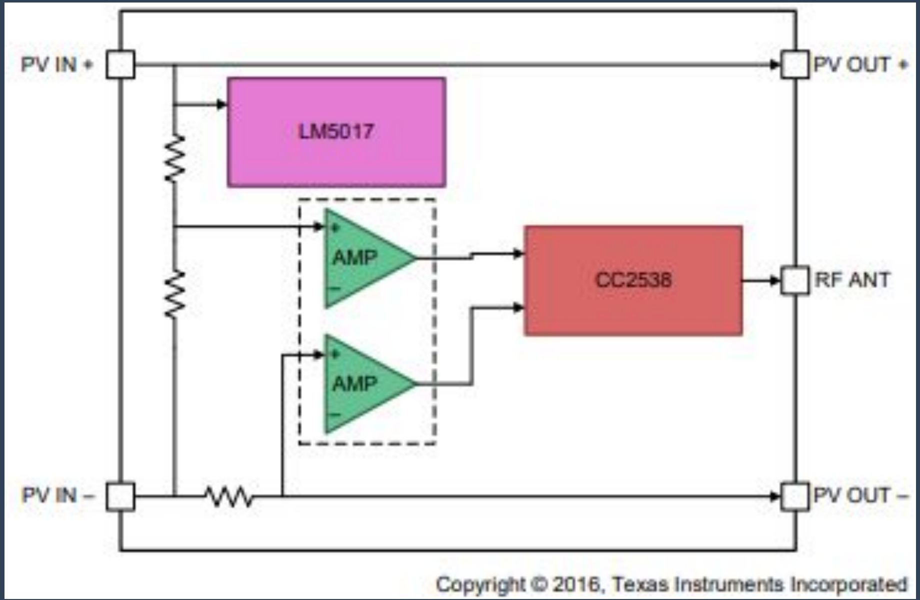
This will enable OUC and other utility companies to better track the health of their solar installations.

The sensor will wirelessly transmit the data to the node, which will be accessible over ethernet to the commission.

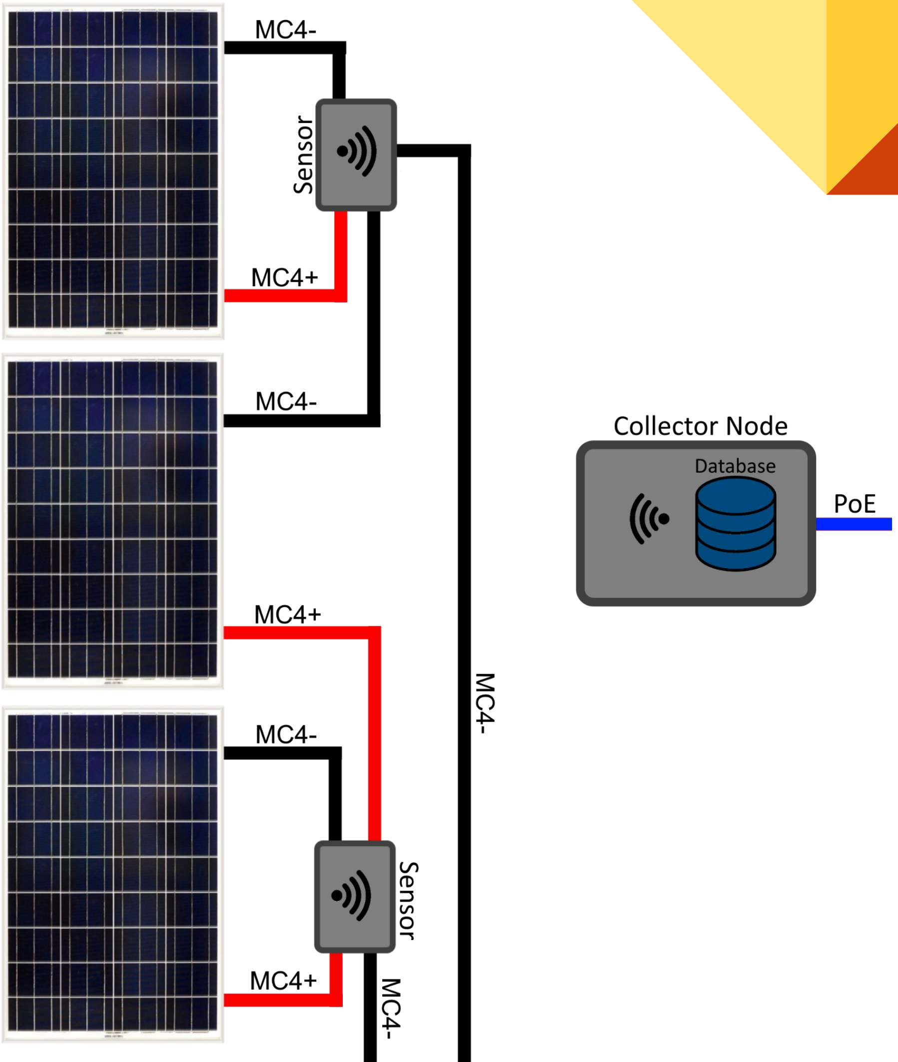
Reference Design

Texas Instruments' TIDA-00640 design provides an overview on how to design a solar module-scale monitoring and communication system.

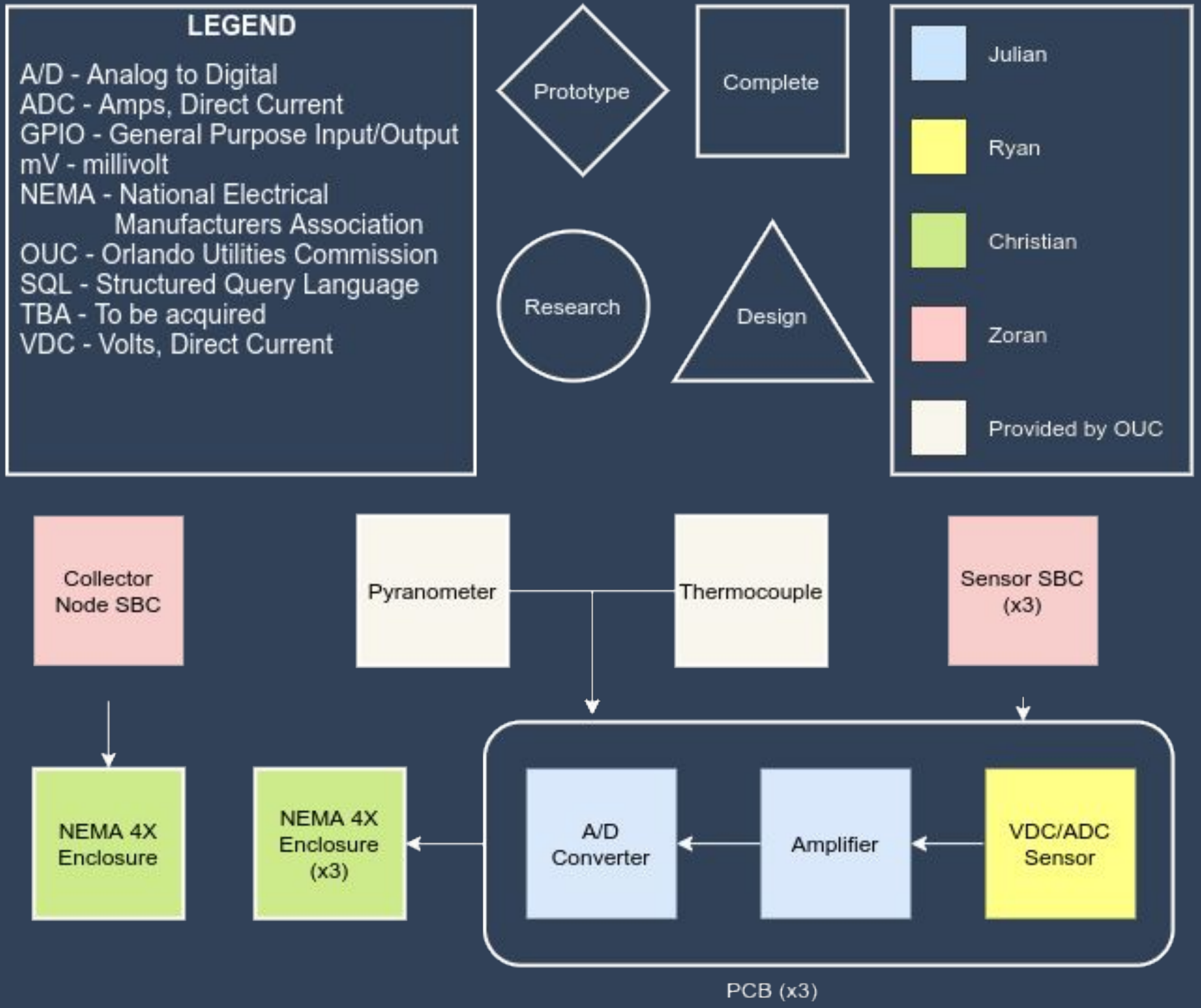
Component	TIDA-00640
PSU	LM5017
Amplifier	TLV342A
ADC	On-board the CC2538
Signal Transmission	CC2538 to RF Antenna



Prototype Visualization

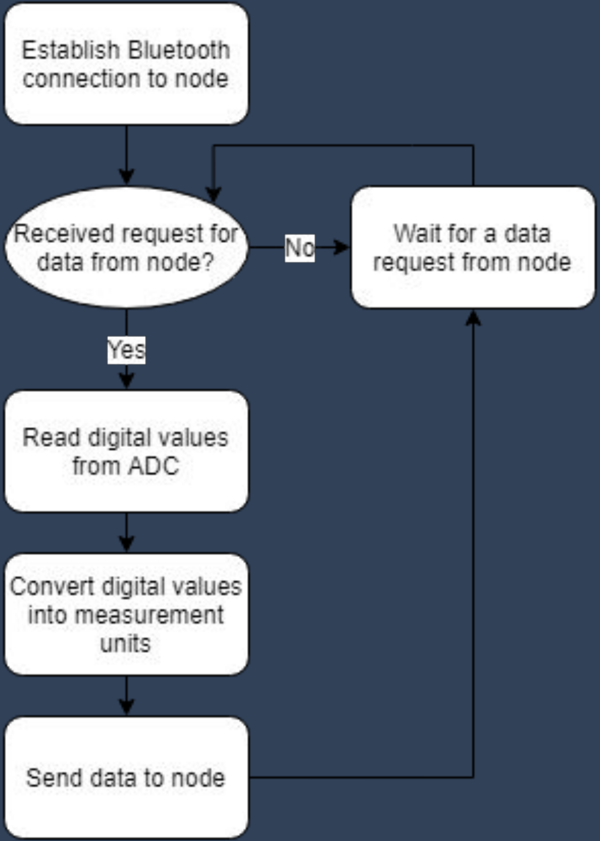


Block Diagram

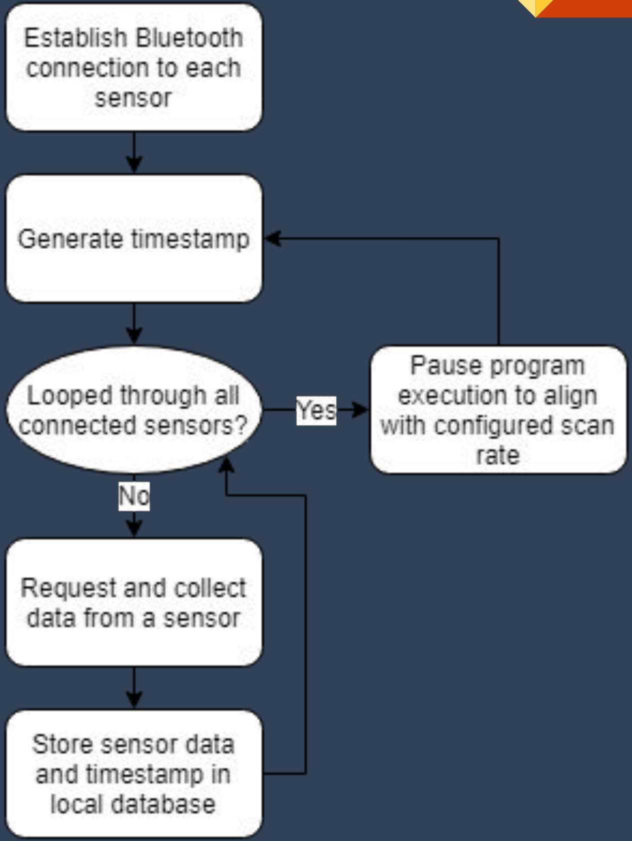


Software Workflow

Sensor



Node



Sensor Hardware Selection

Core Requirements:

- Read an analog input signal
- Wireless communication

Other Considerations:

- Price
- Ease of use
- Size
- Power consumption

Characteristic	Raspberry Pi Zero W	Banana Pi BPI-M2 Zero	Orange Pi i96
Processor	Single-core ARM1176JZF-S 1 GHz	H2+ Quad-core Cortex-A7	Single-core ARM Cortex-A5 32bit
Processor DMIPS/MHz	1.25	1.9	1.57
RAM	512 MB	512 MB	256 MB
Bluetooth Capability	Bluetooth 4.1, BLE	Bluetooth 4.0	Bluetooth 2.1
Operating Temperature Range	0 °C to 70 °C	N/A	-10 °C to 65 °C
Dimensions and Weight	65mm x 30mm 9g	65mm x 30mm 15g	60 mm x 30mm 30g
Price	$10.00	$30.00	$12.00

Raspberry Pi Zero W

Why the Pi?

- Documented compatibility with MCP3008 ADC
- Bluetooth and Bluetooth Low Energy capable
- Only $10.00
- Lots of community support
- Very small (66.0mm x 30.5mm x 5.0mm)
- Less than 1.0W power consumption with Bluetooth on

Node Hardware Selection

Core Requirements:

- Bluetooth communication
- Expandable storage

Other Considerations:

- Price
- Ease of use
- Size
- Power consumption

Characteristic	Raspberry Pi 4 Model B	Banana Pi BPI-M5	NanoPi M4B
Processor	Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz	Amlogic S905X3 Quad-Core Cortex-A55 @ 2.0 GHz	Dual-Core Cortex-A72 @ up to 2.0GHz + Quad-Core Cortex-A53 @ up to 1.5GHz
RAM	1 GB - 8 GB	4 GB	2 GB
PoE Support	Yes - w/ PoE HAT ($20.00)	No	No
Bluetooth Capability	Bluetooth 5.0, BLE	None	Bluetooth 5.0
Operating Temp. Range	0°C to 70°C	N/A	-20°C to 70°C
Price	$30.00	$60.00	$70.00

Raspberry Pi 4 Model B

Why the Pi?

- Bluetooth and Bluetooth Low Energy capable
- Only $30.00 for 1GB RAM model
- Lots of community support
- Fits easily within our enclosure
- Less than 6.5W power consumption under full load
- Approximately 3W idle power consumption

Circuitry Hardware Selection

Core Requirements:

1. Read voltage across and current through the panel
2. Have an onboard power supply convert panel voltage to board voltage
3. Amplify the voltage and current values for ease of conversion
4. Convert the analog values to digital and transmit

Other Considerations:

1. Power consumption - we need to avoid having full power (300 W) on the PCB
   We chose low-power components and high-value resistors to ensure this
2. Price - total cost of parts + board should be under $20
   We chose common, general purpose parts to keep the cost low
3. Size - should be similar in size to a Raspberry Pi - handheld
   Since we have small parts, we accomplished this
4. Ease of use - should be able to plug-in and start measuring data
   The hardware will always start up right away, and the software automatically starts up after the RPi Zero W boots up.

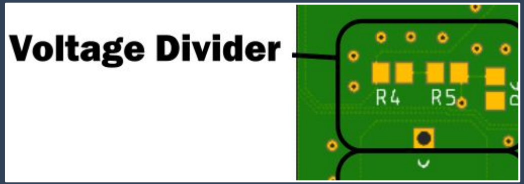
The Amplifier

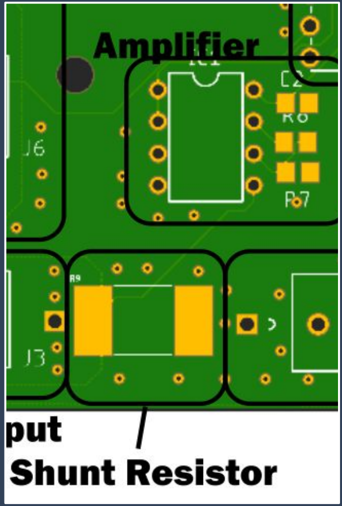
This part of our design takes the analog measurements from the solar panel and prepares them for conversion through amplifying them.

The voltage reading, being divided by 8 through the voltage divider, is amplified by a gain of 1. This gets rid of the Loading Effect as well.

The amperage reading, being represented by a voltage from the shunt resistor, is multiplied by 85, as it starts as a small voltage and needs to be larger for the ADC to pick it up.

Voltage	Voltage Divider Reading	ADC Value
8V	1V	205
12V	1.5V	307
16V	2V	410
20V	2.5V	512
24V	3V	615
28V	3.5V	717
32V	4V	819





The Amplifier

Our first choice was the TL072, as it seemed the best for our maximum voltage.

Op Amp	Channels	GBW (MHz)	Max Supply	Output Current	Temperature Range (°C)	Cost (each)
TL072	2	3	30 V	10 mA	0-70	$ 0.075
NE5532	2	10	30 V	38 mA	0-70	$ 0.296
RC4558	2	3	30 V	10 mA	0-70	$ 0.055
LM358B	2	1.2	36 V	30 mA	-40-85	$ 0.051
LM741	1	1	44 V	25 mA	0-70	$ 0.236

Table 9: Operational Amplifier Comparison

The DC-DC Converter

Our priorities for the DC-DC converter:
1. High efficiency
2. Low BOM cost and count
3. Low ecological impact

Option	Part #	Efficiency (%)	BOM Cost ($)	Footprint (mm^2)
1	LMR36506RF3	64	1.29	112
2	LMR50410X	81.6	0.70	142
3	LMZM23600V3	79.5	2.32	41
4	TPSM265R1V3	71.7	1.98	40
5	LM317	9.8	0.4	357

Table 8: Potential Power Supply Designs

The Analog-to-Digital Converter

Our priorities for the analog-to-digital converter:

1. Run efficiently from 5 V supply voltage
2. Ease of interfacing with the Raspberry Pi Zero
3. Have reasonably high resolution; enough for 2-decimal place accuracy.

Why the MCP3008?

- No need for higher resolution and the corresponding price
- Use of SPI rather than I2C protocol
- Ease of use

Over the length of our project, the ADC was one of the most stable and robust parts of the overall design, so we did not need to change it out for a better package.

ADC Device	MCP3008	ADS1015	ADS1115
Channel Count	8	4	4
Resolution	10-bit	12-bit	16-bit
Sample Rate	200,000	3,300	860
Cost	$3.75	$9.95	$14.95
Interface	SPI	I2C	I2C

Table 13: The summarized characteristics of the prospective ADCs.

The Pyranometer

Our priorities for the pyranometer:

1. Read the irradiance surrounding the panel
2. Transmit the value to the ADC
3. Do it all at a low cost

Option	Design	Self-powered?	Output	Price
1	Thermopile	Y	Calibrated output of up to 100 mV	$333
2	Silicon Cell	Y	Calibrated output of up to 400 mV	$233
3	Thermopile	N	Internally converts output to digital	$433
4	Silicon Cell	N	Internally converts output to digital	$323

The Pyranometer

Why the SP-110-SS: Self-Powered Pyranometer?

- Lightning fast response time
- Self-powered
- Inexpensive
- Fits our design without superfluous features
- Best mV output range for the ADC

The Thermocouple

Our priorities for the thermocouple:

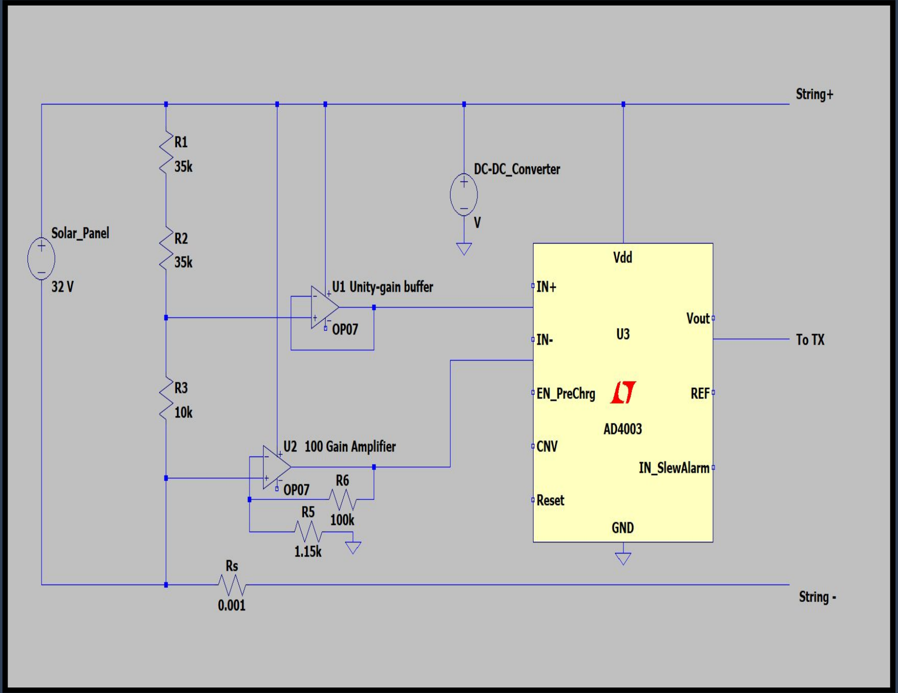
1. Read the temperature of the immediate panel area
2. Transmit the value to the ADC
3. Do it all at a low cost

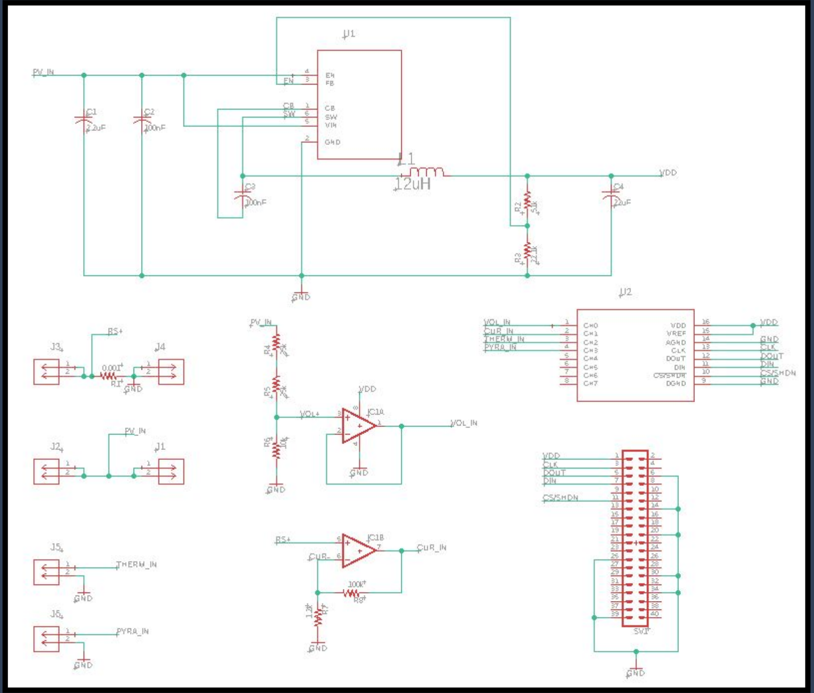
Why the T-type thermocouple?

- -330 - 600 °F range
- Margin of error of 0.4-0.75%

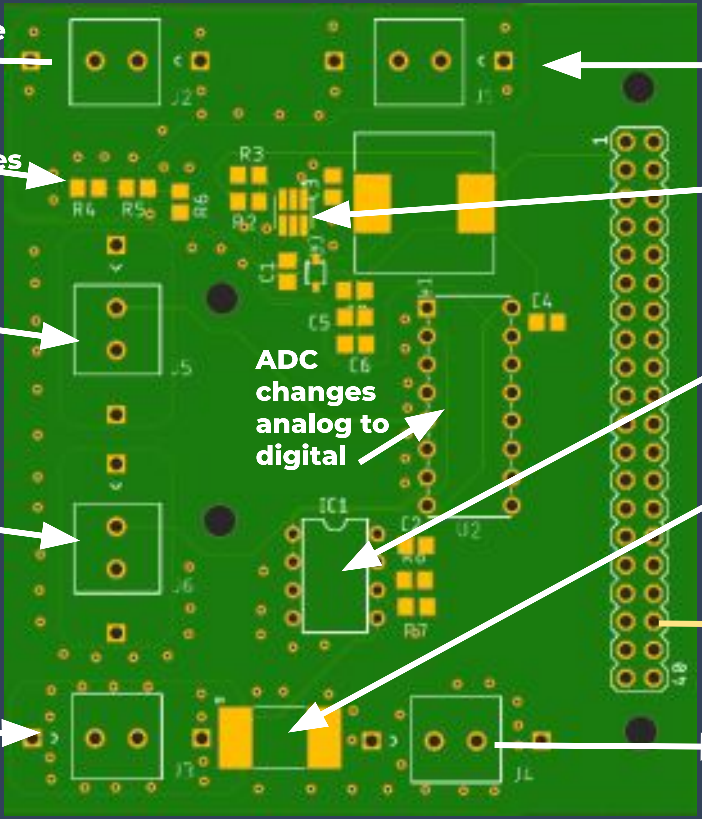
Type	Metallic Composition	Temp. Range (°F)	Margin of Error (%)
K	Nickel, Chromium, Aluminum, Manganese, Silicon	200 - 2300	0.4 - 0.75
J	Iron, Constantan	200 - 1400	0.4 - 0.75
T	Copper, Constantan	-330 - 600	0.4 - 0.75
E	Nickel, Chromium, Constantan	200 - 1650	0.4 - 0.5
N	Chromium, Silicon, Magnesium, Nickel	1200 - 2300	0.4 - 0.75
S	Platinum, Rhodium	1800 - 2640	0.1 -0.25
R	Platinum, Rhodium	1600 - 2640	0.1 - 0.25
B	Platinum, Rhodium	2500 - 3100	0.25 - 0.5

Initial Design: Version 1.0





How Our Design Works



Current to single solar panel

Voltage Divider takes input voltage and divides it by 8

Input from thermocouple

Input from pyranometer

Current from single solar panel

ADC changes analog to digital

Current from string of solar panels

PSU takes input and generates constant 5 V out to power the board

Amplifier multiplies voltage reading by 1 and current reading by 85

Shunt resistor generates a voltage (mV range)

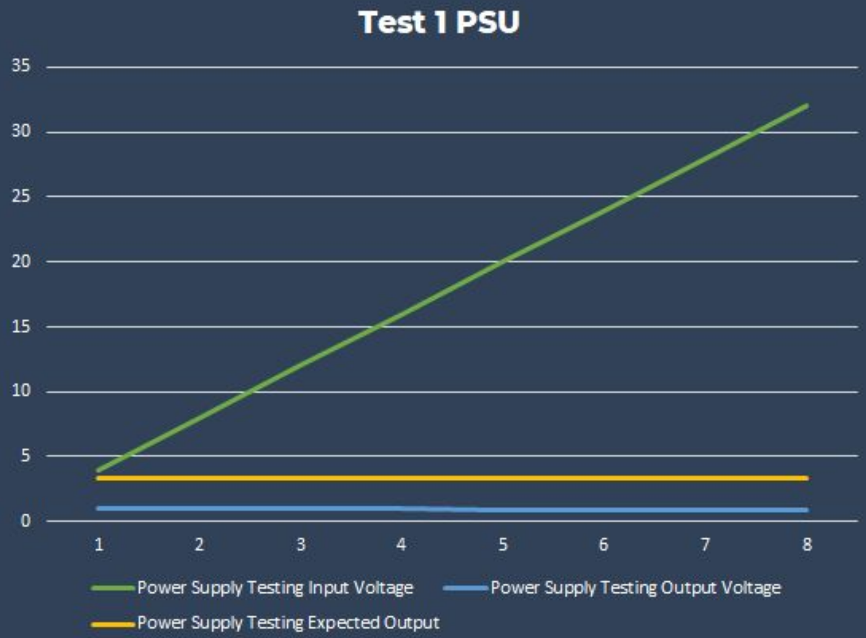
Output values to RPi Zero W for transmission

Current to string of solar panels

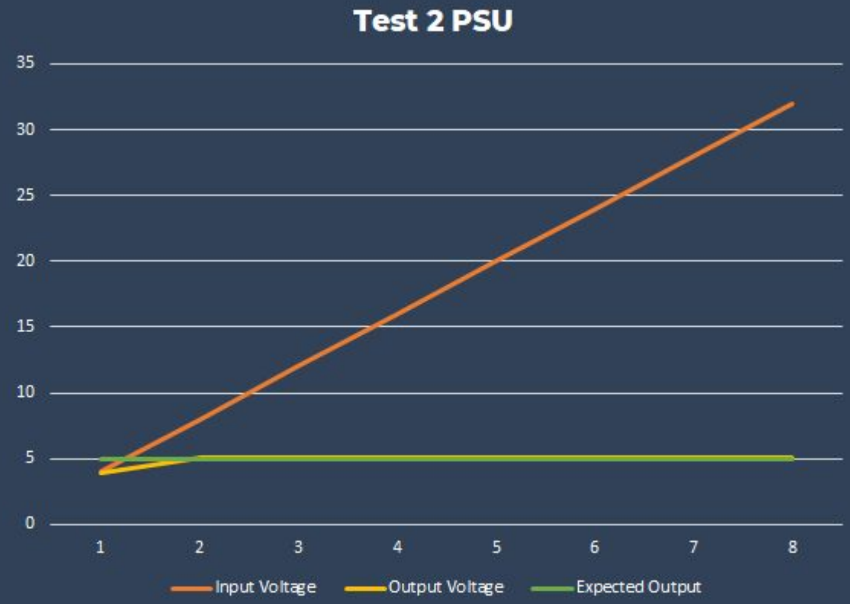
Testing 1.0

Power Supply

Testing Round 1: Power Supply gave a constant output, but wrong value.



***Testing Round 2:** Circuit restructuring gave us the output we need, consistently.*



Amplification

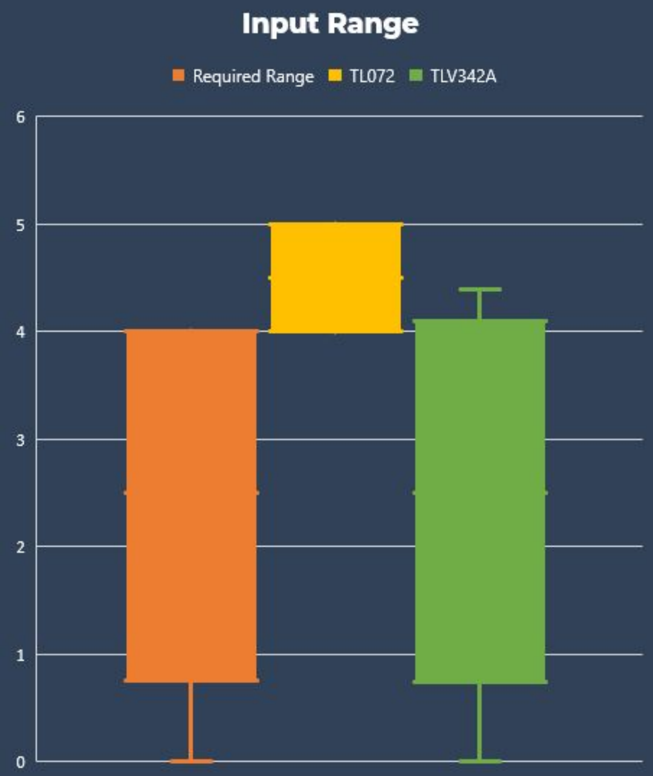
Data so far:

Input 1 (Range): 1-3 V
Input 2: 0.01 V

Need input range of 0-4 V

TL072 range - 4-5 V inputs
TLV342A range - 0-4.4 V

This is assuming a 5 V value for VCC.



ADC

Testing

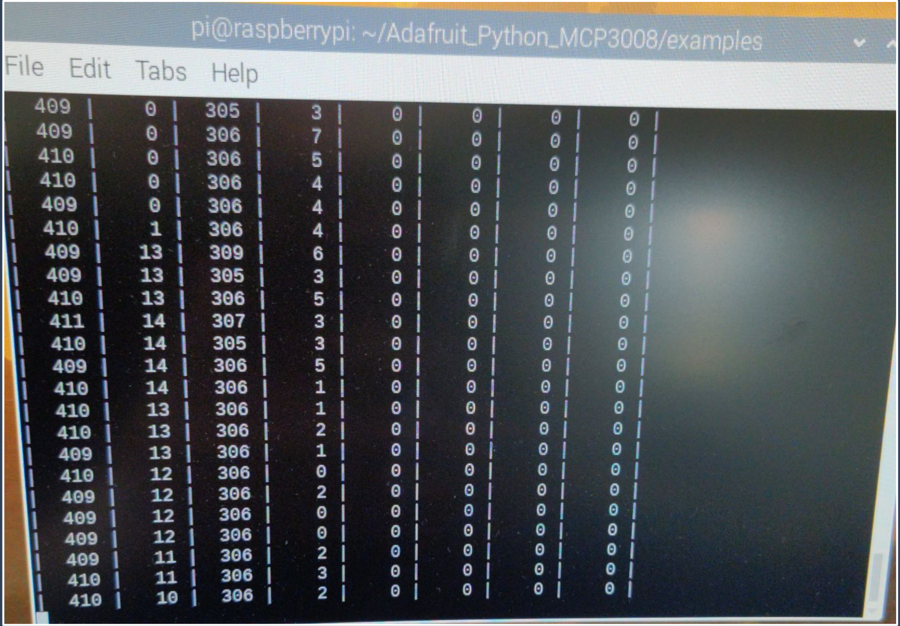
The testing setup was simple:

- Connect to the Raspberry Pi
- Use Power Supply as analog
- Convert to digital
- Transmit and read data

The columns represent the different inputs of the ADC.

VCC = 5V w/ 1024 steps → 0.00488V/step

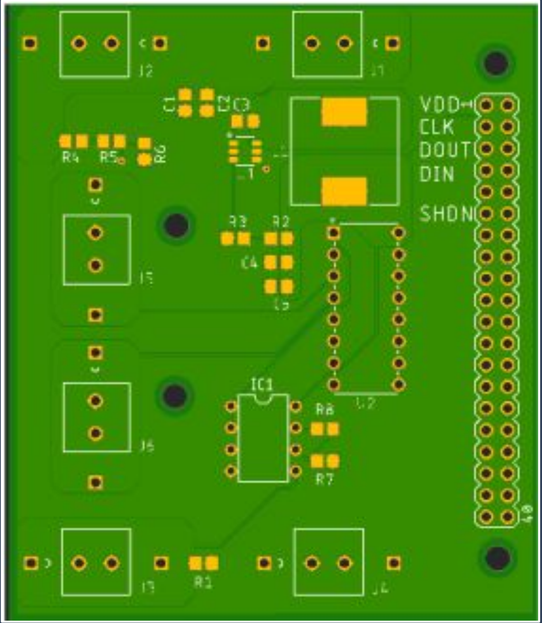
Column 1 = 2V   Voltage Reading
Column 2 = 0.06V   Pyranometer
Column 3 = 1.5V   Current Reading

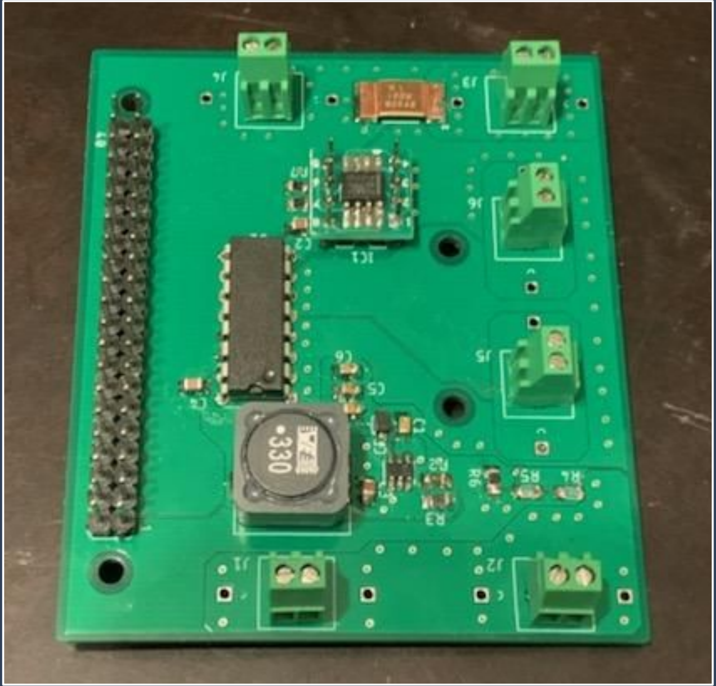


1 2 3

Initial PCB

- Once we verified that the design functioned properly, we ordered the first version the PCB:

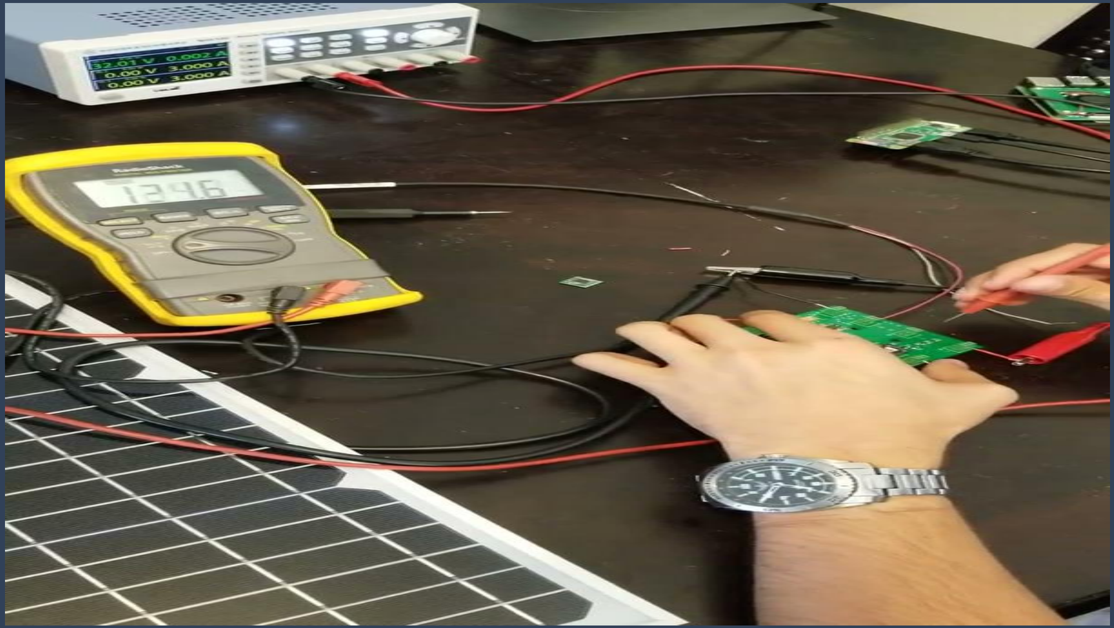




Testing 2.0

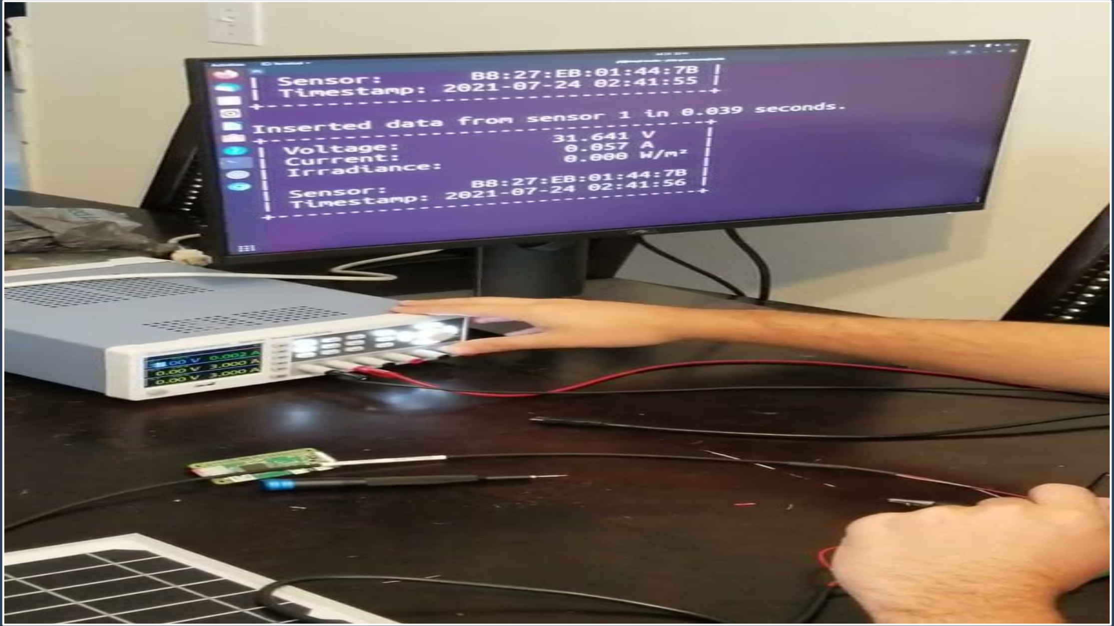
Testing 2 (w/ the initial PCB)

Testing the amplifier circuit and the PSU.



Testing 2 (w/ the initial PCB) (ctd.)

Testing the data communication.



PCB Design 2.0

After realizing we would not have enough power supplies, we realized we needed to purchase more. However, the LMR50410X was on backorder.

Fortunately, we were able to secure its sister components: LMR14010ADDCT and LV2862XLVDDCR. They both had the same layout, only differing in the values of the various components in the layout.

Converter	Efficiency	BOM Cost	Footprint
LMR50410	81.6%	$0.70	142 mm^2
LV2862	87.7%	$1.35	246 mm^2
LMR14010	86.4%	$1.41	218 mm^2

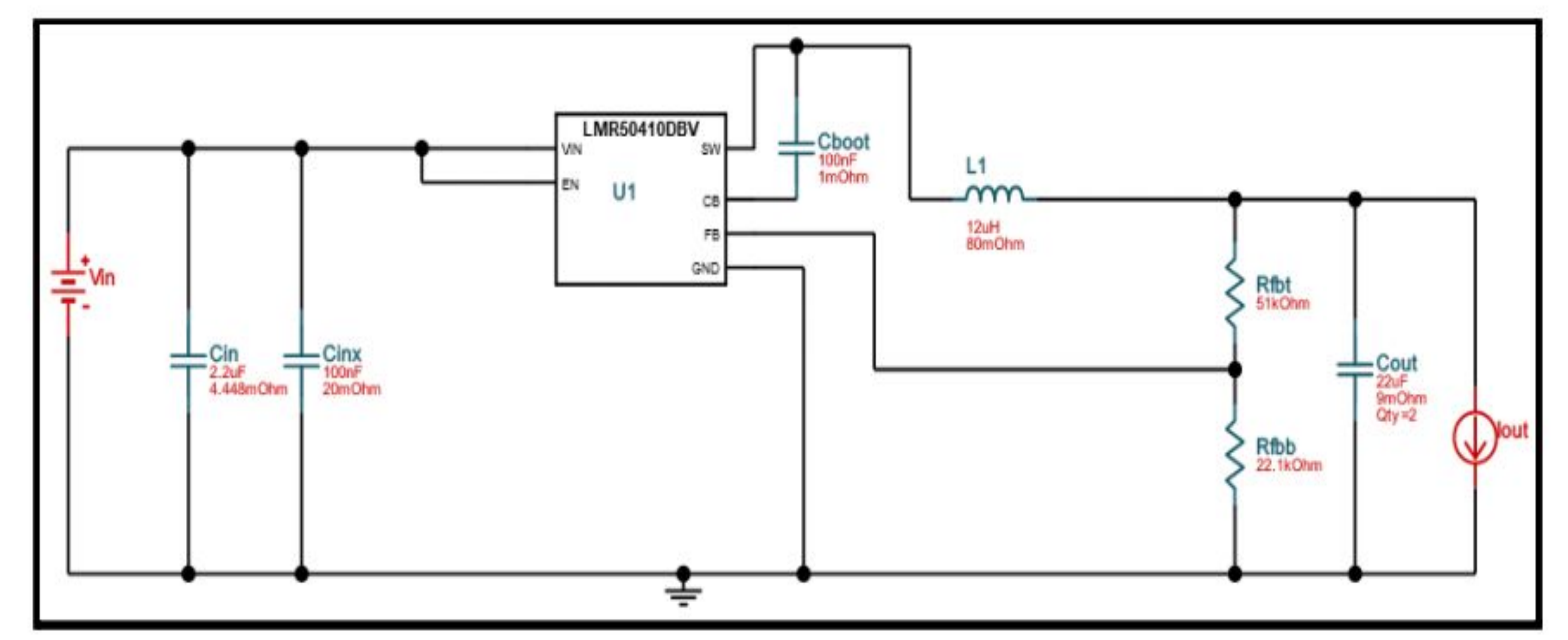
PCB Design 2.0 (ctd.)

The two power supplies did require slight changes on the PCB design, however. These changes included:

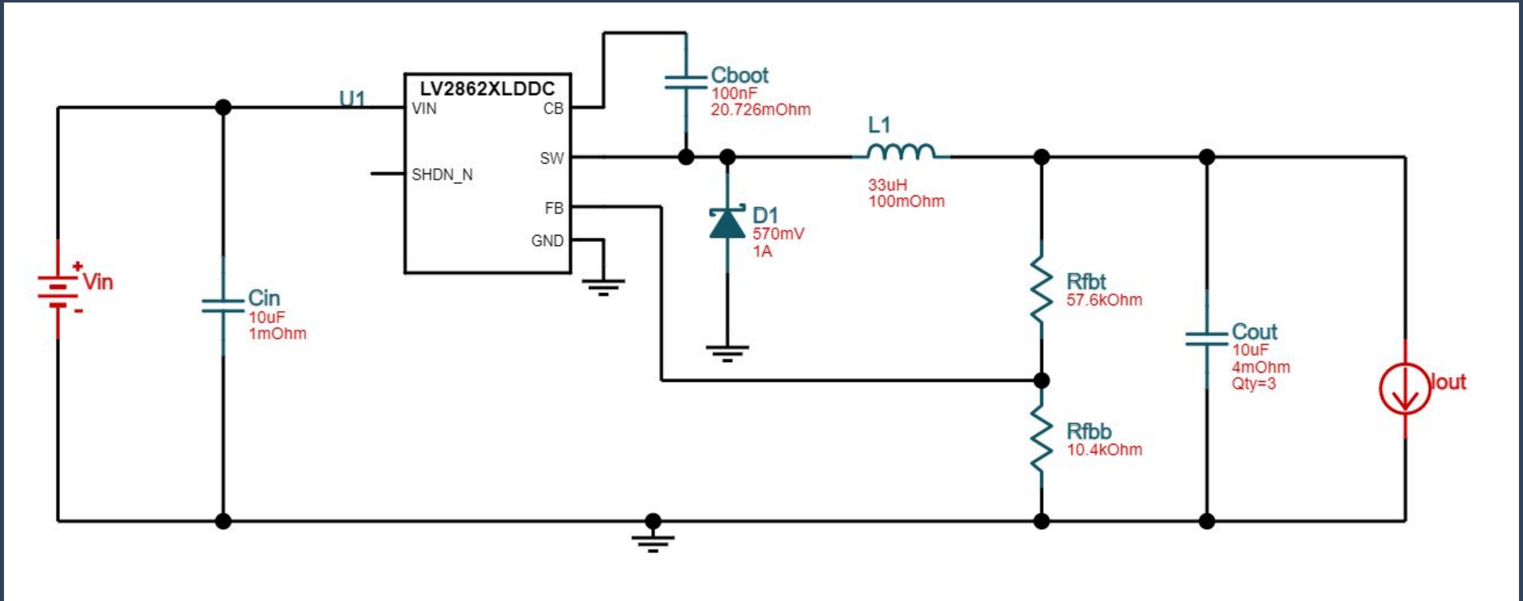
- A schottky diode
- More capacitors

We also changed the board layout by moving the capacitors closer to the PSU IC in order to reduce the effects of ripple voltage.

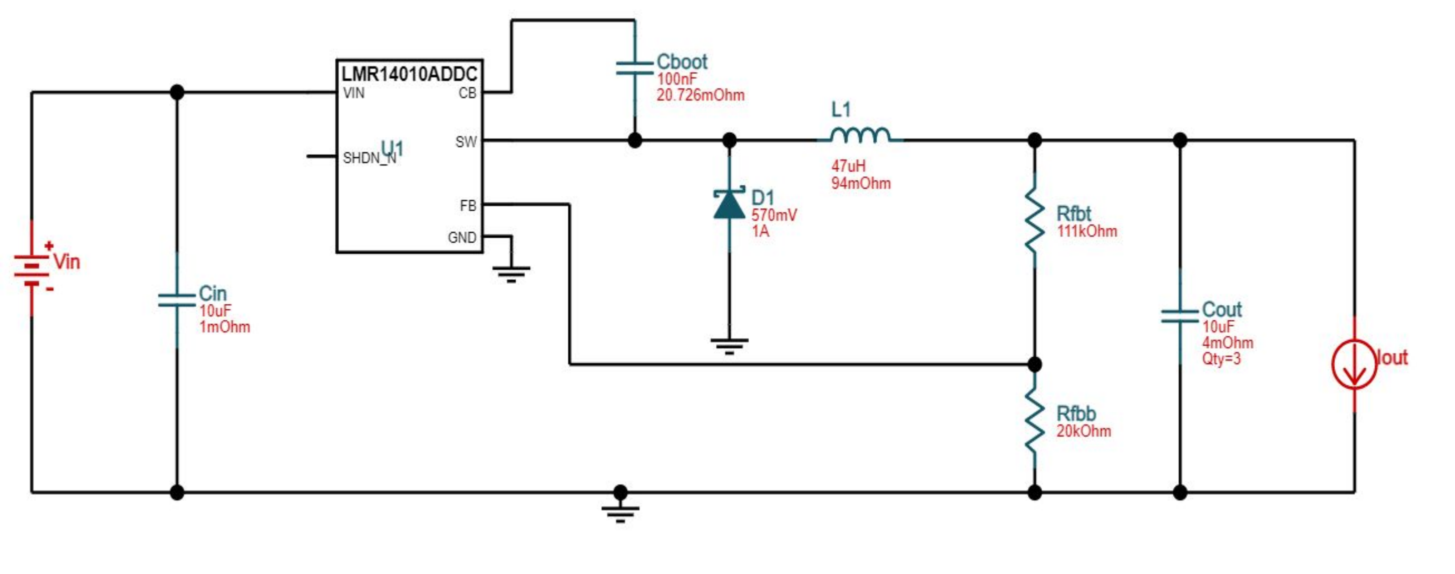
PCB Design 2.0 (ctd.): LMR50410X Schematic



PCB Design 2.0 (ctd.): LV2826 schematic



PCB Design 2.0 (ctd.): LMR14010 schematic



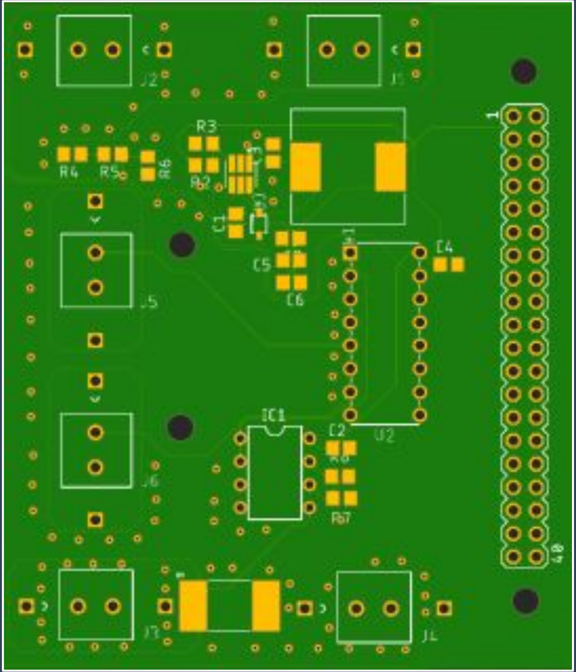
PCB Design 2.0 (ctd.)

- We saw in testing that the minimum voltage of the amplifier was not low enough.
- We decided on getting the TLV342A, which had a minimum voltage input of 0 V.
    - **However, the input offset voltage was high enough that it interfered with the amperage reading.**
- Then we got the TSZ122IDT Because of its input offset of only 8 uV.

Amplifier	Manufacturer	Offset Voltage	Cost
TL072	Texas Instruments	6mV	$0.08
TLV342A	Texas Instruments	0.3mV	$0.33
TSZ122IDT	STMicroelectronics	8uV	$2.50

PCB Design 2.0 (ctd.)

- Note the Raspberry Pi mounted onto the board.

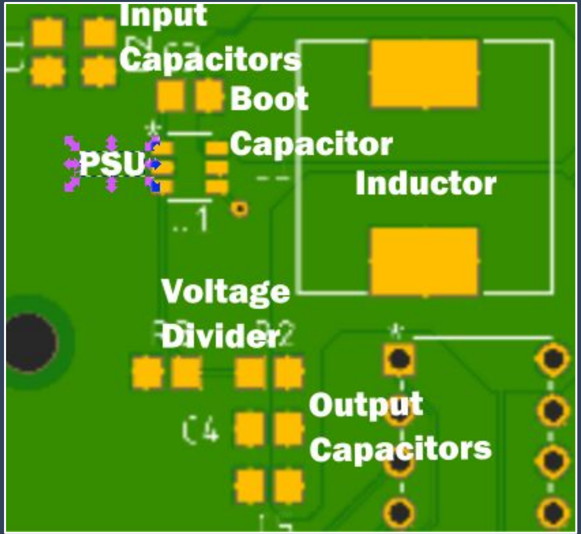


PCB Design 2.0 (ctd.)

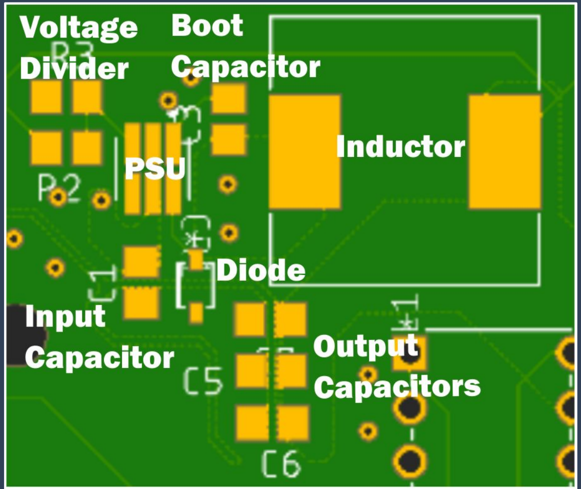
There are a few things to note in differentiating between the two versions of the PCB.

- The PSU layout becomes more robust.
- The shunt resistor package greatly increases.
- The GPIO header is flipped to accommodate the Pi Zero.
- Capacitors are placed closer to components.
- The signal planes get more streamlined.

Old Design



New Design

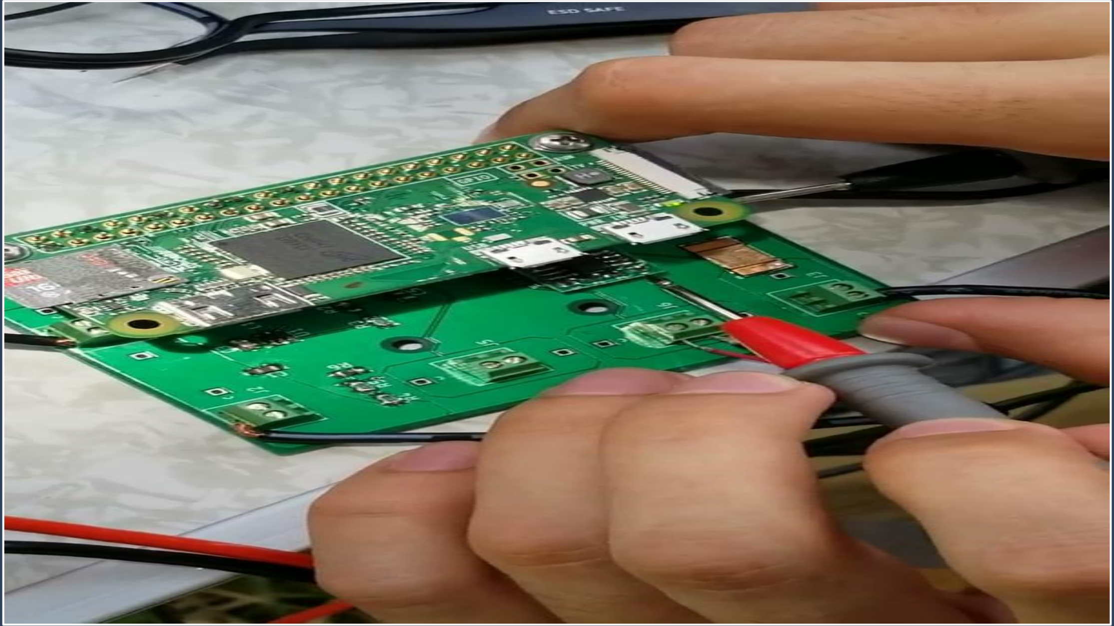


Testing 3 (w/ the PCB 2.0)

Testing the PSU.

Testing 3 (w/ the PCB 2.0) (ctd.)

Testing the amplifier circuit and the ADC circuit.



Results (Voltage Accuracy)

The final prototype contains a fully functional power supply unit (PSU).

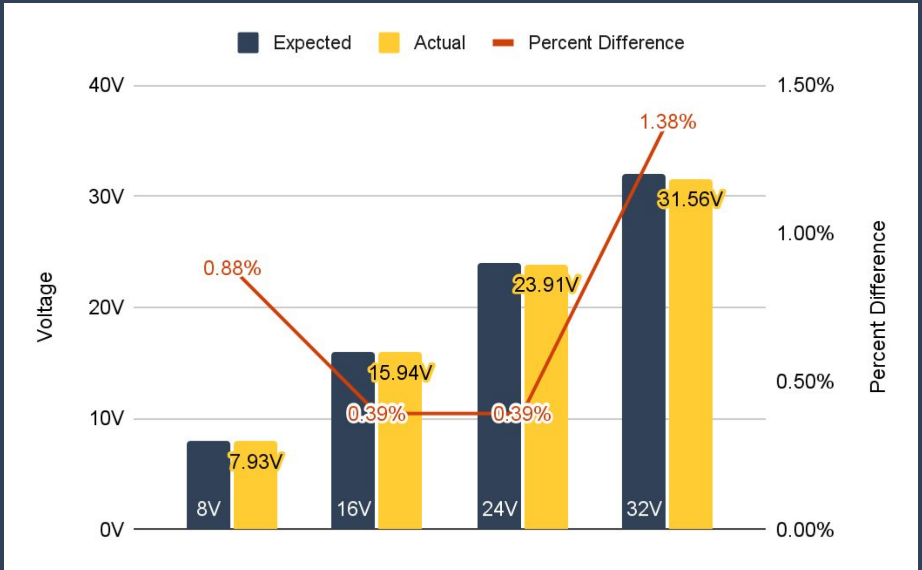
Input Voltage (V)	8.000	16.000	24.000	32.000
PSU Output (V)	5.000	5.000	5.000	5.000
Percent Error	0%	0%	0%	0%

With a steady 5V power supply from the PSU, the (voltage) amplifier functions properly and accurately as well.

Specification:
Voltage measured within 5% of real value.

Result:
Average percent difference between expected and actual of 0.76%, with a maximum of 1.38%.

Expected vs. Actual Voltage Measurement



Results (Amplifier)

The amplifier also is responsible for measuring the current flowing through the panel. However, our amplifier could not get an accurate reading of the input current.

- The low current consumption by the sensor could be so small that the amplifier circuit could not register the value properly.

- Another possibility could be the input offset voltage of the amplifier. The amplifier we are using (TL072) may have an input offset voltage that is too high, causing the amplifier to malfunction.

Results (ctd.)

The ADC is also able to translate the pyranometer values as well.

Results (ADC Circuit)

Although we were able to obtain a functioning ADC circuit, we were not able to transmit the temperature values. Even while using the thermocouple provided by OUC, the readings from the thermocouple were always inaccurate.

The voltage measured between the two leads was consistently inaccurate.

This issue could be rectified in potential future designs by supplying a voltage to the thermocouple from the 5 volt DC power converter, which would allow the ADC to detect changes in voltage input due to changes in the thermocouple resistance due to temperature. Regardless, this was a low priority for our sensor.

Results (Data Transmission)

The data transmission time is measured from when the node requests data from a sensor, to when that data is inserted into the local database on the node.

Tracking this transmission time across 10,000 data transfers revealed an average of **50 milliseconds**.

The maximum transfer time was 672 milliseconds.

Administrative Content

At This Moment In Time

Our design required tweaking, but we believe it is sound. Field testing has been completed.

Milestone	Status	
Part Selection	100%	- Initial Design/Schematic
Protoboard Design	100%	
Protoboard Testing	100%	- Breadboard Testing
Analog to Digital Signal Conversion	100%	
Bluetooth Transmission	100%	- Code Testing
Database	100%	
Construct First Prototypes	100%	- Field Testing
Field Testing	100%	
PCB Design	100%	- Ordering/Final Design
Enclosure Design	100%	

Developmental Budget

Component	Quantity	Cost per Each	Estimated Total Cost
NEMA 4X Enclosure	4	$71.97	$287.88
Pyranometer	3	~~$223.00~~	Provided by OUC
T-Type Thermocouple	3	~~$10.00~~	Provided by OUC
Mounting Materials	Varies	Varies	$167.74
RPi Zero W	3	$10.00	$30.00
RPi 4B	1	$30.00	$30.00
Raspi PoE Hat	1	$20.00	$20.00
PCB	8	$3.75	$43.50
ICs	3 (5 copies ea.)	Varies	$58.90
Various components	104	Varies	$77.65

Grand Total
$715.67

Cost per Sensor

Component	Quantity	Cost
NEMA 4X Enclosure	1	$71.97
Mounting Materials	Varies	$4.96
RPi Zero W	1	$10.00
PCB	1	$3.75
MCP3008 ADC	1	$3.75
TSZ122IDT Amp	1	$2.50
LMR50410X PSU[1]	1	$1.47
LMR14010ADDCT PSU[1][2]	1	$1.08
LV2862XLVDDCR PSU[1][2]	1	$1.36
Various Components	14/15	$10.45/$11.20

Total Cost for One Sensor (w/o enclosure)
$34.91

Total Cost for One Sensor (w/ enclosure)
$111.84

[1] Only 1 of the three PSUs are required
[2] Requires diode (extra component)

In The Future

- Learn more about the DC optimizers used in the array, and why they behaved as they did when our device was connected.
- Confirm accuracy of the current measurement when the input amperage is higher, as well as when using the newest and most precise amplifier.
- Route power to thermocouple and calibrate software to provide an accurate temperature reading.
- Standardize the distance between thermal vias on the PCB.
- Install device in enclosure to test prolonged exposure to weather.

Work Distribution

Task	Christian Avalos	Julian Gentry	Ryan Kehrmeyer	Zoran Kolega
Standards Research	⭐	⭐	⭐	⭐
Past Effort Research		⭐		
Software Research				⭐
Hardware Research	⭐	⭐	⭐	⭐
Software Implementation				⭐
Hardware Implementation		⭐	⭐	
PCB Design	⭐	⭐	⭐	
Enclosure Design	⭐			


That's all Folks!