Solar Integrated Battery Bank

CPR E 492 Group 2 Final Report

December-2022

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To Dr. Cheng Huang whose advice and experience has given our group countless learning opportunities and further insight into various topics.

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Thanks again to everyone who has assisted our group throughout this project.

Introduction

Problem and Project Statement

During the duration of senior design, our team's ideas have changed greatly regarding what should be delivered at the end of our project. Starting from the beginning, our team has had a list of functional and non-functional requirements for redesigning a product that our sponsor currently makes. The project's main goal was to upgrade the battery size, implement a maximum power point tracking circuit (MPPT), implement USB-C as an input/output port, and cut the number of circuit boards used down from two to one. Some other requirements were that the product be lightweight, compact, durable, and fit basic requirements wanted by backpackers, survivalists, and ham radio users. Below, Table 1 shows how the requirements were satisfied.

Previous Design	**Future Design**
2 input ports, and 3 output ports (5 total)	3 input ports, and 3 output ports (4 total by use of 2 bi-directional USB-C's)
2 printed circuit boards (PCB)	1 printed circuit board (PCB)
Fixed point power tracking	Maximum power point tracking (MPPT)
60Wh battery capacity	85Wh battery capacity
2 end caps / ends with ports	1 endcap / end with ports

Table 1: Changes in Design

Operational Environment

The design created was tested in a laboratory with a machine that simulated sun irradiance. Since the new design did not affect any outer protective components, it is assumed that the previous durability and water resistance should remain the same. The product is intended for outdoor use and, therefore, should be robust enough to withstand temporary contact with water, a range of temperatures, and dirtiness.

Intended Users and Uses

The redesigned LightSaver Max will be marketed to the same group as the previous product. The brand focuses on the outdoorsy community, with a majority being hikers, backpackers, and adventure enthusiasts. The main use-case of this product is to bring the device out into nature, where the user will charge their personal devices from locations without access to wall outlets. The advantage of the flexible solar panels is that they are fabricated in a way that they are significantly lighter and more durable than a large traditional solid solar cell based panel.

Project Design

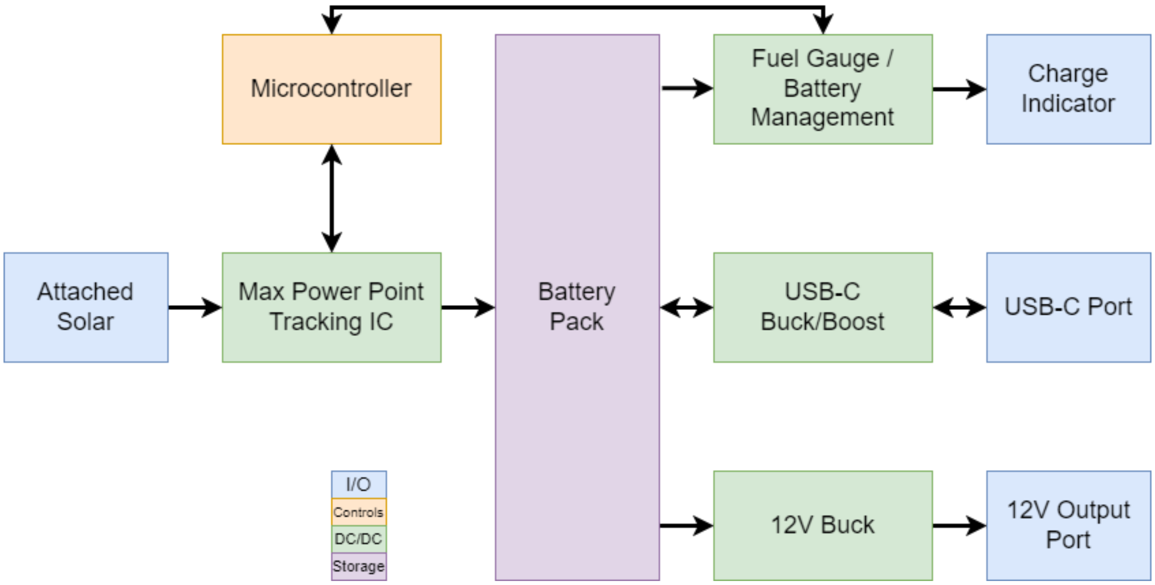


Figure 1 : Functional Block Diagram

Our design is an integrated circuit that uses five different devices connected to a central battery to charge and discharge it. The outputs of our device are regulated by the USB-C and the 12V buck chips. The inputs are regulated by the MPPT and USB-C chips. Finally, the microcontroller communicates with the MPPT and fuel gauge chips using I2C to ensure the battery is being regulated properly.

MPPT

Powerfilm requested we change the solar tracking algorithm in order to maximize the power output of solar that is attached to the Light Saver Max. The previous iteration of the Light Saver Max used a Fixed Power Point Tracker (FPPT), which held the panel at a constant 15.6 volts. The voltage of 15.6 volts was determined by Powerfilm to be near the Max Power Point (MPP) of the panel attached to the battery bank. While simple to implement, the FPPT had the following issues:

- The 15.6V is the MPP when the panel is illuminated in full sun. If the panel becomes covered halfway, the MPP drops to around half of the full sun MPP. However, the panel will be held at 15.6V, causing less power to be produced out of the panel.
- Likewise, if the panel is illuminated below full sun, the MPP will drop, causing the panel to not be held at the MPP anymore.
- If an additional panel with a different amount of cells were attached to the auxiliary panel port, the MPP would differ between the two panels, causing the maximum amount of power to not be produced.

This prompted Powerfilm to recommend us to implement a Max Power Point Tracker (MPPT). In addition, they requested that whatever tracking implementation we use should be capable of inputting at least 90 watts of power to the battery, with around 150W being ideal. That way they could pair one of their large portable solar panels with the Light Saver Max as a combination product.

The MPPT is essentially a DC/DC converter with an adjustable input voltage. The solar panel is the input to the MPPT, and the load (in our case a battery) is the output. The output power is read by sampling Iout and Vout of the DC/DC converter, and then the input voltage is adjusted up or down until the maximum power output is reached.

The first step we did was to see if there were any chips on the market that were capable of MPPT without having to create our own implementation. The BQ25798 looked promising at first, however it would only be able to deliver 75W of power to the battery. Most other off the shelf MPPT solutions had similar power maximums.

Because of this, we decided to implement our own custom MPPT design. Because our solar input voltage ranges from 10 to 25V, and our battery can be anywhere between 11 and 16.8 V, we chose to use a buck/boost converter, the LM34936. This allows the battery to be charged if the solar voltage is either above or below the battery voltage.

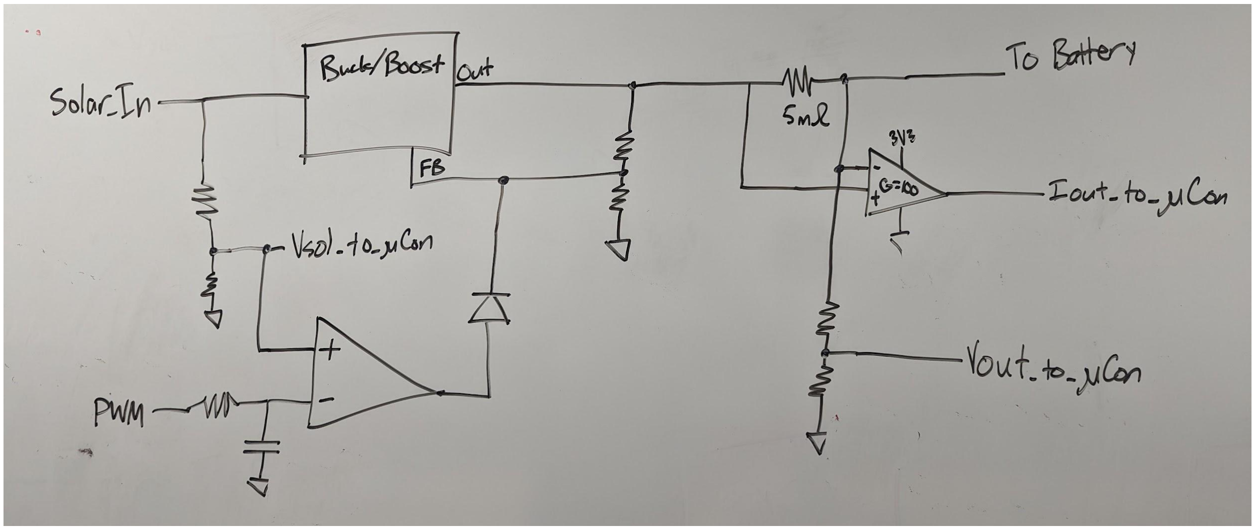


Figure 2: Additional control circuitry to be added to the buck/boost converter

In order to achieve the MPP of the solar panel, additional circuitry needs to be added. A low resistance shunt is added at the output to measure the current going out of the MPPT, in addition to a voltage divider at the output. These signals are sent to a microcontroller which multiplies the two together to determine the power. The solar input voltage is increased and decreased by changing the PWM output value from the microcontroller. When V_sol is greater than the average PWM voltage, the buck/boost converter operates normally. When V_sol is less than the average PWM voltage, the buck/boost converter is disabled so the capacitors on the solar input can charge. Using a comparator with a relatively low hysteresis loop, we are able to achieve a tight set point voltage on the panel.

USB-C

Another major request for the redesign focused on the modernization of the I/O ports on the LightSaver Max. The original design had designated input and output USB-A ports, separated on either end of the device. This was spread out so that all the input ports were on one end and the outputs were on the other - and thus each end had its own PCB taking up much of the real-estate inside the aluminum tube.

Even though our device is a powerbank and will not be transferring data in and out, the USB-C is quickly becoming the standard cable for transferring power between devices. For our design we opted to have 2 USB ports on the device, set up for bidirectional power delivery, so that a user can charge their phone from the powerbank or just as easily - and from the same port - plug the bank into the wall outlet when they get home to recharge on a rainy day.

However when considering USB plugs you must also consider the protocols involved with the connection. When a new device is attached, there needs to be a handshake between the two so that devices can agree on the job of each. Our power bank needs to be able to communicate with the connecting device and let it know that it will not be sending data, and is capable of transferring power. At the same time it needs to be open to receiving an incoming flow of power from an outside source. This is a complex problem, and the folks over at Texas Instruments have an integrated circuit built for the sole purpose of managing the handshake of USB devices, and passing on power delivery requirements.

The TPS25750 IC manages the handshake, communicating with the device on the other end of the USB-C port, and in the case that the other device is a power source it lets the connected BQ25792 buck/boost chip know thus enabling it to buck or boost the incoming voltage to match the battery voltage based on the differential. Thanks to this simplification of a very complex problem, we have opted to add these two ICs to our final design.

12V Buck

This circuit will be dedicated to using a buck converter to bring the 16.8V battery down to a 12V barrel output. This was already accomplished in the previous design but it was recommended that we redesign this. This is because they desired a higher current output than what was previously. When creating this design we were tasked with not just stepping down the voltage but also keeping the signal minimally noisy. We plan to accomplish this by first designing a buck PCB for testing purposes and then adding a linear regulator if the output noise is too excessive. Finally, when designing the buck chip the output current had to maintain 5A nominally and be able to handle up to 10A briefly.

Battery and Fuel Gauge

When considering an upgrade to the battery size, our team had initially wanted to have the current battery pack manufacturer design a pack with a larger and more powerful configuration.

After discussions of the entire first semester, our team was at a spot where we were under the impression that we would be able to do this. However, as the second semester started, we were told that the quantity that our sponsor requested was too small and that they could not supply us. Shortly after contacting another company to fill that same role, it became apparent that the battery prototype would have to be designed and produced by our team due to high initial costs and lead time. As one of the main requests of the project, the capacity of the battery pack needed to be increased. In doing this, we had several design considerations: battery chemistry, discharge voltage and current, and layout of cells. As per request, our team was to provide a quality product with low voltage ripple and high current output to feed HAM radio equipment. To fit the user's needs, our team decided to use a cheap and efficient Li-Ion battery pack in the configuration of four cells in series parallel with another set (4s2p). The design specifications yielded the values shown below in Table 2. The battery management system protects the cells from overcharge, over discharge, and fault conditions. A diagram of how it is connected can be seen below in Figure 3. Plans for the fuel gauge include displaying the state of charge for the battery over a single LED with different colors representing different healths (0 - 20% = Red, 20 - 50% = Yellow, 50 - 100% = Green).

Nominal Voltage	14.8V	3.7(nominal voltage of one) * 4 = 14.8
Nominal Capacity	24Ah	8 batteries * 3Ah each = 24
Nominal Energy Density	88.8Wh	3.7(nominal) * 3Ah * 8 = 88.8
Weight	368g	46g each * 8 batteries = 368
Volume	$529.29cm^3$	pi*(18mm)^2 *65mm *8 batteries = 529.29
Maximum Charge Voltage	16.8V	4.2 max charge each * 4 = 16.8
Minimum Discharge Voltage	10V	2.5 min discharge * 4 = 11
Cycle Life	>1000	Each has cycle life from 800-1000< cycles

Table 2: Battery Specifications

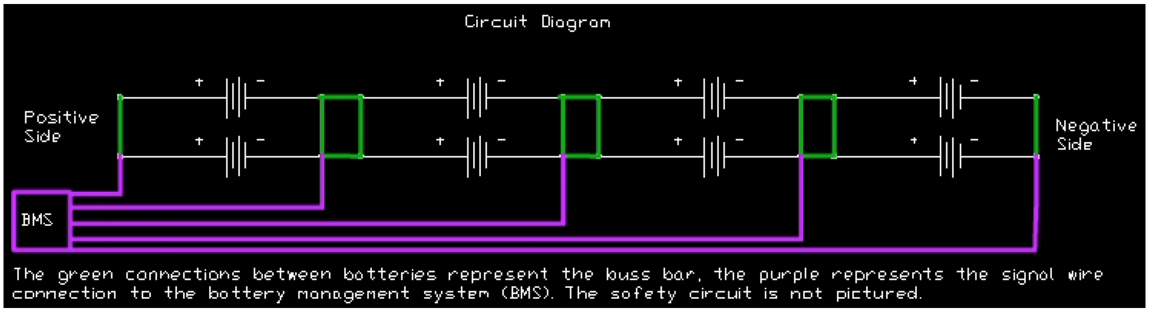


Figure 3: Battery Management System Diagram

Microcontroller

The processing requirements of the LightSaver Max are relatively complex for a battery pack, as it needs to utilize the incoming stream of data from the MPPT IC and modulate a control signal accordingly. However when you compare that computational need to other applications of microcontrollers, it is rather simple.

The nRF52832, designed and manufactured by Nordic Semiconductor, is a low-power highly customizable microcontroller that we have decided will give us the wiggle room to test and create the needed algorithms for managing the MPPT, while still keeping the overall power consumption low so as to keep the battery's charge available for the user's needs.

Functional and Non-Functional Requirements

Functional requirements for our project include adding an MPPT circuit to increase the efficiency of charging, bidirectional USB-C power, increase the battery capacity, and lessen the amount of PCBs used to ease manufacturing. Some other non-functional requirements were that the device be portable, durable, easy to operate, and that it be robust.

Standards

The following standards are to be used for the final finished product:
IEEE 802.15.1 - Bluetooth standards
This standard defines physical layer and MAC specifications for wireless connectivity with fixed, portable, and moving devices within or entering a personal operating space. This relates to our design because we planned to have bluetooth capabilities to allow remote monitoring of the battery's status.

IEEE 1823-2015 - Power delivery connection standards
This standard is to ensure that devices ranging from 10W to 240W (portable or fixed) can be connected more universally versus having unique brand/device specific cables. This standard will help us pick the proper connections for our input and output ports on our device. For example the 12V barrel connector and the USB-C connector.

IEEE 1725-2021- Battery standards
This standard was created mainly to regulate Li-Ion batteries in cell phones but these standards can also be used in other small scale applications. It regulates battery pack electrical and mechanical construction, packing technologies, pack and cell level charge and discharge controls, and overall system considerations. This applies to our device due to our use of Li-Ion batteries in our custom construction of our power bank.

Constraints

The constraints for this project include the fabrication of our PCBs and the limitations we might have when creating them. However, this is more of an issue for the future because we are designing and testing our various components independently, thus freeing up the amount of space we have. However, in the future, our PCB will be limited in size due to it needing to fit in the aluminum tube, thus making the organization of the various components more difficult. Our second constraint, as stated previously, is the aluminum tube that will contain our device. We will be able to adjust the size of the aluminum tube but it has to remain lightweight and portable. Finally, the heat dissipation from our device has to be little to none to ensure that the device operates safely and efficiently.

Security concerns

The only relevant security concern relevant to our project is the safe and controlled transfer of electricity in and out of the battery pack.

Implementation

MPPT

After deciding on our components, we used Texas Instruments design tool WeBench in order to get a basic schematic of what our buck/boost converter should look like. Then, using KiCAD, we duplicated the schematic and added our extra components necessary for the additional feedback loop of the MPPT (Figure 4). We made sure that signals being outputted to the microcontroller were divided down to the point in which the signals were in the range of 0-3.3V.

After attributing each component a footprint, we moved over to the PCB layout phase. Using a set of layout recommendations from TI, such as ground isolation, power paths, and gate paths, we created the PCB that was used to test the MPPT (Figure 5). The board measures just under 50 x 50 mm, consists of 4 layers to increase signal integrity across the board, I/O for the microcontroller placed on the bottom, and solderable pads for attaching the solar input and battery output.

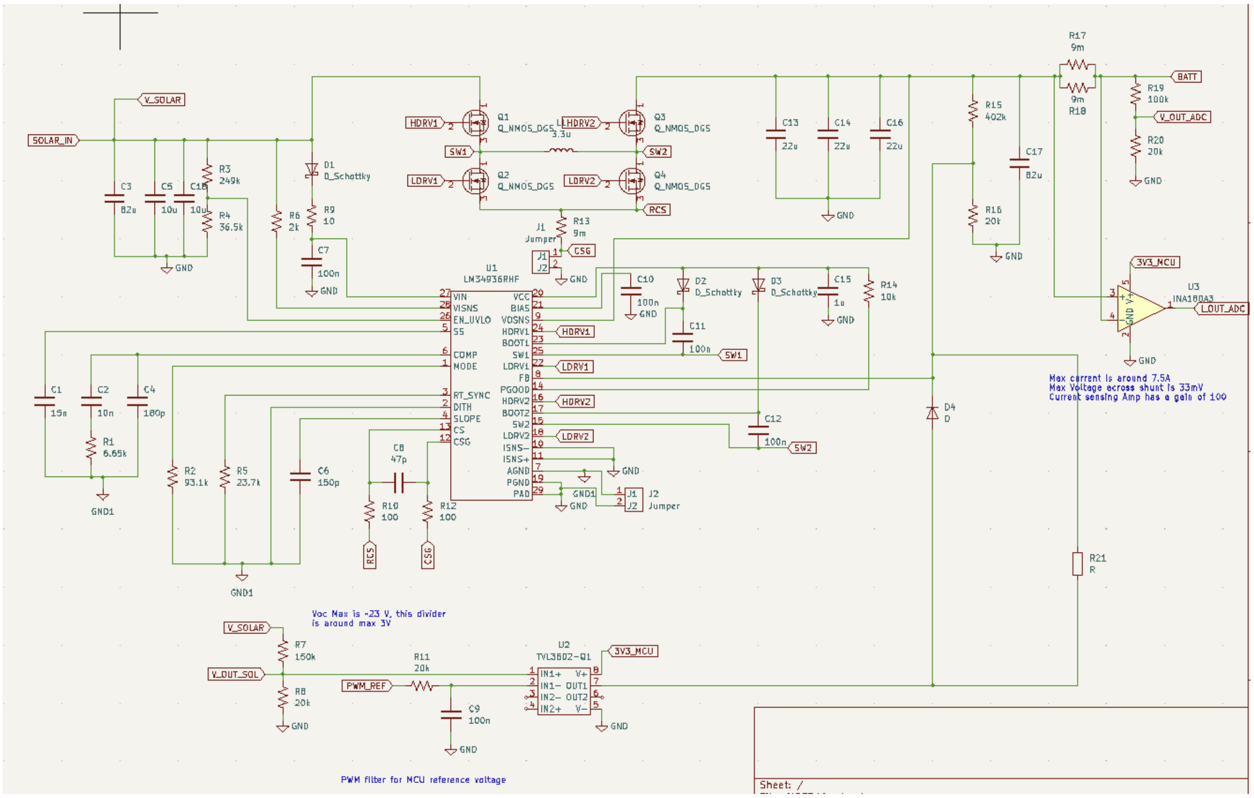


Figure 4: Schematic of the MPPT

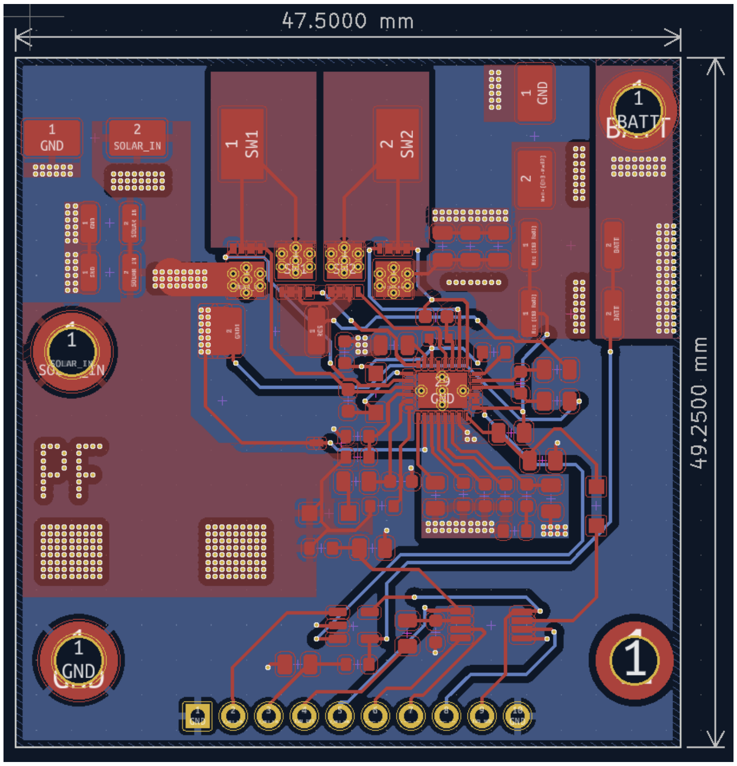


Figure 5: MPPT PCB Layout

After ordering the boards, we decided to change out the comparator for a cheaper one, however we did not realize it had a different pin numbering compared to the one we planned to use. In order to not have to order a new board, we superglued the exchanged part upside down on the board, and then used patch wires to meticulously solder each pin to the correct pad. We used a multimeter to ensure that no two wires were shorting after.

Another issue after receiving the boards is that the ground pad on the battery side was not connected to the ground on the board. This was solved by soldering an 18 gauge wire from the battery ground pad to the solar ground pad.

We assembled the MPPT using solder paste, tweezers, and a reflow oven. The board was inspected underneath a microscope and additional rework was needed to clean up bridged solder joints. The finished MPPT board is shown in figure 6.

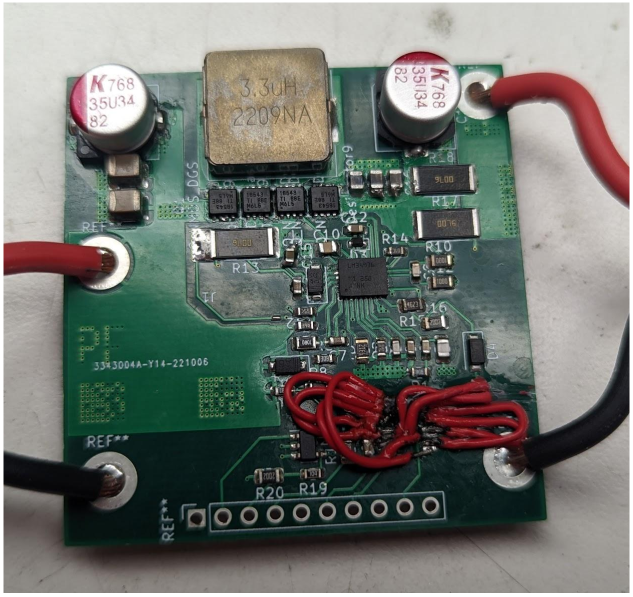


Figure 6: Assembled MPPT board

After assembling the MPPT, we asked Powerfilm to provide some panels we could use with the MPPT. The panels they provided were the same ones they plan on using on the final design. We then used Powerfilm's Solar IV curve to determine the parameters of the project such as MPP voltage, current, power, and fill factor. For the panel we were using, the MPP voltage was 16.6 V and MPP current was 613 mA. The IV curve is shown in figure 7.

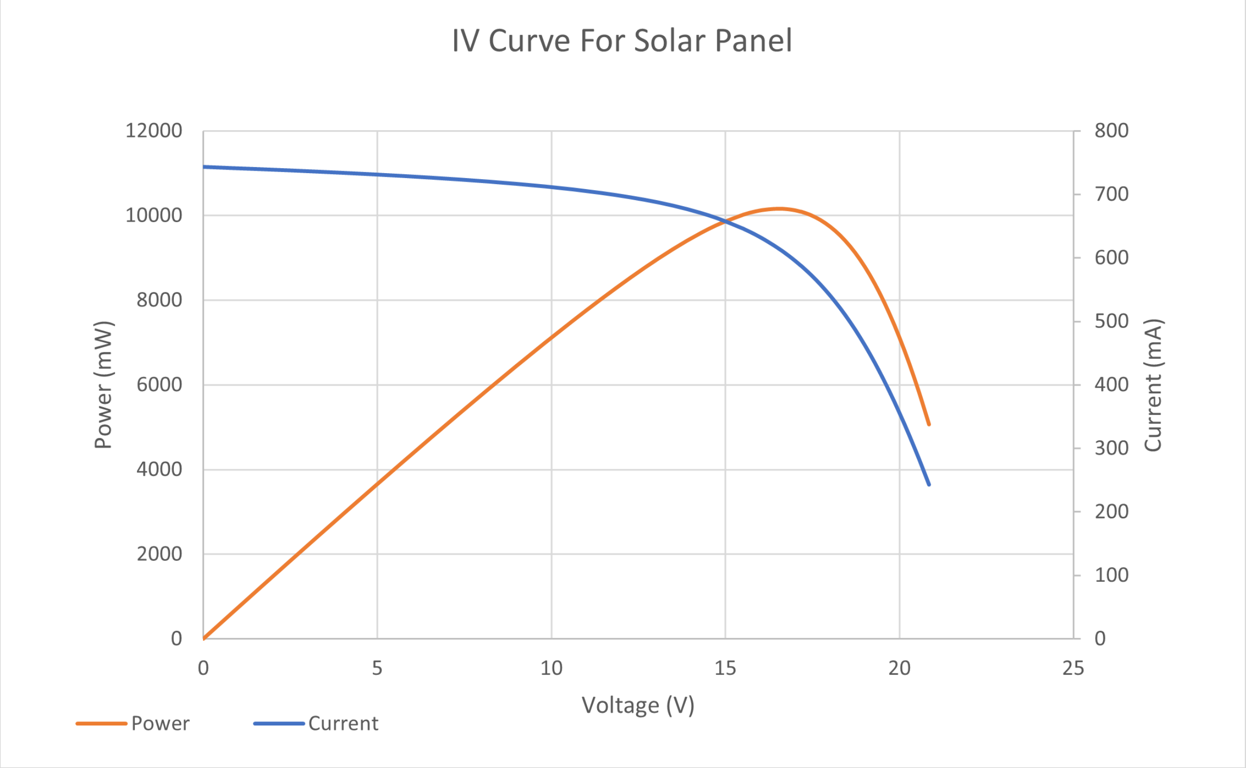


Figure 7: IV curve for the provided solar panel

Knowing the MPP voltage and currents of the panel, we were able to test the MPPT. Putting the panel under a light source that mimics full sun power, we connected the MPPT to a load meter and configured it to pull a constant current. For testing purposes we altered the PWM input using a potentiometer to increase and decrease the solar set point. With the electronic load configured to pull a constant .5 A, we collected both current and voltage values coming off the solar panel, and also logged the output voltage of the MPPT.

Vin(V)	Iin (A)	Pin (W)	Pout (W)
9.1	0.536	4.8776	4.27643
10.1	0.53	5.353	4.74549
11.1	0.522	5.7942	5.0898
12.1	0.51	6.171	5.5389
13.5	0.49	6.615	5.8383
14.5	0.467	6.7715	6.1876
15.5	0.439	6.8045	6.3872

16	0.421	6.736	6.4371
17	0.375	6.375	6.0878
18	0.313	5.634	5.6886
19	0.228	4.332	4.07184

Table 3: Input vs Output power of MPPT

Looking at the table, we can confirm that the MPP is near what we measured using Powerfilm's tools. After gathering these data points, we decided to read Vout, Iout, and Vsol using the microcontroller (discussed in the microcontroller section). However, we noticed that our signals were incredibly noisy which was causing the tracking to skew up and down from where it should be. We attempted to determine the cause of this noise using an oscilloscope. Figure 8 shows the waveform of I_{out} on the oscilloscope (Vout and Vsol were of similar noise levels).

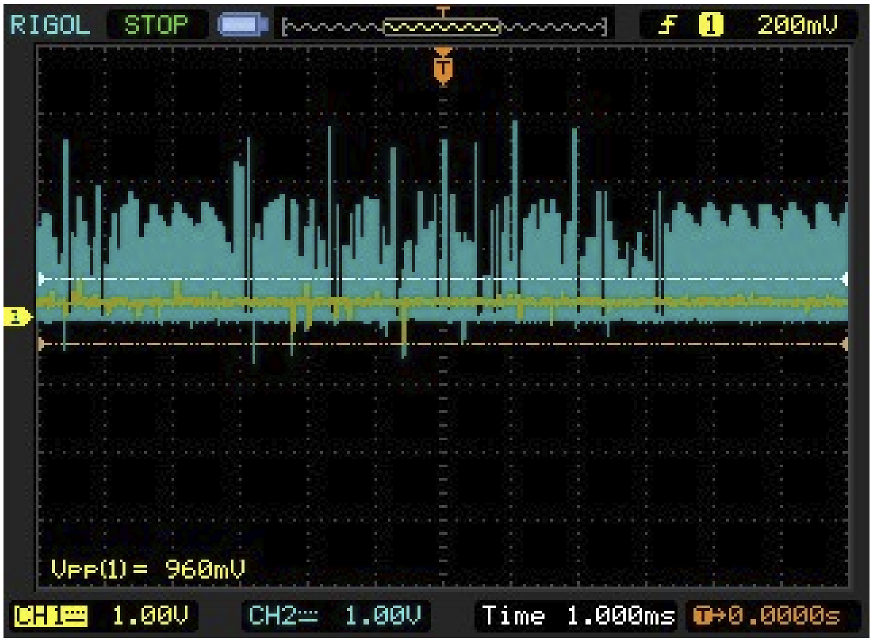


Figure 8: Signal I_{out}, Pre-filtered in blue, post-filtered in yellow

In order to reduce the noise we tried three methods:

- Add a low pass filter with corner frequency at .7 Hz on each of the signals outputs
- Move each of the ground connections that are tied to output signals to AGND instead of PGND using patch wires (an oversight during the PCB layout)
- Increase the output and input capacitance

Each of these assisted in creating a cleaner signal, however we could not achieve a signal that was stable enough to be read by the microcontroller. In the future, a board redesign may be required in order to reduce the noise in the output signals, in addition to decoupling capacitors to to reduce noise further.

USB-C

For our testing and prototyping purposes, we were able to find and order the USB-PD-CHG-EVM-01 (Figure 9). This test board is designed to show and experiment with the TI ICs: BQ25792 and TPS25750. With this test board we have been able to customize, and fit the needs of a 4s battery while creating a working interface via USB-C for both input and output charge. Hooked up to the battery we were able to both charge and discharge following USB standards.

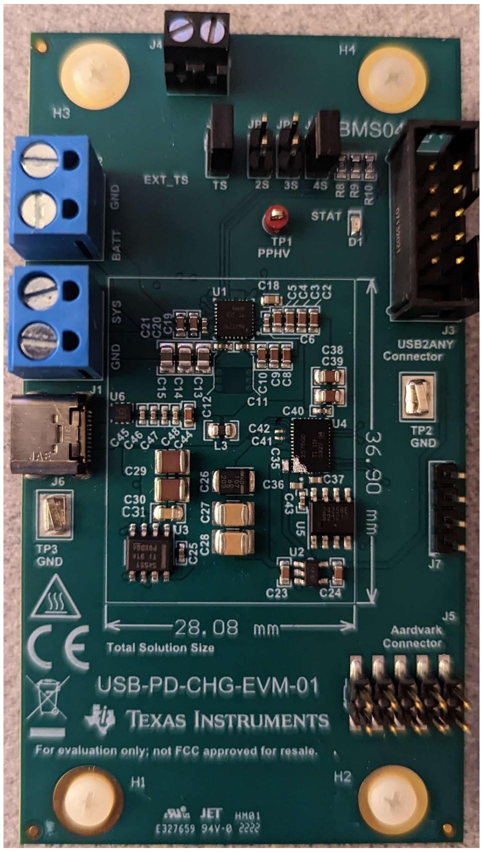


Figure 9: USB-C + PD Eval. Board

12V Buck

The buck converter we settled on was the LM25116. However, one of the Powerfilm employees suggested that we have 13V for our output to better match the 14V nominal voltage of the ham radios that are often used with this output port. This led us to change our buck chip to the LM5141-Q1. This chip had all the capabilities we were looking for, 13V 5A output at a consistent clean DC. The design of the PCB was fairly trivial due to the datasheet of the chip being clear about how to construct and design the PCB by adding some components. It also provided some examples and recommended using WEBENCH to assist in the design. The PCB that ended up being designed was not as efficient as it could have been but that was mostly due to it being a test board for the proof of concept. Below is the schematic and PCB layout of the device.

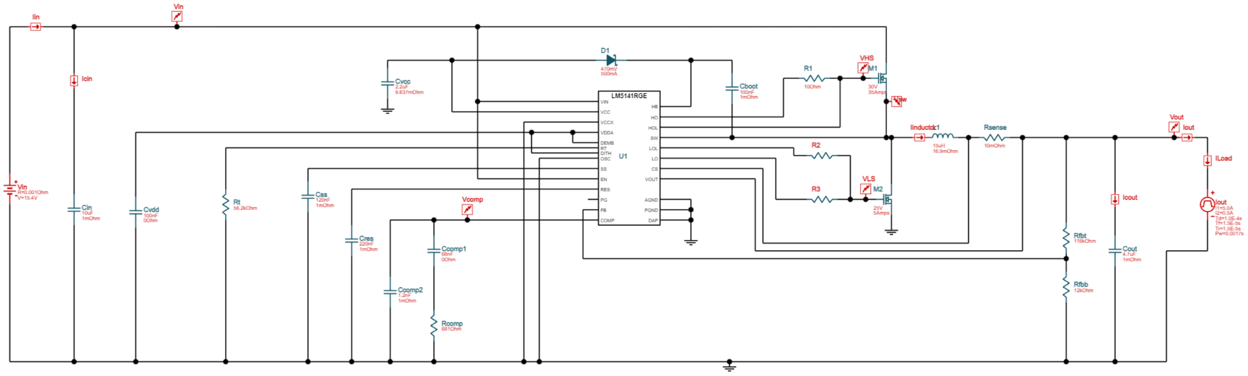
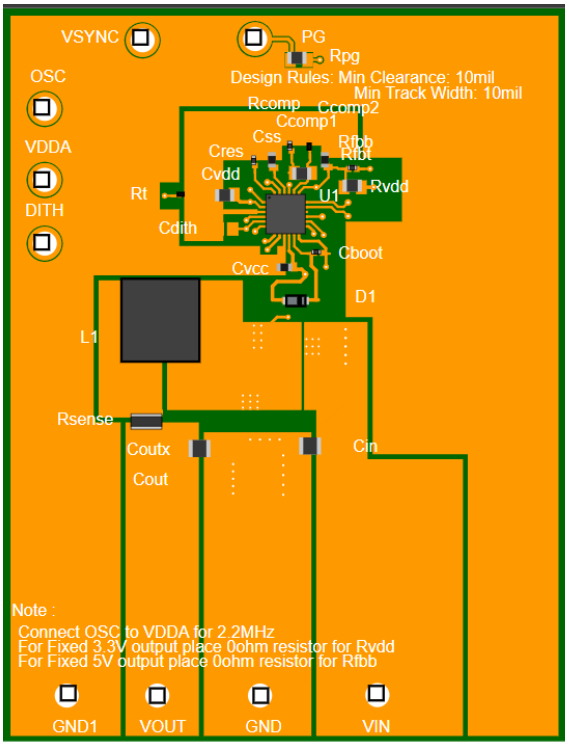
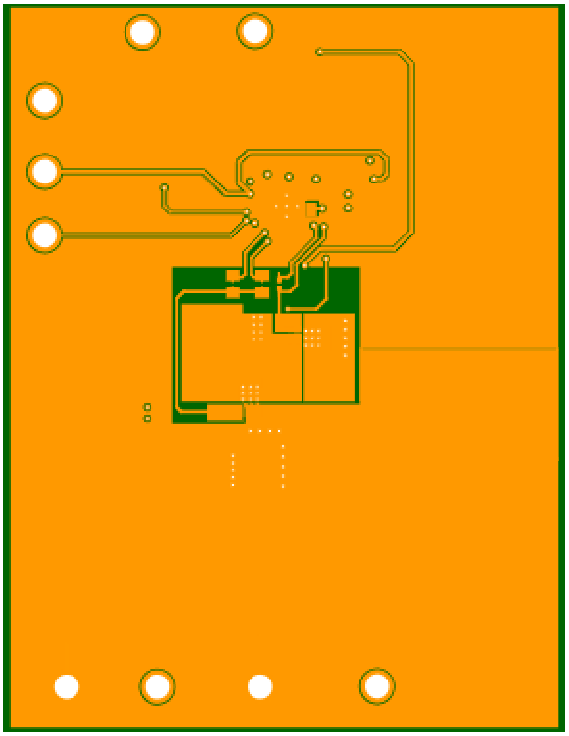


Figure 10: 12V buck schematic



Figures 11: 13V buck PCB top



Figures 12: 13V buck PCB bottom

This is the extent of what I could accomplish however. This is due to the PCB that we designed and ordered never arriving thus making any plans for testing impossible. The only workaround we had available was to simulate different types of transients using the TI designer. Below is the 13V buck load transient.

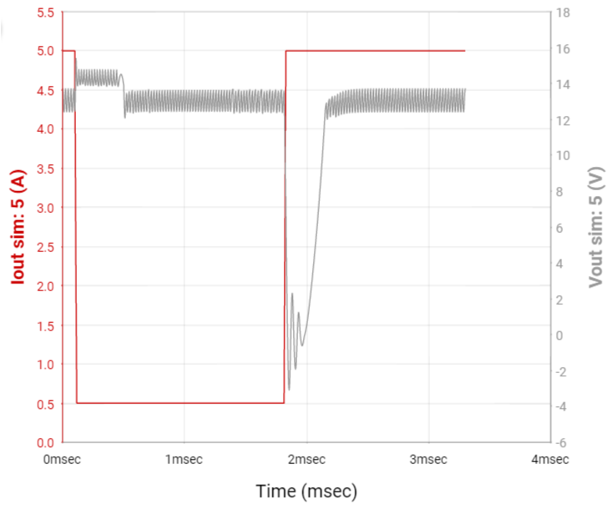


Figure 13: 13V buck load transient

As you can see, the voltage ripple is fairly large with a V_{pp} of 1V. As mentioned in the design portion I would try to remedy this by using a linear regulator thus reducing the magnitude of the voltage ripple. In conclusion, if we were to do this again we may be able to get around shipping issues by only ordering the chip and creating the PCB in house or by ordering the PCB from another company after the initial delay.

Battery and Fuel Gauge

While testing and implementing our battery pack prototype, our team decided to settle with a proof of concept as battery manufacturing companies will most likely design their own packs anyways. The layout, as mentioned above, is a 4s2p design to connect the individual Samsung 30Q 18650 cells together. As a part of this process, we soldered nickel bus bar to the ends to achieve a connection and we were then able to bend it to shape. In between each junction, we also connected a wire to connect to the BMS for cell balancing. Figure 14 shows a picture of our pack's appearance after it was covered with blue shrink wrap. As part of trying to test the capabilities of our battery layout, we selected the BQ40Z80 battery management chip to protect, control, and gauge our cells. An evaluation board with this component on it was used for our prototype as it allowed us to assess its full functionality through a GUI and create parameters that can then be copied onto the individual chip during future programming of the condensed PCB of the battery management system. The fuel gauge also has been monitored on the evaluation board due to the onboard LEDs that display the state of charge. Although this is not the method of gauging that will be used on the final product, the chip we selected has capabilities to detect the state of charge and communicate it to the microcontroller to then be shown on a single LED. Figure 15 shows a graph of the voltage and current of the pack discharging onto an electronic load as well as the measured watt-hours.

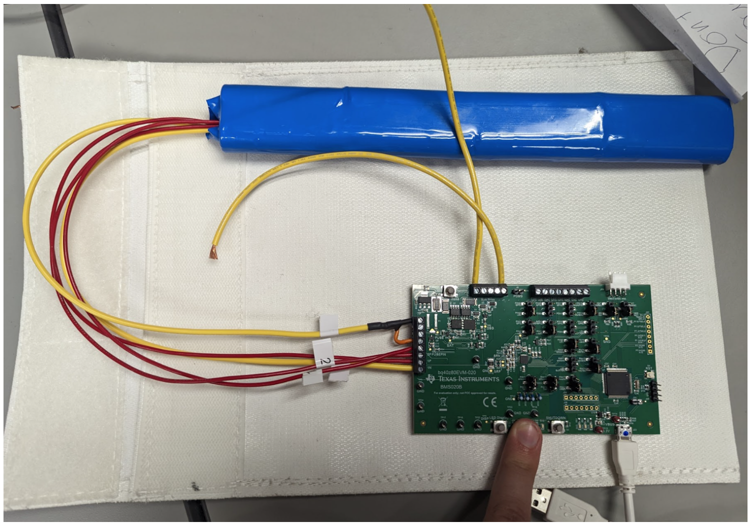
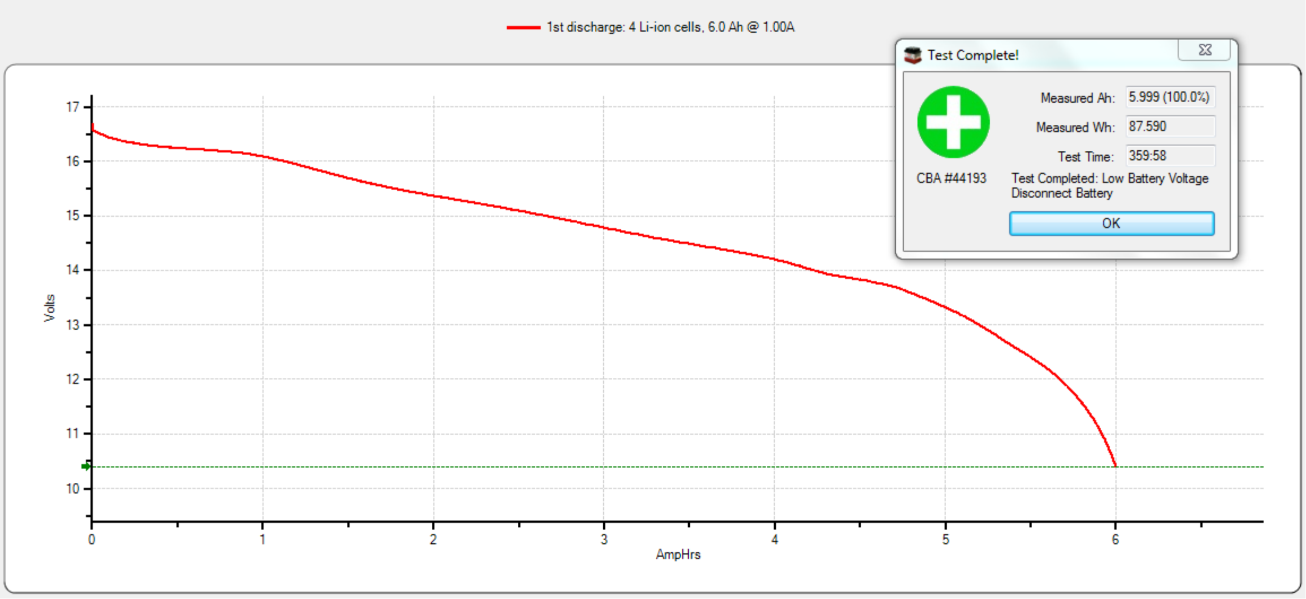


Figure 14: Image of Prototype



Measured Ah: 5.999 (100.0%)
Measured Wh: 87.590
Test Time: 359:58
CBA #44193
Test Completed: Low Battery Voltage
Disconnect Battery

Figure 15: V/I Discharge Curves

Microcontroller

Full implementation and testing of the microcontroller was delayed while the rest of the parts were being ordered and developed but was still able to be worked on. The microcontroller used I2C and PWM in order to communicate with battery and PWM respectively. I2C uses a single library header and arduino has built-in analog functions for communication with PWM.

Conclusion

In conclusion, our group learned a lot about buck/boost capabilities, battery design, coding microcontrollers, USB-C connections and much more. A lot of skill sets were utilized and over all a lot was learned. The team faced a lot of adversity along the way and had to find around it and our problem solving skills are much better for it. After renovating every component inside the base of our solar powered battery bank our team completed a proof of concept for each component and we were able to test some components to the extent they will be used. Overall, our short-comings on the project were due to an idea of our final design in our first semester and insufficient time. To add on to this project in the future, testing all components together would be a good first step that our team couldn't accomplish due to several restraints. That would include ordering a battery pack from the manufacturer and ordering 13V buck PCB. Before doing that the signal noise and the gauging of the state of charge should be addressed further. Then adding all reduced components to one PCB and optimizing the overall layout.

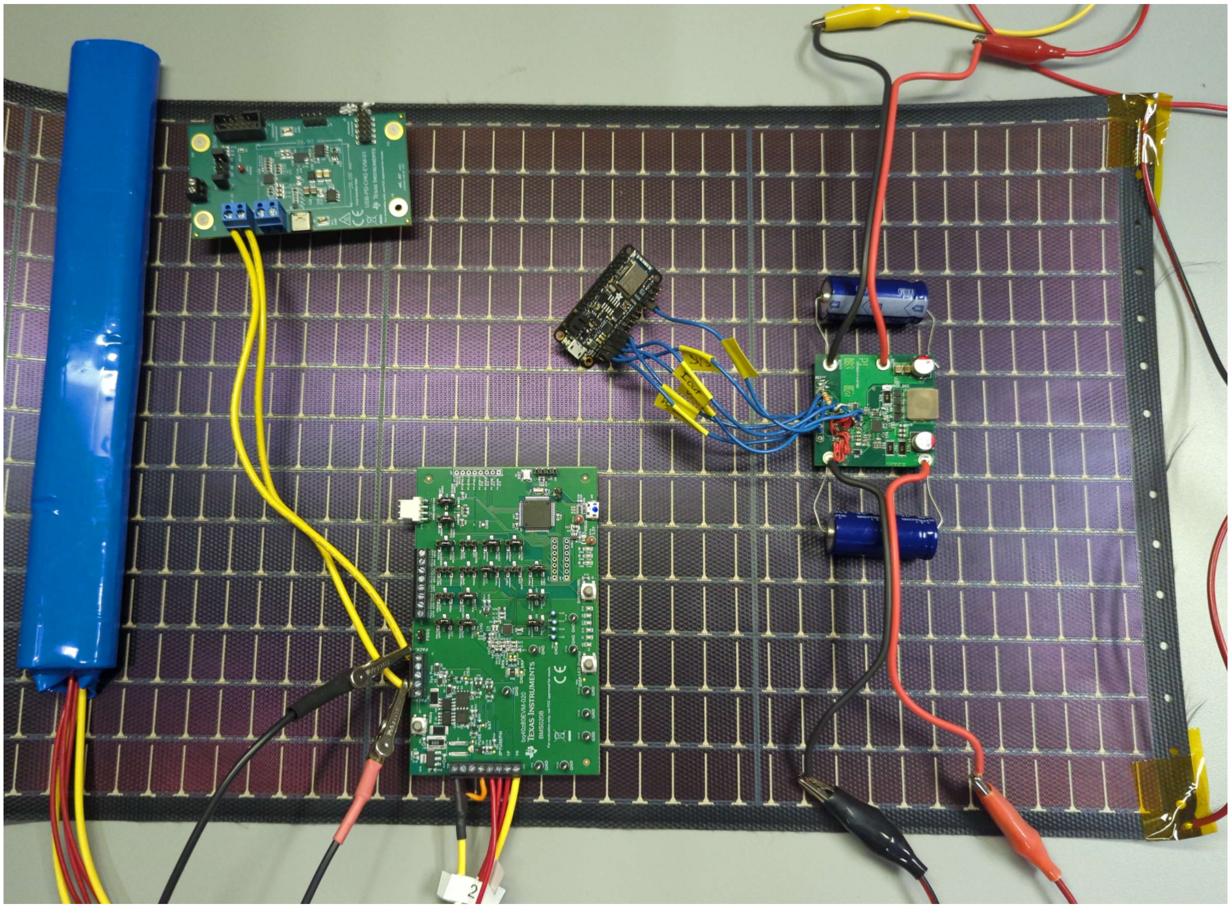


Figure 16: Final assembly of prototype

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Appendix 1 - Operation Manual

Charging the LightSaver Max

To charge the device there are two options: power from the solar panel, and power from USB-C. When using the attached solar panel, fully unroll the panel and place the device in full sun. When charging through USB-C, plug the battery pack into an alternate power source (i.e. wall outlet, another powerbank, etc). Then wait for the LED to show full indicating that the device is successfully charging.

Discharging the LightSaver Max

To charge personal devices with the LightSaver Max, connect the device via USB-C or via 12V barrel jack. The power bank will soon begin charging your device(s). Then wait until the personal device is sufficiently charged or the LED indicator is showing low power.

Caring for Your LightSaver Max

- Avoid physical damage. While the housing may be aluminum, the solar panel is not.
- Pay attention to charging temperatures. Excessively hot and excessively cold temperatures are harsh on the batteries. Most effective between 35F and 115F (2C-45C). When charging it is recommended to tuck the aluminum tube under the solar panel to keep it out of direct sunlight.

Battery Care

When at very low battery charge, it will take longer to get back to a usable state. It is ideal to keep the charge between 20-80% when leaving the device sit for extended periods of time.

Appendix 2 - Alternative initial versions of the design

Originally we had intended to use a prebuilt MPPT (BQ25798) however, the parameters of this design did not end up meeting our wattage needs thus leading to a custom made MPPT.

The next thing we had to adjust was the design of our battery pack. Despite trying to order it through a company, they ended up declining our order due to the quantity of battery packs being too small. Thus we had to create our own battery pack. This battery pack assembly did lead to a couple of issues namely it shorting out a couple of times but our current design now has intermediary wires to monitor the individual capacitance and voltage of the batteries. It has also yet to short.

We also went from a 12V buck design using the LM25116 chip to the LM5141-Q1 chip because it was recommended to us that we have a 13V output to better match the 14V nominal that the lead batteries in ham radios operate on.

Appendix 3 - Other Considerations

This may be a lesson in safety and fire hazards but our custom made battery pack was more volatile than we thought. After our final presentation in EE 491, John was bringing the battery pack back to Powerfilm and it started to short in his bag making it become excessively hot. Thus some of the team members got together to create a new battery pack of the same kind but doing so a little more carefully while also adding additional wires for battery sensing purposes.

Appendix 4 - Code (maybe, maybe not)