Cooking With Solar

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12/16/2019

Capstone Design ECE 4440 / ECE4991

Signatures

Statement of work:

Hieu Le

Hieu is responsible for most of the calculations of this project. We needed to figure out the exact power budget that we have to work with. To fit in our final design, we only have a total power of 9W at full sun. There will be 3 main subsystems we need to power: fan's motor, MSP430[1] microcontroller, its supporting IC hardware, and the Lithium-Ion battery pack. We did some calculation and estimation, the maximum power consumption for the fan will be 1.92W, 1.28W for the microcontroller, and 8.2W left for recharging the battery. The battery will be fully charged in roughly 3 hours without using the fan and 5 hours if using the fan at the same time.

Also, Hieu is responsible for designing the schematic and PCB layout. Each subsystem of the design needed to be thoroughly researched. Hieu was responsible for designing the circuit which managed power flow from the solar panels to the battery and the fan allowing for simultaneous charging and cooling. In addition, Hieu was responsible for converting the schematic into a PCB design in Ultiboard[2].

Kristian Johnson

Kristian was responsible for researching other products on the market that were potentially similar to The S.P.E.C.I.A.L. Project. Through his research, we were able to pinpoint the necessary features that our product will contain. We chose to eliminate excessive features found in competition, such as a Bluetooth speaker, that will drive the production cost upwards. We also chose to design our fan, such that it will have the ability to charge the photovoltaic panels while simultaneously powering the fan. This was a feature not found in many of the more inexpensive models that were found on the market.

Kristian also chose the primary component of The S.P.E.C.I.A.L. Project. Our group was indecisive about choosing the motor and fan. We wanted to have a larger fan blade, as well as a motor that wouldn't break easily. Ultimately, through research and with the advice of Professor Harry Powell, Kristian found a Brushless DC Fan with a built-in motor and PWM functionality that will allow us to vary the speed settings of the fan. The PWM functionality also allows us to adjust the speed setting when the power is running low. We had to settle on a smaller size blade; but we were able to undercut our fan and motor budget. Kristian has also completed and submitted all of the order forms for the components that we have purchased. He also aided in the process of creating test plans for the circuit schematics, and he was responsible for soldering all of the components to the PCBs once they were tested.

Jack Craddock

Jack was responsible for designing the PWM which controls the speed of the fan. The implementation of this PWM allows the fan to be toggled between five different speeds. When the battery is low, a warning LED will activate to warn the user that the fan is low on battery.

Jack was responsible for calculating which ADC input values corresponded to low battery levels and for implementing the algorithm to toggle the fan speed on the pushbutton press.

Jack also contributed to the design of the PCB board in the location where the MSP will be integrated. A key part of this design was incorporating the logic shifter between the PWM output from the MSP430 to boost the 3.3-volt square wave to a 5-volt square wave before being passed to the PWM input to the fan. Additionally, a voltage divider was required to reduce the voltage from the battery before it was passed the ADC in the MSP in order for the voltage to be within the range readable by the ADC.

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Abstract

Solar Powered Electronic Cooling In Any Location, or The S.P.E.C.I.A.L Project, is a portable, low-cost, durable, solar-powered fan to be used primarily in developing countries. This project will be designed to be affordable, to withstand everyday use, to be easy to repair and maintain, and most importantly, to efficiently provide cool air to those around it. The fan is designed primarily for outdoor use and is intended to provide simultaneous charging and cooling; where cooling is defined as the redistribution of air directly and autonomously induced by the fan.

Background

The S.P.E.C.I.A.L. Project was chosen to provide a solution to developing countries' cooling issue. "Cooling in developing countries is a major problem that affects health, disease treatments and hunger… Many developing countries do not have access to electricity and consequently do not have proper cooling systems either… Although air conditioning ownership has gone up from 2 million in 2006 to 5 million households in 2011, that number still only represents around 3 percent of Indian households. Restricted energy access prevents many from being able to purchase air conditioners."[3]

There are other solar powered fans available on the market; but they don't properly address the needs of these developing countries and impoverished locations. The other options on the market are either too high priced, with several unnecessary features that drive the cost upwards, or so inexpensive that there is no durability; and the product isn't worth repairing when it inevitably breaks. The inexpensive models are also designed such that the fan cannot be on while the solar panel is charging the battery, and the battery cannot be charging while the fan is on. The S.P.E.C.I.A.L. Project is a perfect medium. It will only feature aspects that are required to provide cool air without normal means of electricity. This allows our product to be more affordable than the majority of the quality, solar-powered fans on the market. The S.P.E.C.I.A.L. Project will also durability and ease of maintenance. This allows the users to carry on with their everyday lives without the fear of damage to the product. In addition, if the product were to be damaged, disassembling The S.P.E.C.I.A.L. Project would be a breeze. The low-cost parts allow for replacement by the user, and the design allows for simultaneous solar-powered charging and power to the fan. These qualities provide The S.P.E.C.I.A.L. Project with an advantage over all of its competition on the market.

Hieu is an Electrical Engineering major and he has experience with solar panel technology and he is also familiar with AutoCAD software. Kristian is also an Electrical Engineering major who has some AutoCAD experience and 3D printing experience as well. Jack is a Computer Engineering major who will be using his programming skills with the MSP430 that will be used in our project. All of the members in this group have experience with designing a PCB with MultiSim and UltiBoard. In addition, we are all capable of testing with the Virtual Bench, and programming in Code Composer Studio.

Constraints

Design Constraints

Throughout the design process, there were several constraints to take into account. Because of the short timeframe for which to complete the project, only components currently held in stock by approved vendors were acceptable to order. This significantly affected our choice of fan component as there were many viable models which were out of stock. Eventually the component had to be ordered through Amazon. This process came with its own constraints as the proper forms needed to be filled out, the proper personnel needed to be notified, and a significant processing delay had to be taken into account.

In addition to processing delays for Amazon orders, there were several other delays which needed to be taken into account. First, there were delays when ordering any parts through any vendor similar to the ordering process from Amazon. Second, there was the delay for manufacturing each PCB that was ordered. These delays usually took one or two weeks and were extremely disruptive to the design process. In addition to these delays, there was also a delay for professionally soldering the battery management chip to each PCB. This delay could take up to a week because of the limitations in the professionals' schedule and the group's schedule and was moderately disruptive to the group. Since the exterior components to the fan were 3D-printed, there was also a delay incurred while printing the components that was a noticeable inconvenience to the group.

While time delays were the most noticeable manufacturing constraint, several design constraints needed to be taken into account as well. The 3D-printer that was designated for use by the group had extreme dimensional limitations which required each component to be printed within an area of approximately 250 cm^2 which was significantly smaller than previously desired.

Economic and Cost Constraints

It seems that some components required to complete a prototype for this project may already be owned by the department. These items include an MSP430 Launchpad, LEDs, and a DC motor. Some materials will require a custom design which will encompass the PCB board, and the frame of the fan. Additional materials are also required, such as a solar panel configuration with sufficient power supply to power the fan and a rechargeable battery. Given this part list, the total cost is estimated to be in the \$50 to \$100 range.

Since the goal for this project is to produce solar-powered cooling solutions for developing countries, it is essential to keep the fan as cheap as possible while still maintaining complete functionality. One of the most expensive examples of prior art examined[4] was priced at $75 which was well above the price point that the team is aiming for. However, this design has several extraneous features such as functioning as a flashlight and music player simultaneously. The plan was to create a similar fan but to hit a significantly reduced price point by removing these extra features. On the opposite side of the spectrum, we examined a significantly cheaper fan[5] that was priced at about $7 which did not quite have all the desired functionality. Specifically, the goal for this fan was to allow for simultaneous charging and cooling, which this fan did not offer. Given these examples of prior art the final target price point for the design should be between $30 and $35. However, since this design is a prototype, the costs for the individual fan were significantly greater than they would have otherwise been if buying in bulk were an option.

One specific example of a cost constraint that was encountered was in the 3D-printing domain. The initial CAD design for the fan outer shell would have cost over $1000 to print via a third party. Because of this, each component had to be individually printed on university printers limited in both quality and scale. In addition to the quality reduction, there was also a significant delay entailed in printing each part personally which ended up causing several days of delay.

External Standards

All of the standards that we followed for this project include: UL 1642 - Standard for Safety for Lithium Batteries[6], UL 2054 - Standard for Household and Commercial Batteries[7], UL 2056 - Outline of Investigation for Safety of Power Banks[8], UL 2595 – Standard for Safety for General Requirements for Battery-Powered Appliances[9], along with the electronics assembly standards IPC J-STD-001[10] and IPC-A-610[10]. These are standards that address the potential hazards including overheating, fire, electrical shock from battery chargers, thermal burns, exposure to alkaline battery electrolytes, and high-velocity ejected internal components of batteries. High-energy chemistry batteries include lithium-ion, lithium-ion polymer, and lithium metal batteries that are thinner, smaller, lighter weight, and contain more energy than traditional rechargeable and non-rechargeable batteries. The combination of high-energy volatile chemistries, such as lead-acid, pose fire, and explosion hazards, packed into a small volume requires special safeguards to minimize potential hazards.

High-energy density batteries need enhanced safety systems and additional care when using and handling, both in or when removed from the product; and batteries must be properly tested with the product, with its intended use and with the charger as a system. Our charger control system using the MP2610 chip is designed specifically to charge a Li-On battery in 3 stages to ensure complete safety. Moreover, we also have taken precautions and used the fully tested battery that has overheating, over-discharging, and over-charging protection.

The PCBs were soldered and assembled in accordance with the electronics assembly standards IPC J-STD-001 and IPC-A-610. Each through-hole component was ensured to have at least 75% of the hole filled with solder (most of which had 100% hole fill) such that a connection is indefinite. In addition, all of the leads were trimmed such that there would be a short circuit caused by excess lead length on the bottom of the PCBs.

Tools Employed

Beyond the ECE lab equipment, the required hardware tools that we used for this project are Ender3 Pro[11], UltiMaker[12], UltiMaker extended[13]. The required software tools are AutoCAD[14], MultiSim[15], UltiBoard[2], C/C++ in Code Composer IDE[16], VirtualBench[17], and Cura[18].

We had been learning and using AutoCAD to design all of the external 3D parts of the project. We used Multisim to design the schematic and Ultiboard to design the board layout. We used C/C++in Code Composer IDE to program our MSP430 chip. We used the VirtualBench for all of the testing of this project. We used Cura to slice all the 3D models and produce a printable code for the printers. In order to print all the parts we needed, we used three different printers: the Ender3 Pro, the Ultimate Maker, and the Ultimate Maker extended.

Ethical, Social, and Economic Concerns

Ethical Issues

The areas of the most ethical concern for this project are predominantly related to how the device affects the environments where it is deployed to and how it affects the environment from which its materials are sourced from. The process of developing the components to build the fan is not only the responsibility of the manufacturers but also the responsibility of those who purchase those components which is why they are worthy of such heavy scrutiny. In addition to how the creation of the fan affects the environment, the disposal of the fan must also be taken into account. If there is not a viable method to dispose of each component of the device without significantly affecting local ecosystems then it may be best for the solution to be withheld until there is a plan for how the device will be managed throughout its life cycle.

Environmental Impact

This device is primarily intended for use in developing countries. Most developing countries have poor waste management systems as well as weak regulations for protecting the environment. Because of this combination of circumstances, it is highly likely that the battery, plastic, and solar panels of this device may not be disposed of properly. In these regions, improper waste management can be particularly harmful to ecosystems in which complex human waste does not already have a significant presence. It is important to take this perspective into account because the effects of improper waste management disposal can have devastating effects on long established ecosystems.

Sustainability

The major sustainability concern is the rechargeable battery required for the design. The battery, which uses Lithium, will most likely require a highly energy intensive process to produce.[19] In addition, the process of mining Lithium often pollutes nearby water supply, introducing severe health risks to local communities and animal populations.[20] The vast majority of Lithium is mined from developing countries in South America where a significant portion of the biodiversity relies on the wetlands for their food and shelter. Polluting these biomes can have severe repercussions to the local ecosystems and could cause permanent damage to that region's wildlife. The major tradeoff which must be weighed in this case is the portability provided by the battery against the footprint of the battery.

Health and Safety

The goal of this project is to provide accessible cooling technology to developing communities. The intent is for solar powered fans to contribute to regulating the body heat of users. This should allow users to expend less energy throughout their day, which will contribute to a healthier lifestyle and help to reduce the prevalence of heat related injuries such as heatstroke.

The primary health concern of portable fans is for the system to erupt into flames. This consequence is especially relevant to this project considering that using the product is intended for use while camping in the woods. An oversight in this area could potentially start a wildfire. In addition, solar panels may also be a contributor to starting fires if connected improperly.[21] In order to combat these issues, the product will abide by the Underwriters Laboratories Standard for Safety for Electric Fans, UL 507[22]. The specific points of failure which will have to meet this standard are the DC motor and the internal wiring.

In the prototype, the connections are soldered together and insulated with electric tape. While these connections work functionally, they leave much to be desired in terms of long-term durability. In order to meet the above standard, it will be necessary to create more a more detailed path for the wires in the interior of the device. In addition, the current prototype has yet to be insulated from potential water damage. If this issue were left unpatched in the final production, it could damage the integrity of the device after coming into contact with water, which could, in the worst case, cause damage to users or private property.

Manufacturability

The project is required to be cheaply and easily manufacturable. When the project is ready for the manufacturing stage, the PCB and MSP430 chip should be replaced by a significantly more compact device in order to produce the fan as cheaply as possible and to make the design as durable as possible. In addition, the cost of 3D-printing the exterior shell can be greatly reduced by creating a mold from which the exterior can be produced. Although the mold would cost a great deal the incremental cost for each additional fan would be reduced significantly. This reduction of variable cost would significantly reduce the price of the fan to consumers. Another area to explore is adjusting the model of solar panels used from small, developer quality panels to production quality panels with a more custom size. This measure should also lower overall costs since the number of solar panels required to power the fan would decrease. This change would also increase the durability of the design as there would be fewer joints contained in the design and thus fewer locations where breakage is likely to occur.

Intellectual Property Issues

The S.P.E.C.I.A.L. Project is not an entirely new invention - as there are other solar-powered fans that exist on the market. The “High efficiency solar powered fan” (U.S. Patent No. 7662035B1, 2006)[23], is also a portable solar-powered fan that provides housing for supporting the fan blades and the motor. However, this patent design is large and has one photovoltaic panel that rests on wheels, and is connected via a cable to the fan that is also mounted on wheels - while The S.P.E.C.I.A.L. Project has five solar panels and no wheels.

The “Solar Powered Fan” (U.S. Patent No. 20080152482A1, 2006)[24] is also listed as a portable solar-powered fan. This design allows for power to the fan through the single photovoltaic panel, a rechargeable battery pack, or even a home charger. Similar to the “Solar Powered Fan,” The S.P.E.C.I.A.L. Project’s fan can also be powered through a rechargeable battery pack or solar power through a photovoltaic panel. However, in contrast to the “Solar Powered Fan,” The S.P.E.C.I.A.L. Project has five times as many solar panels, and the fan cannot be charged through a home charger. The “Solar Powered Fan” is also primarily handheld - while the option to place the fan onto a stand is possible. The S.P.E.C.I.A.L. Project is designed to be placed on a flat surface.

The “Solar powered fan for portable enclosure” (U.S. Patent No. 7455582B2, 2006)[25] is another solar-powered electrical fan that allows the fan to be powered additionally by a rechargeable battery. However, this product is designed such that the photovoltaic panels would be exposed to the sun on the outside of a small enclosure (i.e. a portable restroom), while the fan would be on the interior of the enclosure to provide cooling within. The S.P.E.C.I.A.L. Project’s design is similar and could also accomplish this idea - due to the fan's enclosure being removable from the main enclosure that houses the photovoltaic panels.

As mentioned before, The S.P.E.C.I.A.L. Project is not an entirely new invention. However, it does provide a cost-effective alternative to some of the other existing products. The majority of the competition is either too expensive to purchase for developing countries, or too fragile and ineffective that it isn't worth the little money that these countries have. For example, the more inexpensive products cannot have the fan powered on while collecting solar energy through the photovoltaic panels - while The S.P.E.C.I.A.L. Project allows for simultaneous charging of the battery and power to the fan. In contrast, The S.P.E.C.I.A.L. Project also portable - unlike the larger fans that are also able to provide simultaneous charging of the battery and power to the fan. For these reasons, we believe that The S.P.E.C.I.A.L. Project is patentable due to its advantages over the competition.

Detailed Technical Description of Project

The Solar Powered Electronic Cooling In Any Location, S.P.E.C.I.A.L, is a solar-powered fan that is also portable, low-cost, and highly durable. The device will be designed to be affordable, to withstand everyday use, to be easy to repair and maintain, and most importantly, to efficiently provide cool air to those around it. The device is designed primarily for outdoor use and is intended to provide simultaneous charging and cooling. The design will have two primary components: the main housing and the fan. The main housing contains five photovoltaic panels[26], a power management PCB, and a battery[27]. When the user places the device into an open space and opens up all the foldable, solar panel wings to face directly towards the sun, the energy collected from the solar panels will be processed through the power management PCB then power the fan[28] and store accessible power within the battery. The other part of the device is the fan which contains a button[29], the 4 wire fan, MSP430 PCB, and LED[30] indicators. The fan is designed to be detachable from the whole unit and is connected to the main housing with wires. When the user clicks the button the fan will turn on, and it will turn off after four clicks. There are three LEDs on the fan, one will indicate whether there is a sufficient amount of power input to power management PCB, another will indicate if the battery is charging, and the last one will indicate if the battery is low.

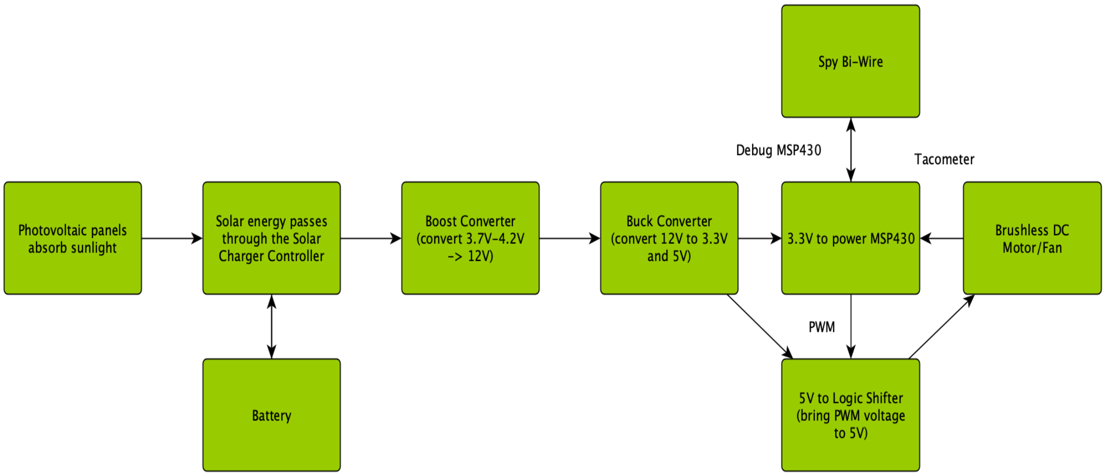


Figure 1: Power distribution block diagram

The user will place the unit into an open space and open up all the foldable solar panel wings to face directly towards the sun. As in Figure 1 shown above, the process begins with the solar panel generating 12.5W in full sunlight. The solar panel is connected to the power management PCB which converts the fluctuating voltage and current to a steady 4.1V voltage and ~1.2A current to charge the battery. The power management PCB designed to prevent overcharging the battery, hence lengthening the life of the battery, and preventing the over-discharge of the battery itself. It also has two built-in output LEDs to indicate if there is a valid power input and if the battery is charging. At the input voltage of the battery node, we connected a 12V boost converter circuit to output 12V - to power the fan and the MSP430 PCB. When there is no power generated by the solar panels, the device will switch to use the power from the battery. At the MSP430 PCB, the 12V input voltage will be split into 3.3V and 5V using the buck converter circuits. The 3.3V output will be used to power the MSP430 chip and the 5V output will be connected to the signal translator chip. The MSP430 will be programmed to alert the condition of the battery using LEDs. It will also be programmed to control the speed of the fan using PWM signals. The 4-wire-fan required a 5V PWM signal, but the MSP430 can only provide a 3.3V signal. Therefore we need to use a signal translator to boost it up to 5V. PWM will be used to regulate the output voltage, which will determine how fast the user wants the fan to spin. It has four-speed settings after the fan is turned on: 40%, 60%, 80%, and 100% maximum speed. The fan as a whole will be specifically designed to be detachable from the whole unit. It will be connected to the unit by wires, which also allows the user to charge the battery and use the fan at the same time.

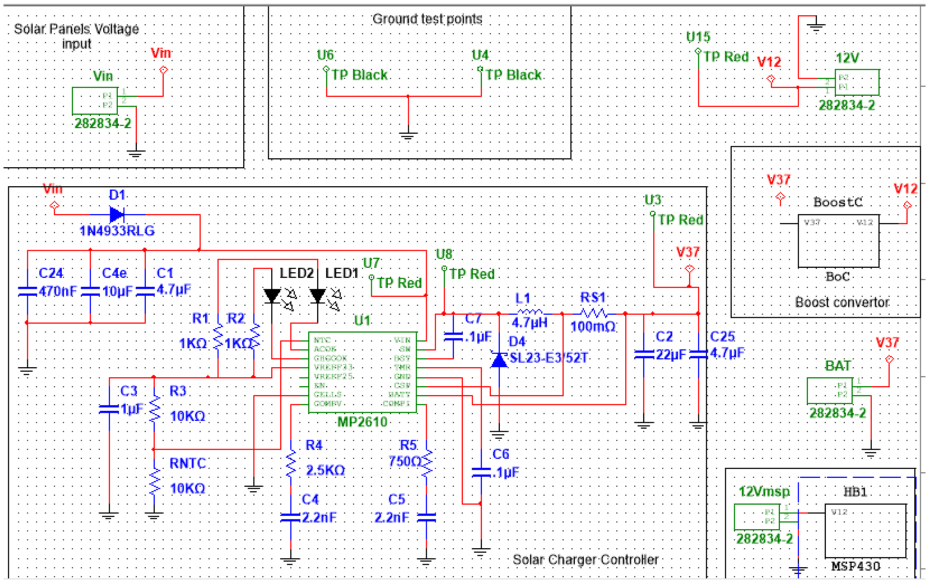


Figure 2: Power Management Schematic

First, we started with our power source section, shown in Figure 2, which is generated from all of the solar panels. We wired all the solar panels together and then tested them in full sunlight. We used a total of five solar panels that each provides 2.5W. We connected the solar panels with three in parallel and two in series to produce a total of 15V, 0.83A, and 12.5 Watts in theory. When tested, they produced a total of 18V, 0.65A, and 11.7 Watts. That is 93.6% accuracy from the information that the manufacturer provided. When the valid power supply is delivered to the Vin node at the Solar Charger Controller section shown above in Figure 2, it will first go through diode D1 [1N4993RLG][31, p. 4]. Diode D1's purpose is to prevent voltage from going back to the solar panel when there is no light. At the Vin pin of the MP2620[32], three bypass capacitors of different values (430nF[33], 10uF[34], and 4.7uF[35]) are placed to prevent the sudden surge of voltage. At the Cells pin, pin 7, we grounded the pin for 1-cell operation. At the switching pin, the SW pin, we placed a Schottky Diode SL23-E3/52T[36] as instructed by the manufacturer. The Diode SL23-E3/52T was chosen specifically because it can take a maximum of 30V and 5A. At the ACHOK pin, the Valid Input Supply Indicator, we use a Red LED and a 50-ohm resistor[37]. We chose the 50-ohm resistor because it prevents excess current from rushing into the LED, and it gives a good amount of luminance. Similarly, for the ACHOK pin, we chose a Green LED and a 50-ohm resistor for the Charging Completion Indicator (CHGOK) pin. At Vout, at pin BATT, we placed another two bypass capacitors (22uF[38] and 4.7uF). Again, the bypass capacitors are placed to prevent the voltage from extreme fluctuation. The battery is connected to the BATT pin. For all of the other pins, we followed the instructions of the schematic and used the correct components to support the chip. The next section is the Boost converter section, shown below in Figure 3. For the boost converter we used is the LM2731[39] adjustable. We chose this chip because it is a built-in chip within Multisim - allowing us to be able to simulate it. We took extra caution and placed another bypass capacitor, 10uF, to prevent the voltage from extreme fluctuation. At the SW pin, we used the Schottky Diode SL23-E3/52T because it met the required voltage and current values of 12V and 0.8A. At the feedback pin, the FB pin, we used 13.3k[40] for R8, because of the recommendation of the manufacturer. We were able to find the value of R6 using this equation given in the datasheet, Rf = R8((Vout/Vfb) - 1). We want Vout to be 12V so we plugged in all of the values to calculate that Rf = 118kOhm. We couldn't find the resistor value from anywhere, so we used two resistors in series, R6 = 100k[41] and R18 = 18k[42]. At the V12 node, we placed another two bypass capacitors (10uF and 4.7uF).

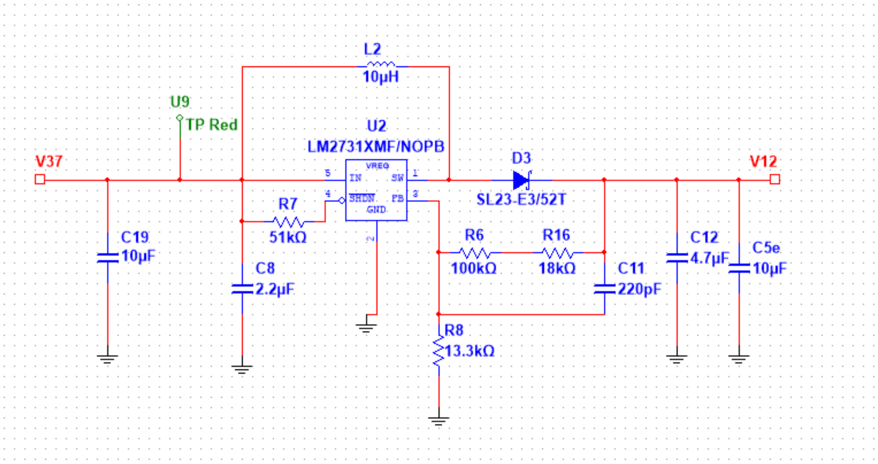


Figure 3: Boost Converter Schematic

The schematic is shown in Figure below, Figure 4, is the MSP430 PCB schematic. At the buck converter section shown in Figure 5, the 12V input voltage will be split voltage into 3.3V and 5V using the 5V buck converter chip[43] and the 3.3V buck converter chip[44]. The 3.3V output will be used to power the MSP430 chip, and the 5V output will be connected to the signal translator chip. Both of the buck converter chips are fixed converters, so we only needed to place the bypass capacitors at Vin and Vout. The next section is the MSP430 chip, which we powered with the 3.3V power at the DVCC pin. We used pin 1.0 as an ADC battery sensor pin. The MSP430 chip can only take 3.3V or below, so we needed to use a voltage divider to split it in half. We used 10K[45] for both R12 and R11 to achieve this. We used pin 1.3 for the input Button, and we connected a pull-up resistor to 12V to keep the logic at HIGH if the button is not being clicked. We used pin 1.5 as an LED indicator for the status of the battery's power. We used the 50 Ohm resistor for this pin. We used pin 1.6 to send the PWM signal. A previously explained, the 4-wire-fan required a 5V PWM signal, but the MSP 430 can only provide a 3.3V signal. Therefore, we needed to use a signal translator (logic shifter) to boost the voltage up to 5V. The logic shifter will take in the 3.3V power supply, the 5V power supply, and the 3.3V PWM signal in order to produce a 5V signal. At the power supply pins of the logic shifter, we also placed two 4.7uF capacitors to ensure the stability of the voltage. We wanted to be able to debug the MSP430 from the board; therefore we connected Spy Bi-Wire components. The Spy Bi-Wire section was followed directly from the manufacturer's datasheet[46].

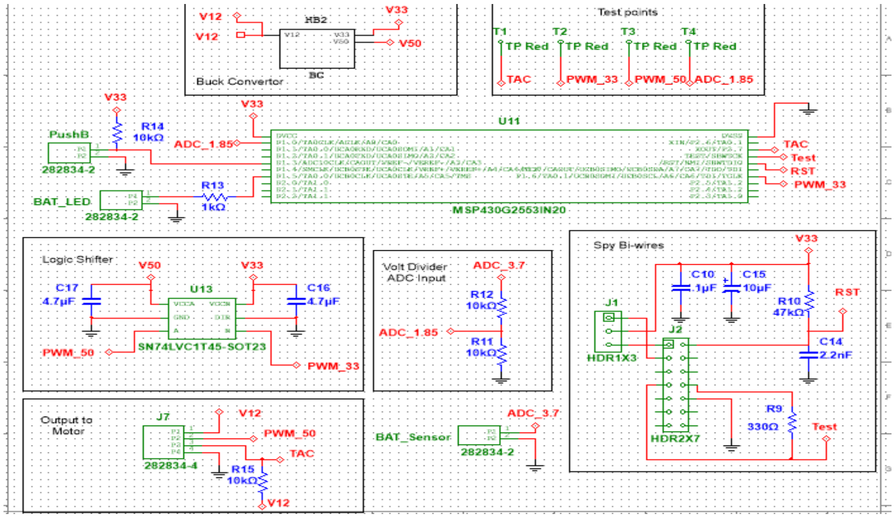


Figure 4: MSP430 Circuit Schematic

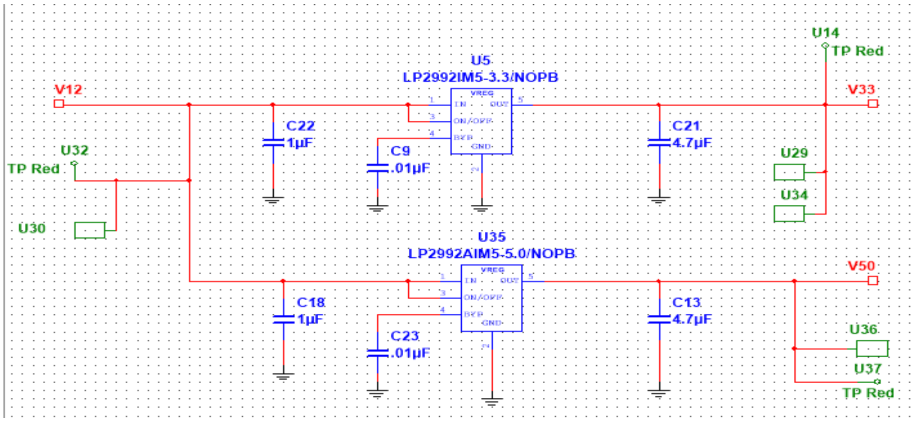


Figure 5: Buck Converter Schematic

We designed the board layout to follow the schematic layout as closely as possible - it is shown in Figure 6 below. For the MP2610 chip, we wanted to place it in the middle of the board and leave some extra room around it. Since it is a very small chip, it could potentially cause us problems soldering it on the board. Leaving extra room will make it somewhat less difficult. For all of the bypass capacitors, we tried to place them as close to the voltage inputs/outputs as possible. Also, for all the test points (except for the ground ones), we placed them as close to the point we wanted to test as possible. For the MSP430 chip, we used a DIP20 socket[47] to connect the chip to the board. In this way, if we accidentally fry the chip, it can be easily replaced. Finally, we placed all of the output/input blocks at the edge of the board to have easy access to all of them. The final soldered PCBs are shown below in Figure 8 and Figure 9.

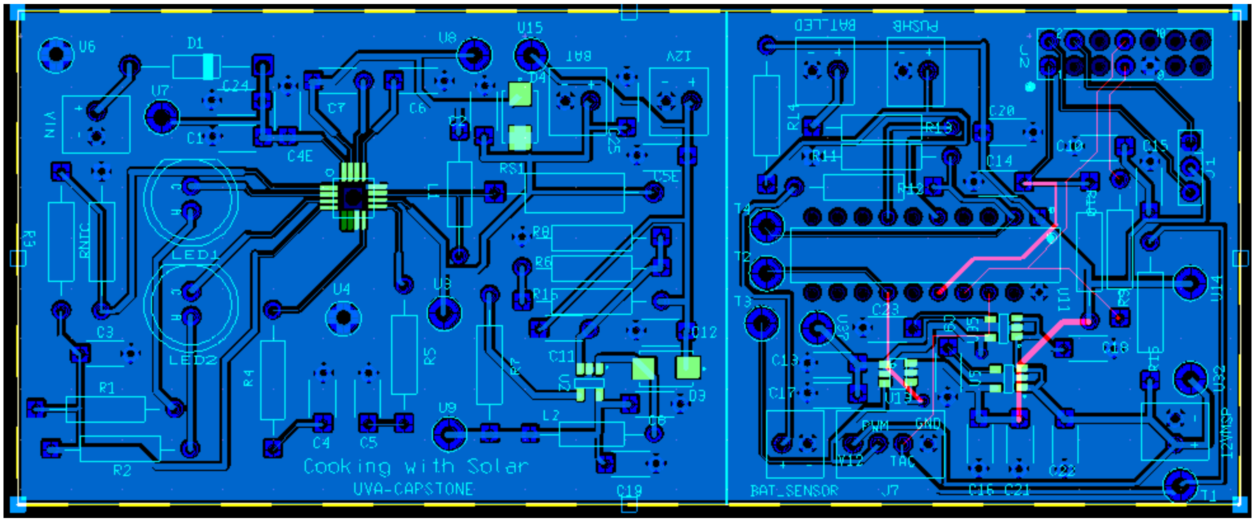


Figure 6: Ultiboard PCB

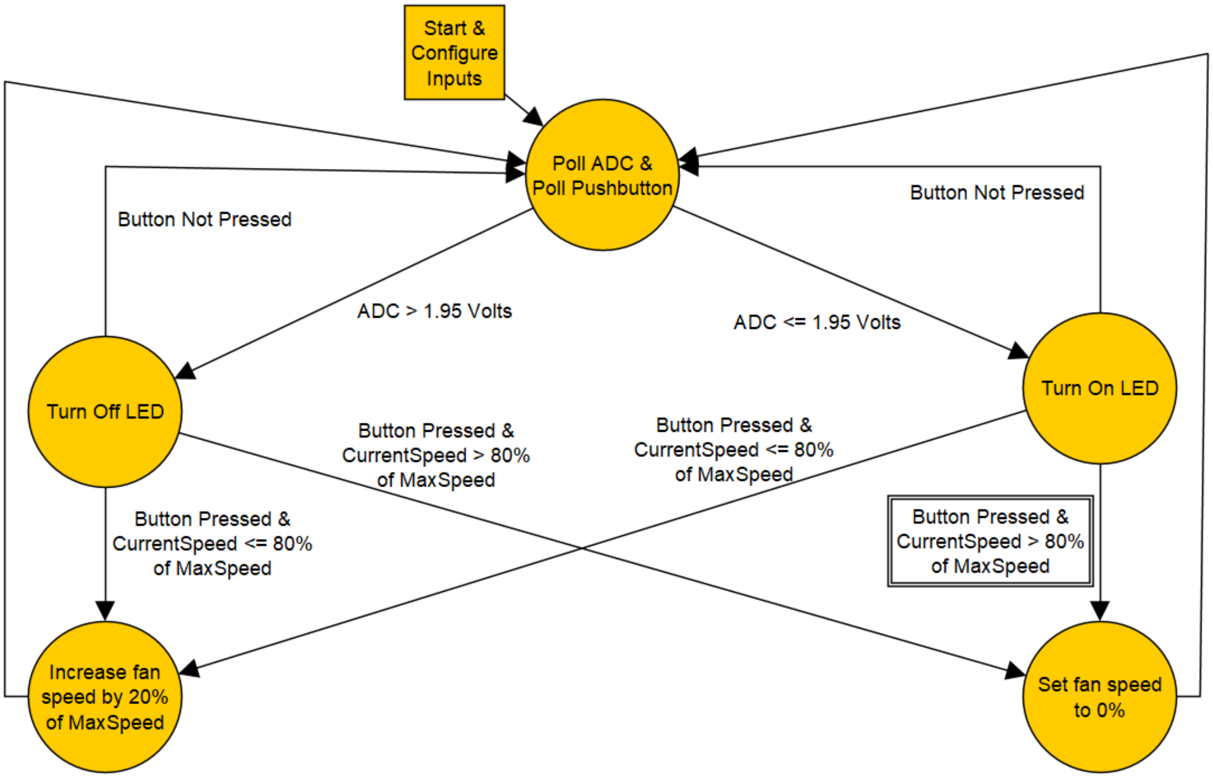


Figure 7: Software Flowchart

The software for this project is capable of taking an ADC input from the battery and input from a pushbutton. The software can then determine whether the battery is low or not via the

ADC and limit the maximum PWM output in order to save power during that time. When the button is pressed the PWM will increase the duty cycle of the PWM by 10% unless the PWM is at the maximum value in which case the duty cycle goes to 0%. The maximum value of the PWM is 100% when the battery is at a healthy charge and 50% when the battery is at a low charge, which is defined as when the voltage across the battery is 3.6 volts or less. We are currently in the process of testing the software with the virtual bench. We have tested the system with an ADC input of 0 volts, 1.5 volts and 2 volts and the system behaved in low battery mode when 0 volts and 1.5 volts were applied but operated at high battery mode when 2 volts was applied.

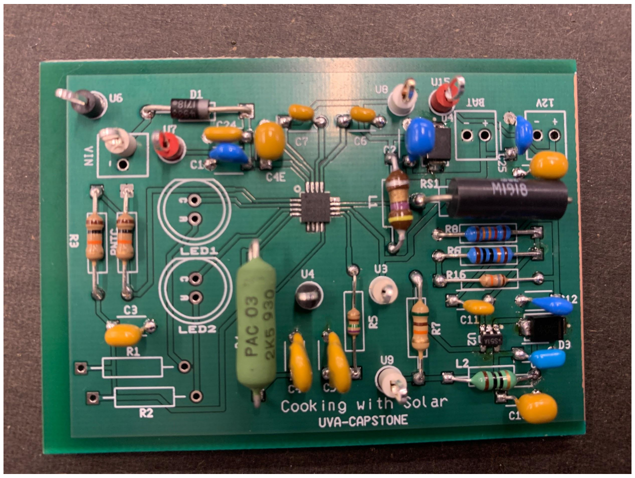


Figure 8: Soldered Solar Charger Controller PCB

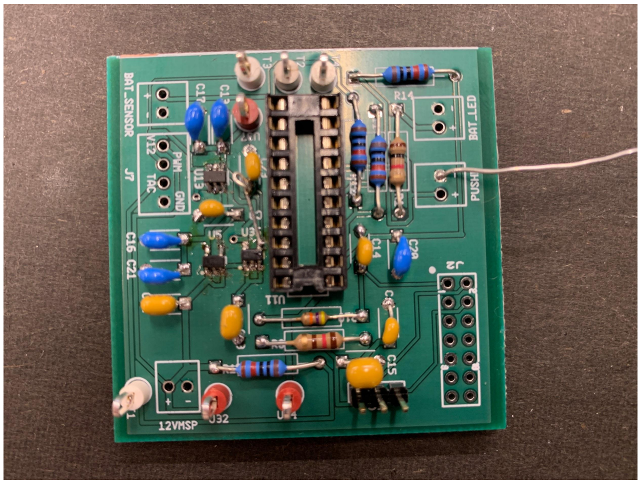


Figure 9: Soldered MSP430 PCB

The solar panels we used, similar to all other solar panels, do not completely produce the amount of power that the manufacturer advertised. We solved this problem through intensive testing to find the upper and lower limits. Since most of our testing was done inside the lab, we replicated that amount of power the panels provided, and successfully powered our project using the VirtualBench. The MP2610 is a small surface mount chip. Soldering it onto the board is an extremely difficult job. We solved this problem by outsourcing it to a nearby company called 3W Electronics[48]. They were very helpful and completely reliable, all of the chips soldered by 3W worked properly. When we soldered all of the components needed and powered the chip with the VirtualBench, everything worked as expected - for 3 minutes. The MP2610 overheated and the VirtualBench indicated that the board had a short circuit. When we measured the voltage at the output of the MP2610, it gave us a much larger voltage than expected at 19V. This also meant that the voltage exceeded the amount that the Boost converter could take, causing the Boost converter chip to burn out. After several attempts, and one and a half months later, we figured out that our diode did not meet the voltage requirement - which causes the MP2610 chip to also burn out. We solved this problem by redesigning the board and replacing the diodes with new and improved ones that met the manufacturer's requirements. We designed our device's case to be entirely 3D printed. The pros were that we were able to have a tremendous amount of space for our creativity. However, 3D printing technology is still very limited and expensive. We could not print everything we wanted with the amount of budget that we had. We solved this problem by redesigning the whole unit to be printable and within the budget range. We utilized the 3D printers from the University of Virginia's library. Even though we made a lot of compromises, such as cutting down the quality of the prints, removing the waterproof components of the unit, and slimming down all of the protective parts, we were able to print out everything we needed and have a completed final prototype in the end. The 3D modeled components for the final prototype are shown below in Figure 10.

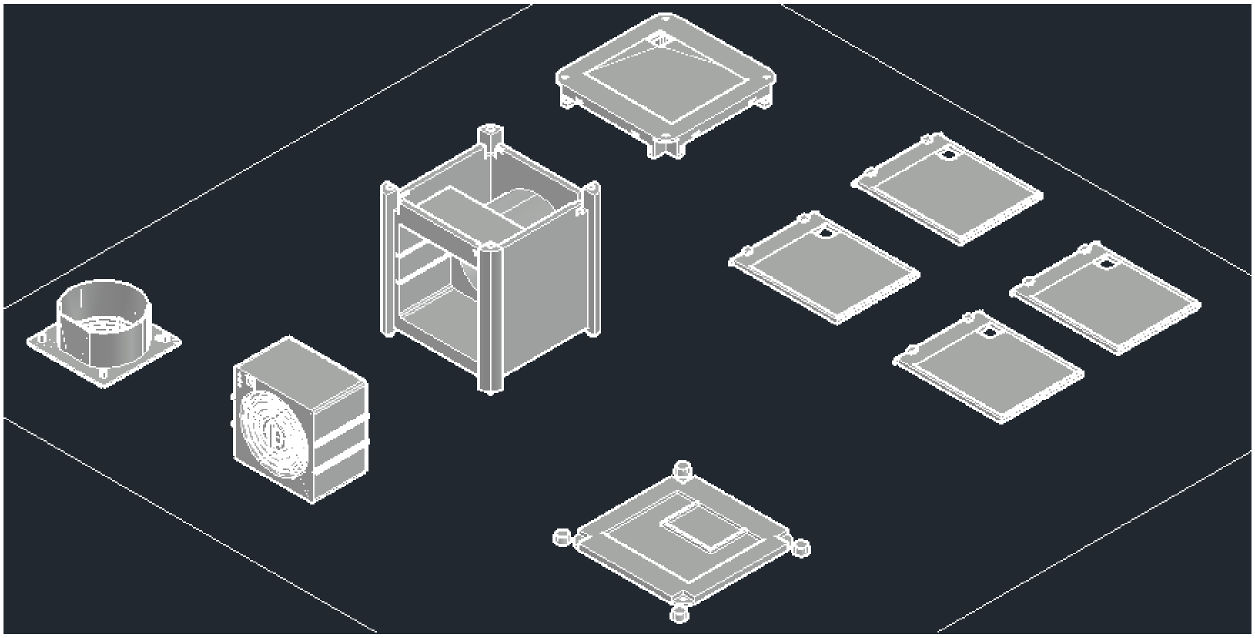
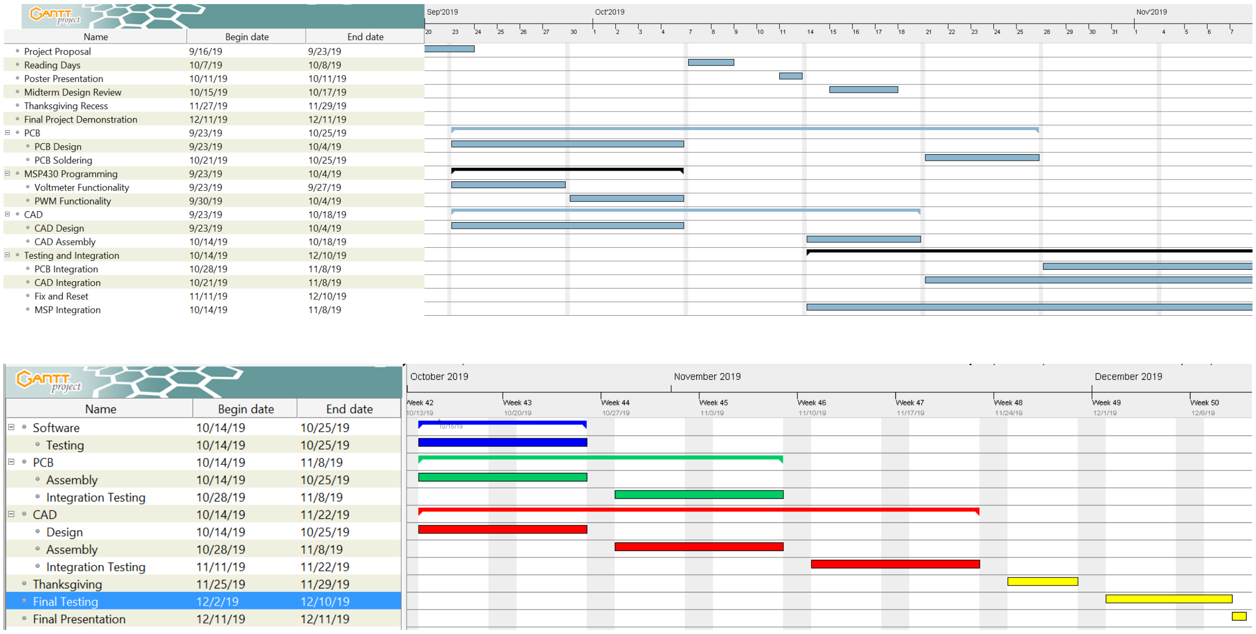


Figure 10: AutoCAD Design

Project Time Line



Name	Begin date	End date
Project Proposal	9/16/19	9/23/19
Reading Days	10/7/19	10/8/19
Poster Presentation	10/11/19	10/11/19
Midterm Design Review	10/15/19	10/17/19
Thanksgiving Recess	11/27/19	11/29/19
Final Project Demonstration	12/11/19	12/11/19
PCB	9/23/19	10/25/19
PCB Design	9/23/19	10/4/19
PCB Soldering	10/21/19	10/25/19
MSP430 Programming	9/23/19	10/4/19
Voltmeter Functionality	9/23/19	9/27/19
PWM Functionality	9/30/19	10/4/19
CAD	9/23/19	10/18/19
CAD Design	9/23/19	10/4/19
CAD Assembly	10/14/19	10/18/19
Testing and Integration	10/14/19	12/10/19
PCB Integration	10/28/19	11/8/19
CAD Integration	10/21/19	11/8/19
Fix and Reset	11/11/19	12/10/19
MSP Integration	10/14/19	11/8/19

Name	Begin date	End date
Software	10/14/19	10/25/19
Testing	10/14/19	10/25/19
PCB	10/14/19	11/8/19
Assembly	10/14/19	10/25/19
Integration Testing	10/28/19	11/8/19
CAD	10/14/19	11/22/19
Design	10/14/19	10/25/19
Assembly	10/28/19	11/8/19
Integration Testing	11/11/19	11/22/19
Thanksgiving	11/25/19	11/29/19
Final Testing	12/2/19	12/10/19
Final Presentation	12/11/19	12/11/19

Figure 11: Gantt Chart

The Gantt chart shown in Figure 11 illustrates the original schedule for developing the final product. The three main systems of the product are Mechanical Engineering, Electrical Engineering, and Computer Engineering. In order to achieve maximum efficiency, these systems were started in parallel and then integrated together to form the final product. The project started with the programming being implemented and with the PCB and CAD models. Then the models were then created remotely and then assembled together with the MSP430 to create a working fan. When creating the initial Gantt Chart, the team made sure to consider the important deadlines for the project, specifically the Midterm Design Review on October 15th and the Final Design Presentation on December 11th. In addition, the dates of school breaks were considered so as to not overestimate the amount of work that could be completed during those times.

Comparing the original Gantt Chart to the final Gantt Chart, the programming was wrapped up within a week of when it was initially planned to be complete. The PCB design was originally completed early, but assembly took much longer than expected because a part was chosen with a current tolerance lower than necessary which delayed the construction of the final PCB by two weeks. However, this extra time was accounted for in the original Gantt Chart by providing a sufficient amount of time for testing. This testing period allowed the PCB design to meet the final deadline without any scrambling. The CAD design was by far the most delayed component. It was completed five weeks after the original goal. This delay can mostly be attributed to the goal of completing all three aspects of the project in parallel. The CAD design was much easier to implement after determining which electrical components would be used for the system. No one on our team had much experience with CAD design before this project so the lack of understanding of what was involved also contributed to the early approximated date of completion.

Hieu’s primary responsibility was the CAD design of the fan’s housing and his secondary responsibility was designing the PCB layout for the battery management chip. Jack’s primary responsibility was the Programming design of the PWM and his secondary responsibility was designing the PCB layout for the MSP430 chip. Kristian’s primary responsibility was researching the electric components to use in the project and his secondary responsibility was constructing and debugging the PCBs. Each team member not only completed their primary and secondary responsibilities for this project, but they also each contributed to outreach to faculty and other groups via papers and presentations. In addition, they each contributed to the final construction of the prototype which involved integrating the Mechanical, Electrical, and Computer components of this project.

Test Plan

Our test plan begins with the Photovoltaic Panel subsystem. Each of the panels will be tested individually in full sunlight to ensure that each one outputs approximately 5 volts, 0.5 amps, and 2.5 watts. If our measured values do not match these specifications, we will have to order new parts - as the ones we have will be declared defective. We will then connect the five photovoltaic panels together - with three of the panels in parallel and two of the panels in series. The combined expected output is approximately equal to 15 volts, 0.83 amps, and 12 watts. If our measured values are too far off from the calculated values, then we will check our wired connections and measure the values again. Once the measured values are relatively close to the expected values, it can be concluded that the Photovoltaic Panel subsystem is functioning correctly and we can continue on to test the Solar Charger Controller subsystem. A flowchart of the algorithm used to test the Photovoltaic Panel subsystem is shown below in Figure 12: Photovoltaic Panel Test Plan.

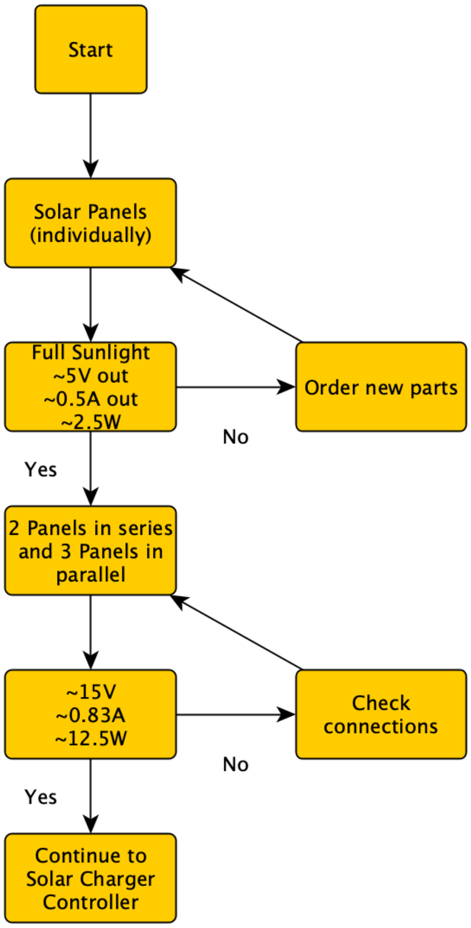


Figure 12: Photovoltaic Panel Test Plan

In order to test the Solar Charger Controller subsystem, we first will test the voltage coming into the circuit. This voltage is expected to be approximately 19.3 volts with no drastic fluctuation. If our measured value is not as expected, we will recheck the capacitor values in the circuit, potentially replace some of the capacitors with different values, and then see if we are now reading 19.3 volts as the voltage coming in. Once our V_in value is as expected, we will then test our voltage at the end of the circuit. This value is expected to be within the range of 3.7 volts to 4.2 volts. If the measured value does not fall within this range, we will ensure all of the connections and component values are correct. Once V_out falls within 3.7 volts to 4.2 volts, we will then connect the Solar Charger Controller circuit to the battery pack. If the battery pack becomes warm to the touch, we will disconnect it and start the entire process over. If the battery pack remains a normal temperature, it can be concluded that the Solar Charger Controller subsystem is functioning correctly and we can continue on to test the Boost Converter subsystem. A flowchart of the algorithm used to test the Solar Charger Controller subsystem is shown below in Figure 13: Solar Charger Controller Test Plan.

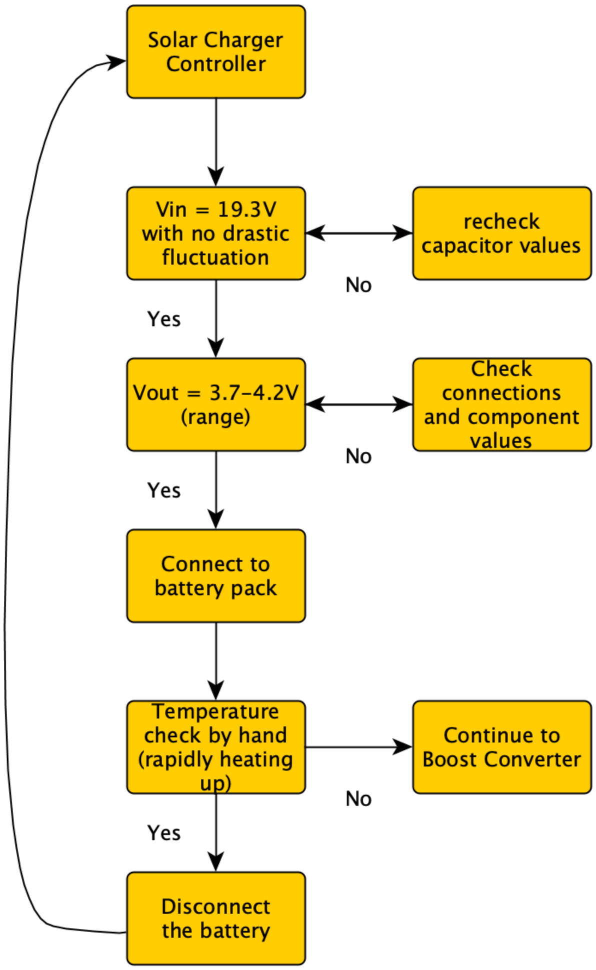


Figure 13: Solar Charger Controller Test Plan

In order to test the Boost Converter subsystem, we first will test the voltage coming into the circuit. This voltage is expected to be within the range of 3.7 volts to 4.2 volts with no drastic fluctuation. If our measured value is not as expected, we will recheck the capacitor values in the circuit, potentially replace some of the capacitors with different values, and then see if we are now measuring within the expected range for the voltage coming in. Once this value is as expected, we will measure the voltage coming out of the Boost Converter circuit. This value is expected to be 12 volts. If the value we measured is actually 0 volts, we will check to see if the SW Pin is a square wave. If it is a square wave then we need to replace our diode in the circuit and begin testing the Boost Converter subsystem from the beginning. If the SW does not have a square wave, we need to replace the LM2731 component and begin testing the Boost Converter subsystem from the beginning. If our measured V_out value is greater than 0 volts but not 12 volts, we need to ensure that our voltage divider components are correct. Once the measured V_out value is 12 volts, it can be concluded that the Boost Converter circuit subsystem is functioning properly and we can continue to test the Buck Converter subsystem. A flowchart of the algorithm used to test the Boost Converter subsystem is shown below in Figure 14: Boost Converter Test Plan.

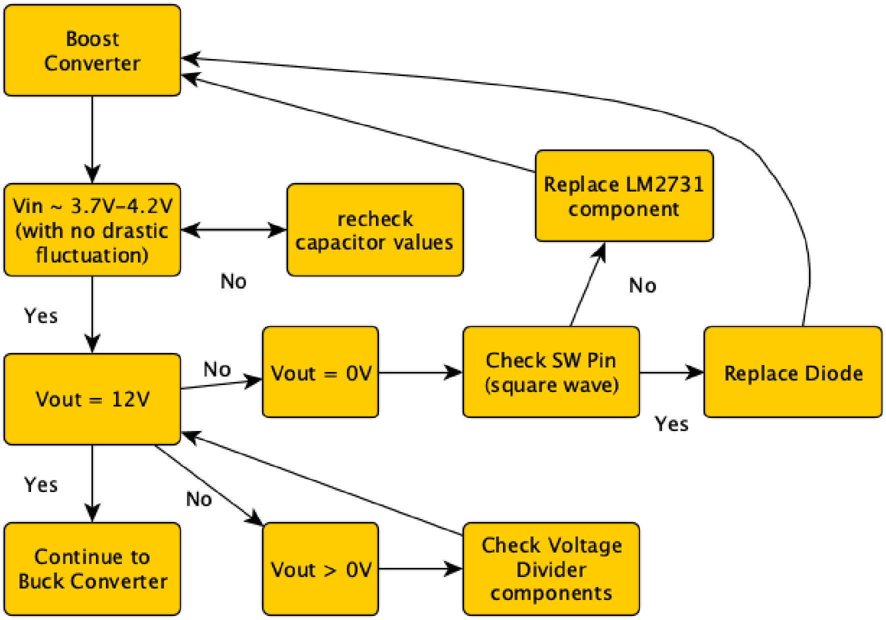


Figure 14: Boost Converter Test Plan

In order to test the Buck Converter subsystem, we have to test both the 3.3 volt Buck converter and the 5 volt buck converter. We will test the 3.3 volt Buck Converter first. The voltage coming into the circuit is expected to be 12 volts. If the measured value does not match the expected value, we will ensure that the PCB connections are correct. Once the measured value matches 12 volts, we will then test the voltage coming out of the 3.3 volt Buck Converter. If the measured V_out value is 0 volts, we need to replace the LP2992 component and start over testing the 3.3 volt Buck Converter. If the measured V_out value is 3.3 volts, we will then check to see if the value is fluctuating. If the 3.3 volts is fluctuating, we will ensure that the bypass capacitors are the correct values. If the 3.3 volts is not fluctuating, we can continue to test the 5 volt Buck Converter.

For the 5 volt Buck Converter, we will first test the voltage coming into the circuit. The expected V_in value is 12 volts. If the measured value does not match the expected value, we will ensure that the PCB connections are correct. Once the measured value matches 12 volts, we will then test the voltage coming out of the 5 volt Buck Converter. If the measured V_out value is 0 volts, we need to replace the LP2992 component and start over testing the 5 volt Buck Converter. If the measured V_out value is 5 volts, we will then check to see if the value is fluctuating. If the 5 volts is fluctuating, we will ensure that the bypass capacitors are the correct values. If the 5 volts is not fluctuating, it can be concluded that the Buck Converter circuit subsystem is functioning properly and we can continue to test the MSP430 subsystem. A flowchart of the algorithm used to test the Buck Converter subsystem is shown in Figure 15: Buck Converter Test Plan.

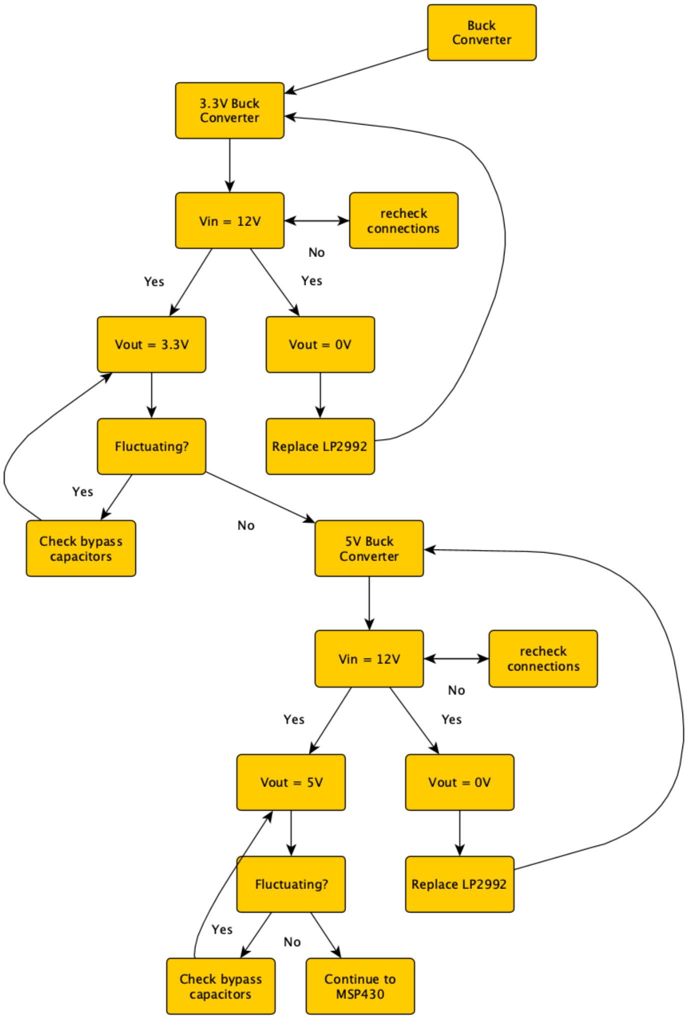


Figure 15: Buck Converter Test Plan

In order to test the MSP430 subsystem, we first will test the V_cc value. The expected value for V_cc is 3.3 volts. If the measured value does not equal the expected value, we will check the PCB connections. Once V_cc matches the expected value, we will check Pin 1.6 to see if there is a Pulse Width Modulation (PWM) signal. If there is no PWM signal present at Pin 1.6, the socket will need to be replaced and the MSP430 Test Plan will need to be restarted. If there is a PWM signal at Pin 1.6, it can be concluded that the MSP430 subsystem is functioning properly and we can continue to test the Logic Shifter subsystem. A flowchart of the algorithm used to test the MSP430 subsystem is shown in Figure 16: MSP430 Test Plan.

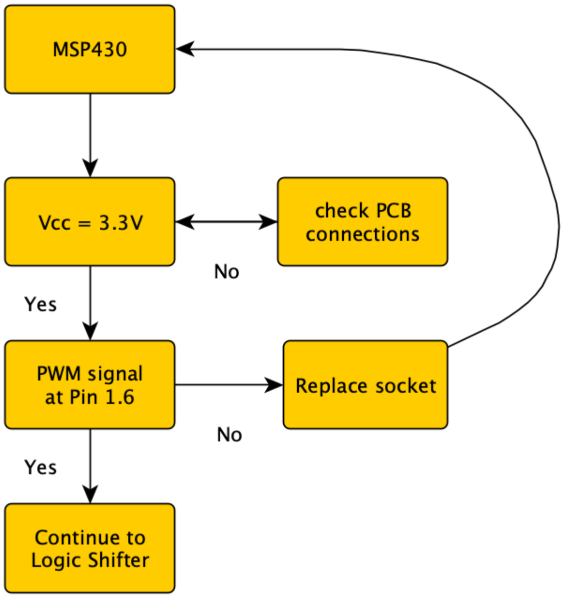


Figure 16: MSP430 Test Plan

In order to test the Logic Shifter subsystem, we have to test both Vcc_a and Vcc_b. Vcc_a is expected to have a value of 5 volts and Vcc_b is expected to have a value of 3.3 volts. If either of the measured values does not equal the expected value, we will ensure that the PCB connections are correct. Once both of the measured values are equal to the expected values, We will check Pin B for a PWM square wave of 3.3 volts. If there is not a PWM square wave of 3.3 volts at Pin B, we will again check the PCB connections. Once the PWM square wave of 3.3 volts is present at Pin B, we will check Pin A for a PWM square wave of 5 volts. If there is not a PWM square wave of 5 volts at Pin A, the SN74LVC component will need to be replaced and the Logic Shifter test plan will need to be restarted. If there is a PWM square wave of 5 volts present at Pin A, it can be concluded that the Logic Shifter subsystem is functioning properly and we can continue to test the Motor subsystem. A flowchart of the algorithm used to test the Logic Shifter subsystem is shown in Figure 17: Logic Shifter Test Plan.

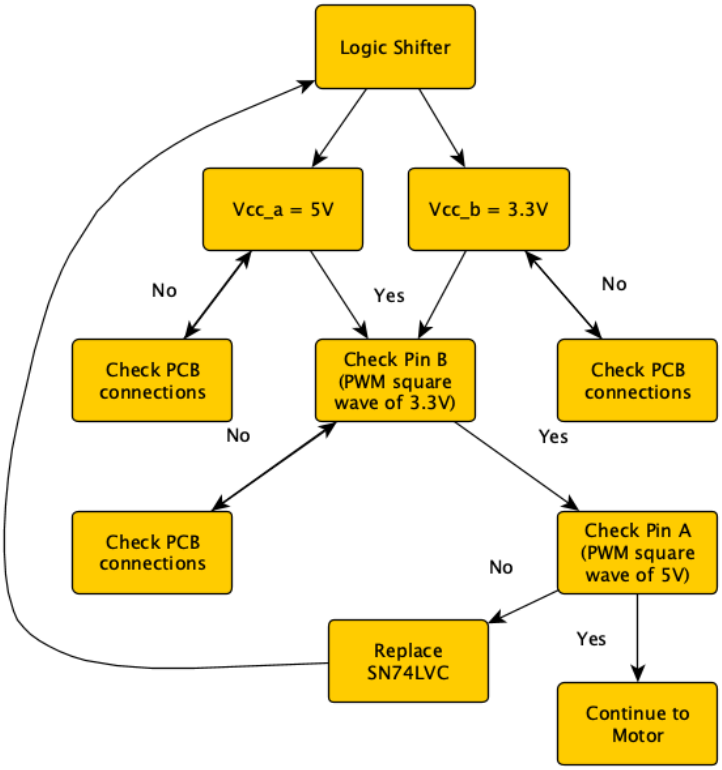


Figure 17: Logic Shifter Test Plan

In order to test the Motor subsystem, we first will test the P1 value. The expected value for P1 is 12 volts. If the measured value does not equal the expected value, we will check the PCB connections. Once P1 matches the expected value, we will check Pin 2 to see if a PWM square wave of 5 volts is present. If there is no PWM square wave of 5 volts present at Pin 2, we will check the PCB connections. Once there is a PWM square wave of 5 volts present at Pin 2, we will check Pin 3 to see if a square wave is present. If no square wave is present at Pin 3, we will check the connection to the motor. Once there is a square wave present at Pin 3, we will check to see if we have a variable motor speed. If we do not have a variable motor speed, we will again check the connection to the motor. If the connection to the motor is correct and we still do not have a variable motor speed, the motor will need to be replaced and the motor test plan will need to be restarted. However, if we do have a variable motor speed, it can be concluded that the Motor subsystem is functioning properly and we can continue to test the Spy Bi-Wire subsystem. A flowchart of the algorithm used to test the Motor subsystem is shown in Figure 18: Motor Test Plan.

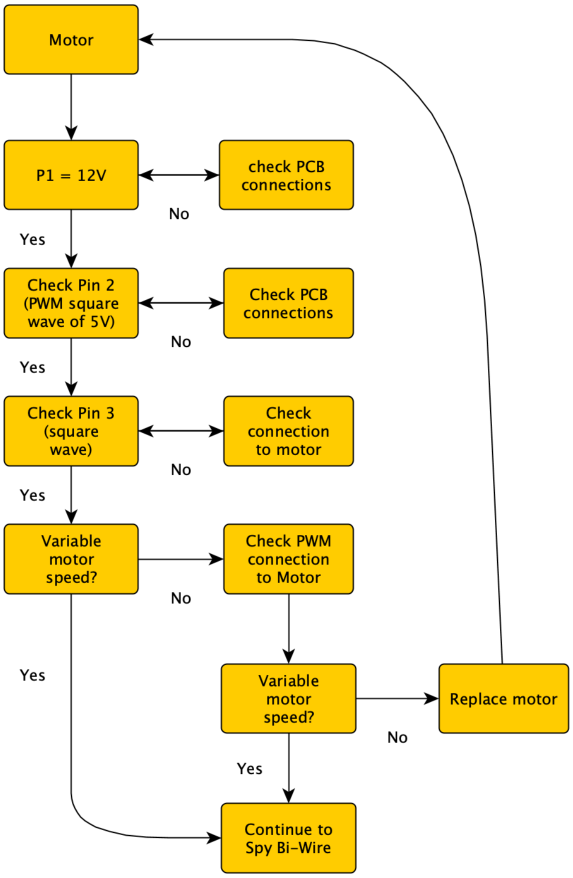


Figure 18: Motor Test Plan

In order to test the Spy Bi-Wire subsystem, we will test the voltage going into the circuit. The expected value for V_in is 3.3 volts. If the measured value does not equal the expected value, we will check the component values. Once V_in matches the expected value, it can be concluded that the Spy Bi-Wire subsystem is functioning properly and our testing of all of the subsystems is complete. A flowchart of the algorithm used to test the Spy Bi-Wire subsystem is shown in Figure 19: Spy Bi-Wire Test Plan.

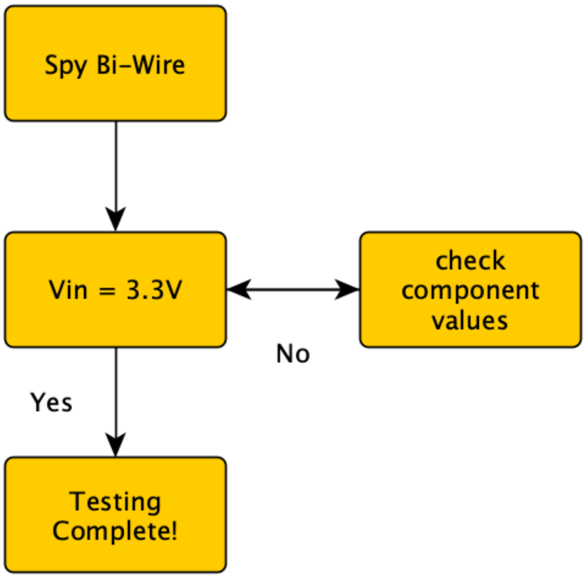


Figure 19: Spy Bi-Wire Test Plan

Final Results

Figure 20: The Final Prototype

The final prototype has two main parts, shown above in Figure 20. The main unit produces power captured from the sun, powers the fan, and stores the excess energy within the Lithium-Ion battery. The three LEDs on the fan indicate valid solar power input, battery charging status, and if the battery is rather low and needs to be recharged. When the button is clicked, the fan will turn on. The fan has four-speed settings once it is turned on: 40%, 60%, 80%, and 100% maximum speed. The fan as a whole can be detachable from the entire unit, as shown below in Figure 11.

All of the subsystems include: the solar panel power outputs, the MP2610 performance, the battery, the Boost and Buck converter performance, the MSP430's PWM, the Logic shifter, the battery sensor LED, and the 3D printed parts. All of the subsystems work flawlessly and the Project as a whole came together superbly in the end.

When tested in full sunlight, the solar panels produced a total amount of 18V, 0.65A, and 11.7 Watts. This is 93.6% accuracy from the information that the manufacturer provided - we considered this a very good result. We also tested the panels indoors and they produced a wide range of voltage from 9V-13V - but they were very low on current, producing a little less than 0.05A. On demonstration day, we couldn't produce enough light indoors to generate a sufficient amount of power; therefore, we utilized power from the VirtualBench's power supply.

The MP2610 works flawlessly at the end, even with all of the errors that we had with it before. At the BATT pin, we received a flat 4.1V, which is exactly as we expected without the battery - without any notable fluctuations. At the switching pin (SW), the voltage we measured is a constant 4.1V without the battery. The LEDs indicate that sufficient input power and battery charging completion works exactly as we predicted. To be more specific, when the battery is finished charging with its voltage at ~4.25V, the battery charging completion LED will turn off. We also tested the chip to see how it would react when charging a completely depleted battery. The chip lowered the charging voltage and slowly increased it as we expected.

We tested the battery very thoroughly. We ensured that even with an overvoltage, it will automatically cut off as we expected. We also tested the over-discharge protection functionality of the battery, it automatically cut off when a short circuit was detected. We also depleted the battery and charged it again to ensure that it works properly.

All of the buck and boost converters work without any drawbacks. The boost converter produces 12V when using either the power supply from the VirtualBench or battery power. It is also the same for two buck converters, they produced 3.3V and 5V continuously without any unaccounted fluctuation.

In order to control the speed of the fan, an MSP430 was used to create a PWM signal to pass to the fan's built-in PWM sensor. The fan works with six speeds. In addition to off, the fan can run with a duty cycle of 20%, 40%, 60%, 80%, or 100%. A pushbutton is used to toggle between these speeds, transferring from off to 20% and upwards until it reaches 100% speed at which point it loops back around to 0%. In order to warn users if the fan reaches a low battery level, the analog to digital converter monitors the voltage across the battery and will light up a designated low battery LED. The threshold that was chosen for this particular battery was 3.9 volts through a process of thorough trial and error.

The logic shifter worked without any problems on the first try. We tested it using a Function Generator from the VirtualBench. The logic shifter will take a 3.3V power supply, a 5V power supply, and a 3.3V PWM signal in order to produce a 5V PWM signal as we expected. We used the signal generated from the MSP430 in order to send it to the logic shifter; and it produces the 5V PWM signal without any unaccounted fluctuation, as predicted.

All of the 3D printed parts came back from the printers in somewhat rough shape. However, after using a decent amount of sanding paper, glue, and tape, the final product came together as a solid unit, as Figure 21 shows below. In addition, we were able to demonstrate how the fan can be detachable from the main unit.

Figure 21: The Finished Fan

Costs

One of the goals of The S.P.E.C.I.A.L. Project was to provide a more inexpensive alternative to the competing products - without compensating in functionality. In total, The S.P.E.C.I.A.L. Project prototype cost approximately $150 - without including the cost of the PCBs and the 3D printed housing (see Figure A1 in the Appendix for a more detailed cost breakdown). We used two PCBs in the final prototype - each costing approximately $33 within the prototype phase. There were also a few components that were taken from the lab kits used within the Fundamentals of Circuits classes at the University of Virginia. This was due to some last-minute calculations that did not allow enough time to submit another part order (i.e LEDs and different values of capacitors and resistors). However, there were some leftover components that were unused from a few of the part orders. In addition, we did have to solder duplicate components into different iterations of our prototype - as we made changes throughout the lifetime of the project.

If The S.P.E.C.I.A.L. Project were to be manufactured in much larger quantities, the cost would be significantly less. Using the same calculations as above, producing 10,000 units of The S.P.E.C.I.A.L. Project would total at approximately $95 plus the cost of PCBs and the 3D printed housing. However, as mentioned before, several of the components would not be needed because we would be producing a final product - not a prototype with several iterations that caused for leftover and duplicate components. If being manufactured in large quantities, the PCB cost would be far less than $33 each; and the 3D printed housing would probably be replaced with a plastic mold. The mold would cost a large amount upfront - but be far less expensive in the long run for each unit. The photovoltaic panels, the lithium-ion battery pack, and the Noctua PWM cooling fan would all be replaced by more industrial components that would be easily mass-produced. These items were chosen for the prototype to demonstrate functionality. The MSP430 chip would also be replaced by a more inexpensive chip for manufacturing purposes.

This chip was chosen for the prototype for producing a PWM signal. In conclusion, if the S.P.E.C.I.A.L. Project were to be manufactured in quantities above 10,000 units, the cost would be estimated to be within the $35 range per unit. This estimate puts The S.P.E.C.I.A.L. Project at a reasonable price range below the competing products - without sacrificing functionality.

Future Work

One area of improvement for this project is in durability. In order to be successfully deployed to developing regions for outdoor use, the fan must be significantly durable and waterproof, which the current prototype is not. It was difficult to create a sufficiently durable prototype given the constraints of the 3D-printer, and a future study on creating a strong outer shell and securing the interior wiring would greatly improve the quality of the product.

This project could also be improved by changing the user interface. In this prototype, a single button was used to switch between the speeds of the fan. While it is a very simple interface, it may be easier to use if the speeds were selected with either two buttons, one to increase the speed and one to decrease the speed, or a rotary encoder. Such improvements would require updates to the code embedded in the MSP430 in addition to the acquisition of the parts themselves.

In addition, it is difficult for solar-powered devices to achieve their maximum power input because the sun is constantly changing position. If these fans were to be relatively stationary and designated for public uses, it would be of great benefit for the solar panel arrays to aim themselves toward the sun in order to produce the greatest power yield.

Finally, there is room for improvement in the size of the fan itself. While the speed of the fan's rotation was fast enough to produce the desired cooling effect, the small scale of the fan left a great deal of potential cooling out of the prototype. Ideally, the next iteration of this design would have a fan blade in the neighborhood of a fifteen-inch diameter in order to balance surface area with portability. Such design changes would be likely to alter the power budget required to power the fan as well and would, therefore, lead to significant changes to the battery management chip design.

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Appendix

Team Name	Quantity	Manufacturer	MFG Part Number	Vendor Part Number	In stock qty	Hyperlink	Price	10,000 units			Component
Cooking With Solar	3	DigiKey	LM2731XMFX/NOPB	296-35165-1-ND	4825	link	2.06	0.94276	6.18	2.82828	Boost Switching Regulator
Cooking With Solar	3	DigiKey	ED20DT	ED3054-5-ND	6,984	link	0.26	0.1056	0.78	0.3168	20 pin socket
Cooking With Solar	3	DigiKey	LP2992IM5-3.3/NOPB	LP2992IM5-3.3/NOPBCT-N	23,234	link	1.14	0.61924	3.42	1.85772	Voltage Regulator
Cooking With Solar	3	DigiKey	LP2992AIM5-5.0/NOPB	LP2992AIM5-5.0/NOPBCT-	18,029	link	1.14	0.61924	3.42	1.85772	Voltage Regulator
Cooking With Solar	3	DigiKey	SN74LVC1T45DBVR	296-16843-1-ND	73,446	link	0.6	0.23113	1.8	0.69339	Logic Shifter
Cooking With Solar	3	DigiKey	61300311121	732-5316-ND	113,819	link	0.13	0.061	0.39	0.183	3 pin header
Cooking With Solar	6	DigiKey	SL23-E3/52T	SL23-E3/52TGICT-ND	1,353	link	0.55	0.3294	3.3	1.9764	Schottky Diode
Cooking With Solar	2	DigiKey	SI4431BDY-T1-E3	SI4431BDY-T1-E3CT-ND	2400	link	0.92	0.39371	1.84	0.78742	MOSFET
Cooking With Solar	2	DigiKey	CF14JT120R	CF14JT120RCT-ND	127903	link	0.1	0.00729	0.2	0.01458	120 ohm resistor
Cooking With Solar	5	DigiKey	C322C224M5U5TA7301	399-13914-1-ND	13585	link	0.41	0.10817	2.05	0.54085	0.22 microfarad capacitor
Cooking With Solar	5	DigiKey	C330C474K5R5TA7303	399-14092-1-ND	16273	link	0.49	0.16906	2.45	0.8453	0.47 microfarad capacitor
Cooking With Solar	5	DigiKey	C324C106K3R5TA	399-13950-ND	9168	link	0.79	0.2338	3.95	1.169	10 microfarad capacitor
Cooking With Solar	5	DigiKey	FG14X7R1E475KRT06	445-173134-1-ND	2341	link	0.52	0.15309	2.6	0.76545	4.7 microfarad capacitor
Cooking With Solar	2	DigiKey	MR5FT50L0	MR5FT50L0CT-ND	9363	link	1.62	0.8778	3.24	1.7556	0.05 ohm resistor
Cooking With Solar	2	DigiKey	CF14JT1K00	CF14JT1K00CT-ND	715340	link	0.1	0.00729	0.2	0.01458	1 kohm resistor
Cooking With Solar	5	DigiKey	C315C104M5U5TA7303	399-9859-1-ND	33061	link	0.24	0.05026	1.2	0.2513	0.1 microfarad capacitor
Cooking With Solar	2	DigiKey	78F820J-RC	M10145-ND	10141	link	0.27	0.102	0.54	0.204	82 microhenry inductor
Cooking With Solar	3	DigiKey	B78108S1472K000	495-5567-1-ND	16995	link	0.4	0.152	1.2	0.456	4.7 microhenry inductor
Cooking With Solar	3	DigiKey	78F100J-TR-RC	78F100J-TR-RCCT-ND	111861	link	0.31	0.1173	0.93	0.3519	10 microhenry inductor
Cooking With Solar	3	DigiKey	1N4933RLG	1N4933RLGOSCT-ND	3258	link	0.23	0.04544	0.69	0.13632	Rectifier Diode
Cooking With Solar	3	DigiKey	MBR0520L	MBR0520LCT-ND	269349	link	0.34	0.06592	1.02	0.19776	Schottky Diode
Cooking With Solar	3	DigiKey	MBRA210LT3G	MBRA210LT3GOSCT-ND	23241	link	0.48	0.18101	1.44	0.54303	Schottky Diode
Cooking With Solar	3	DigiKey	K221K15X7RF5TL2	BC1068CT-ND	11524	link	0.26	0.05343	0.78	0.16029	220 picofarad capacitor
Cooking With Solar	3	DigiKey	RDER71H225K2M1H03A	490-9164-1-ND	12580	link	0.74	0.25061	2.22	0.75183	2.2 microfarad capacitor
Cooking With Solar	6	DigiKey	C330C105K5R5TA7301	399-9886-1-ND	32710	link	0.55	0.18	3.3	1.08	1 microfarad capacitor
Cooking With Solar	3	DigiKey	FG11X7R1C226MRT06	445-173115-1-ND	2902	link	0.86	0.36	2.58	1.08	22 microfarad capacitor
Cooking With Solar	6	DigiKey	CF14JT10K0	CF14JT10K0CT-ND	489371	link	0.1	0.00729	0.6	0.04374	10 kohm resistor
Cooking With Solar	3	DigiKey	PAC300002501FAC000	PPC3D2.5KCT-ND	1404	link	0.85	0.4466	2.55	1.3398	2.5 kohm resistor
Cooking With Solar	3	DigiKey	LVR03R1000FE70	LVRB-.10RCT-ND	4019	link	1.92	0.92896	5.76	2.78688	0.1 ohm resistor
Cooking With Solar	3	DigiKey	CFM14JT750R	S750QCT-ND	31848	link	0.1	0.00758	0.3	0.02274	750 ohm resistor
Cooking With Solar	3	DigiKey	CF14JT51K0	CF14JT51K0CT-ND	6160	link	0.1	0.00729	0.3	0.02187	51 kohm resistor
Cooking With Solar	3	DigiKey	MFR-25FBF52-13K3	13.3KXBK-ND	9948	link	0.1	0.01057	0.3	0.03171	13.3 kohm resistor
Cooking With Solar	1	Amazon	n/a	n/a	n/a	link	13.9	13.9	13.9	13.9	Noctua NF-P12 redux-1700 PWM, High Performance Cooling Fan
Cooking With Solar	3	Mouser	MP26101DR-LF-P	946-MP26101DRLFP	337	link	4.32	1.98	12.96	5.94	Battery Management Charger
Cooking With Solar	3	Mouser	70247-1451	538-70247-1451	1,765	link	2.5	1.29	7.5	3.87	14 pin header
Cooking With Solar	1	DigiKey	MSP430G2553IN20	296-28429-5-ND	3,742	link	2.69	1.1843	2.69	1.1843	MSP430G2553IN20
Cooking With Solar	1	DigiKey	282834-4	A98335-ND	3,231	link	2.68	1.05244	2.68	1.05244	4 pin terminal blocks
Cooking With Solar	7	DigiKey	282834-2	A98333-ND	26812	link	0.88	0.34852	6.16	2.43964	2 pin terminal blocks
Cooking With Solar	2	Amazon	B074TYH68Z	n/a	n/a	link	12.99	12.99	25.98	25.98	Allpowers Photovoltaic Panels
Cooking With Solar	1	Amazon	YDL2018032985	n/a	n/a	link	15.49	15.49	15.49	15.49	Lithium Polymer Ion Battery Pack
									148.89	94.92164	

Figure A1: Prototype Cost Breakdown