Distributed Smart Solar Charge Controller for UVA Solar Car

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Bachelor of Science, School of Engineering

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Kyle Clemente

Ethan Ermovick

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Adam Barnes, Department of Electrical and Computer Engineering

Distributed Smart Solar Charge Controller for UVA Solar Car
Watt's Up Sun

12/6/24

Gabriel Gladstone, Ethan Ermovick, Kate Renner, Kyle Clemente, Eizaku Asai

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I. Abstract

The Distributed Smart Solar Charge Controller (D.S.S.C.C.) optimizes the power output of the UVA Solar Car Team's solar panels during a race under variable light exposure conditions. It does so by adjusting the voltage and current outputs of each solar panel depending on those variable conditions. Our project will be a scaled down version of what the Solar Car team needs. We will be using three solar panels and a smaller battery than those used in the Solar Car, so this project is a proof of concept that will be easy to replicate and scale up for the Solar Car Team's needs. The overall goal of our project was to prove that our smart distributed MPPT system is more efficient and cost-effective than Solar Car's current model and to write thorough documentation so that our design can be replicated.

II. Statement of Work

The following is a statement of each member's contributions to the project.

A. *Ethan Ermovick*

My contributions to the project were multi-faceted. In chronological order, the first major part of the project I did was to design the overall architecture of our Distributed MPPT. I selected a design with buck/boost converters in between each panel, achieving a design that is both efficient and feasible to build. One of the next major things that I have done, throughout the project, has been liaising with solar car. As a solar car member, I have been the primary one to communicate with the solar car executives, discussing requirements such as cost and maximum voltage. I have additionally worked with solar car to source components, and leveraged my reactor to retrieve the three solar panels for testing. Next, I made significant contributions to multiple slides on our presentations, architecting the slides on the design, as well as other slides. I have also made minor contributions to the schematic design, determining how some of the pins of the buck/boost converter should be connected. I made less minor contributions to soldering both iterations of the boards, as well as shaving down some of our oversized resistors in order to fit mistakenly designed footprints. I also made various contributions to the software side of things, creating a system to monitor global extrema in the metrics for the dashboard, as well as inventing a system to prevent the STM controller from overvolting the battery. Next, I also assisted in various debugging activities, identifying a major problem with the way that our current sensor was set up (shorting the panels), as well as concluding that we needed the I2C isolators to deal with the multiple grounds. I also took the lead on soldering our last minute components to perf boards, which was especially difficult due to the small size of the SMD components. Finally, I also helped to write both this final report, as well as the project proposal.

B. *Gabriel Gladstone*

My primary contribution to the project was the metrics dashboard to validate the efficiency of our system. I designed a multi-page dashboard with the DJango framework that would persist data between sessions. I also worked on the interfacing with the STM32. The dashboard is important because it provides our clients, and later their telemetry team with a means to easily evaluate the MPPT system. In the early stages of the project, I also led the architecture design. I heavily researched different distributed architectures and made significant contributions to the poster session, by creating the system block diagram, key goals/relevance of the project, and communicating the project during the session. Although we ended up pursuing a simpler distributed architecture after the poster session. Although I didn't work on the embedded software, I helped Zach troubleshoot the IC communication and found many issues with our initial design of the ICs including using the wrong resistor magnitudes, improper connections, and missing grounds/supply voltages. I then worked to provide the needed jumps and cuts to the boards to remedy these errors and move our testing of the PCBs forward. I also made significant contributions to soldering the V1 board. Of course, I also helped with writing the midterm design review and Final report. The whole team helped to gather client information on panels, battery, and design requirements. Overall, I tried to contribute throughout the project and play to my strengths of software, organization, and writing.

C. Kate Renner

I contributed to this project by engaging in both hardware design and project organization and management tasks. I contributed to our PCB development in many ways. Here are some examples: I calculated our component values so that they aligned with the datasheets and project requirements, added bypass capacitors as needed, organized the layout to untangle the ratsnest, and incorporated mounting holes into our design. I also contributed to integration by collaborating on soldering components, including MOSFETs where I had to modify leads to fit the boards, and driving our boards out to WWW to solder surface mount components. I helped the rest of the team with testing and modifying our design, and I organized testing logs for better documentation and report preparation. I maintained a focus on project management by tracking our budget, updating spreadsheets for organization, and streamlining access to datasheets and parts. I played a huge role in preparing this final report, and I utilizing feedback from the proposal to refine sections. I also helped with our midterm design review slides, preparation, and organization, ensuring clear communication of project goals and progress. Although I joined the team late and was not able to contribute to our proposal, I was able to quickly catch up and contribute as a team member.

D. Kyle Clemente

I served primarily as the hardware designer for this project. I was the lead for the large task of designing the hardware schematics and PCBs. This included the task of coordinating with the team to select, purchase, and integrate custom components from online retailers such as DigiKey and Mouser to create accurate schematics. I had to learn a new software tool in KiCad which proved to be useful as I could import custom footprints for parts found online. I worked closely with Kate to calculate and determine the appropriate ranges of values that would work with the schematic that I created. I routed the traces for the PCBs imported from the schematics and verified the final outputs were manufacturable. Once the PCBs arrived, I played a large role in soldering the components and troubleshooting the hardware with the team. I updated the schematics and PCBs with each iteration of changes so that the team always had an up-to-date schematic and PCB on hand. I also created an entirely new schematic and PCB routing for an I2C isolator board to fix our issues with grounding our I2C lines. While this board wasn't manufactured, the schematic and routing I created served as a valuable resource when connecting our isolators on a perfboard to test our I2C communication. I created our initial Gantt Chart and kept it up-to-date throughout the semester to accurately track our progress and assess our schedule. For each deliverable throughout the semester (such as the initial presentation, poster session, midterm design review, and final report), I contributed as much as I could in my areas of expertise and worked with the team to deliver satisfactory products.

E. Eizaku Asai

I mainly focused on the embedded software ensuring that our microcontroller could interface with the integrated circuits that we chose by referencing their datasheets. This involved establishing functions that used Inter-integrated circuit (I2C) communication to read and write to each of the devices as well as configure constants stored in the registers. I developed a variation of the Perturb and Observe algorithm for our distributed MPPT where the microcontroller interprets the sensor readings and changes the converter outputs. When creating our second PCB design, I helped Kyle pick out better footprints for components and added test points to isolate sections of the circuit to create a better testing experience. Testing has been my main focus when completing the project which includes verifying the accuracy of voltage and current readings, I2C and USART communication were working properly, and the output of the converters changing as intended. I have also helped with assignments throughout the semester including the proposal, midterm design review, and final project report.

III. Background

According to [1], solar power is expected to make up the majority of new energy production in 2025, bringing solar generation up to 7% of US energy production.

There have been many advances in solar charging that have brought significant increases in charging efficiencies which is why it is important to quickly adopt advances in research. Our team's Solar Charge Controller (SCC) design stems from Stuart Watkinson's 1985 invention of the first MPPT SCC [2]. Solar Charge Controllers change the voltage-current output from the solar panel until the panel reaches a combination that will produce the maximum power. An MPPT controller, compared to previous PWM controllers, converts excess voltage into current. This leads to a 5-30% increase in energy extraction efficiency [3]. Future advancements in SCCs have focused on the algorithms that determine the best voltage-current combination and the architecture of the whole system.

The current industry standard for conventional systems is to connect the solar panels in series forming a solar array and use a central controller that determines the operating point for all panels combined with a simple non-intensive algorithm. This setup works fine in uniform systems where the solar panels experience similar conditions and have similar max operating points, but it is not the most efficient. Over time, solar panels develop imperfections from normal environment exposure. Under varied sun exposure, solar panels will have different optimal operating points. The SCC can only optimize for one operating point, leading to an inefficient power charging process. Inefficient systems with mismatch losses are particularly harmful as a whole for two reasons. First, solar cells in series must all have the same current, but shading can cause their currents to vary [4]. The minimum current generated by a solar panel in that line then becomes the limit for the total current, lowering the total power output of the system [4]. Second, mismatch losses can cause solar panel damage due to issues like the hot spot effect [5].

One remedy to solve mismatch issues is to use bypass diodes which are placed in line with the solar panels. When a panel is producing less current than the surrounding panels, the corresponding bypass diode will conduct current, "bypassing" the affected panel [6]. This solution is not perfect, as the bypass diode completely cuts off power from the shaded panel rather than providing the power that is still generated [6].

A better remedy for mismatch issues is the Distributed Maximum Power Point Tracking device (MPPT) where a buck/boost converter is placed on each panel [7]–[10] using a module cascaded converter (MCC) architecture [11]. The converters on each panel match the output current, allowing all panels to provide usable power to the system [8]. According to [7], a Distributed MPPT architecture can mitigate mismatching losses, ensuring that even shaded panels are providing power output. The system will enhance Solar Car's current system because the SCCs feed into Solar Car's current MPPTs. This will increase Solar Car's power charging capability because the sum of local maximum power point charging is greater than global maximum power point charging.

As mentioned, our client is the UVA Solar Car Team, a club at the University of Virginia (UVA), that designs, builds, and races a solar powered electric vehicle. They use the bypass diode solution discussed where the system of panels and bypass diodes are connected to a single main MPPT. The team has expressed interest in the production of a distributed MPPT system for several reasons. First, they would benefit from the power gain of the system during a race. Second, our design is more easily repairable and customizable than their current design. Third, our design is much less expensive than their current MPPTs. Our project budget is $500 while the Solar Car's current MPPTs were purchased for $3000 total. Our project differs from prior art due to the unique design and specifications of the Solar Car Team [7]–[10].

Designing a solar charge controller will be a challenge, but we believe our team has the background and necessary training to succeed. We have developed a strong understanding of electrical engineering fundamentals and control systems to design the MPPT PCB. We have experience working with embedded systems, especially the STM32, both in and outside of class. One of our group members, Ethan, is the Embedded lead at Solar Car. We also have a strong foundation in algorithms and software development that will help us build the metrics dashboard. Below are lists of the electrical, embedded, and software based courses that our team members have taken that have helped us throughout this project:

- **Electrical Classes**
  - ECE Fundamentals (I - III)
  - ECE 6850 Intro to Control Systems
  - APMA 2130 Ordinary Differential Equations
- **Embedded Classes**
  - ECE 3430 Intro Embedded Computer Systems
  - ECE 6501 Advanced Embedded Systems
  - ECE 6750 Digital Signal Processing
- **Software Classes**
  - CS 3240 Advanced Software Development
  - CS 3100 Data Structures and Algo 2
  - ECE 4501 ML and Image Analysis
  - APMA 3100 Probability

IV. Project Description

A. Performance Objectives and Specifications

Our project is a distributive Maximum Power Point Tracking (MPPT) controller that optimizes power transfer from several solar panels to a battery or load. MPPT systems typically maximize the power output of multiple panels in series by using a single controller coupled with an algorithm such as Perturbation and Observation or Incremental Conductance. Our design uses a buck-boost converter between each of the solar panels to deal with power loss from unmatched currents. We decided to purchase buck-boost converters to streamline our design process and to ensure it is consistent across the boards and works without issue. Our microcontroller, the STM32NUCLEO-F401RE, utilizes voltage/current I2C sensors to determine each panel's output voltage and current so that the buck-boost converters can be adjusted as needed to reduce power loss. Because the Solar Car team uses lithium-ion batteries, we designed our project to charge lithium-ion batteries, tailoring our design specifically to our customer. Due to testing concerns and costs of high-capacity batteries, we decided to use lower voltage configurations. The objectives of this system are to complement Solar Car's existing MPPT, further reducing power loss and enhancing the ability to locate the global maximum power point. As the project's performance and efficiency is imperceptible, we created a program to show live measurement data from the microcontroller.

B. How it Works

We designed a module cascaded converter MCC as described in Al-Smadi's work [11]. Each solar panel is connected to a buck-boost converter, and each converter's output is determined by the microcontroller's algorithm. As shown in Fig. 1, MCC architecture connects the output of the converter modules in series. An inverter of DC voltage regulator may be used to fix the string voltage for an AC or DC system output. This is because the output current is common to all output terminals, so the regulator will sink current to maintain the string voltage. The DMPPT system will also maximize under certain constraints. For instance the MPP current of each module must be greater than the string current. Because we use a buck-boost converter, there are less constraints on the V_{mpp} related to $Voutpv_i$. If this condition is met, then each solar array can be brought to its maximum power point.

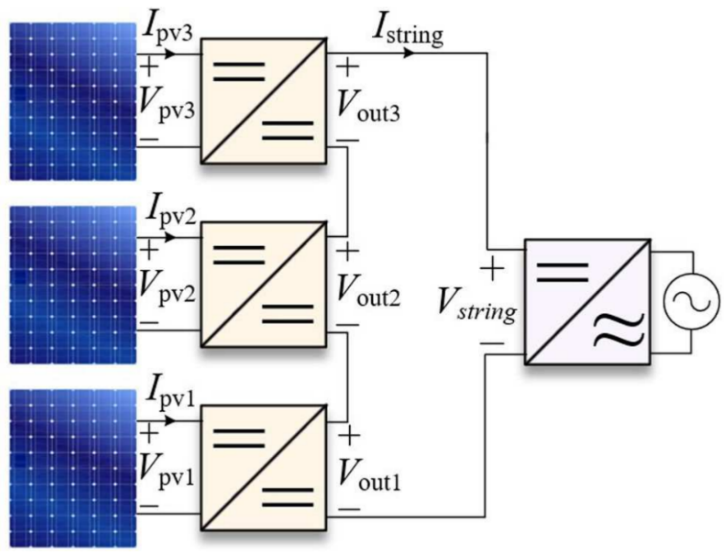


Fig. 1: Module Cascaded Converter Architecture

C. Block Diagrams, Schematics, and Board Layouts

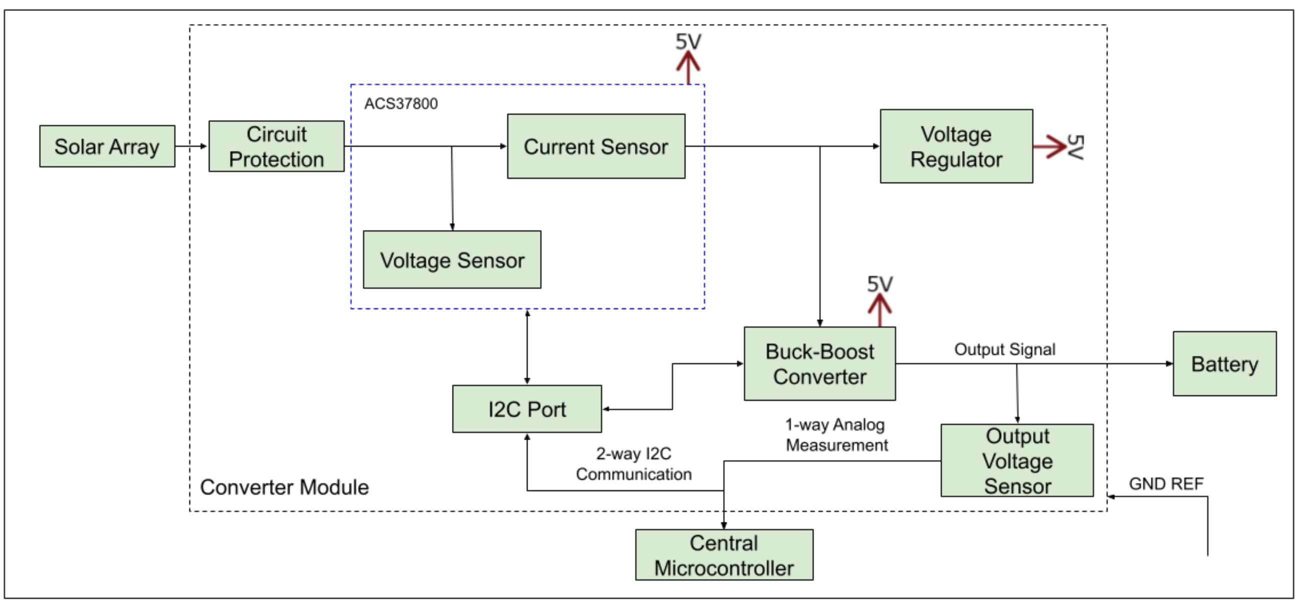


Fig. 2: Converter Block Diagram

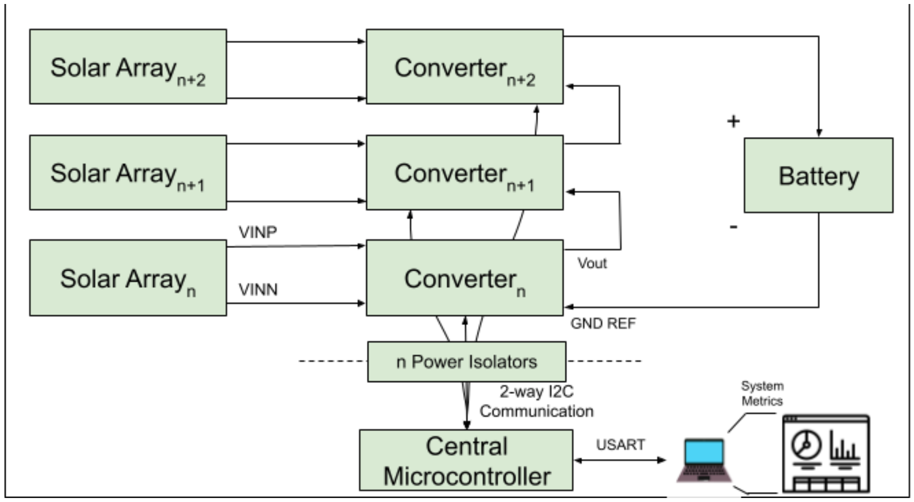


Fig. 3: System Block Diagram

Fig. 2 shows a hardware-block level view of a module in our system. The parts of the module will be explained in the technical details section.

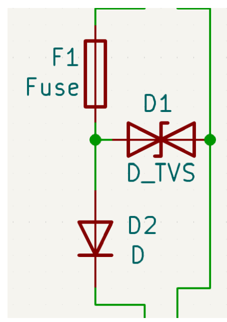


Fig. 4: Circuit Protection Schematic

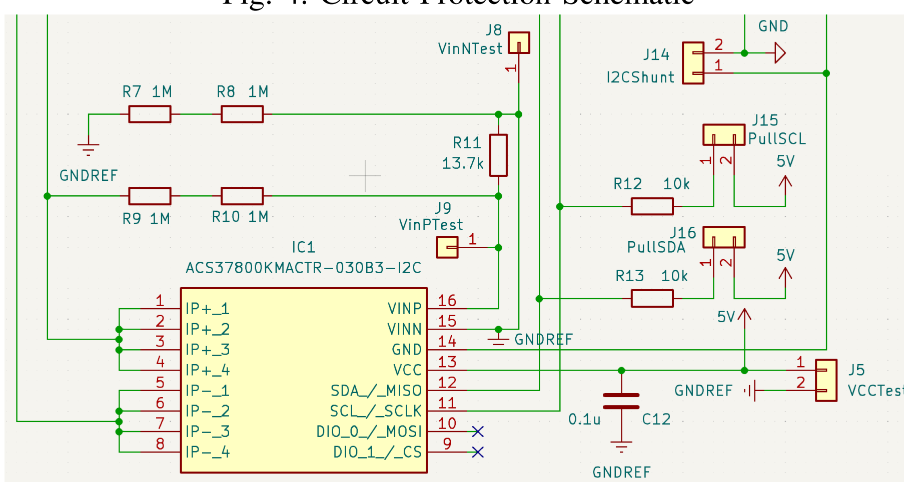


Fig. 5: ACS37800 Current Sensor Schematic

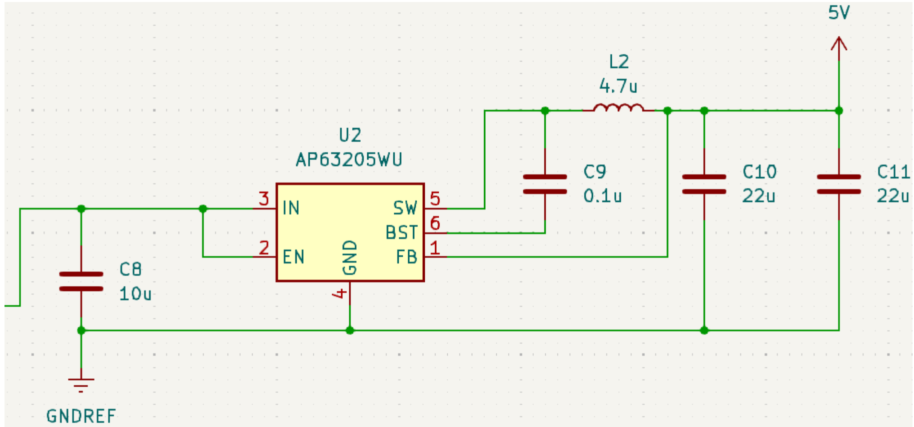


Fig. 6: AP63205WU Voltage Regulator Schematic

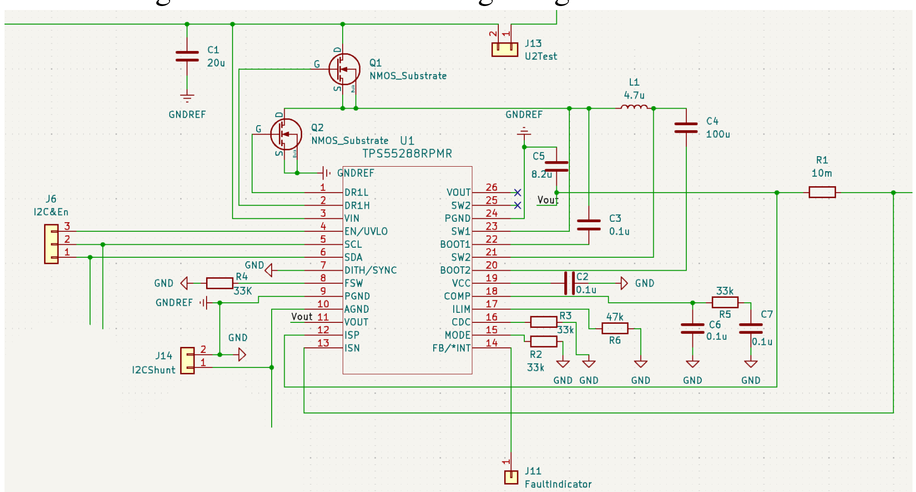


Fig. 7: TPS55288RPMR Buck-Boost Schematic

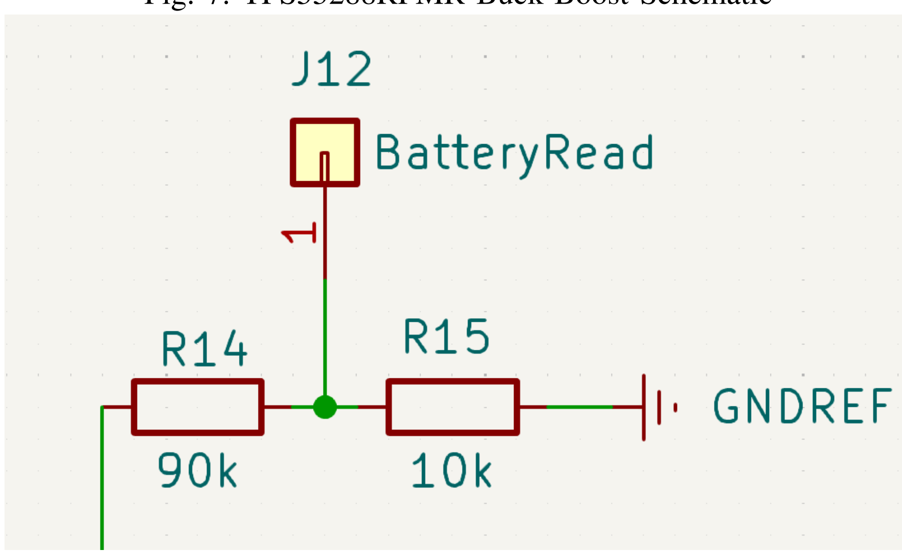


Fig. 8: Output Voltage Sensor Schematic

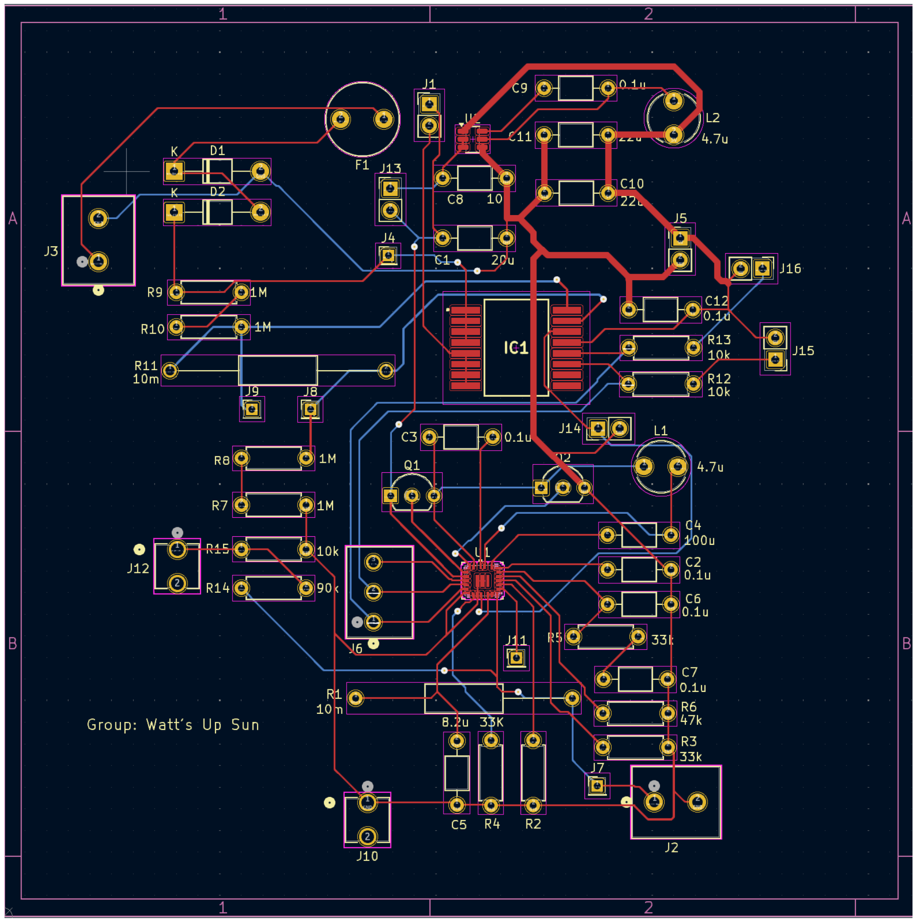


Fig. 9: Final PCB Layout

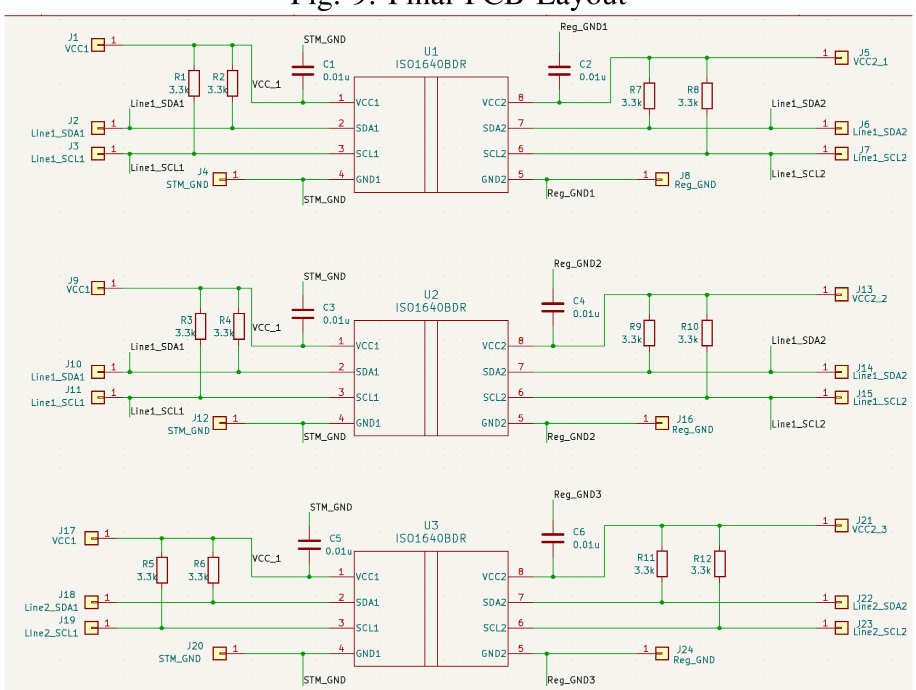


Fig. 10: Isolator Daughter Board Schematic

D. Hardware Technical Details

Our system has the following general blocks: Circuit protection, input voltage and current sensor, voltage regulator, buck-boost converter, output voltage sensor, and external system connections as shown in Fig. 2. This section will explain the design decision of each of these blocks.

1) Circuit protection: Fig. 2 shows a converter module-level view of our DMPPT system. The circuit schematic is depicted in Fig. 4. The solar cell array is first connected to the Circuit Protection subsystem. This subsystem consists of a fuse to protect against large currents and a transient voltage suppression (TVS) diode to protect against large voltages. This step is important to protect the microcontroller, current sensor IC, buck-boost converter, and battery from extreme behavior.

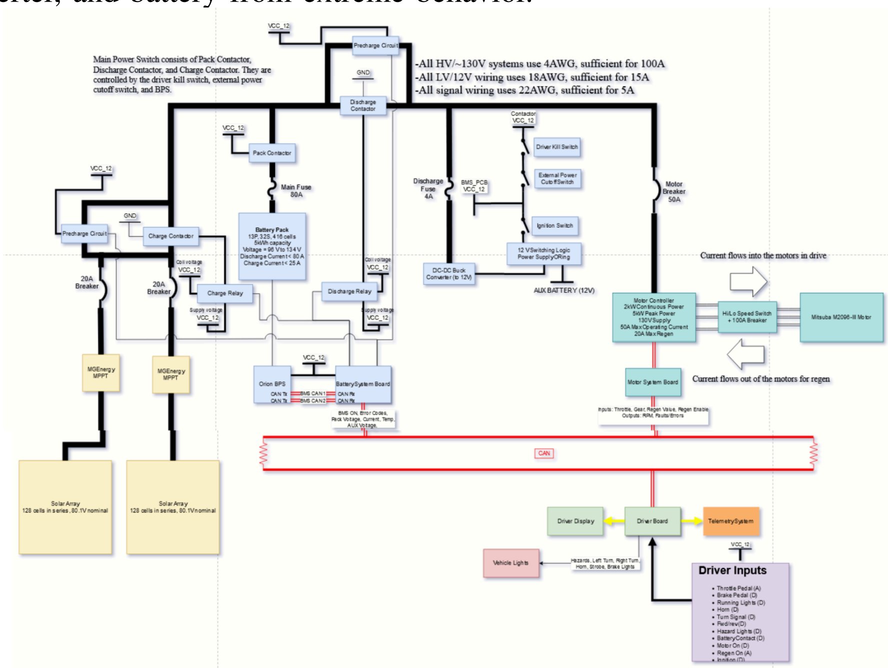


Fig. 11: Rivannna 2S Functional System Diagram

As shown in Fig. 11, circuit protection is only included at the beginning of the system because we plan to extend Solar Car's current battery-charging system. This means that these converters will be connected to at least a few solar panels, and the output of the system will be fed into the Solar Car's MPPT. The Solar Car also has a battery management system (BMS), fuses, and charge contactors that will protect the battery.

Fuse and TVS component values may depend on the expected solar array input. In our experiment with 3 solar panels, our components are more than capable of handling current and voltage variations from the panels. Our test battery has an excess current threshold of 3A [12]. Our current sensor can also support a range of -30A to 30A as well as built-in overcurrent and overvoltage protection [13]. Our buck-boost converter supports an input voltage range of 2.7V to 36V with an average inductor current limit of 16A [14].

As discussed in the External Standards section, the National Electrical Code (NEC) recommends fusing any string where the short-circuit current from other parallel strings exceeds the panel's rated current by 1.25-2 times. This is because large solar arrays with multiple strings may send excess current through a faulty string and damage the panels [15].

If we were to include a fuse we would use a value of twice the short circuit current of the panels in the 12. The table shows the short-circuit current and open-circuit voltage measurements of our 3 test panels. The open circuit voltage measurements were taken by connecting the leads of a multimeter directly to the positive and negative terminals of the solar panel. Short-circuit current measurements were taken by measuring the voltage drop through a shunt resistor and applying $I = \frac{V_+}{R_{shunt}}$.

The solar array in our test panel consists of one panel and a string is a set of panels in series, so our testing setup will not run a faulty string causing damage. However, we do have a fuse option because Solar Car may use a Solar Array configuration that will have multiple strings of panels. If we were to use a fuse in our system, we would have to find a fuse around $2 * 6.7 = 13.4mA$. Fuses at this low of

Panel	Environment	Isc (mA)	Voc (V)
1	Indoor Full Light	6.6	12.6
2	Indoor Full Light	8.3	12.8
3	Indoor Full Light	5.2	6.5
Avg	Indoor Full Light	6.7	10.63
1	Panel Shading	2.73	10.53
2	Panel Shading	2.1	10.6
3	Panel Shading	3.8	5.37
Avg	Panel Shading	2.877	8.833
1	No Light	0.0029	0.02
2	No Light	0.0023	0.03
3	No Light	0.0022	0.065
Avg	No Light	0.00247	0.0233

Fig. 12: Test Panel Isc and Voc Measurements

a current rating are very expensive (about $30 to $40 per fuse) so we decided it was not worth adding them in.

The TVS diode protects the system from transient spikes including lightning strikes or other power surges. The TVS diode will not affect the system until a voltage breakdown threshold is reached. At this point, it will shunt current to ground, protecting the ICs. We chose a TVS diode that has a typical breakdown voltage of $36V$ [16], which is the same as the max input voltage of our buck-boost converter. The buck-boost converter provides output voltage protection but doesn't have input voltage protection, so this is an important addition to our system to prevent user error.

Overall, this block provides overcurrent protection to both solar panels and ICs and overvoltage protection to ICs.

2) Input Sensor: After the input signal from the solar panel is validated to be safe, we take current and voltage measurements. We need both current and voltage measurements at either the input or output to the buck-boost in order to control the system. The microcontroller will observe the power generated at the current and previous state and decide the next output voltage, affecting the voltage and current readings. The goal is to maximize the power output of the solar array. There were multiple design decisions that went into the input sensor block as follows.

First, we needed to decide how we would communicate with the microcontroller and its communication scale. Scalability was an important factor in our design because a distributed system should be able to support many modules. For communication, we could communicate with the microcontroller through either an analog signal or a digital signal. Analog communication would require the use of an ADC pin, meaning the system would be bottle-necked by the number of ADC pins on the converter. We decided to choose a sensor that used digital communication,the I2C communication protocol. We were familiar with this standard protocol from previous embedded courses. Additionally, only 2 I2C lines, SCL and SDA, would be needed for communication. With proper multiplexing, the system would be able to scale utilizing 1 I2C bus for communication.

Second, we chose a sensor that found both voltage and current readings as well as could support the signal range from our panels.

Because of these considerations, we chose the ACS37800 sensor. We integrated the current sensor as shown in the typical application Fig. 32 without the MCU and our schematic Fig. 5. The input signal from the solar panel would pass through the circuit protection block to IP+, where the VINP and VINN pins would allow the sensor to calculate the voltage of the signal and the Hall-effect sensor array from the signal passing to IP- would allow the sensor to calculate the current of the signal. The output from

IP-, which should minimally affect the characteristics of the signal, would then pass on to the rest of the system. Following the typical application, we used $1M\Omega$ isolation resistors. However, the ACS37800 GND and the neutral terminal of the voltage input act as the same ground. So, the VINN isolation resistors were not needed.

One design decision we had to make regarded the value of R_{sense}. R_{sense} determines the voltages seen at VINP and VINN. For this IC, the voltages at the these pins must be $< \pm 250mV$. This prevents output saturation which would lead to inaccurate readings. However, we wanted to design R_{sense} such that VINP and VINN are as close to $250mV$ as possible to get a more fine-grained sensor reading. R_{sense} was designed as the following:

$$R_{sense} = \frac{\Delta VIN(P/N)_{max}}{V_{LineMAX} - \Delta VIN(P/N)_{max}} * R_{ISO}$$

$$R_{sense} = \frac{245mV}{36V - 245mV} * 2M\Omega$$

$$R_{sense} = 13.704k\Omega \approx 13.7k\Omega$$

$36V$ was chosen because that is the maximum input for the buck-boost converter. The isolation resistors on the VINN line can be ignored as the ground is the same. Thus, $R_{ISO} = \sum R_{ISO_i} = 2M\Omega$. A conservative $VINP_{Max}$ or $VINN_{Max}$ would target $245mV$ instead of the maximum. This results in approximately $13.7k\Omega$.

With this implementation, the ACS37800 sensor should provide accurate measurements in an easy-to-communicate format within the system's voltage bounds. For testing purposes, we added test pins at every pin of the current sensor Fig. 5 since it was important for us to validate its function and we were having testing problems in our initial board.

3) Voltage Regulator: The voltage regulator provides power to the current sensor and buck-boost converter. When choosing a power supply, we had to first decide whether the supply would be integrated into the converter module or used externally. Because we wanted these modules to be plug-and-play for the user, we decided to integrate the power supply into the module. The two ICs that needed power were the current sensor and the buck-boost converter. The current sensor can be powered by $3.3V \leq VCC < 6.5V$. The buck-boost converter can be powered by $4.75V \leq VCC < 5.5V$ with $Icc \geq 100mA$.

From these two VCC requirements, we chose to implement the typical application of the AP63205WU synchronous buck converter. The typical application of this IC will output a fixed voltage of $5V$, which will provide adequate power to both ICs.

However, because this is a buck converter, it limits the lower bound signal that the module will support because the solar array will have to provide enough voltage for the power supply to produce 5V. We thought this was an acceptable limit because even with 1 panel in indoor light as shown in Table 12, we were able to surpass this limit.

Its design is shown in Fig. 6, and no changes were made to the typical application as shown in Fig. 33. The inductor value followed the recommended component selection [17].

4) Buck-Boost Converter: This section will discuss the hardware implementation of the converter shown in Fig. 7 following the typical application of Fig. 34. The Embedded Technical Details section will discuss the design and communication decisions on the software side.

The goal of the buck-boost converter is to set the output reference voltage dictated by the microcontroller through I2C communication. The output reference voltage is controlled by the duty cycle switching the MOSFETs in the buck-boost circuit. The duty cycle in turn affects the load impedance seen by the solar panel which will change its voltage and current signal.

We chose a buck-boost converter IC because we wanted the module to be able to be used for a variety of battery packs. We also chose this because our test environment would be using a small battery requiring a buck converter. In contrast, Solar Car has a large battery pack that will require a boost converter. We chose an IC that supports I2C communication because this would allow the system to easily scale (as seen with the current sensor). Lastly, we chose an IC that implements a synchronous four-switch buck-boost converter. We replaced diodes with MOSFET switches that are driven by a PWM signal. We used one on the high and one on the low side the buck and boost converters. Synchronous switching is more efficient for higher current system (about 1A) than non-synchronous switching as there isn't a constant voltage drop from a diode [18]. While our test system does not meet this efficiency threshold, Solar Car's system is expected to do so. However, preventing a short and handling the switching process can be challenging which is why we chose the TPS55288RPMR that handles this process.

The values for the supporting circuit components for the buck-boost converter were chosen according to its datasheet, allowing us the greatest tolerance in its use cases. The value of the mode setting resistor R_2 varied between boards as this resistor set each converter's I2C address. We left two of the three boards with R_2 open and one board with R_2 set to $75k\Omega$ to have two converters on one I2C line while the other converter was on the other line. This allowed us to communicate with all three boards from one microcontroller.

We connected the power and signal grounds of the converter to prevent floating and/or isolated grounds that would cause errors and inconsistencies with I2C communication. The current limiting resistor R_6 was set to $47k\Omega$ to account for the datasheet's maximum output current of 16 A with a safety factor of 2 (leaving us with 8 A).

$$R_{lim} = \frac{min(1, 0.6 * V_{outmax}) * 300,000}{I_{lim}}$$

$$R_{lim} = \frac{min(1, 0.6 * 36) * 300,000}{8} = 41,250\Omega$$

We had easy access to $47k\Omega$ resistors, so we pursued the most time-efficient and economic option of using those. Our output current wasn't expected to reach anywhere near the maximum output current, so we did not anticipate running into any issues with this approximation.

All other values for the components for the supporting circuitry were industry-standard values (such as the $4.7uH$ inductor, the $0.1uF$ bypass capacitors, and the $33k\Omega$ grounding resistors. The MOSFETs used for the buck-boost converter were standard MOSFETS with parameters that would contain our maximum voltage and current values.

5) Output Voltage Sensor: The output voltage sensor schematic is shown in Fig. 8. This sensor measures the output voltage of the buck-boost converter. The J12 pin on the voltage divider was planned to be either used for testing or fed into the ADC pin of the microcontroller. We chose the R14 and R15 resistor values based on the 3.3V + 0.3V ADC pin voltage maximum of the microcontroller and the expected voltage input of up to 22V from the buck-boost converter. With the buck-boost converter in place, the J12 pin will display an acceptable voltage $\frac{1}{10}$ the actual output voltage. At max input of the system, the J12 pin will display 3.6 which is still an operable range.

$$V_{out} = \frac{R15}{R14 + R15} V_{in}$$

$$V_{out} = \frac{10k}{90k + 10k} 22v = 2.2V$$

The sensor was a last minute addition to give the microcontroller more data to determine the efficiency of the buck-boost converter. However, since the buck-boost converter's output reference voltage is programmable and the IC is accurate in reaching this reference voltage, the voltage divider was not needed in validating the reference voltage.

6) I2C Isolation: The converter modules in our DMPPT system as shown in Fig. 3 have different relative grounds. This necessitates power isolation between the modules and the microcontroller for I2C communication. Because the microcontroller is grounded to $0V$, all microcontrollers that have different grounds must have an isolator for communication, so we need $n-1$ isolators.

We chose to use the ISO1640BDR digital isolator that supports bidirectional communication [19]. The microcontroller must be able to send signals to both the buck-boost and current sensors, and receive data. We realized we needed isolators later in development, so we built the isolation circuit on a daughter board as shown in Fig. 10. Future improvements would integrate the circuit into the current board. The ISO1640BDR digital isolator follows the typical application circuit as shown in Fig. 36. The pull-up resistors were included in the schematic, but are not needed as pull-up resistors are already included in the module schematic and handled by the microcontroller. The ISO1640BDR isolators expect a VCC range of $\approx 3V - 5V$. Unfortunately, the daughter board was not implemented in the final product due to time constraints. For simplicity, the grounds and VCC on the STM32 end were connected on the board for the 3 isolators.

7) External System Connections: This section encompasses the design decisions for all external connections to the module. This includes type of port, placement of port on the PCB, and placement of port within the schematic. As can be seen in a comparison between our V1Fig. 39 and V2Fig. 40 schematics, many more test pins were added around the current sensor as it was not setup correctly in the V1 board and we wanted more points to troubleshoot.

Because our converter modules are meant to be plug-and-play, we decided to use screw terminals that would allow the user to easily secure and remove wire connections. Our V1 board had one of the screw terminals in the middle of the board. While this was fine, we decided to move all screw terminals to the edges of the board for user ease-of-use.

E. Embedded Technical Details

The microcontroller we chose was the STM32F401RE. This board was chosen because a similar board, the STM32G071RB, was used in a prior course. The embedded software can be broken up into communication with the sensor, buck-boost converter, algorithms to adjust the converter outputs, and Universal Synchronous Asynchronous Receiver Transmitter (USART) communication to a computer.

1) Sensor and Buck-boost Communication: The communication with the sensor and buck-boost converter utilized Inter-integrated circuit (I2C) communication. I2C was initially chosen because of its wide device addressing range; however, after selecting the sensor and buck-boost converter to use, it was discovered that the converters only supported up to two different addresses. This led to having to use several I2C lines on the STM32 to support more than two solar panels. To configure each of the converter boards, the index of the device has to be determined and with that the I2C line can be determines by integer dividing the number by two and adding one. With this information, the device can be wired up to the appropriate I2C line and the internal address of the current sensor can be configured. This process also ensures that peripheral addressing circuit of the current sensor is disabled while also putting the sensor in DC mode and setting the number of samples. The output of the buck-boost converters are also enabled to begin conversion by setting its internal duty cycle to correspond to the reference voltage stored in a register. In use, the microcontroller will read the sensor voltage and current to determine the current state of the system and update the reference voltage stored in the buck-boost converter accordingly.

2) MPPT Algorithm: The algorithm chosen to be implemented is an extension of the Perturb and Observe algorithm for central MPPT designs. This algorithm finds the maximum power point of each of the panels and increases the output current of the panels with lower maximum power points as to not hinder the currents of the other panels.

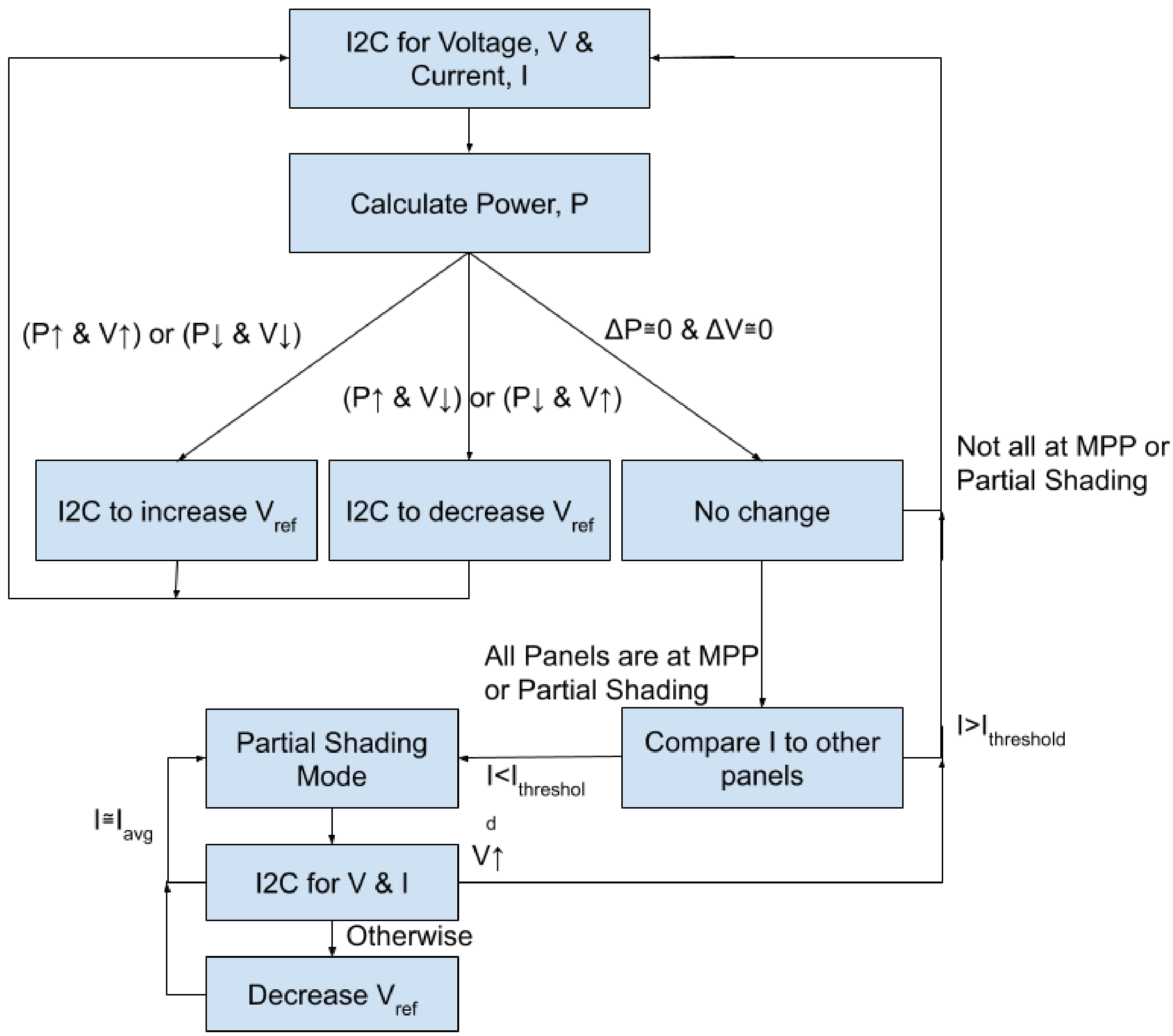


Fig. 13: Perturb and Observe Software Flow Chart

As seen in Fig. 13, the voltage and current measurements are read from the sensors and the algorithm updates the state according to previous measurements. By following the characteristic power-voltage curve of the maximum power point, depending on the changes seen in the current and voltage, the output voltage is updated by changing the reference voltage in the buck-boost converter. If all converter boards are determined to be at maximum power point, then converter boards that are significantly below the average current have their output currents increased to mitigate the power lost in the whole system.

3) USART Communication: To visualize the maximum power point tracking, voltage and current readings are transmitted through USART to a computer. The computer then interprets those values and displays them on live plots to examine the power being delivered to the battery. The microcontroller also supports different modes that can be changed by sending bytes over USART from a computer to change the current mode or request measurement data.

F. Metrics Website Technical Details

The goal of the metrics website is to validate the power output and system performance through real-time metrics collection. The driving theory behind a decentralized MPPT system vs a central system is that the sum of all local MPPT of subgroups of a solar array is greater than the global MPPT of the solar array. The metrics website will validate this by allowing collection of power along with voltage and current measurements from the microcontroller while providing a method of visual comparison. The real-time mock-up is shown in Fig. 14. The user, or in our case, the Solar Car Telemetry team, can track the system performance such as the live power output. This idea was then fully implemented in Fig. 15 and Fig. 16, allowing the user to connect, record, and analyze the system within the website.

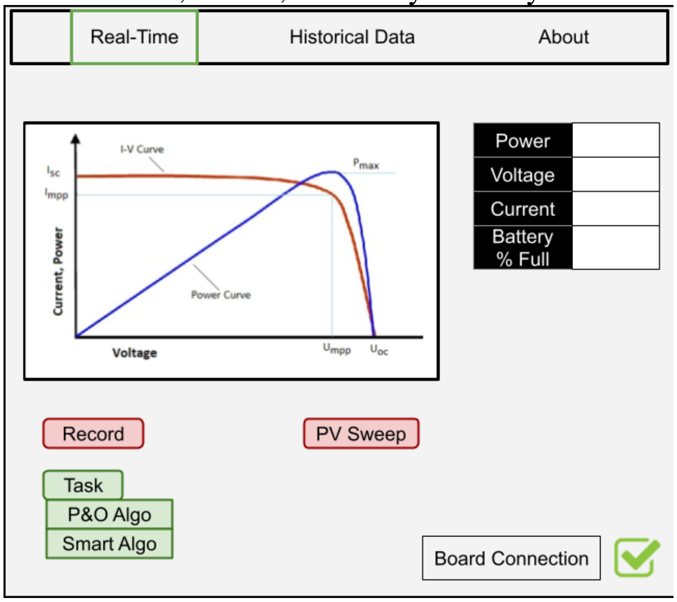


Fig. 14: Dashboard Wireframe

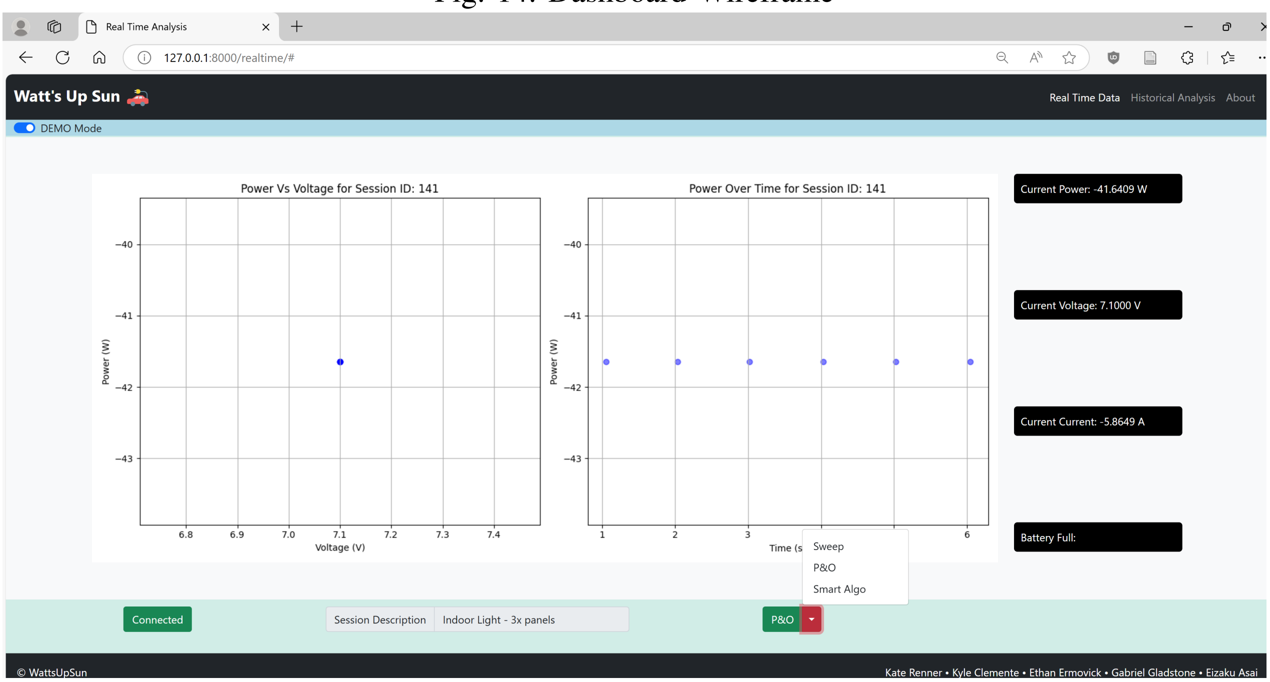


Fig. 15: Dashboard Recording Session

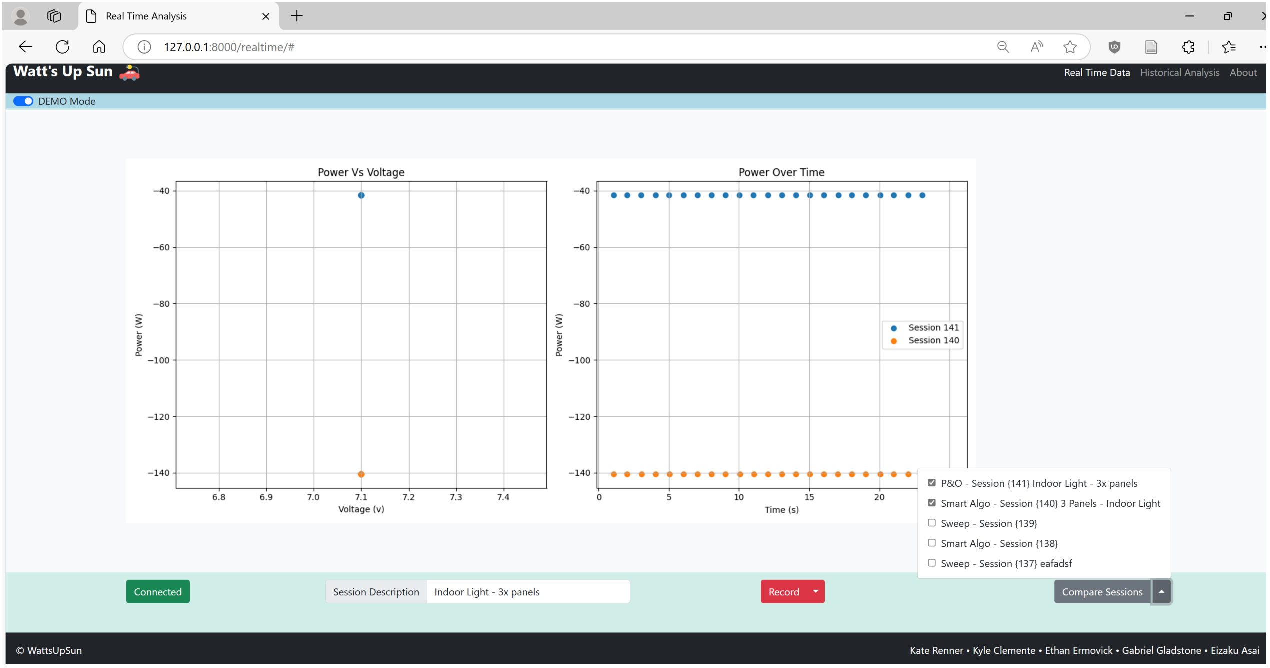


Fig. 16: Comparing Dashboard Sessions

As shown in Fig. 17. The website has 2 control flows that allow it to communicate with the user and communicate with the microcontroller. This gives the user a central command tool to interact with the project.

Control Flow 1: The User want to view data.

1) User opens the real-time page.
2) Django maps URL to View.
3) View retrieves data from model, which is a object oriented representation of the data stored in the database.
4) View uses the Template to render the final HTML.
5) The View returns final HTML content to the browser.

This control flow allows the user to quickly interact with the DMPPT system through a standardized protocol. We used DJango to build the website, and this design consideration is further explained in the Tools Utilized section.

Control Flow 2: Microcontroller streams real-time data.

1) Website requests readings from the microcontroller at a set rate through UART.
2) Website request triggers an asynchronous interrupt on the microcontroller which will then send current buffered readings.
3) The website will update the real-time display and store the readings for further analysis.

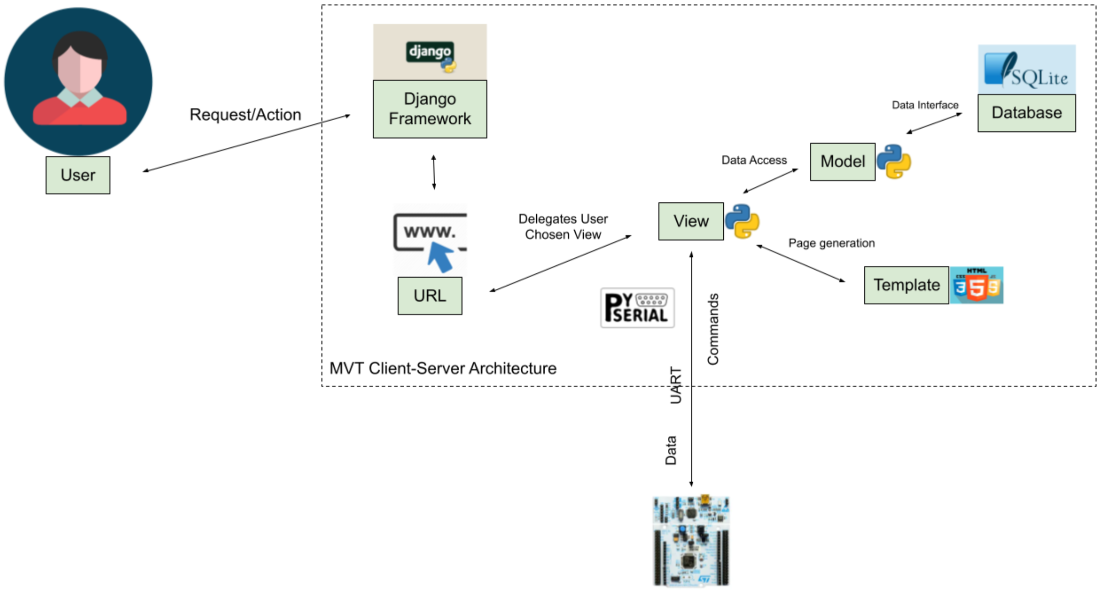


Fig. 17: Dashboard System Design

We wanted the website to be as user-friendly as possible, so there were several control flow checks in place. First, the user cannot record a session without connecting the device and choosing an algorithm for the microcontroller to implement. If the user tries to do so, they will receive a pop-up message that instructs them on the issues they need to remedy. Second, a user cannot record a session and compare two sessions at the same time. To avoid confusion, we hide the compare button when the user is recording. We also prevent the user from changing the name of the recording during recording. Finally, if the user wants to get to know our website, we provide a demo mode version which doesn't require a microcontroller plugged in and can be toggled in the top right.

G. Test Plans

1) Battery Discharging: In our test setup, we charged a Li-Ion L148A26 battery [12]. However, we didn't use the charge on the battery. Thus, we needed a way safely discharge the battery so we could continue testing. We decided to use power resistors to discharge the battery. A power resistor is designed to dissipate large amounts of power. The L148A26 holds a 2600 mAh at maximum charge and can discharge at a maximum current of 3Ah. This means that at max rate the L148A26 can discharge in $\frac{2600mAh}{3000mAh} = 0.868hrs$. However, we did not plan to discharge 100% of the battery for battery longevity reasons [20], so we tried to keep the state of charge over 25%.

Our battery testing setup consists of 2 power resistors in parallel connected to the battery. The resistors are connected in parallel to increase the current flow. The setup provides a stable current draw of $28.11mA$. At this rate, the battery will 100% discharge in $\frac{2600mAh}{28.11mAh} = 92.49hrs$ and will 75% discharge in $\frac{2600mAh*0.75}{28.11mAh} = 69.37hrs$. While the discharge time is slightly longer than we would prefer, we believe it is suitable for our testing purposes.

2) DC Input Test: A flowchart of our DC Input Test Plan can be seen in Fig. 18.

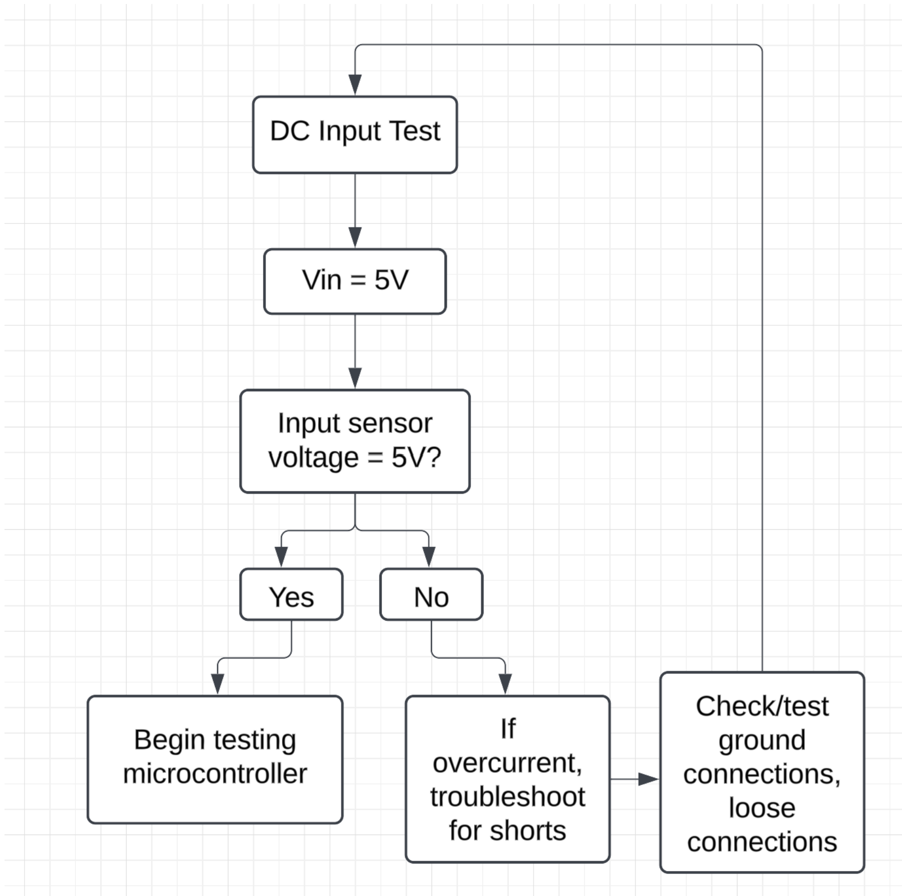


Fig. 18: DC Input Test Flowchart

After we soldered our first iteration of the PCBs, we decided to perform a simple DC input test as part of our test plan. We immediately encountered an issue on the AD2 which said that there was overcurrent. We believed it was likely a short at the input. We initially questioned if the TVS diode in our original schematic was shorting the circuit, so we scoured the datasheet [16]. It said that the TVS diode is used for overvoltage protection and will greatly increase conduction when it reaches the breakdown voltage. This voltage is around 36V, and we did not reach this value in our tests. We concluded that the TVS diode was not the issue. We ended up figuring out that we placed the current sensor in parallel (one end at the positive terminal, one end at ground) rather than in series. This was in fact the reason that the circuit was shorted. Our solution to this was to scratch out traces and add jumpers Fig. 41, change the schematic to reflect these new traces, and order new PCBs once we verified there were no other problems with the original schematic Fig. 39. After scratching out the traces and adding jumpers, we again performed a DC input test which passed. There was a slight, insignificant voltage drop. Then, we performed a voltage regulator test which also passed (we inputted a 5v signal and got a 4.6V output, which worked for our setup). Our main issues lay with the current sensor.

3) I2C Serial Communication Testing: To test the I2C communication register, reads and writes were attempted. Initial tests were not successful due to wiring issues on the PCB and required several changes before the ICs on the board were enabled. Once enabled, the I2C communication was working for the most part. The issues encountered were that the sensor was unable to write to the EEPROM memory and the buck-boost always reloaded memory to default values on boot up. These issues were accounted for by using a customer access code that could be written to the sensor to enable writing to EEPROM memory. Additionally, the only register value that mattered in the buck-boost was the output enable which can be enabled on start up. After these changes were made, the read and writing operations worked properly.

4) Current Sensor Testing: We then proceeded to test the current sensor. To begin, we simulated DC voltage input sources using the virtual bench to imitate the solar panels. We used voltage ranges of 5V-18V. This resulted in current ranges between 6-20 mA to provide appropriate power. While our voltage readings from the current sensor were accurate in the lower portion of this input range, the readings became inaccurate once the input was above 8V. Additionally, the current readings were inaccurate for all input conditions. Upon review of our schematic, we determined we needed to ground the negative input of the current sensor for more accurate readings, connect the VCC pin of the sensor to the corresponding pin of the voltage regulator, and fix the bypass capacitor of the current sensor to be in parallel rather than series. Once these changes were made, we continued to input DC voltage conditions we were using before.

We used a perfboard to integrate I2C isolators into the current sensor's communication with the microcontroller next. We aimed to ensure consistent grounding between the current sensor and microcontroller, hoping this would increase the accuracy of our voltage and current measurements. This bore no fruit, however, as our measurements were no more accurate than they were before. We theorized that the current sensor itself may be the issue, so we consulted its datasheet to find information regarding its sensitivity. Since the current sensor had a 30A range, it turned out that was not fine-tuned enough at small current ranges to give accurate measurements. Our current inputs ranged between 6-20 mA, so they were much too small to be read accurately by the sensor.

The current sensor voltage and current readings are contained in many forms in the device registers. These registers include an average (RMS register), average over one second (AVGONESEC register), average over one minute (AVGONEMIN register),and live readings (Codes register). The current sensor gave results that had no correlation as stated before. The voltage readings did have accurate readings and can be seen in 19. The second and codes registers have inaccurate results; however, the RMS register holds a relatively accurate reading that can be divided by a constant of about 1600 to determine the input voltage.

Voltage input (V)	Average	Second	Codes (5000 samples)	RMS Slope	Sec Slope	Codes Slope
5	10980	234	113000	2196	46.8	22600
6	12590	48	148000	1610	-186	35000
7	14214	138	193000	1624	90	45000
8	15840	230	237700	1626	92	44700
9	17470	61	26400	1630	-169	-211300
10	19100	148	71400	1630	87	45000
11	20710	225	111400	1610	77	40000
12	22320	46	150000	1610	-179	38600
13	23928	120	186400	1608	74	36400

Fig. 19: Input Voltage and Register Readings

5) Output Voltage Regulation Testing: The buck-boost was also tested to compare reference voltage settings in the device register to actual output voltages using a virtual bench to supply an input voltage and oscilloscope the outputs. A $15V$ input was used when performing these tests and the results can be seen in 20. The register value for the voltage reference (Vref) shows a constant multiple of about 0.024 to get the output voltage.

6) Individual Solar Panel Testing: Using a single solar panel under good light conditions, we were able to supply the system with about $15V$ and $8mA$. This was able to power the ICs without the need of a virtual bench and enabled I2C communication as well as output regulation. Because of issues with current measurements we were not able to do thorough testing of the algorithm and multiple panel systems.

7) Metrics Website Testing: Selenium IDE was used to automate the user testing process as shown in Fig. 21. Selenium allowed us to record user sessions that we could run to validate the website after large

Vref Value	Output Voltage (15 V input)	Vout Slope
0	1.37	
32	1.99	0.0621875
64	2.6	0.040625
96	3.23	0.033645833
128	3.85	0.030078125
160	4.49	0.0280625
192	5.1	0.0265625
224	5.73	0.025580357
256	6.38	0.024921875
288	6.99	0.024270833
320	7.64	0.023875
352	8.25	0.0234375
384	10.4	0.027083333
416	11.7	0.028125
448	12	0.026785714
480	12.3	0.025625
512	12.7	0.024804688
544	13.2	0.024264706
576	14	0.024305556
608	14.4	0.023684211
640	15.2	0.02375
672	15.9	0.023660714
704	16.7	0.023721591

Fig. 20: Voltage Reference Register Value and Output Voltage

production changes. If there was a noticeable error in our project, the Selenium tests would not pass and we would know that something is wrong with the update. The website has 3 pages: Real Time Data, Historical Analysis, and an About page. The Historical Analysis and the About page are static pages, so were easy to validate. Thus, our tests revolved around the user interaction with the real-time data page. The inner workings of this interaction are outlined in Control Flow 1. Additionally, as described in the Metrics Website Technical Details section, we had certain control flow checks before a recording session could take place so that the user could not break these checks.

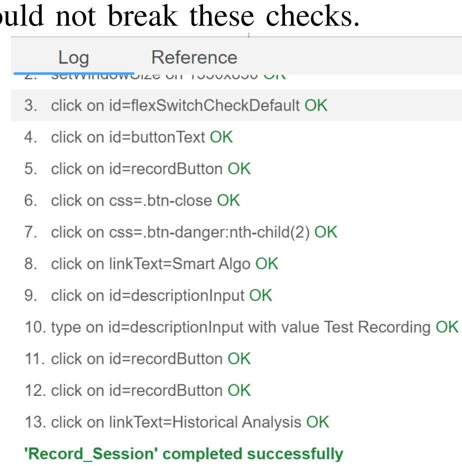


Fig. 21: Successful Selenium Test Log

Our core test cases are listed below.

- A user must connect to a device and choose an algorithm before recording.

- A user cannot change the session description while recording.
- A users recording session will be saved if they end recording or even switch pages.
- A user must select 1 or more previous recordings to compare.
- A user can start a recording or compare session end it and start another recording or compare session.

V. Physical Constraints

A. Design and Manufacturing Constraints

There were several physical constraints that we faced, the most difficult of which to overcome was the integration of the MPPT with solar car's specific setup. Mounting the MPPTs on the panels was challenging, as space constraints on the car required the MPPT to be compact, even though MPPTs are typically larger than PWM controllers [21]. Additionally, coordinating with the solar car team was a challenge at times due to the limited availability of the vehicle as well as schedule coordinating. This wasn't as large of an issue as anticipated, but since Ethan is on the Solar Car team, that made it much easier to access what we needed and coordinate with the team. Testing our design under racing conditions to simulate partial shading, high load, and variable sunlight was a significant challenge. We used software simulations as much as possible, but real-world testing was still crucial. Another constraint we faced was making sure the PCB layout accommodates proper heat dissipation. This was crucial, especially given the high power and partial shading conditions that can generate hot spots [22]. A constraint that was more easily overcome was STM32 pin allocation. We needed enough GPIO pins for external components and sensors, so we decided to use I2C rather than SPI to solve this issue. There were also virtual bench testing limitations. There were not enough testing points to verify the accuracy of the current sensor. The system required a minimum voltage input, and at a certain operating point, the virtual bench would switch from constant current to constant voltage mode. This, in turn, would give a non-correlated result. Within our testing range, we could only generate 3 to 4 points to verify the current sensor under constant current mode, which was not enough for calibration. As for part availability, most components required for this project were readily available, although we did use some unconventional resistor and capacitor values. For critical components like the STM32 microcontroller, availability is generally not an issue due to its common use in embedded systems. Similarly, the current and voltage sensors, along with capacitors, inductors, and resistors, are easily accessible. However, the following components were more challenging for us to find and took a lot of research:

- Screw hole connectors: These are generally readily available, but the specific ones we chose took us a long time to find.
- MOSFETs: We found MOSFETs that worked with most of our design constraints, although we had to twist the leads for them to fit our PCB footprints.
- DC-DC Converter (Boost/Buck Converter): finding the exact Buck/Boost converter for our design was challenging.

B. Tools Utilized

The following tools were utilized, and we have included descriptions for the role each tool played in our work as well as which tools we had to learn.

- STM32CubeIDE
  - As learned in our previous Embedded class, we used the STM32CubeIDE to program our STM32 microcontroller. We were all fairly familiar with this IDE, since we had to use it for a whole semester in many assignments, so there was not too much to learn from scratch there.
- MultiSim
  - We used Multisim to do a simulation of our Solar Cells to gather data about our panels. We began using Multisim for our schematic, but we quickly realized that we needed software that

would allow us to import exact parts. Similarly to the STM32CubeIDE, we have used Multisim in many previous classes, so we were all very familiar with this software.

- KiCad Schematic and PCB editors
  - We chose KiCad for our design schematic and PCB creation because it allowed us to import exact parts, making the PCB as accurate as possible. In comparison, Multisim lacks this capability, limiting our ability to model real-world components precisely. Accurate part dimensions, footprints, and electrical properties are critical for our design, especially when considering factors like component spacing, thermal management, and signal integrity. However, learning how to import these parts in KiCad was challenging and time-consuming. First, we had to find compatible part libraries like Digi-Key that offer KiCad compatible footprints and symbols. Then, we needed to import the libraries after downloading them. Lastly, we needed to assign footprints to the parts to ensure correct dimensions for the PCB. Using the KiCad PCB editor was the natural next step, as trying to import this into Ultiboard would have been tedious. The two PCB editors were very similar, so it was not difficult to learn how to use this new tool.
- GitHub
  - We used two GitHub repositories to collaborate on the website and STM32 code. Many of our group members were familiar with using this version control system, so it was a simple integration into our workflow.
- Django Framework
  - The Django Framework was used to simplify the implementation of a metrics dashboard to validate the efficacy of our system. We chose to use Django because it supports a Python back-end which allowed us to use Pyserial, a powerful library for USART communication along with the STM32 microcontroller. We chose Django because it has many resources, is taught in the UVA CS curriculum, and is an industry standard framework. This will allow the telemetry team to easily integrate this tool into their system. The website supports two functions: communicating data with the user and communicating data with the microcontroller. Django uses a Model-View-Template (MVT) architecture to separate system needs as is the best practice in industry. When a user makes a request, such as to compare multiple graphs, Django maps the request to a view. The view will interact with the model to fetch data from the database. The view will then use the template to render that final HTML that will be displayed to the user. Using the Django framework allows modularity in our system to replace the database with one that can be hosted in the cloud or to use a different front-end for better communication with the user.
- Visual Studio Code
  - Visual Studio is a free code editor, which we used to work on the code for the website.
- Soldering and Desoldering Tools
  - We soldered most of our components onto our PCBs by hand and sent the surface mount device (SMD) components to 3W to be soldered. All of our group members were knowledgeable on how to both solder and desolder from previous ECE Fundamentals classes, so we were able to solder and desolder (after making component placing errors) without trouble. We choose to solder the through hole components on our own in order to save cost.

C. Cost Constraints

MPPTs are generally two to three times more expensive than traditional PWM controllers [2]. Given our budget of $500, we wanted to leave lots of room for error in case of unforeseen expenses such as PCB revisions. With our first PCB iteration, we kept our overall parts and manufacturing costs under $300. This left us with plenty of flexibility for adjustments and replacements, ensuring that we could complete the project within budget. As predicted, we faced a challenge with our design and needed to reorder our PCBs along with our surface mount components. Because we budgeted well in the beginning, we were able to account for this and had plenty left over to use. None of our parts were particularly expensive with the exception of our ICs which were still under $7 each. Additionally, our micro-controller was under $13.83. If we were to create a production version of our project where we sold each board separately, the cost of all three boards combined as we have in the overall price spreadsheet (Fig. 37) would be around $133. This can be seen in the ideal price for one board Spreadsheet (Fig. 38). This is expensive because this process would order an entire STM32 micro-controller and battery pack for just one board. Ideally, if this were to be manufactured, it would be in bulk. This is discussed more in the Costs section of this report.

D. Considerations for Product Version

To transition our prototype to a production ready version, we would need to make several changes to ensure durability, performance, and scalability. First, we would select more robust, higher-quality integrated circuits (ICs) to withstand extended use and harsh operating conditions. Additionally, switching from I2C communication to SPI communication with a multiplexer would improve data transfer rates and reliability with multiple components. Developing dedicated computer software for flashing specific parameters rather than manually altering code would streamline the converter configuration. This would make the process more efficient and user-friendly. Finally, we would design a custom PCB with an integrated STM32 microcontroller instead of relying on a debug board. This would reduce overall size, improve performance, and tailor the hardware to our specific needs.

VI. Societal Impact

As coal, oil, natural gas, and other non-renewable energy resources become scarcer and efforts to limit the use of greenhouse gasses become stronger, it is more important than ever to find reliable ways to power our society's growing demand for energy [23]. Solar energy has emerged in recent years as a frontrunner to produce large amounts of power to mitigate the energy loss from the reduction of fossil fuel use. This source of energy could account for up to 11 percent of global energy production by 2050 according to the International Energy Agency [24]. This means it is as important as ever to optimize the efficiency of solar technology to maximize the effectiveness of solar energy. Maximum Power Point Tracking (MPPT) technology aims to do exactly that by extracting energy from solar cells in the most efficient manner. Solar charge controllers are also vital to the longevity and efficiency of all solar systems including home devices, IOT devices in remote areas, agricultural systems, and more [25]. Solar charge controllers manage the power transfer from solar panels to a battery. They prevent the battery from overcharging or undercharging due to a load as well as protect the panels from reverse current. Our goal is to develop an MPPT from scratch that at least matches the efficiency of the UVA Solar Car team's existing MPPT technology while minimizing the cost and complexity such that our model can not only potentially be integrated into the UVA Solar Car but expanded upon to improve MPPT technology on a larger, broader scale. Our MPPT will be complete with safety features such as overvoltage and reverse current protection, and it will not rely on any forms of power for its integrated circuits such as external batteries. This will not only satisfy the small-scale stakeholders of the UVA Solar Car team but benefit large-scale stakeholders of the entire world's society as we will be making needed improvements to solar power technology.

VII. External Standards

ASTM E2481-12(2023): [26]

The ASTM E2481-12(2023) standard ensures the safety and reliability of photovoltaic systems by evaluating how well solar modules manage hot spots caused by partial shading or defects, which can lead to overheating and fire hazards. In our project, this standard is directly applied through the implementation of circuit protection (For example, TVS diodes) and the distributed MPPT design, which mitigates mismatch losses and prevents overheating by independently optimizing each panel's output. Through testing and validation, such as current sensor and voltage regulation tests, we ensure the solar panels perform safely under various conditions, aligning with the standard's focus on reliable and safe operation. Additionally, our distributed MPPT design isolates panels to prevent system-wide failures caused by a single hot spot, ensuring safety in line with the standard.

IEEE 1547-2018: [27]
The IEEE 1547-2018 standard discusses the interconnection of distributed energy resources (DERs) with the grid, ensuring safe and effective integration. While it is not directly implemented in our project, this standard provides a framework for future grid compatibility if we expand our Distributed MPPT system. By addressing key aspects like voltage regulation, power quality, and system protection, it ensures that DERs, such as our solar-powered system, meet technical requirements for seamless operation with grid infrastructure. This alignment supports potential scalability and integration with broader energy systems, ensuring compliance with established interconnection protocols.

IEEE 1526: [28]
The IEEE 1526-2020 standard provides recommended practices for testing the performance of stand-alone photovoltaic (PV) systems, offering detailed protocols for system evaluation under real-world and simulated conditions. In our project, this standard guides the development of rigorous testing protocols for our MPPT system to ensure it operates efficiently and reliably under varying conditions. By adhering to its recommendations, we can validate system performance, assess autonomy, and improve troubleshooting through standardized methods. This alignment ensures our design meets high-performance benchmarks and facilitates effective system validation. For example, we simulate varying irradiance levels using a solar simulator to ensure our MPPT maintains peak performance under real-world conditions. The current and voltage sensors we use are calibrated to validate energy output effectively and troubleshoot inefficiencies using standardized methods.

IEEE 519: [29]
The IEEE 519 standard addresses harmonics and voltage regulation, critical aspects of power quality in electrical systems. In our MPPT project, this standard is directly relevant because it provides guidelines to manage harmonics generated during power conversion processes. Our MPPT system addresses this by using a filter at the DC-DC converter output to suppress high-frequency harmonics generated during power conversion. Additionally, our microcontroller monitors output voltage stability, ensuring the system remains compliant with the standard's guidelines to reduce voltage fluctuations and harmonic distortion. This alignment with the standard enhances power quality, reduces losses, and prevents potential interference with connected equipment, supporting the reliability and safety of our MPPT design.

IEEE 280-2021: [30]
The IEEE 280-2021 standard provides standardized letter symbols for quantities used in electrical engineering, ensuring consistency and clarity in technical documentation. In our project, this standard directly supports the clear representation of quantities and units related to our MPPT design, such as electrical current, voltage, and power. By adhering to these conventions, we maintain uniformity in our documentation and communication, minimizing errors and ensuring our project aligns with professional and academic standards.

IEC 61730: [31]
The IEC 61730 standard is a safety qualification standard for photovoltaic (PV) modules, focusing on ensuring their performance and safety under various conditions. In our project, this standard ensures that the PV modules integrated with our MPPT system meet essential safety and performance criteria. By adhering to this standard, we can verify that the modules operate reliably, even in challenging conditions like high temperatures or partial shading, aligning with the standard's guidelines for component testing

and thermal stress management. This ensures the overall safety and effectiveness of our design.

IEC 61853: [32] The IEC 61853 standard provides testing methodologies for photovoltaic (PV) modules to evaluate their performance under varying irradiance and temperature conditions. In our project, this standard is directly relevant as it enables us to measure whether our MPPT effectively manages the energy output from PV modules across a range of real-world conditions. We use its protocols to evaluate our solar panels by connecting them to the MPPT and monitoring their energy output during simulated shading or high-temperature scenarios. These tests validate whether the MPPT maximizes efficiency under dynamic conditions, ensuring alignment with the standard.

ISO 15118-1:2019: [33]
The ISO 15118-1:2019 standard focuses on the vehicle-to-grid (V2G) communication interface, detailing protocols for communication between electric vehicles and the grid, which are essential for smart charging and energy management. While not directly implemented in our current project, this standard would become relevant if we expand our design to include grid integration. Adopting this automotive standard ensures compatibility with V2G systems, facilitating seamless energy exchange and efficient integration with smart grids.

IEC 61427-1: [34]
The IEC 61427-1 standard provides requirements for secondary batteries used in photovoltaic energy systems (PVES), particularly for off-grid applications. In our project, this standard is directly relevant to evaluate the performance and reliability of the batteries integrated with our MPPT system. This applies to our lithium-ion battery pack used for energy storage. By following the standard's methods, we ensure the batteries meet the necessary standards for energy storage, supporting consistent and reliable operation in off-grid PV systems.

IEEE 1562-2021: [35]
The IEEE 1562-2021 standard provides recommended practices for sizing stand-alone photovoltaic (PV) systems, including detailed methodologies for determining the appropriate size of PV arrays and battery storage. In our project, this standard is directly applied to ensure the optimal sizing of both the solar panels and batteries to meet the energy demands efficiently and reliably. By adhering to its guidelines, we can account for variables such as system losses, load demand, and solar irradiance, ensuring our MPPT design is robust, cost-effective, and well-suited for stand-alone applications.

FIA Appendix J 2024 - Article 259 E: [36]
The provided standard outlines technical regulations for electric sport vehicles, covering specifications for electric powertrains, safety requirements, and performance standards. In our project, this standard is directly relevant as it ensures that the electric powertrain components, such as battery systems, comply with stringent safety and performance criteria. This aligns with the project's goals of optimizing electric vehicle energy management and ensures adherence to industry standards for safety and efficiency.

Formula Sun Grand Prix (FSGP) 2025 Regulations: [37]
These regulations are critical to our design as they are directly derived from the rules of the races that the UVA Solar Car team competes in. They ensure safety, performance, and compliance in solar racing by guiding the structural and electrical systems, including specifications for battery protection, vehicle dimensions, and power systems. By adhering to these standards, our project maintains uniformity with competing vehicles while ensuring it meets rigorous safety and performance requirements mandated for the Formula Sun Grand Prix.

VIII. Intellectual Property Issues

Relevant patents:

- US20090078300A1 [38]: "Distributed maximum power point tracking converter."
- US10615594B2 [39]: "Distributed maximum power point tracking system, structure and process."
- EP4113828A2 [40]: "Photovoltaic system and maximum power point tracking control method for photovoltaic system."
- CN102096418B [41]: "Maximum power point tracking device of solar assembly."
- US9800053B2 [42]: "Solar panels with integrated cell-level MPPT devices."
- US20100286836A1 [43]: "Distributed maximum power point tracking system, structure and process."
- US7248946B2 [44]: "Inverter control methodology for distributed generation sources connected to a utility grid."

In our project, there are two main features that we thought have the potential to be patentable: Perturb and Observe (P&O) Algorithm. Isolated Grounds for Each Buck-Boost Converter. The P&O algorithm is a widely recognized method for Maximum Power Point Tracking (MPPT) in solar energy systems. Given its broad adoption, it is unlikely to be patentable unless significant, non-obvious innovations are introduced. While our implementation of P&O is tailored to the unique requirements of the UVA Solar Car, these modifications are primarily optimizations for a specific use case. Such tweaks are often considered logical extensions of existing technology and may not meet the threshold for patentability. Existing patents, such as US20090078300A1 [38], provide flexibility for implementing MPPT algorithms, and CN102096418B [41] highlights that innovations in MPPT algorithms must substantially enhance performance to qualify as patentable. While our P&O implementation may improve performance, it does not appear novel or non-obvious enough to justify a patent. In the event that a particular part of our optimization were both novel and non-obvious and therefore justified a patent, the value of pursuing a patent on such detail might not offset the costs necessary to pursue that patent. This further reinforces the conclusion that a patent application on the software isn't likely to be a good use of resources. Further diminishing the value of the P&O patentability is our use of Open Source software in the algorithm design. Depending on the open source licensing, this use may require us to not only open the software to the public but also all of the untold parts of the design. The isolated grounds for each buck-boost converter in our system present a more promising case for potential patentability. This configuration offers clear functional benefits, such as preventing ground loops, enhancing system safety, and enabling fault isolation. These advantages are particularly relevant in systems with multiple converters operating in series. Notably, none of the reviewed patents - such as US10615594B2 [39], US9800053B2 [42], or US7248946B2 [44]- explicitly discuss isolated grounds for series-connected panel arrays. This suggests that our design could introduce a novel element to the field. However, the concept of isolating components using separate grounds to mitigate noise is well-known in the general field of electrical engineering, which raises questions about whether our specific application of this technique would be considered non-obvious. Furthermore, it is important to recognize that better performing designs typically avoid isolated grounds due to increased cost and complexity, raising questions about the practicality and efficiency of this approach. Even if this feature is patentable, its niche application in our specific circuit limits its broader utility and commercial value.

IX. Timeline

A. Initial Timeline

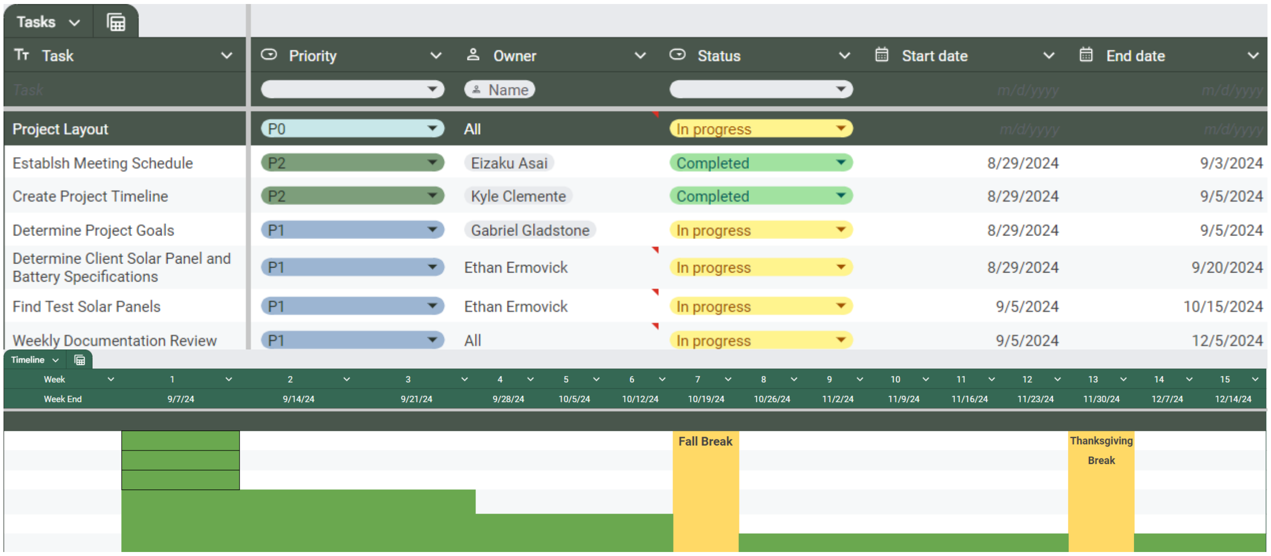


Fig. 22: Project Layout Section of Initial Gantt Chart

Fig. 22 lists the broad-level project specifications that were used to determine the specifications for individual subsystems and components of the project as well as team-wide goals to reach during each part of the semester. The initial tasks such as the project timeline and goals were intended to be completed in the first week of the schedule. Many of these tasks were set up to be accomplished in parallel such as the weekly documentation review. These tasks were designed to be constantly performed throughout the semester, leaving ample room for other such tasks to be performed at the same time. They were assigned to individuals, but for project layout tasks, they were very collaborative as team-wide communication was necessary in this area.

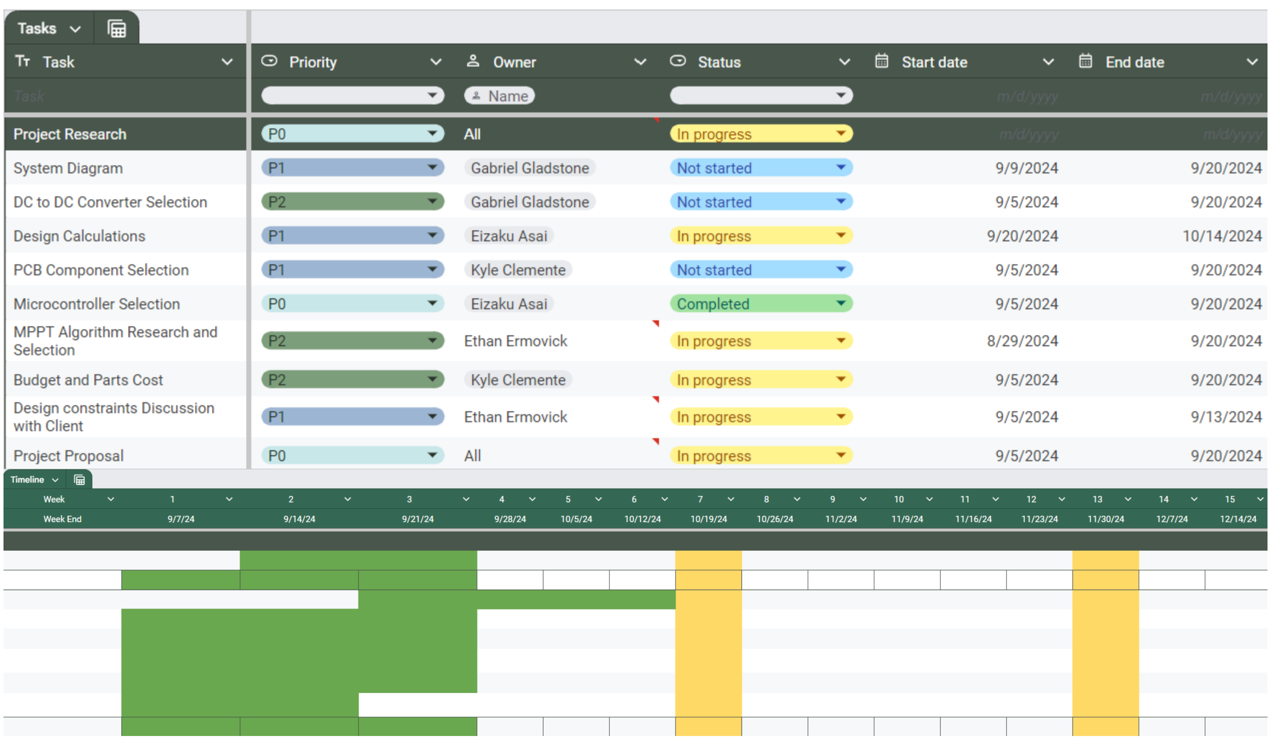
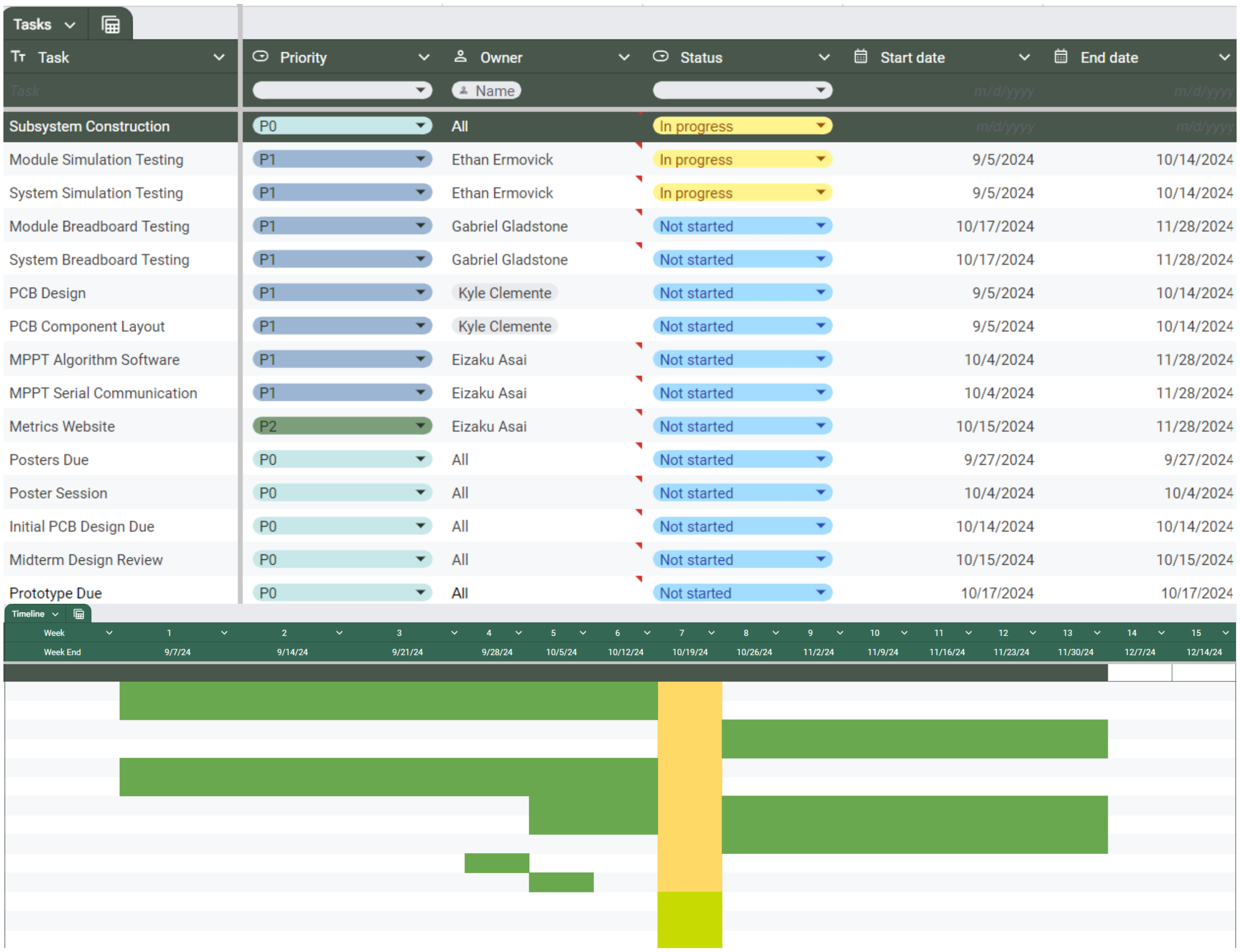


Fig. 23: Project Research Section of Initial Gantt Chart

Fig. 23 lists the research that was conducted for this project and the allotted time for such research to occur. Much of this section was completed in parallel such as the system diagram, PCB component selection, and microcontroller selection. However, the calculations and costs were completed sequentially after such decisions were made. These tasks were assigned individually based on the team members' specialties due to the division of labor into software, embedded work, and PCB work. These tasks required excellent communication with the UVA Solar Car team, as they were designed to provide the specifications necessary for compatibility with our project. Most of the tasks in this section were intended to be completed by the end of September to ensure our team would be on schedule for the later half of the semester.



Task	Priority	Owner	Status	Start date	End date
Subsystem Construction	P0	All	In progress		
Module Simulation Testing	P1	Ethan Ermovick	In progress	9/5/2024	10/14/2024
System Simulation Testing	P1	Ethan Ermovick	In progress	9/5/2024	10/14/2024
Module Breadboard Testing	P1	Gabriel Gladstone	Not started	10/17/2024	11/28/2024
System Breadboard Testing	P1	Gabriel Gladstone	Not started	10/17/2024	11/28/2024
PCB Design	P1	Kyle Clemente	Not started	9/5/2024	10/14/2024
PCB Component Layout	P1	Kyle Clemente	Not started	9/5/2024	10/14/2024
MPPT Algorithm Software	P1	Eizaku Asai	Not started	10/4/2024	11/28/2024
MPPT Serial Communication	P1	Eizaku Asai	Not started	10/4/2024	11/28/2024
Metrics Website	P2	Eizaku Asai	Not started	10/15/2024	11/28/2024
Posters Due	P0	All	Not started	9/27/2024	9/27/2024
Poster Session	P0	All	Not started	10/4/2024	10/4/2024
Initial PCB Design Due	P0	All	Not started	10/14/2024	10/14/2024
Midterm Design Review	P0	All	Not started	10/15/2024	10/15/2024
Prototype Due	P0	All	Not started	10/17/2024	10/17/2024

Fig. 24: Subsystem Construction Section of Initial Gantt Chart

Fig. 24 lists the design, testing, and construction tasks of the subsystems of the project. Much of this section was sequential, as simulation fundamentally comes before testing and testing before prototyping. However, the different types of testing was intended to be done in parallel (such as the different subsystems of the PCB tested on breadboards). The simulation, testing, and design tasks were mostly assigned individually based on each team member's role but the team-wide project tasks (such as the poster session) were completed all together. The initial simulation, testing, and PCB design was intended to be completed by mid-October so that the team had ample time to test the PCBs when they arrived. The later testing, verification, and software integration was intended to be completed by the end of November to give our team time to prepare the final product at the beginning of December.

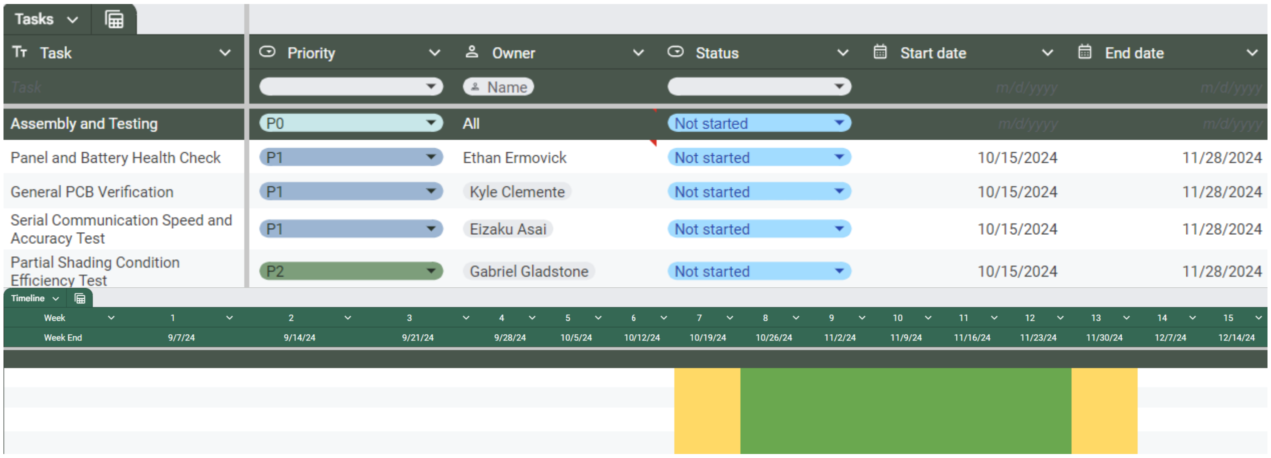


Fig. 25: Assembly and Testing Section of Initial Gantt Chart

Fig. 25 lists the steps required to put together and verify the physical project. These steps were designed to almost all be done in parallel (with the only restriction being if a system was currently undergoing another test). Each task in this section was individual as each test fell under a different category and therefore under the responsibility of a different team member. The physical system's assembly and testing was intended to be completed by Thanksgiving so that the short amount of time after Thanksgiving break could be allocated to preparing the final product, report, and demo video.

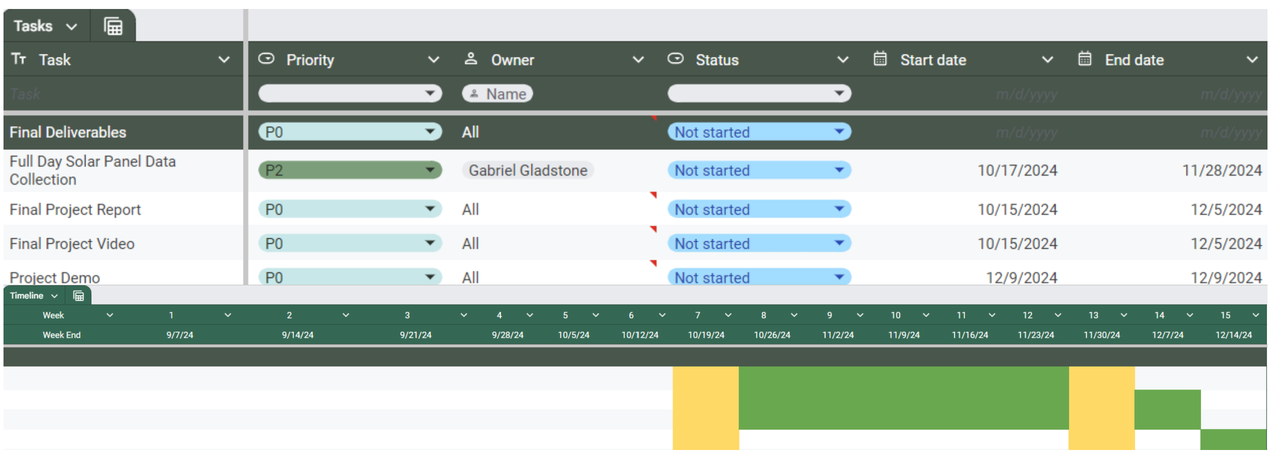
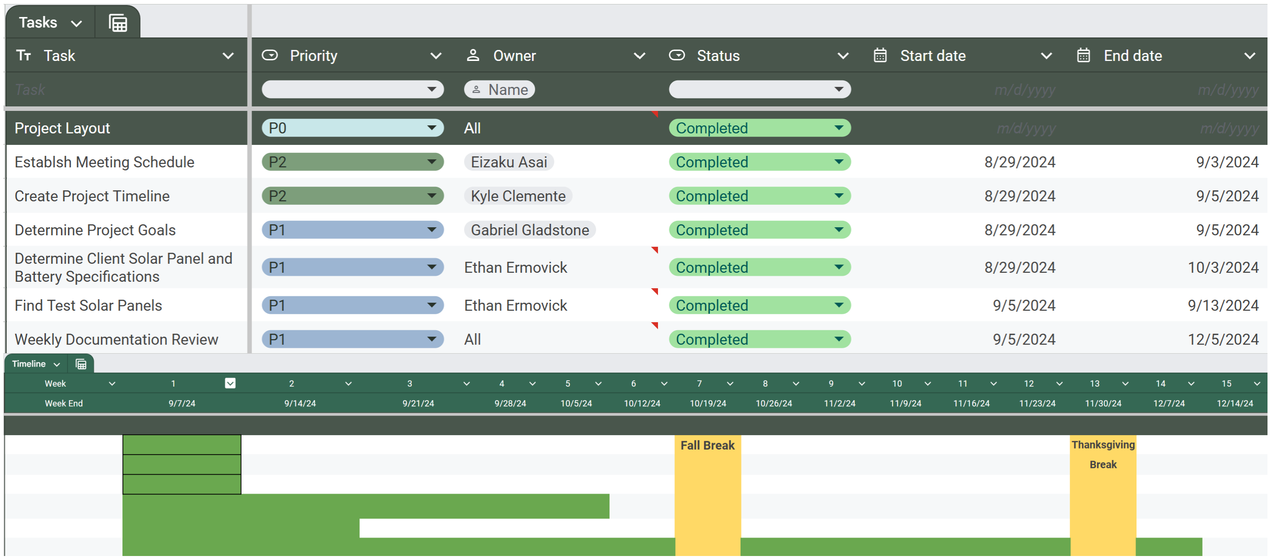


Fig. 26: Final Deliverables Section of Initial Gantt Chart

Fig. 26 lists the final products we intended to produce. These products could be partly in parallel (except for the data collection which was needed for the final report). However, these tasks needed to be completed collaboratively as these large deliverables were a result of team-wide efforts. These deliverables were due at the end of the semester, so we allocated an optimistic start date to maximize the amount of time we could spend on them.

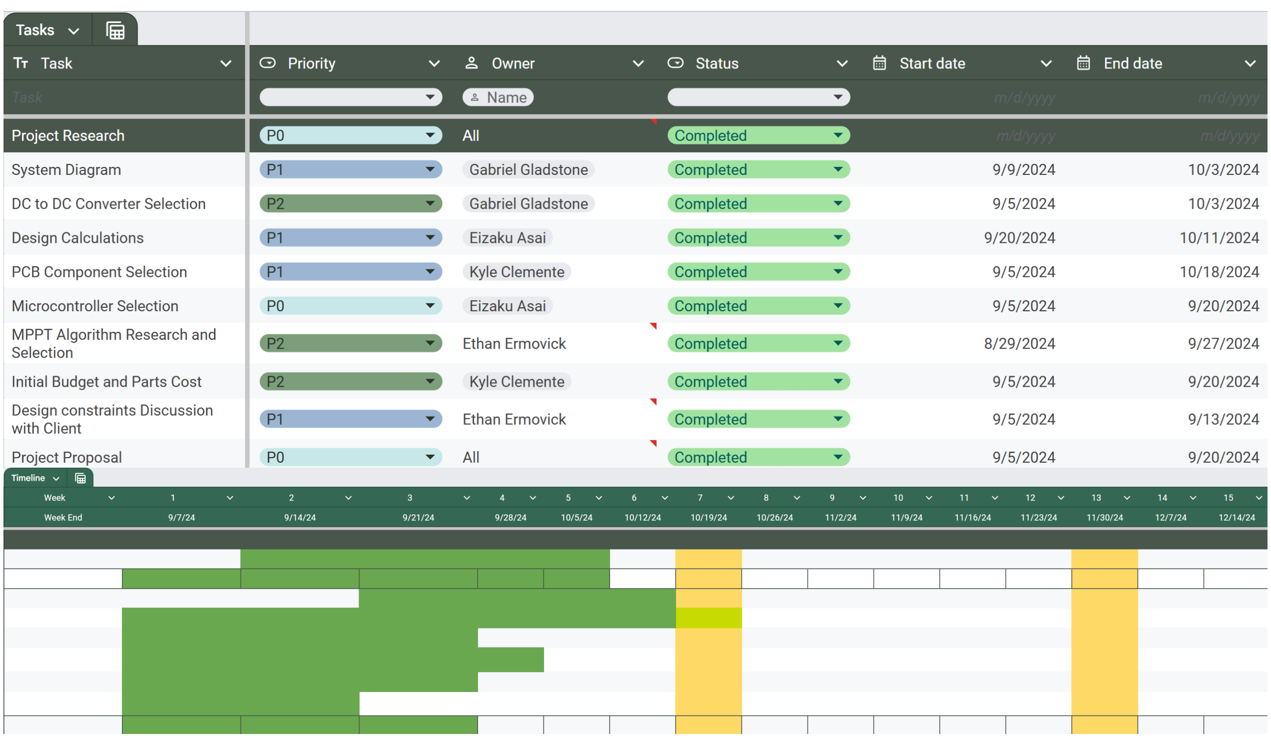
B. *Final Gantt Chart*



Task	Priority	Owner	Status	Start date	End date
Project Layout	P0	All	Completed		
Establsh Meeting Schedule	P2	Eizaku Asai	Completed	8/29/2024	9/3/2024
Create Project Timeline	P2	Kyle Clemente	Completed	8/29/2024	9/5/2024
Determine Project Goals	P1	Gabriel Gladstone	Completed	8/29/2024	9/5/2024
Determine Client Solar Panel and Battery Specifications	P1	Ethan Ermovick	Completed	8/29/2024	10/3/2024
Find Test Solar Panels	P1	Ethan Ermovick	Completed	9/5/2024	9/13/2024
Weekly Documentation Review	P1	All	Completed	9/5/2024	12/5/2024

Fig. 27: Project Layout Section of Final Gantt Chart

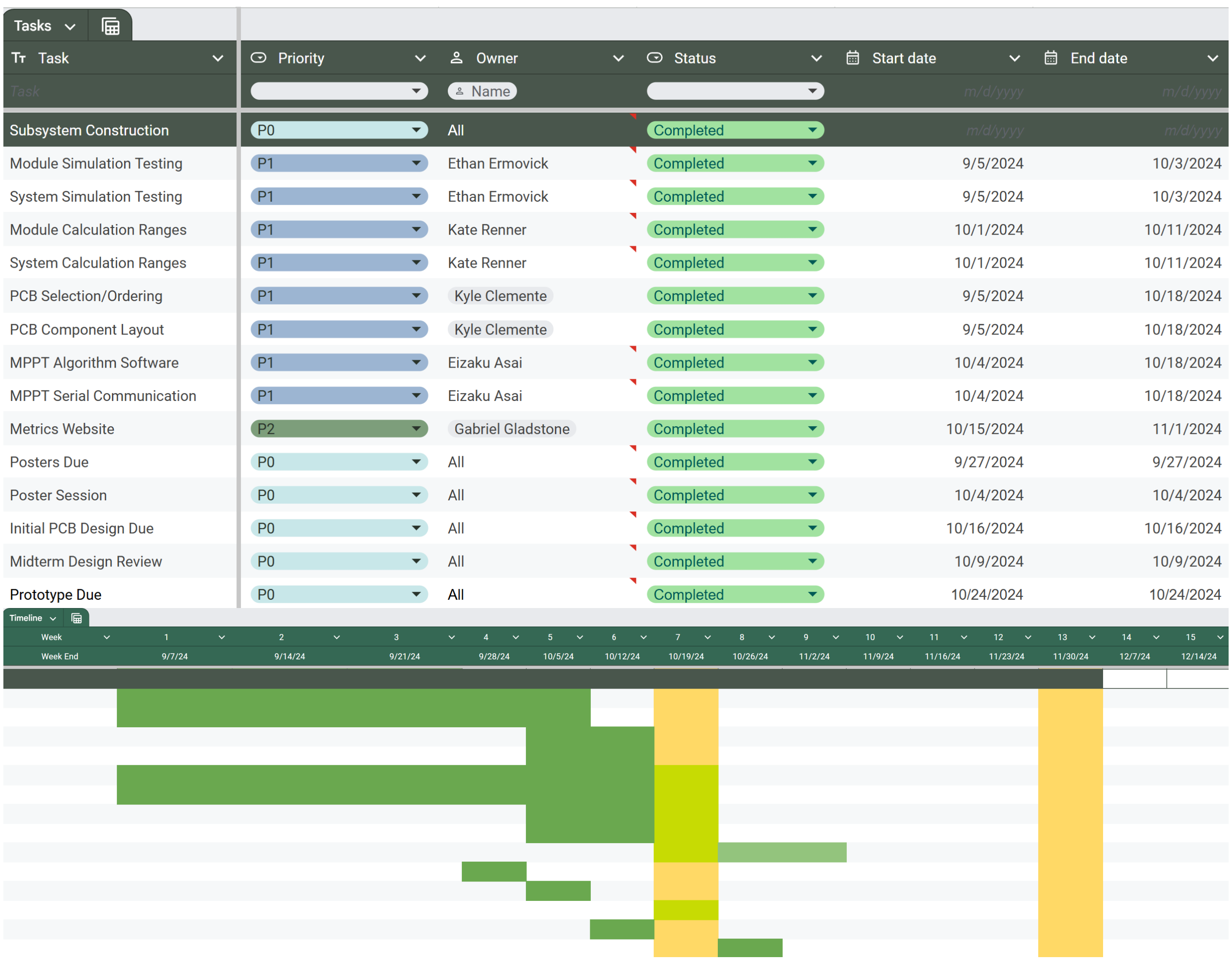
Fig. 27 lists the final broad-level project specifications that were used to determine the specifications for individual subsystems and components of the project as well as team-wide goals to reach during each part of the semester. Our initial setup tasks for the project (establishing the meeting schedule, creating the project timeline, and determining project goals) were all completed on schedule. The task of determining the client's solar panel and battery specifications was completed a week ahead of schedule, and the task of finding test solar panels was completed a month ahead of schedule. This was the result of meeting with members of the UVA Solar Car team and visiting their workspace near the beginning of the semester. Our weekly documentation review was largely unnecessary in retrospect as we took good care in organizing our reference documents throughout the semester, so this task was treated as complete on schedule.



Task	Priority	Owner	Status	Start date	End date
Project Research	P0	All	Completed		
System Diagram	P1	Gabriel Gladstone	Completed	9/9/2024	10/3/2024
DC to DC Converter Selection	P2	Gabriel Gladstone	Completed	9/5/2024	10/3/2024
Design Calculations	P1	Eizaku Asai	Completed	9/20/2024	10/11/2024
PCB Component Selection	P1	Kyle Clemente	Completed	9/5/2024	10/18/2024
Microcontroller Selection	P0	Eizaku Asai	Completed	9/5/2024	9/20/2024
MPPT Algorithm Research and Selection	P2	Ethan Ermovick	Completed	8/29/2024	9/27/2024
Initial Budget and Parts Cost	P2	Kyle Clemente	Completed	9/5/2024	9/20/2024
Design constraints Discussion with Client	P1	Ethan Ermovick	Completed	9/5/2024	9/13/2024
Project Proposal	P0	All	Completed	9/5/2024	9/20/2024

Fig. 28: Project Research Section of Final Gantt Chart

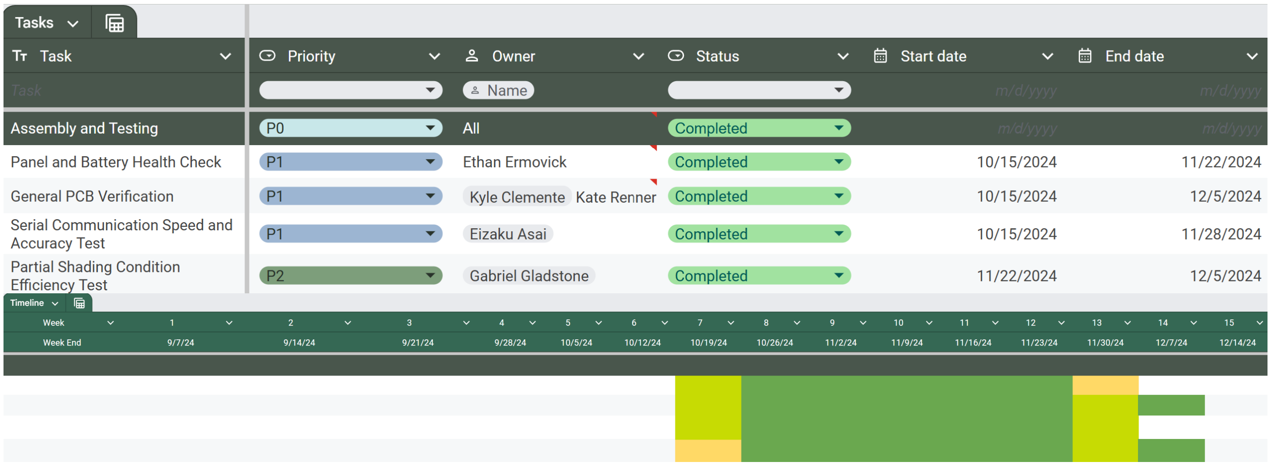
Fig. 28 lists the final research that was conducted for this project and the allotted time for such research to occur. The system diagram and DC to DC converter selection tasks were completed two weeks behind schedule due to difficulties consolidating our research into a design that would support a buck-boost converter that was available for purchase. However, our design calculations were completed several days ahead of schedule as we had defined our existing solar panel and battery specifications beforehand. Our PCB component selection lagged behind this process, though, as we needed to select our exact models from retailers such as DigiKey. It was difficult to design our PCB without these models, but it was equally difficult to select these models without a finalized PCB. Our microcontroller selection did not encounter these issues, though, as we decided to have our microcontroller as an external feature. That task was completed on time as a result. Our MPPT algorithm research and selection was completed a week behind schedule as a result of our previous backlogs, so there wasn't a large concern with this task. The tasks of the initial budget and parts cost estimate, design constraints discussion, and project proposal all followed this trend and were completed on time.



Task	Priority	Owner	Status	Start date	End date
Subsystem Construction	P0	All	Completed	m/d/yyyy	m/d/yyyy
Module Simulation Testing	P1	Ethan Ermovick	Completed	9/5/2024	10/3/2024
System Simulation Testing	P1	Ethan Ermovick	Completed	9/5/2024	10/3/2024
Module Calculation Ranges	P1	Kate Renner	Completed	10/1/2024	10/11/2024
System Calculation Ranges	P1	Kate Renner	Completed	10/1/2024	10/11/2024
PCB Selection/Ordering	P1	Kyle Clemente	Completed	9/5/2024	10/18/2024
PCB Component Layout	P1	Kyle Clemente	Completed	9/5/2024	10/18/2024
MPPT Algorithm Software	P1	Eizaku Asai	Completed	10/4/2024	10/18/2024
MPPT Serial Communication	P1	Eizaku Asai	Completed	10/4/2024	10/18/2024
Metrics Website	P2	Gabriel Gladstone	Completed	10/15/2024	11/1/2024
Posters Due	P0	All	Completed	9/27/2024	9/27/2024
Poster Session	P0	All	Completed	10/4/2024	10/4/2024
Initial PCB Design Due	P0	All	Completed	10/16/2024	10/16/2024
Midterm Design Review	P0	All	Completed	10/9/2024	10/9/2024
Prototype Due	P0	All	Completed	10/24/2024	10/24/2024

Fig. 29: Subsystem Construction Section of Final Gantt Chart

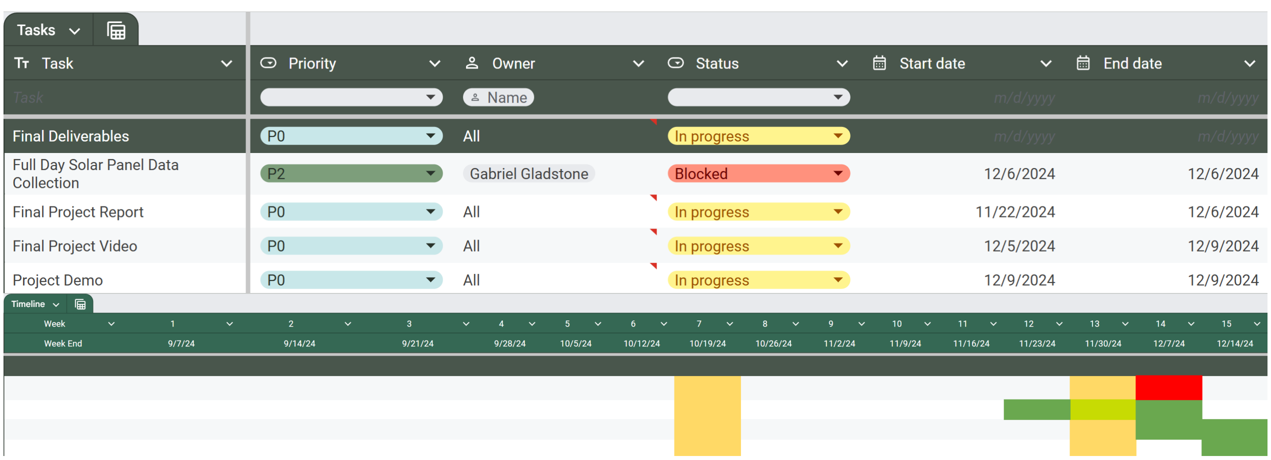
Fig. 29 lists the design, testing, and construction tasks of the subsystems of the project. The amount of simulation testing we were able to do was limited due to our software's incompatibility with our existing solar panels, so we performed small-scale simulations of solar cells and DC-to-DC conversions. This caused us to finish these simulation tasks nearly two weeks ahead of schedule. Our breadboard testing was removed entirely as it was economically and chronologically infeasible to spend valuable time and money on breadboard components that may or may not be compatible with our integrated circuits. Instead, we developed calculation ranges from 10/1 to 10/11 to account for variance and tolerance of our input conditions and integrated circuits. The PCB design and component layout tasks were completed a couple days behind schedule as our group wanted an extra meeting with the professor to have him take one more look at our PCB layout to verify there were no errors we overlooked. The MPPT algorithm software and serial communication tasks were completed over a month ahead of schedule. Our team had considerable experience working with I2C communication, so we were able to produce working software quickly. The metrics website followed this trend, as it was completed almost a month ahead of schedule due to experience constructing websites. Our deliverables (minus the couple days' delay ordering the PCB) such as the poster session and midterm design review were all completed successfully on time.



Task	Priority	Owner	Status	Start date	End date
Assembly and Testing	P0	All	Completed		
Panel and Battery Health Check	P1	Ethan Ermovick	Completed	10/15/2024	11/22/2024
General PCB Verification	P1	Kyle Clemente Kate Renner	Completed	10/15/2024	12/5/2024
Serial Communication Speed and Accuracy Test	P1	Eizaku Asai	Completed	10/15/2024	11/28/2024
Partial Shading Condition Efficiency Test	P2	Gabriel Gladstone	Completed	11/22/2024	12/5/2024

Fig. 30: Assembly and Testing Section of Final Gantt Chart

Fig. 30 lists the steps required to put together and verify the physical project. The panels and battery were verified to produce acceptable voltages and proved to be compatible with our system. This was able to be completed a week ahead of schedule even though we were experiencing difficulties reading current values from our current sensor. Verifying the PCB took an extra week, however, as debugging our initial design revealed that we had several key flaws that were addressed throughout the final stretch of the semester. Our serial communication speed and accuracy test was completed on schedule, though, as it was proven in our debugging process that our I2C communication with each of our integrated circuits was satisfactory. The partial shading condition efficiency test was a week behind schedule as we had to address the initial issues that stemmed from our PCB flaws before we were able to accurately vary input conditions and record results.



Task	Priority	Owner	Status	Start date	End date
Final Deliverables	P0	All	In progress		
Full Day Solar Panel Data Collection	P2	Gabriel Gladstone	Blocked	12/6/2024	12/6/2024
Final Project Report	P0	All	In progress	11/22/2024	12/6/2024
Final Project Video	P0	All	In progress	12/5/2024	12/9/2024
Project Demo	P0	All	In progress	12/9/2024	12/9/2024

Fig. 31: Final Deliverables Section of Final Gantt Chart

Fig. 31 lists the final products we intended to produce. We were unfortunately unable to collect a full day's data from our solar panel with our system as our debugging process was started to late and lasted too long due to many setbacks. Our final report was completed on schedule though, and our project video and demo showing our results are tentatively projected to be completed on time.

X. Costs

A detailed spreadsheet of the exact costs and parts can be seen in Fig. 37. Each item and service that we purchased can be seen in this spreadsheet. As mentioned, there was a mistake with our first PCB, so we had to reorder many of our parts. Also, we got new PCBs manufactured and our surface mount components soldered on. This explains some of the high numbers of parts ordered and higher costs. Without this mistake, we had originally spent less than $280 which was slightly higher than our original estimates in our proposal ($218 without optional components and $273 with optional components). Because we foresaw issues, we budgeted well enough to recover and stayed below the $500 limit at the end of our project. Our total manufacturing costs added up to $69.57, our overall parts costs added up to $328.52, and extra shipping and tax costs for parts orders added up to $33.08. As mentioned in the cost constraints section, none of our parts was particularly expensive except for our ICs (which were still under $7 each) and microcontroller (which was under $13.83). Additionally, the battery pack was fairly expensive at $66.88 with tax and shipping included. We worked hard to find low-cost parts which certainly contributed to our ability to stay under budget.

If we were to manufacture in 10000 unit quantities, this would significantly lower our costs. After testing this in Digikey and Mouser, the rough cost of ordering in the high quantity parts is roughly $150,000. If you were to take the same quantities of parts that we ordered and scale that up to have 10000 unit quantities, that is over $3,600,000 of costs. Therefore, buying in bulk is roughly 24 times less expensive than ordering in these small quantities. If you scale this down to the per-PCB price, the high quantity order would be around $15-$20. Using automated equipment to assemble our device could significantly influence cost. First, automation reduces the need for manual labor, particularly for repetitive tasks like soldering components or placing small parts. This could decrease labor expenses substantially. Additionally, automated assembly processes are faster than manual assembly, allowing for higher output and reduction of production time. Automated processes are often more consistent with their output quality, and they can reduce errors and material waste. The upfront cost of purchasing or using automated equipment, programming it, and maintaining it would probably be significant, and this is especially detrimental for low-volume production. Overall, if our device was to be manufactured in large quantities, automation could lead to significant per-unit cost reductions. However, for smaller production, which is likely what we would use, the high initial costs may outweigh the benefits.

XI. Final Results

A list of the original criteria for the project and whether or not they were met is below:

- The solar charge controller is working with indication of battery charging.
  - We have not yet completed this goal, although we strongly expect to soon. One of the biggest reasons why we are behind schedule on this goal was due to our PCB design issue, which caused major delays because we had to reorder the PCBs.
- The solar charge controller's data can be easily digested, such as through a real-time metrics dashboard.
  - We met this requirement via the creation of the metrics dashboard.
- Documentation is clear, and the client is confident that they can learn from the product and apply it to their needs.
  - We have created sufficient documentation including multiple GitHub repositories with Readme files on how to run them as well as schematics such as Fig. 40. We additionally plan to provide solar car with our KiCAD schematic files so that they can easily scale up our design.
- DC to DC converters are clearly working and driven by the microcontroller.
  - We have completed this and verified that we can control the output of the buck/boost converters from the Nucleo board.

- PCB is able to interface with a solar panel with sensors for current and voltage detection as well as a DC to DC converter
  - This was completed. We have successfully set up voltage detection, current detection, and control of the DC-DC converter.
- The design is modular and can be easily reproduced to expand an existing system with additional solar panels.
  - We have achieved this constraint. One major feature that led to our achievement of this was our design using multiple grounds, enabling us to arbitrarily scale up the number of panels and thus voltage without worrying about voltage limits on the components.
- Clear documentation that proves the system provides an increase in efficiency from a system with a traditional perturb and observe algorithm.
  - We unfortunately have not met this requirement yet. However we have made significant progress towards testing the efficiency of the system.
- Clear documentation and demonstration that the system is finding the global maximum power point.
  - We have not yet been able to demonstrate that our system reaches the maximum power point. However, we plan to further test that in the near future.
- A viable schematic for a possible system that meets Solar Car's requirements.
  - We have created a viable schematic shown in Fig. 3 and Fig. 40.

According to our original grading rubric in our proposal, 3 features not being met would mean we earned a B+ on this project.

XII. Engineering Insights

A. What We Learned

As mentioned in the Tools Utilized sections of this report, there were several new tools and skills that we developed. These tools are listed below:

- KiCad
- Django
- Simulink
- STM32CubeIDE
- Datasheet Interpretation

Some additional technical skills that we developed were scratching off traces. Since we made a mistake on our first order of PCBs, we wanted to test with those boards while waiting for the new ones. So, we learned how to properly scratch off traces. We also learned how to solder very small components because we did not want to spend money and potentially waste time using WWW. So, we learned to do this ourselves.

B. Other Lessons

We learned many important lessons about the engineering process through this process. To begin, in an engineering team project, time efficiency is key. At the beginning of the semester, we made progress at a slow pace because we did not feel the pressure of the deadlines looming. However, towards the end of the semester, our group was very stressed and worked extremely hard to finish the project on time. Because of this, our morale was low. We could have avoided this if we managed our time better. Being more thorough at the beginning of the project was another lesson that we learned from this. During testing, we had to order brand new PCBs at the last minute because we made a mistake in our schematic. Paying more attention to detail and performing more software tests could have prevented us from spending more money and wasting time. Additionally, attention to detail is extremely important. There are a lot of moving parts in this project, so it is easy to skip over important details in the datasheet or your schematic. We bought resistors that were too thick to fit into our PCBs, so we had to file them down. While this worked, our lives would have been much easier if we had paid more attention to the resistor's datasheet. Another very important lesson we learned was that staying organized is crucial. Until the last few weeks of class, we did not know exactly how much of our budget we had left until we made a cost spreadsheet. Thankfully, we were still well under budget and were able to order new boards. However, doing this at the beginning of the semester could have prevented stress and helped us stay under budget. Lastly, communication and setting expectations in advance is really important to fostering a positive group dynamic and staying organized. There were several times where our team was not on the same page, which caused some miscommunications and confusion. We could have made decisions and gotten tasks done faster had we communicated better.

C. Advice

There are several pieces of advice that we would give a future Capstone student. First, since timing is often an issue, try to get your schematic and PCB design done as quickly as possible. Testing took a lot more time than we anticipated. Additionally, we anticipated more mistakes regarding our budget rather than our time, so we'd recommend to plan for the absolute worst in your Gantt chart. Another piece of advice regards communicating proactively with all of your teammates. Give each other updates whenever you are working on something to avoid miscommunication, save time, and prevent frustration. Lastly, clearly assign and communicate everyone's responsibilities from the start. This can change, but ensure that everyone knows their part and does not feel lost or frustrated. For things like making the Gantt chart and doing parts orders, it's good to have the same person doing that for the whole time so that things do not get confused. Overall, preparing for the worst, communication, and setting expectations are the most important things you can do.

XIII. Future Work

A. Improvements

We designed a full, proper processing distributed MPPT system. If we (or another group) were to improve upon the design of our project, we would suggest the following areas of focus.

First, improve upon the scalability of the distributed system. The buck-boost converters we used operated on one of two addresses for I2C communication. Because only two buck boost converters could communicate per one I2C line, we were forced to use two I2C lines to accommodate all three of our converters. If we were to improve this system, we would integrate an I2C mux to facilitate the conversion. I2C switches such as the PCA9848PW would allow the microcontroller to bidirectionally communicate with up to 8 converter modules that have the same address. Arranging switches in parallel and series would further extend the amount of converters that a central controller can communicate with. While this improvement would take additional setup, it is far more scalable than increasing the amount of I2C lines needed.

Second, use an embedded microcontroller over the Nucleo educational board microcontroller. The STM32 Nucleo board is great for testing and troubleshooting. It allows for seamless programming through its ST Link and comes with useful pinouts such as ADC for sensor integration options and digital pins for I2C communication. These were the main features that we needed from the Nucleo board to interface with the STM microcontroller. While these features were useful, in order to improve the integration of the project into a solar car, we recommend replacing the Nucleo board with just the STM microcontrollers and necessary components. This improvement would allow for better connections through traces to the system instead of many wires connecting to the Nucleo board. It would also decrease the amount of space needed on the Solar Car as well as the cost of the system. Lastly, this would create an opportunity to embed a microcontroller onto each PCB, using multiple local controllers instead of a centralized controller. If the next group wants to integrate this project into a real system, embedding the microcontroller into the PCB is an important step.

Third, redesign the system to be a differential distributed MPPT system instead of a full power processing MPPT system. From our research, we originally planned to create a differential DMPPT. In theory, this should be more efficient than a full power processing (FPP) DMPPT because power is lost when processed through the converters. Thus, by reducing power through the converters while carrying out the same function, more power would be transferred to the batteries. We decided not to pursue this design because it was much more complex than a FPP, and we didn't believe we had the time or expertise to complete this design. There are many differential DMPPT designs, and we believe this architecture would be a further design improvement to pursue.

Fourth, design with more standard components. Throughout our design process, we used component values that wouldn't typically be on hand such as a 10m resistor or a 8.2uf capacitor. This meant that we either had to buy more of these components than needed or to risk hitting a roadblock and waiting for a new shipment if it was damaged. We also realized that these components led to non-standard parts sizes. This caused us problems in our V1 PCB where some resistors' lead lines were too big for the through-holes and some resistors and capacitors were big enough to cause overcrowding in certain areas of our PCBs. Many of these challenges would have been simplified if we used more standard components in a series or parallel combination.

Fifth, design a better custom buck-boost IC. For this project, we used the TPS55288RPMR Buck-Boost Switching Regulator. This IC allows us to set the output voltage with I2C. While it was useful for our project, designing this function can be a project in itself. There are many decisions that go into designing a Switching Regulator. Students would be able to choose an architecture such as Buck-Boost, Buck, Boost, SEPIC, or a Zeta converter depending on needs of the system. Students could choose if the architecture would be synchronous or asynchronous, if it operated in continuous conduction mode (CCM) or discontinuous conduction mode (DCM), and how many switches (ie. 1, 2, 4) if operating in synchronous mode. Students would also be able to choose how they would power the switching and how to ensure that switching is properly carried out where certain MOSFET switches aren't opened at the same time. There are many design decisions that would provide learning opportunities for students and this is the level of depth for a capstone project we would recommend a group of students pursue.

Lastly, improve the layout to be more user-friendly and robust. A minor fix that is important for integrating our design into the Solar Car is how to best connect multiple systems. We used both screw holes and pin connections. We like the screw hole connections because we were able to securely connect and disconnect multiple systems which is important for creating modules. We believed our pin connections didn't provide enough security in a dynamic environment, so they had to be soldered on. The one problem with our connections was their layout on the board. In our V2 design, we moved the connections to the perimeters of the board facing outward. While moving connections may lead to added layout complexity, we thought it added an important user functionality, and we recommend future teams consider connection type and connection placement.

B. Pitfalls

We also have some advice for pitfalls that students should avoid when attempting this project.

We recommend starting early. We made a big mistake on our first boards in wiring the current sensor in series instead of parallel. This was a simple fix that should have been caught earlier with simulation or team review but was immediately caught with initial testing of the PCB. The problem we faced was that the fix took quite a few modifications to the PCB, and our fist PCB was printed quite late in the process. We had a lot of time very early in our Capstone that wasn't utilized efficiently and could have led to less stress towards the deadline. We recommend making incremental progress as soon as possible because troubleshooting Fig. 41 is natural, but enough time to troubleshoot is needed.

Make sure to ask the right questions. A major resource for our capstone were the instructors, especially our advisor that we met with weekly. We had a lot of questions with design decisions were sometimes lost, but we rarely asked these questions to our advisor because we didn't know how to. To remedy this confusion, we recommend meeting with your advisor early and establishing boundaries for how to ask a question, what can be asked, and how much help an advisor can offer. This discussion would make a group more comfortable with asking the right questions.

XIV. References

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XV. Appendix

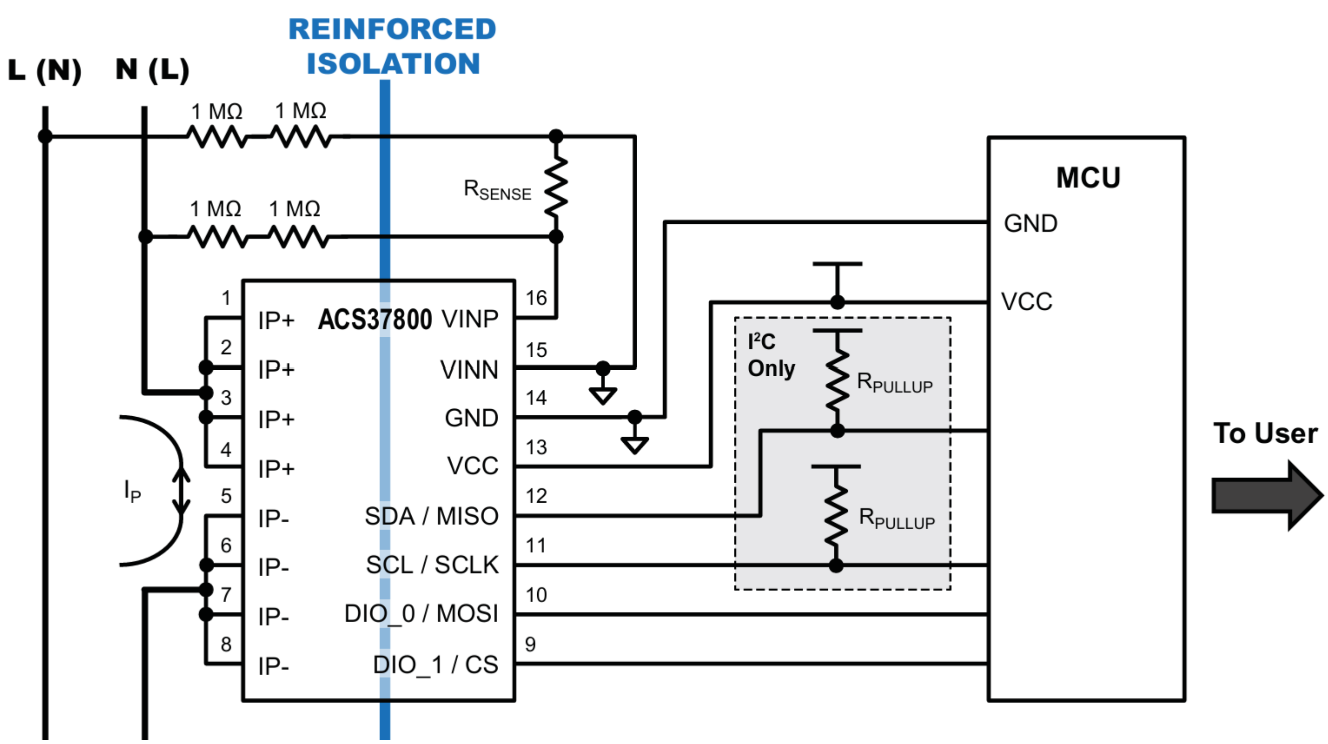


Fig. 32: Typical Application of ACS37800

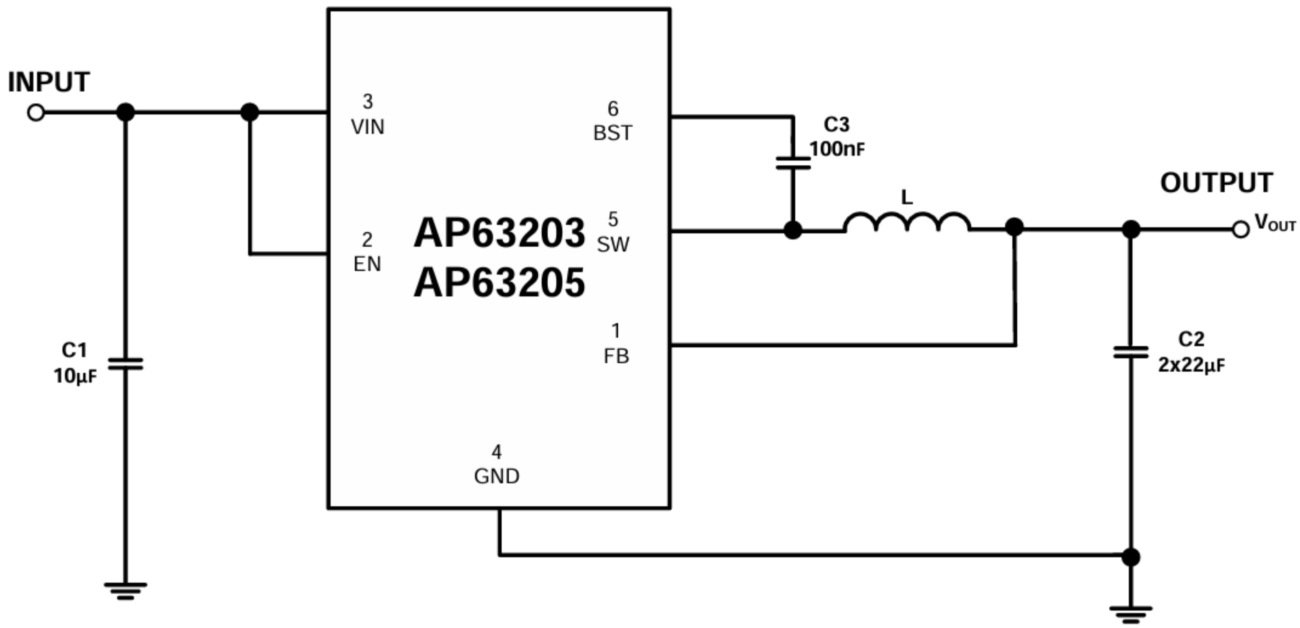


Fig. 33: Typical Application of AP63205

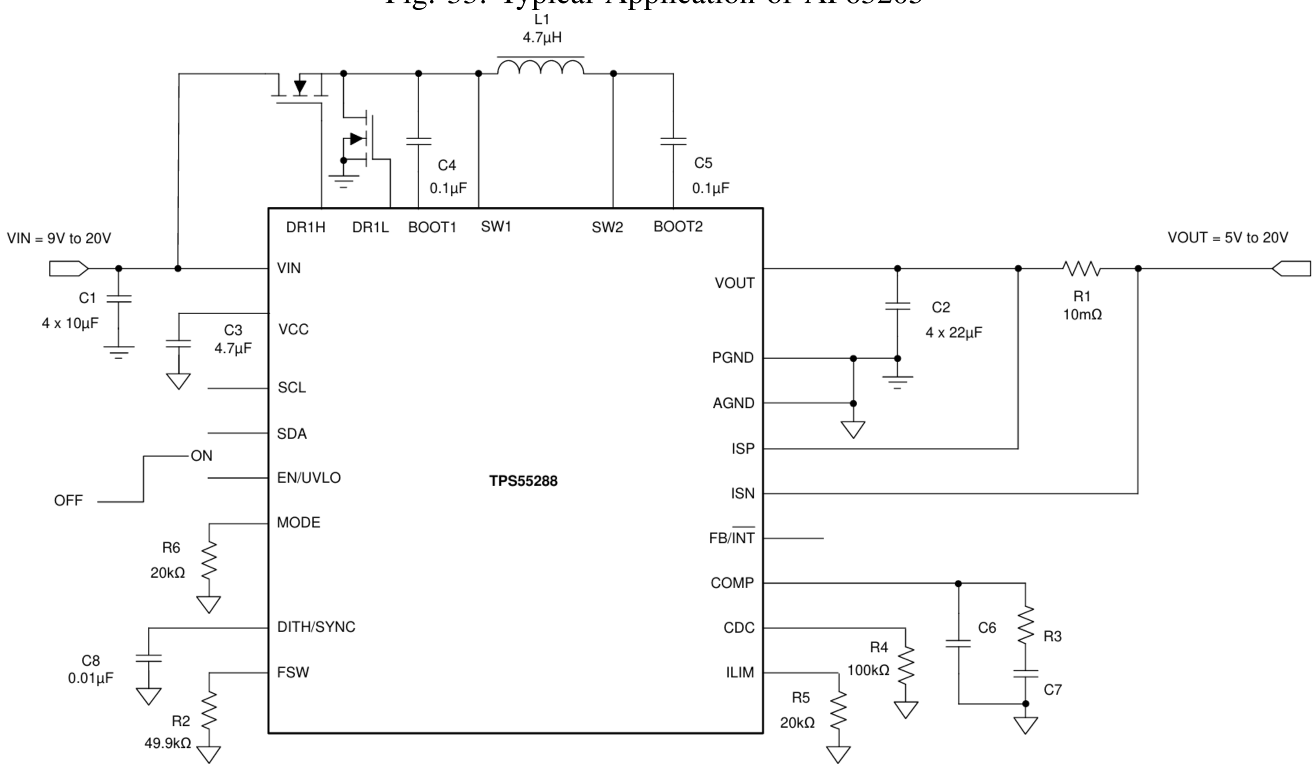


Fig. 34: Typical Application of TPS55288RPMR with 9V - 20V Input Voltage

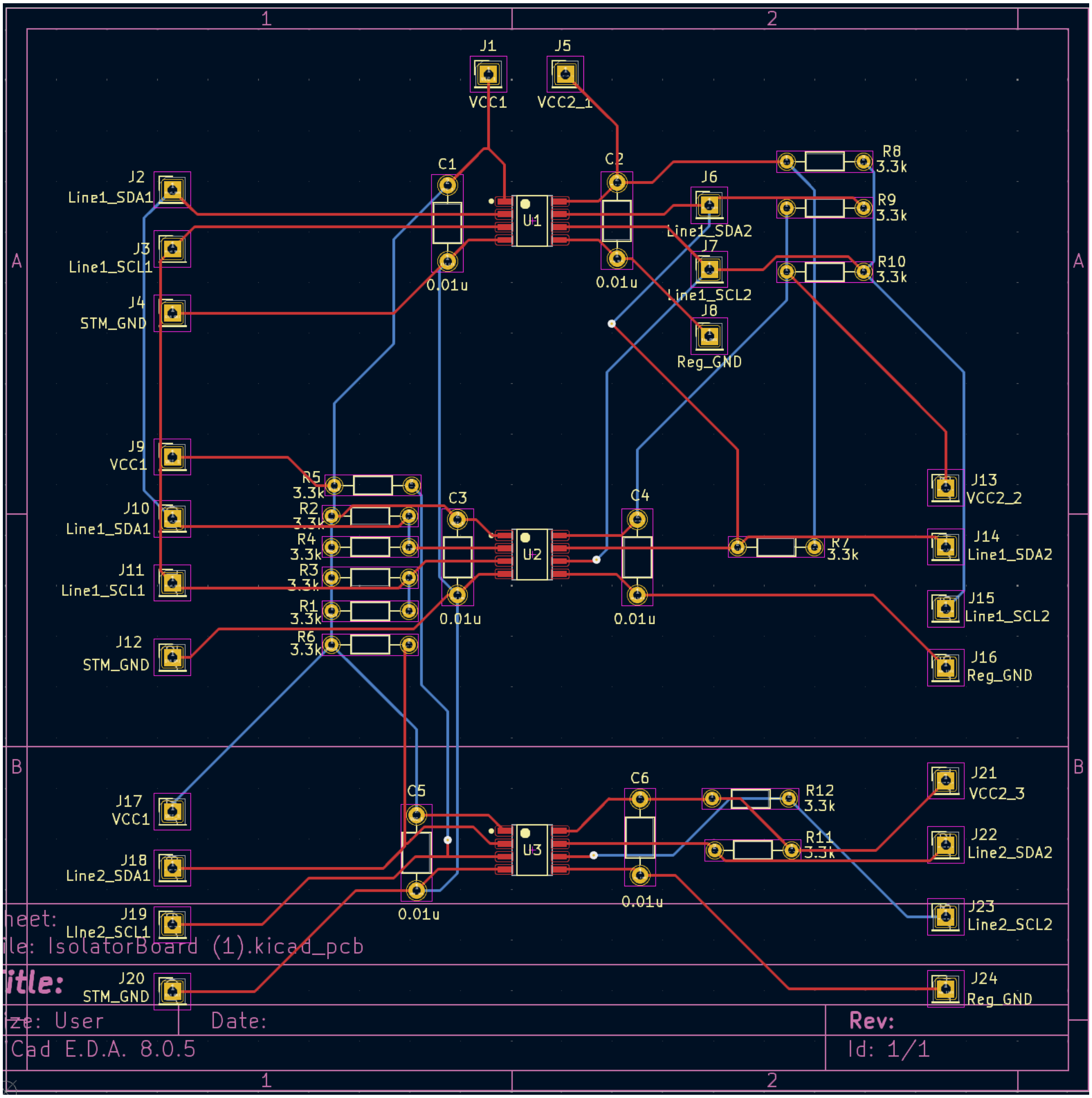


Fig. 35: Isolator PCB

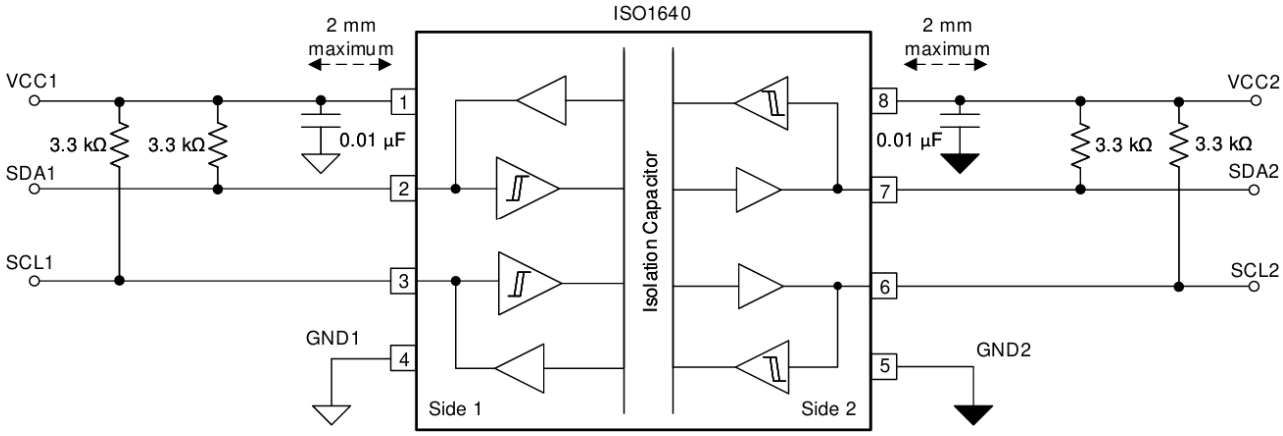


Fig. 36: Typical Application of ISO1640

Parts

Index	Part Description	Manufacturere Part #	Digikey Part #	Mouser Part #	Qty Req'd	Cost
1	STM32 Microcontroller	NUCLEO-F401RE	497-14360-ND		1	13.83
2	USB 2.0 (Cable A Male to Mini B Male)	102-1031-BL-00100	1175-1100-ND		1	3.56
3	Current Sense Amplifier 1 Circuit	INA241A1IDDFR	296-INA241A1IDDFRCT-ND		6	18.84
4	Buck-Boost Switching Regulator	TPS55288RPMR	296-TPS55288RPMRCT-ND		6	38.22
5	1 Pos Horizontal Wire-to-Board Terminal, T	360410	1849-1250-ND		6	6.72
6	2 Pos Horizontal Wire-to-Board Terminal, T	282837-2	A113320-ND		6	4.8
7	1 Pos Connector Header, TH	PH1-01-UA	2057-PH1-01-UA-ND		18	1.8
8	Diode (100V 2A), TH	MBR2100_R2_00001	3757-MBR2100_R2_00001TR-ND		6	1.62
9	3 Pos Horizontal Wire-to-Board Terminal , T	1984620	277-1722-ND		3	3.42
10	Buck Switching Regulator IC	AP63205WU-7	AP63205WU-7DITR-ND		6	7.92
11	TVS Diode (49.9V 12A)	P6KE36CA	497-6468-1-ND		6	3.87
12	2 Pos Connector Header, TH	61300211121	732-5315-ND		3	0.39
13	20uF 400V Electroytic Capacitor	EGXF401ELL200MJ30S	565-4601-ND		6	8.64
14	0.1uF 50V Ceramic Capacitor	C320C104K5R5TA	399-4264-ND		42	7.4
15	90kOhm 0.5W TH Resistor	CMF5590K000BHEB	541-CMF5590K000BHEBTR-ND		6	3.84
16	8.2uF 450V Electrolytic Capacitor	EKXF451ELL8R2MJ16S	565-5061-ND		6	5.16
17	22uF 250V Electrolytic Capacitor	250BXC22MEFCT810X16	1189-4160-1-ND		12	9
18	10mOhm 5W TH Resistor	MR5FT10L0	MR5FT10L0TR-ND		8	17.12
19	4.7uF 25V Ceramic Capacitor	FG28X5R1E475KRT06	445-173577-1-ND		16	4.87
20	Board Mount Current Sensors (P, V, and I)	ACS37800KMACTR-030B3-I2C	620-ACS37800KMACTR-030B3-I2CCT-N	250-KMACTR-030B3-I2C	7	49.49
21	14.8V Lithium-Ion Battery Pack	L148A26-4-18-3WA3	3145-L148A26-4-18-3WA3-ND		2	66.88
22	MOSFET N-ch 600V 1A	STD1NK60-1		511-STD1NK60-1	16	10.04
23	SENSOR CURRENT HALL 30A	ACS71240LLCBTR-030B3	620-2052-1-ND		3	16.56
24	BIDIRECTIONAL I2C DIG	ISO1640BDR	296-ISO1640BDRCT-ND		6	18.78
25	75kOhm 0.25W TH Resistor	RNF14FTD75K0	RNF14FTD75K0CT-ND		10	0.56
26	4.7uH 3.2A Power Inductor	RLB0914-4R7ML		652-RLB0914-4R7ML	16	5.19

Manufacturing

Index	Description	Company	Price
1	Manufacture 5 PCBs	JLCPCB	18.52
2	Solder surface components (3 per)	WWW Electronics	14
3	Manufacture 5 PCBs	JLCPCB	29.05
4	Solder surface components (1 per)	WWW Electronics	8

Total Price	$ 431.17

Separate Tax + Shipping for large parts orders

Index	Description	Price
1	New PCB surface mount components	8.63
2	New PCB other parts	8.09
3	New PCB Isolators + 4.7uF capacitors	8.37
4	New PCB 4.7uH power inductors	7.99

Fig. 37: Overall Cost Spreadsheet

Index	Part Description	Manufacturere Part #	Digikey Part #	Mouser Part #	Qty Req'd	Cost
1	1 Mohm resistor	CF14JT1M00	CF14JT1M00CT-ND		4	0.4
2	10mOhm 5W TH Resistor	MR5FT10L0	MR5FT10L0TR-ND		2	4.28
3	4.7k resistor	CF18JT4K70	CF18JT4K70CT-ND		2	0.2
4	33k resistor	CFM12JT33K0	S33KHCT-ND		3	0.3
5	47k resistor	CFM14JT47K0	S47KQCT-ND		1	0.1
6	75kOhm 0.25W TH Resistor	RNF14FTD75K0	RNF14FTD75K0CT-ND		1	0.1
7	10k resistor	CF14JT10K0	CF14JT10K0CT-ND		1	0.1
8	90kOhm 0.5W TH Resistor	CMF5590K000BHEB	541-CMF5590K000BHEBTR-ND		1	0.64
9	100uF capacitor	35ZLH100MEFC6.3X11	1189-1300-ND		1	0.31
10	10uF capacitor	450BXC10MEFC10X20	1189-1894-ND		1	0.65
11	8.2uF 450V Electrolytic Capacitor	EKXF451ELL8R2MJ16S	565-5061-ND		1	0.86
12	22uF 250V Electrolytic Capacitor	250BXC22MEFCT810X16	1189-4160-1-ND		2	1.5
13	0.1uF 50V Ceramic Capacitor	C320C104K5R5TA	399-4264-ND		6	1.44
14	20uF 400V Electroytic Capacitor	EGXF401ELL200MJ30S	565-4601-ND		1	1.44
15	4.7uH 3.2A Power Inductor	RLB0914-4R7ML		652-RLB0914-4R7ML	2	0.88
16	Diode (100V 2A), TH	MBR2100_R2_00001	3757-MBR2100_R2_00001TR-ND		1	0.38
17	1 Pos Connector Header, TH	PH1-01-UA	2057-PH1-01-UA-ND		8	0.8
18	2 Pos Connector Header, TH	61300211121	732-5315-ND		3	0.36
19	3 Pos Horizontal Wire-to-Board Terminal , TH	1984620	277-1722-ND		1	0.92
20	MOSFET N-ch 600V 1A	STD1NK60-1		511-STD1NK60-1	2	1.74
21	BIDIRECTIONAL I2C DIG	ISO1640BDR	296-ISO1640BDRCT-ND		1	3.13
22	14.8V Lithium-Ion Battery Pack	L148A26-4-18-3WA3	3145-L148A26-4-18-3WA3-ND		1	33.44
23	STM32 Microcontroller	NUCLEO-F401RE	497-14360-ND		1	13.82
24	USB 2.0 (Cable A Male to Mini B Male)	102-1031-BL-00100	1175-1100-ND		1	3.33
25	Current Sense Amplifier 1 Circuit	INA241A1IDDFR	296-INA241A1IDDFRCT-ND		1	2.96
26	Buck-Boost Switching Regulator	TPS55288RPMR	296-TPS55288RPMRCT-ND		1	6.03

Shipping tax

Index	Company	Cost
1	Digikey order	7.44
2	Mouser order	7.99

Total Price	$ 132.59

Manufacturing

Index	Description	Company	Price
1	Manufacture 5 PCBs	JLCPCB	29.05
2	Solder surface components (3 per)	WWW Electronics	8

Fig. 38: Cost Per Board Spreadsheet

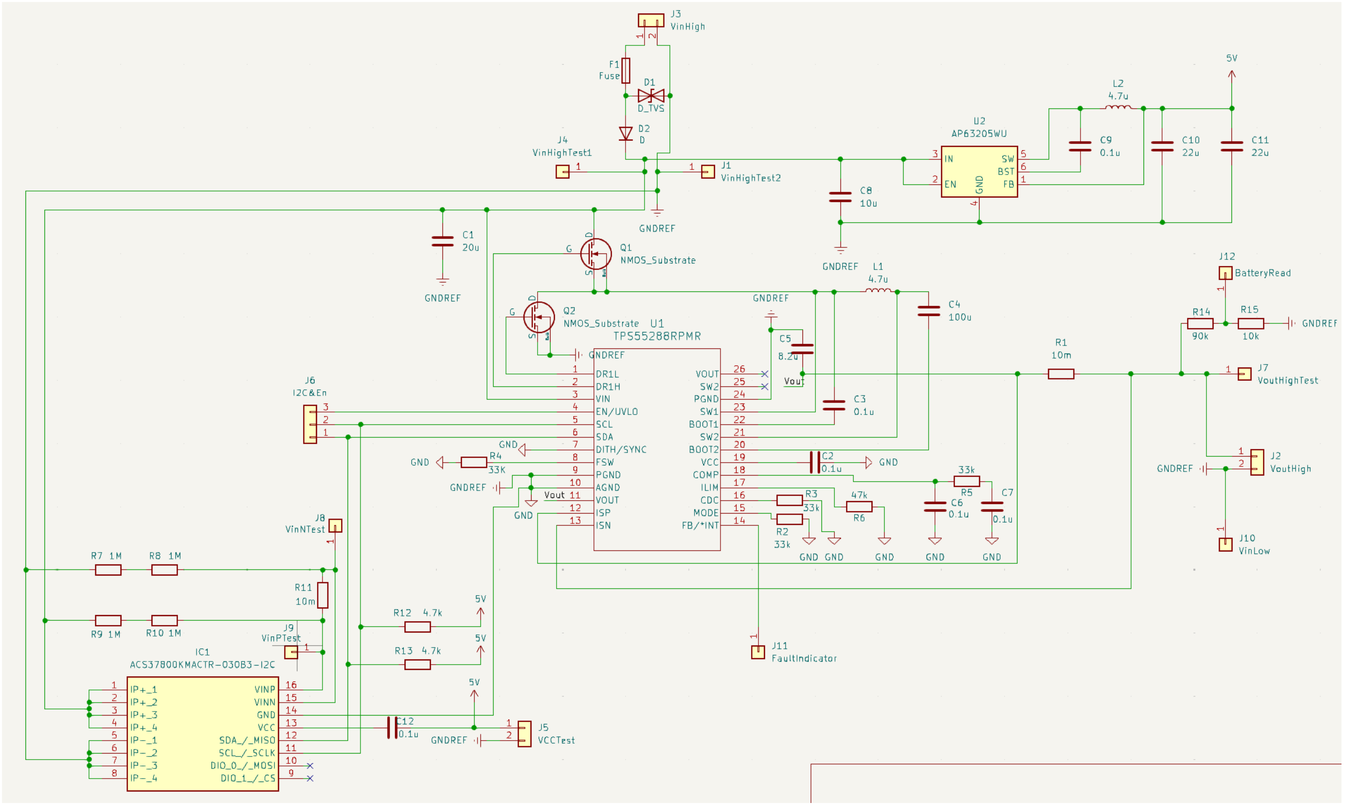


Fig. 39: Full Version 1 Module Schematic

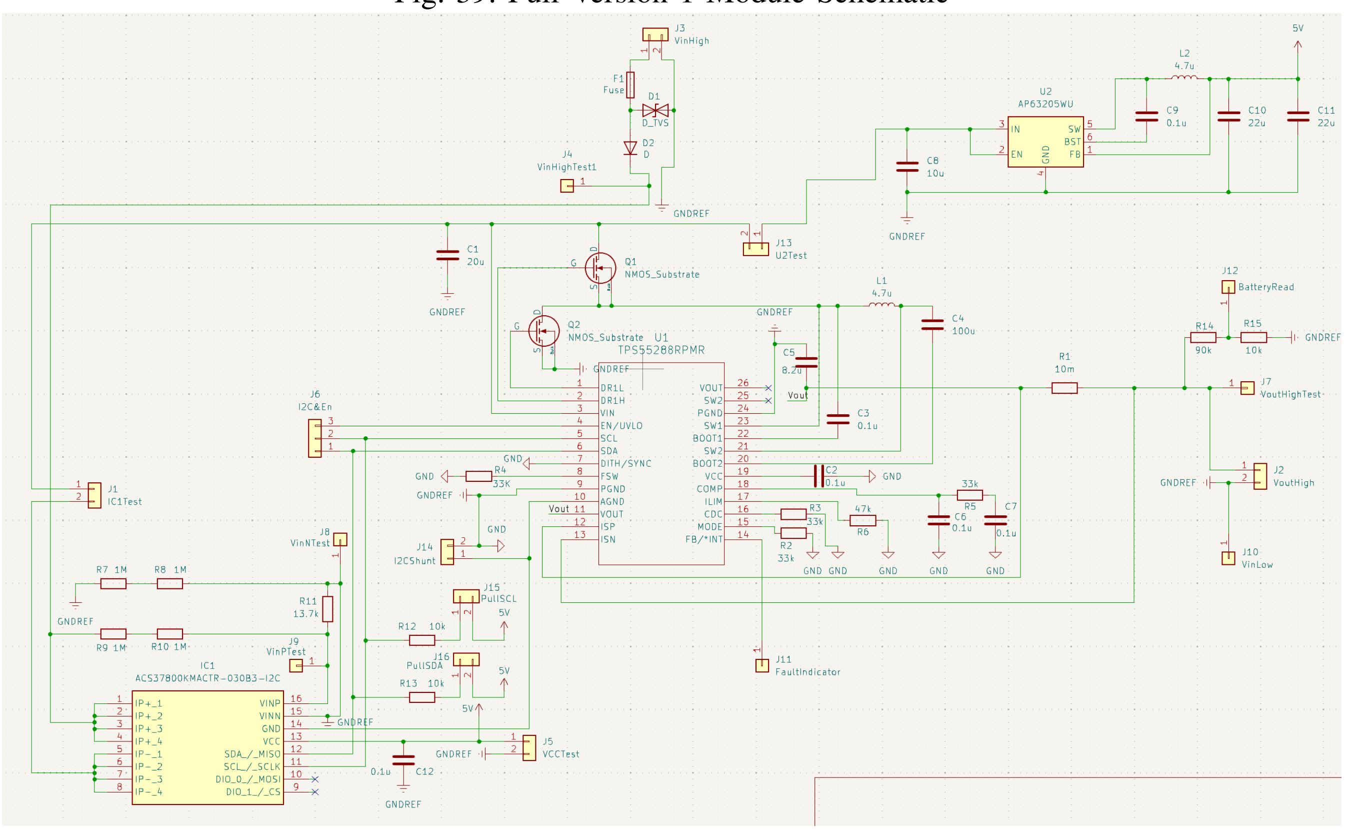
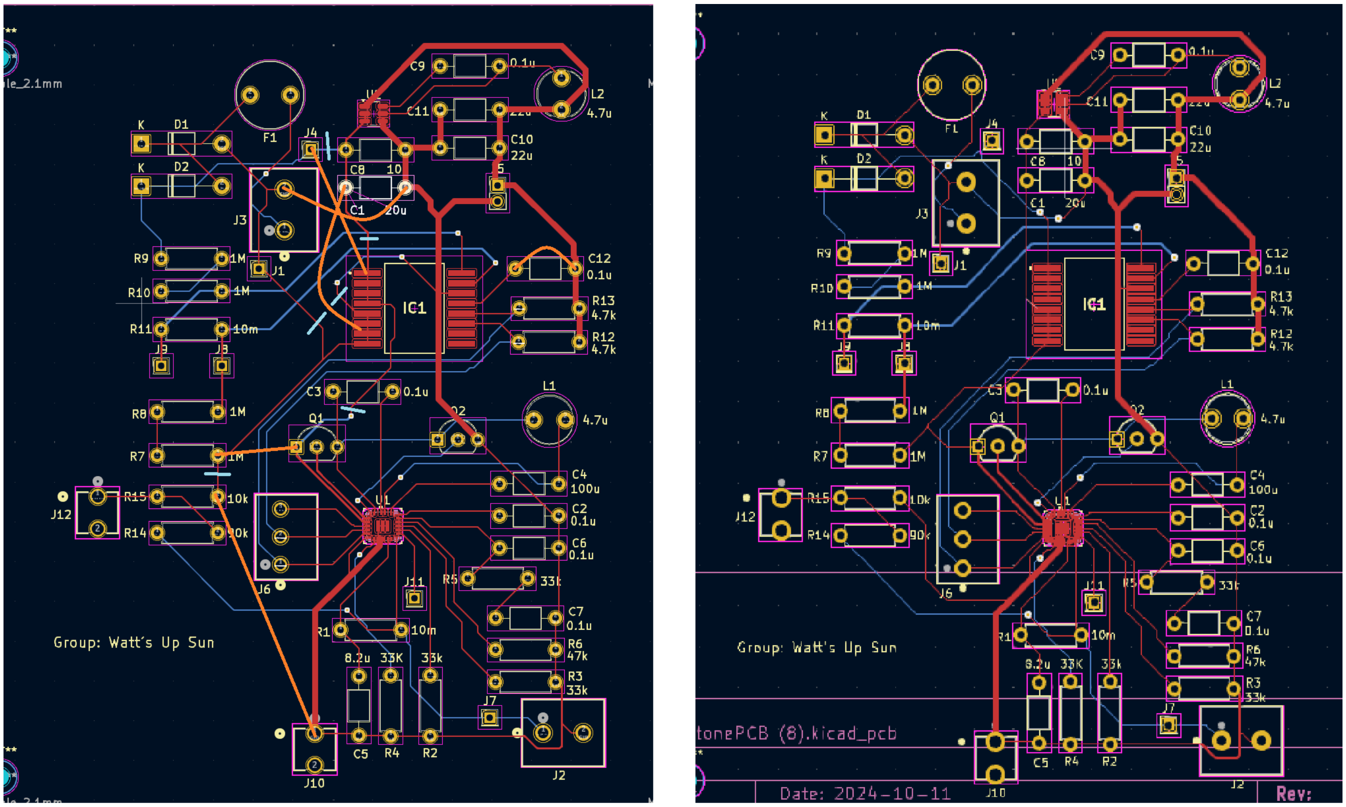


Fig. 40: Full Version 2 Module Schematic



Original

Updated

Fig. 41: V1 Board Fixes (Left) with cuts (light blue) and jumps (orange) V2 Board (Right)