APP CONTROLLED SOLAR POWERED STREET LAMP

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Abstract

The purpose of this project was to create a portable and self-sustainable light source that can be remotely controlled. The system will convert solar energy into a battery, which will be used to provide energy to power a bright Light-Emitting-Diode(LED). The user will be able to monitor the system from their cell phone, which will display the current charge of the battery. The user will also be able to control the brightness of the LED from their phone. This system was found to be suitable for the objectives of the project, and was completely functional in a laboratory setting.

Contents

1. Introduction

1.1 Objective

Lighting is a cornerstone of today's world [1][2]. We believe lighting has three major attributes that determine any particular lights use: Portability, longevity, and control. A grid-connected street lamp certainly provides longevity and control, but it's not portable. A battery-powered flood light can be picked up and moved around, but it can't be controlled without physical contact, and eventually will have to be recharged by the grid. It is rare to find a lighting solution that provides two of these three attributes, and impossible to find one that provides all three.

Our objective was to create a lightning system that not only provides all three of these attributes, but does so while being completely independent of a connected grid, providing substantial illumination, and remaining affordable. Our stand-alone and wireless system can easily be picked up and moved without having to worry about running hundreds of feet of power cords through a yard or down a driveway. The system's solar panel and integrated battery charging circuit provide our lamp the longevity of a lamp plugged into the wall in one's own home. Our engineered lighting and control units, in conjunction with our mobile application allows the user to have complete control over the lamp from anywhere, whether it's from the comfort of their own home or from behind their desk at work.

Our design features three main modules, or blocks, that work together to create the final system. The purpose of the power supply module is to safely convert solar energy into chemical energy in our battery. Safety and longevity of the battery are two key design constraints for this component, and dictate the design decisions for this component. The module includes a solar panel, our battery charging circuit, and a lead-acid battery. To ensure proper functionality, our power supply module was required to safely regulate a large range of potential voltage inputs into proper voltage and current levels that the battery can accept. The solar panel can create a voltage differential of up to 22.5 V and a maximum current of 5.75 A, so our design had to safely regulate this to acceptable levels for the lead-acid battery to accept.

The control module allows the user to remotely control and monitor the lamp, which is a very important attribute of our design. This module includes two physical components: a microcontroller, and the user's cell phone or other Wi-Fi capable device. We designed the control module to allow communication between a cell phone and the lamp of at least 250 feet. We also required that the user must be able to both control the brightness of the LED as well as check the current charge of the battery from their cell phone.

The third and final module of our system is the lighting unit. The lighting unit's primary goal is to illuminate the area, as well as allow the LED to be dimmed to any desired level. The unit consists of two main components: A Pulse-Width-Modulation(PWM) controlled transistor circuit and the LED itself. The PWM circuit was required to allow the control of a 12 V LED by much smaller 3.3 V signals that the microcontroller can provide. We required the ability to generate varying PWM signals with the microcontroller, and successfully change the brightness of the bulb to any desired level.

Figure 1 shows how these three modules come together to create the final system. Every requirement of our design was fully realized, and our final system was functional. This report covers the design of each of our modules, it walks through the verifications of our design, and it provides cost analysis of our project. Accomplishments, uncertainties, ethical considerations, and potential future work are addressed at the end of the report. Appendix B contains the final PCB design in figure 8, and Appendix C shows the final implementation of our design in figure 9.

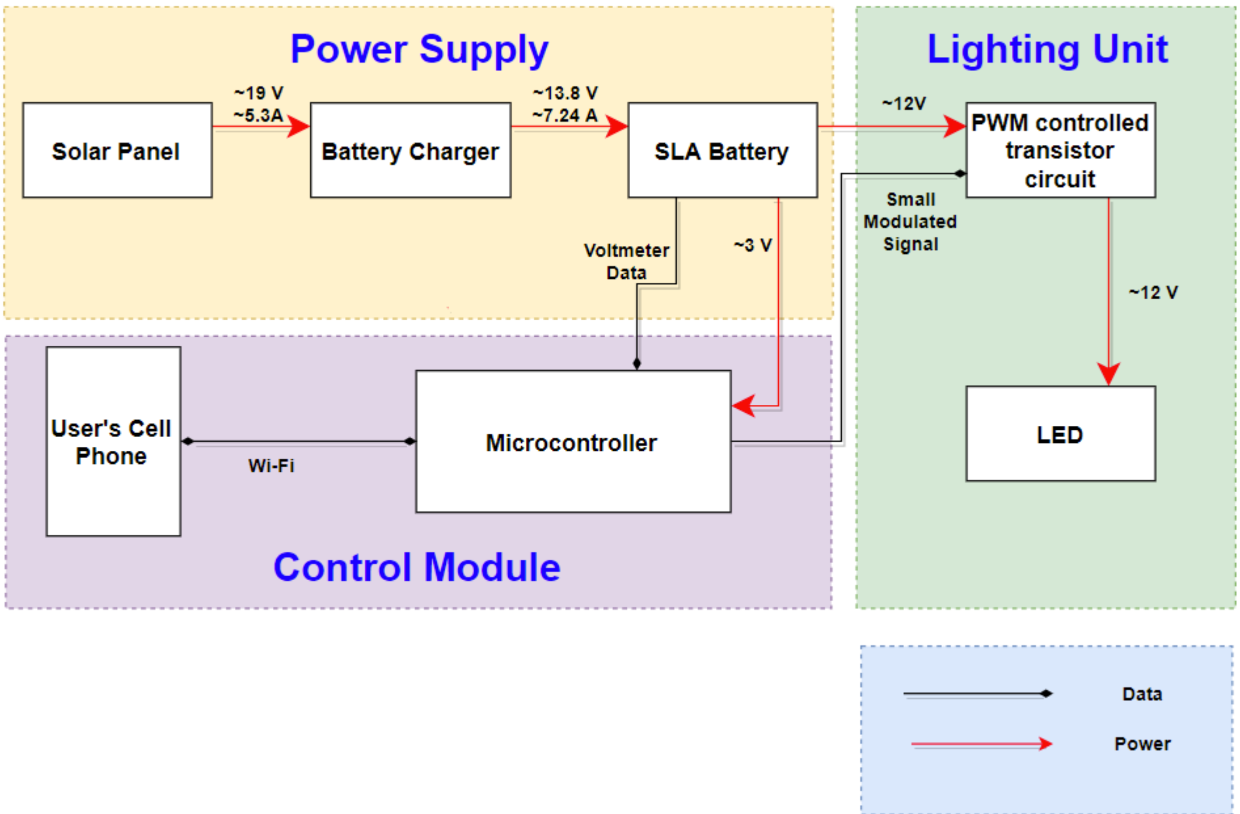

Figure 1. High level block diagram

1.2 Project Goals

During the course of this project, several high-level goals were set by our team. These goals served to keep the project on track and focused, while still allowing our team the freedom to innovate.

- The lamp must be able to sufficiently light a large area and therefore will provide at least 3000 lumens.
- The battery charge must be able to be checked remotely from a cell phone application.
- The brightness of the bulb must be able to be controlled from a cell phone application.
- The battery must be able to be safely charged through the charging circuit.
- The light must be able to be on at full brightness for four hours and at half brightness for another four hours every night.

2 Design

2.1 Power Supply Module

The power supply module controls the power generated by the solar panels and monitors the charging of the SLA battery. This module consists of three separate components: The solar panel, the battery charger, and the SLA battery. Since the solar panel and SLA battery were both components that were purchased and not constructed by our team, the bulk of this section will consist of the battery charger. The power supply module has the high risk for mishaps and physical harm to humans and therefore was considered a top priority in regard to safety and risk management.

2.1.2 Solar panel

The Renogy 100 Watt 12 Volt Monocrystalline Solar panel was selected for to be the primary power generation for our project. During the design phase, the power requirements for our project was determined by assuming the LED would be on with full brightness for four hours a day, and another four hours with half brightness a day. This resulted in an energy requirement of 220 Wh per day. According to solar data found on the NREL website [3], Urbana, Illinois receives about 4.3 suns per day of direct normal irradiance on average throughout the year. Assuming an 85% derate factor, this panel provides 365.5 Wh per day, providing a buffer of 145.5 Wh for days with less sun.

2.1.3 Battery Charger

The battery charger will regulate the power coming in from the solar panel to provide the necessary voltage that our battery will accept. It will also prevent overcharging of the battery by being fed information on the current charge of the battery. This will be implemented using a integrated charge controller for lead-acid batteries. The model number of the charge controller that we will be using is BQ24450. This integrated circuit features regulation of both voltage and current during charging along with precision temperature-compensated reference. The temperature-compensated reference is needed due to the extreme temperature swings that the charging circuit and battery will be subjected to during normal operation. Additional features include two charging modes: Boost Mood, and Float Mode. The voltage from the solar panels will be approximately 18.9V (optimal) and will need to be stepped down to 14.3V for optimal charging. In case of short circuits, this component will have a fuse to prevent any currents over 8A.

2.1.3.1 Design Choices

Figure 2 shows the circuit schematic for the battery charger.

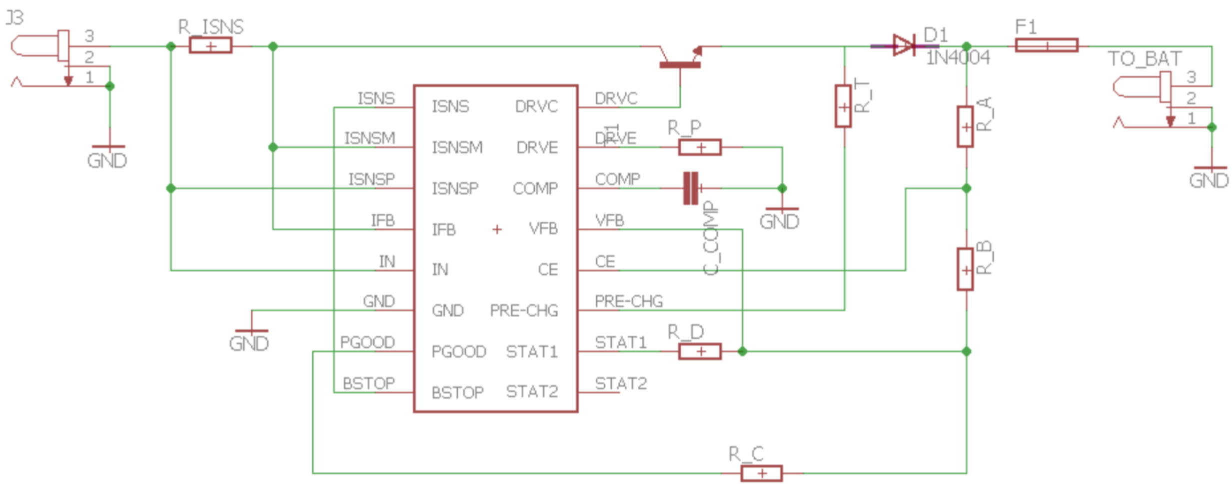

Figure 2. Battery charger circuit schematic.

In order to achieve the proper output voltage and current, the correct size for all the external passive components for the IC BQ24450 had to be known. Using the IC's datasheet [4], the following equations were used to determine the proper values:

$$R_c = 2.30V \div 50\mu A = 46k\Omega \tag{1}$$

$$V_{FLOAT} = V_{REF} \times (R_A + R_B + R_C) \div R_C \tag{2}$$

$$\rightarrow R_A + R_B = 2 \times R_C = 92.8k\Omega \tag{3}$$

$$V_{BOOST} = V_{REF} \times (R_A + R_B + R_C//R_D) \div R_C//R_D \tag{4}$$

$$\rightarrow R_D = 412k\Omega$$

$$V_{TH} = V_{REF} \times (R_A + R_B + R_C//R_D) \div (R_B + R_C//R_D) \tag{5}$$

$$\rightarrow R_B = 10.2k\Omega$$

$$R_A = 92.8k\Omega - R_B = 210k\Omega \tag{6}$$

$$I_{PRE} = (V_{IN} - V_{PRE} - V_{DEXT} - V_{BAT}) \div R_T \tag{7}$$

$$I_{MAX} - C_{HG} = V_{ILIM} \div R_{ISNS} \tag{8}$$

$$\rightarrow R_{ISNS} = 250mV \div 5A = 50m\Omega$$

BQ24450 requires an external BJT to control the current flowing from the input to the output. The choice was made to use the quasi-Darlington scheme. This was chosen due to the high-power requirements that the load requires. TIP142 NPN BIPOLAR 100V 10A was the device determined to be the most suited for the charger's needs [5]. This required another calculation for the external resistor $\mathrm{R_p}$ and can be seen in equation 9.

$$\mathrm{R_p} = (\mathrm{VIN(MIN)} - 0.7\ \mathrm{V}) \div \mathrm{I_{MAX-CHG}} \times \mathrm{h_{FE1}(MIN)h_{FE2}(MIN)} \quad (9)$$

Table 1 below, shows each component of the battery charger and its associated value.

Table 1. Battery Charger Component List with Values

COMPONENT	VALUE
R_A	210kΩ
R_B	10.2kΩ
R_C	46kΩ
R_D	412kΩ
R_T	330Ω
R_P	150kΩ
R_{COMP}	470Ω
R_{ISNS}	50mΩ
C_{COMP}	.22µF
Fuse	8A

2.1.4 SLA Battery

A sealed lead acid battery was chosen to be the best choice for a solar power application. This type of energy storage device was chosen due to the reliability, deep cycling, safety, and affordability of these types of devices. The specific model that was utilized was the Sun Xtender PVX-340T Solar Battery. The PVX-340T is 12 volts with a capacity of 34hA. The smaller capacity was for safety proposes. The voltage was chosen to meet the constraint of the LED light that was utilized for this project. For a more detailed explanation of the of the LED used, refer to subsection 2.2.2 LED in section 2.2 Lighting Unit.

2.2 Lighting Unit

The lighting unit contained all the necessary components to operate the LED. The two main components in this section are the dimming circuit, which controls the brightness of the LED, and the LED.

2.2.1 Dimming circuit

The purpose of the dimming circuit is to allow the dimming of the LED. There are two ways to achieve dimming. One way is to control the current going through the LED, which essentially controls how bright the LED will shine. Our design utilizes pulse width modulation, which adjusts the duty cycle of the LED. This method does not waste power, as in the current manipulation method, and allows for very precise control over the LED. We created code to implement a variable PWM signal from our microcontroller, which allows us to control the duty cycle of a 3.3-volt signal. To allow this small signal to control a much larger 12-volt LED we created the LED dimming circuit seen in figure 3. Using an N-channel MOSFET allows this small signal to essentially control a relay with very fast switching frequency. When the voltage on the gate of the MOSFET is above 2-volts the circuit completes, and the LED turns on.

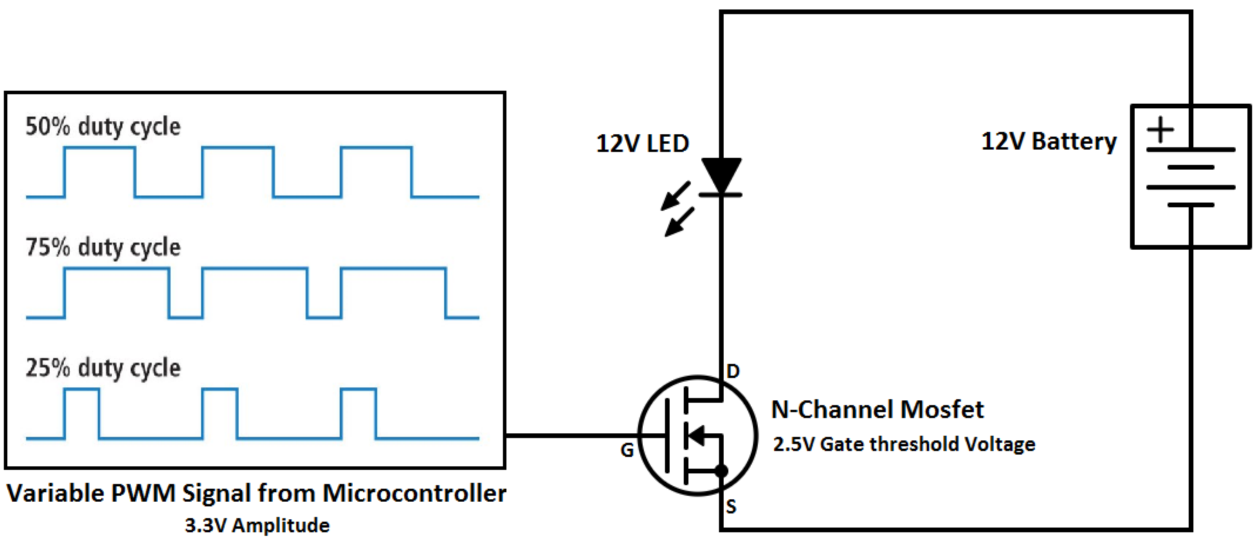

Figure 3. LED dimming circuit schematic.

2.2.2 LED

The LED used for this project was manufactured and sold by 12Monster and had the following specifications:12-24 volts, 33 watts, and 2640 lumens. An added benefit of this LED is that it has a constant current driver to add in the low power consumption required for off grid applications.

2.3 Control Module

2.3.1 Microcontroller

The microcontroller used for this project was the ESP32, which is sold by Espressif Systems. This microcontroller is both Bluetooth and Wi-Fi capable. Because of the increased range of a Wi-Fi connection, we decided to have the microcontroller running as a web server to control our lamp. Using the Arduino platform, we initialized a web server using hard-coded SSID and password for the Wi-Fi network that we were planning on using. Once the ESP32 makes a connection with the Wi-Fi, it then connects to a particular IP address, and then it is able to modify outputs based on the most recent connection to that IP. In our system, the address was http://192.168.92.43/brt/XXX, where XXX corresponds to a brightness value between 0 and 255. This will then output a certain PWM to a specific pin, which will be used to control the brightness. In figure 7, there is an example of the pin output where the brightness value is set at 51, or 20% brightness.

2.3.2 User's Cellphone

The user's cell phone was controlled by a proprietary Android Application that was built specifically for this project. As you can see in figure 4, there is a very simple design for the application. Three main sections of the application are the battery charge check, the on/off switch for the lamp, and the brightness adjustment. Because of the way that we designed the microcontroller, we had similar functions for the on/off switch and the brightness change. We could use the same URL to change the brightness to 0 as we could to turn off the light. It was also very similar for turning on the light. There was a value (*previousBrightness*) that was stored in order to recall the last brightness that was used before the lamp was turned off. The light will then be turned directly to that brightness when the "On/Off" button is pressed. The other central aspect of the application is the battery charge check. This was a mathematical model that we used in order to determine the accurate value of the battery charge percent remaining [6]. This was based on multiple factors: the time of day, the amount of time with the light on, how bright the light is when it is on, the time of sunrise and sunset, the time of year, the power of the sun, and data we took from testing the battery. The state of charge will then allow the user to understand whether or not they can keep the light on for more time.

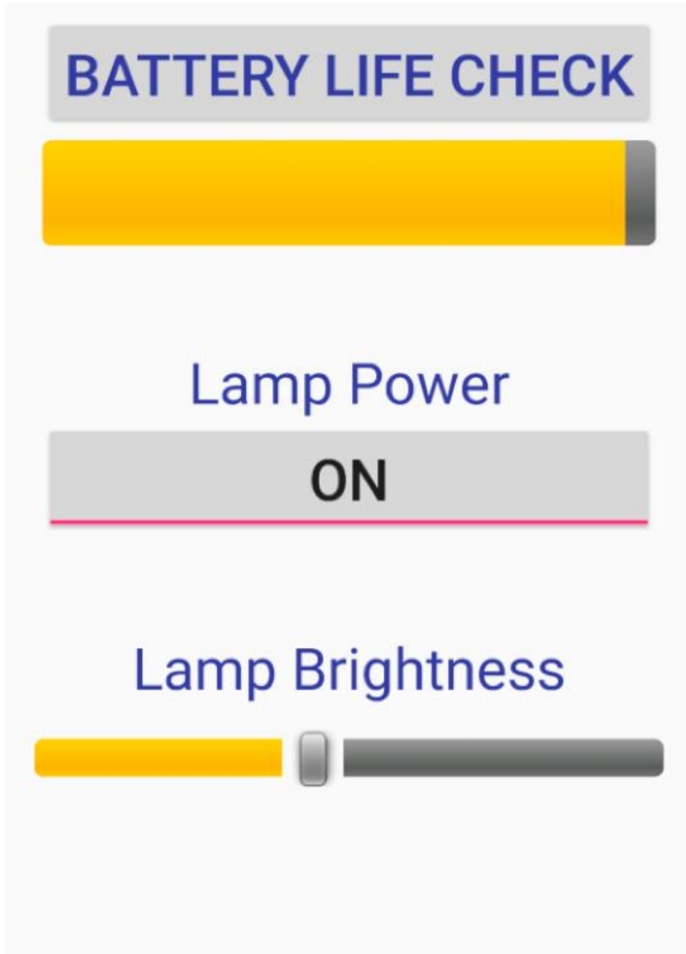

Figure 4. Mobile application's user interface

3. Design Verification

The design verification process that was employed consisted of several steps. The first step verified each individual component functioned as designed, with little to no margin for error. The second step for verification was to integrate each component into a single unit and perform tests to ensure proper operation. A complete requirements and verification table can be found in table 6 in Appendix A.

3.1 Power Supply Module

The power supply module was a main component for our project and therefore, extensive verifications needed to be performed to ensure the power generated from the solar panel was transferred efficiently and safely the energy storage device.

3.1.1 Solar Panel

There were no verifications performed on the solar panels. Renogy provided a detailed datasheet which if needed, could be referenced.[7]

3.1.2 Battery Charger

In order to verify that the battery charger circuit was fully functional and safely charges a battery, the first step taken was to connect a power supply to the input, where the solar panel is designed to connect. The chosen battery was then connected to the charging circuit output, fully charged. Note that the choice to use a fully charged battery was done if the charging current in boost mode was to great. Since the battery was fully charge, the first mode tested was float mode. Once all connections were ensured to be correct, the power supply was turned on. The supply was then ramped up from a voltage of 3V up to 23V. Measurement were taken of the current flowing into the battery to ensure if the charging was being done. Results of this test can be seen complied with the other charging circuit test in table 2. The results of this test show that that a charge of the battery was occurring, and that float mode was working correctly.

The second mode that was verified was boost mode. The procedure for testing this mode was the same as testing for float mode, however, the battery was discharged to half of its capacity. Measurements were taken of the current flowing into the battery and the results of these measurements were compiled into table 2. The results showed that the charging circuit was operating in boost mode with a charging current of 3.02A.

Once both modes were verified to be fully functional, testing started to ensure that the charging circuit could switch modes during normal charging operations. This was done by first discharging the battery to three fourths its capacity and reconnecting it to the circuit. Test procedures were then to ramp the voltage from the power supply up to 18.9V. Once the circuit was energized, measurements of the charging current were taken until 10 minutes after the current reduced to the float mode values. The results of these measurements were tabulated and showed that the charging circuit will change from boost mode to float mode once the battery becomes very close to full capacity. Figure 5 show this abrupt change.

Table 2. Verification Tests for Float and Boost Modes

Float Mode								
Input Voltage (V)	3	6	9	12	15	18	21	23
Charging Current (A)	0	0	0	0	1.01	1.02	1.01	1.01
Boost Mode								
Input Voltage (V)	3	6	9	12	15	18	21	23
Charging Current (A)	0	0	0	0	3.02	3.02	3.02	3.02

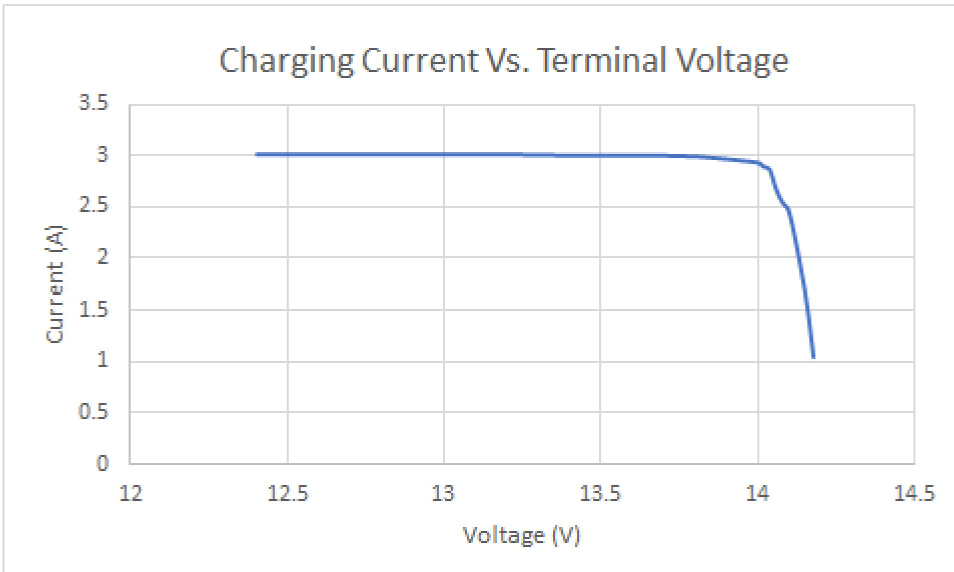

Figure 5. Verification of changing modes.

3.1.3 SLA Battery

There were no verifications performed on the SLA Battery. Sun Xtender provided a detailed datasheet which if needed, could be referenced.[8]

3.2 Lighting Unit

3.2.1 LED

To test the LED, we simply hooked it up to a 12-volt source and observed that the LED did in fact turn on. The verification of the LED is also integrated into the verification of our dimming circuit, as they go hand in hand.

3.2.2 Dimming circuit

To test the dimming circuit, we looked to verify a few major things: That the circuit did actually dim the LED, that dimming the LED reduced our power consumption, and that it did so in a roughly linear fashion which allows for an accurate mathematical model of power consumption from the battery. To test all these things, we fully connected our lighting unit, and ran the power going to the LED through a watt meter. We then set the brightness on our app, and thus the duty cycle from the microcontroller, to various levels and recorded the power consumption at those levels. After tabulating the results, we created a scatter plot out of the data and displayed the linear regression as well as the r-squared value of the regression. This plot is shown in figure 6. Observation of this plot shows that when we increase the brightness value on our application, the LED gets brighter, and burns more power in an almost perfectly linear fashion.

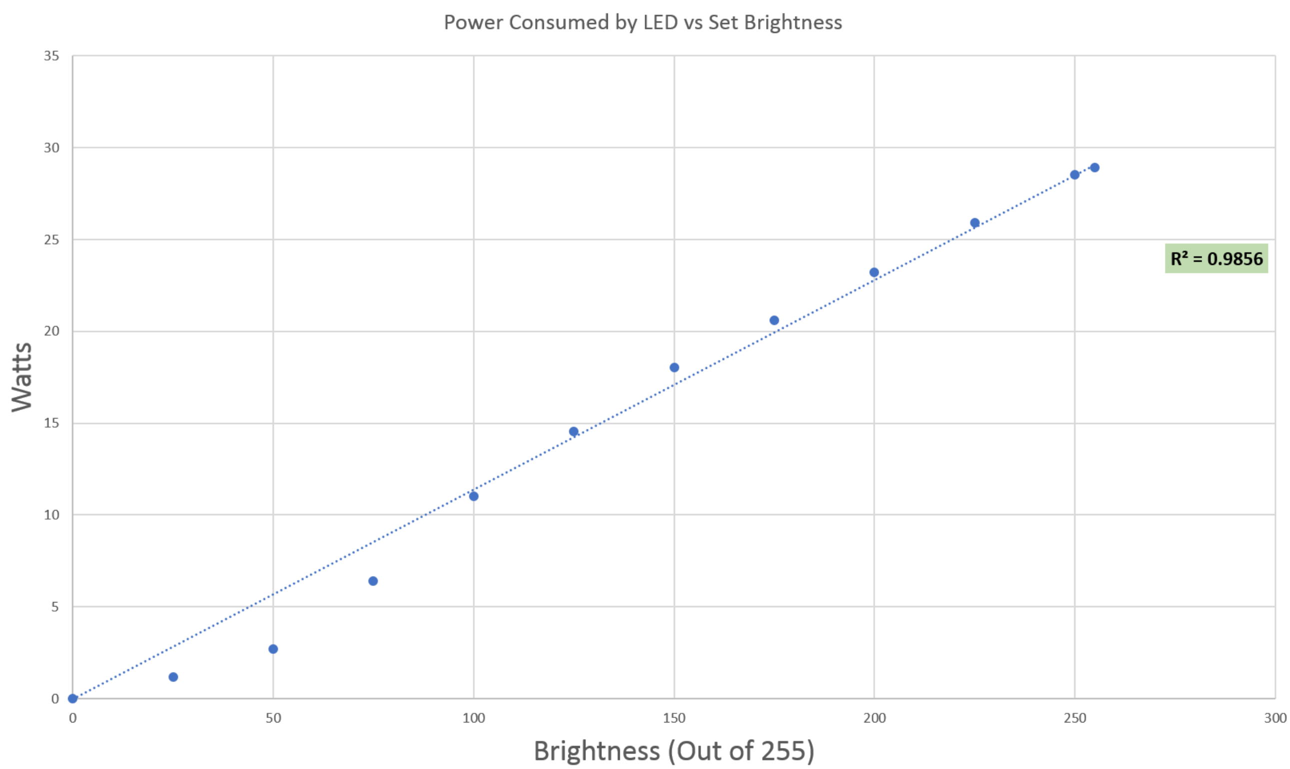

Figure 6. Verification of dimming circuit

3.3 Control Module

The control module was verified by going through simple steps that are directly related to the usability of the control module. The user's experience is directly related to this component.

3.3.1 Microcontroller

In order to test the microcontroller, onboard LED was used to initially test that a proper connection was made with the web server. Once the results were seen from the onboard LED, the code was changed to use the proper output pin. The output from the pins was then put into the oscilloscope to get the output shown in Figure 7. The 20% brightness is directly correlated to the 20% duty cycle. This proved that the output was working correctly.

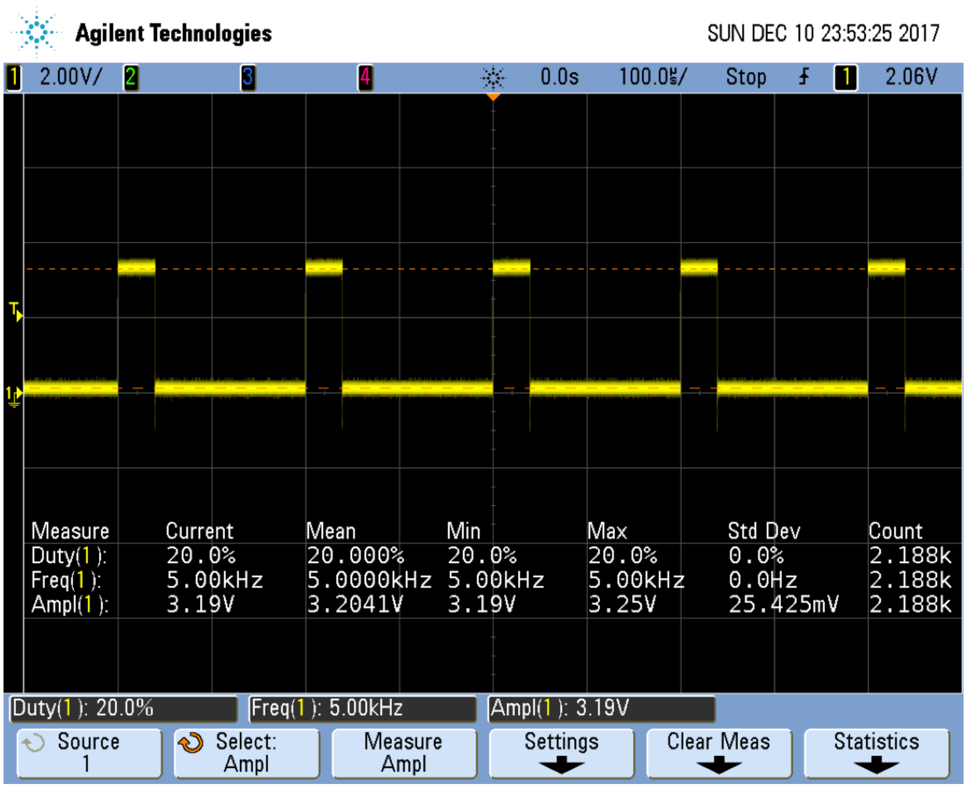

Figure 7. Verification of PWM signal

3.3.2 User's Cellphone

In order to test the application that is used by the user's cell phone, there were various steps that were taken to verify the functionality of the application. The first test was to check the On/Off functionality of the application by connecting to Wi-Fi and walking a specific distance and pressing that button multiple times to see the light go on and off. The next test is to see a distinct change in brightness by opening the application and move the brightness progress bar slowly up the bar until it is at full brightness. The visible change was quite distinct, and the full brightness was extremely bright.

4. Costs

All part costs associated with this project are itemized in section 4.1 Parts and can be seen in table 3. All labor costs incurred during the development of this project are itemized in section 4.2 Labor and can be seen in table 4. The total cost for parts and development can be seen in table 5 in section 4.3 Total Cost.

4.1 Parts Itemized List

Table 3. Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
BQ24450 Integrated Charge Controller For Lead-acid Batteries	Texas Instruments	6.74	3.82	6.74
ESP32 Microcontroller Development board	HiLetGo	11.99	11.99	11.99
RNG-100D 100W Solar Panel	Renogy	139.99	139.99	139.99
33W 12V LED Flood Lamp	12Vmonster	32.99	32.99	32.99
Sun Extender PVX-340T Battery	Sunxtender	125.32	125.32	125.32
TIP142 Quasi-Darlington BJT	ON Semiconductor	1.72	.73	1.72
Passive components	Yageo	1.90	.41	1.90
FQP30N06L 60V LOGIC N-Channel MOSFET	Fairchild Semiconductor	1.43	.61	1.43
8A Safety Fuse	Bussman	1.37	.59	1.37
PCB Fabrication	PCBWay	1.00	.54	1.00
Four Cinch connectors	Cinch Connectivity Solutions Johnson	2.60	1.20	2.60

Total		327.05		318.19

4.2 Labor

Table 4. Labor Costs

Team Member	Hourly Rate	Total Hours	Total Cost(Rate*Hours*2.5)
Kevin Dahm	$35	160	$14,000
Justin Lindstrom	$35	160	$14,000
Brendan Weibel	$35	160	$14,000
Team Total	$35	480	$42,000

4.3 Total Cost

Table 5. Total Costs

Parts	Labor	Total
$318.19	$42,000	**$42,318.19**

5. Conclusion

5.1 Accomplishments

This project successfully implemented a wirelessly controlled portable street lamp lacking only in solar panel integration. While charging the battery with the designed charging circuit was successful, a solar panel was never use. However, integrating a solar panel will require minimal work as the design has accounted for a plug and play interface. Furthermore, the control module worked exactly as designed. A new server was successfully created to control the LED with wireless communication from remote locations, up to at least a 250-foot distance.

5.2 Uncertainties

During the design and implementation process, getting the charge controller to work correctly was our largest concern. The BQ24450 IC proved to be quite difficult to get working within our specifications. The datasheet was used for proper sizing of all external passive components, however, our team could not achieve desirable results. To fix the issue, we needed to oversize the values of R_P and R_T. This was done after we realized the critical roles these resistors play in determining the modes of the IC.

5.3 Ethical considerations

We, the members of ECE445's group 2, realize the impact that our product can have on the quality of living around the globe, and in taking full responsibility of our profession and to the consumers that we do business with, we do hereby commit ourselves to the best professional and ethical standards and agree will all ten of the IEEE Codes of Ethics [9]. More specifically:

Codes #1 and #9 due to the potential that our product can cause bodily harm or death. To ensure no harm befalls our end user, strict protocol will be used to ensure that the mounting pole is stable and will not fail unless unforeseeable "acts of god" occur. Furthermore, all electrical components will have insulating material to prevent any potential shock hazards.

Codes #2, #4, #8, and #10 due to the proximity that we will be working with our peers and the bonds that we share with them. We hold ourselves with high moral standards and integrity, because of this we understand that our peer's work is theirs and theirs alone, and by no means shall we demean ourselves by passing their work as are own.

Codes #3, #6 and #7 due to the vast amount of data readily available, we ensure all credible sources are known and nothing that we publish is false. The result of making false claims would not only cause harm to ourselves, but could bring both mental and physical harm to the end users. A system of checks will be enacted to ensure each member of our group remains honest and open for the entirety of this project.

For our project, safety concerns that we will be responsible for include: LED light housing and support pole falling and causing injury or death. This will be addressed by ensuring that all components are fastened together tightly, and the support pole will have a heavy enough base to prevent it falling during extreme weather events. Next is the battery and circuitry shock hazard causing injury or death. This will be addressed by isolating the high voltage side of our circuit and enclosing it with an intrinsically safe material. The last safety concern is the light increasing in brightness to point of causing temporary or permanent blinding. This issue can be controlled by using LEDs that can only produce a certain amount of lumens.

5.4 Future work

In order for this device to be a fully functional commercial product, there are a few extra design additions that would have to be implemented. The first of which, is adding maximum power point tracking in series with the input of the charging circuit. This will ensure that only the maximum power will be extracted from the solar panel. This will also help with impedance matching of the source and load.

Secondly, adding a linear voltage regulator from the 12V battery to the 5V input of the microcontroller would eliminate the need for a secondary small power source. This would add significantly to the value and usability of the device, as there would be no need to manually recharge the smaller battery. This would be a very easy and inexpensive addition to the overall design and PCB board changes.

Lastly, the current state of charge measurements uses a mathematical model with a high margin of error. This lowers the overall quality and reliability of the mobile application due to the consumer being unable to determine if the LEDs is actually emitting light. To remedy this, switching to a far more complex and less intuitive electronic method should be done. This would be the most difficult and costly addition, however, the end results would improve the overall value of the device.

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Appendix A: Requirement and Verification Table

Table 6. System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
Battery Charger		
1. Regulates a voltage input of 12V to 23V to a safe charging voltage of 13.14V to 14.5V *Input 17.5 +/- 10%; Output 14.3V +/- 10%*	A. 1. Generate 3V input. 2. Monitor output voltage and save data. 3. Slowly step up input to 23V while measuring. 4. Maintain 23V for an hour to see temperature changes. 5. Verify it stayed in desired range. B. 1. Connect Battery charger to fully discharged SLA battery. 2. Measure voltage and current at battery terminals. 3. Ensure all charging stages are met.	Y
LED Driver		
1. Able to provide 12V to the LED with option to dim the LED at the user's will. *input 12V +/- 5%; output 12V +/- 5%, 2.50A +/- 1%, 33w minimum*	*1. Place a 12V voltage source at circuit input.* *2. Monitor voltage and current near LED.* *3. Ensure LED is lit while pin GPI0 0 of the microcontroller is at 100% duty cycle.* *4. Modify duty cycle to ensure LED dims.*	Y

Microcontroller		
1. Must be able to communicate with a cell phone over Wi-Fi from a range of 250 feet 2. Must be able to calculate battery charge displayed as a percentage	A. 1. Configure the ESP32 to connect to the cell phone with the SoftAP via bluetooth 2. Place the lamp 250 feet away 3. Connect to Wi-Fi (blufi_softap) on the cell phone 4. View value of charge on cell phone from this connection B. 1. Fully charge battery 2. Use Ammeter to find the values for the discharged current at any time, t. 3. Plug values into the Coulomb counting equation in order to find correct value 4. Compare calculation to value displayed on cell phone (which is the result of the microcontroller's calculation)	Y
APP		
1. Must be able to view the battery charge and turn off/on the light from a mobile application	1. Once user opens the app, user can see a value of percent charge of the lamp as well as a visual representation of that percentage. 2. The user also sees a large switch on the screen which has on and off buttons in order to turn the lamp on and off.	Y

LED		
1. Must sufficiently illuminate dark area while using 33W	1. Use Voltmeter to find the current and voltage drop through the device while it's on. 2. Ensure it is drawing 33W of power over 12V. 3. Turn off other lights and ensure it provides adequate lighting to the surrounding area	Y

Appendix B: PCB Design

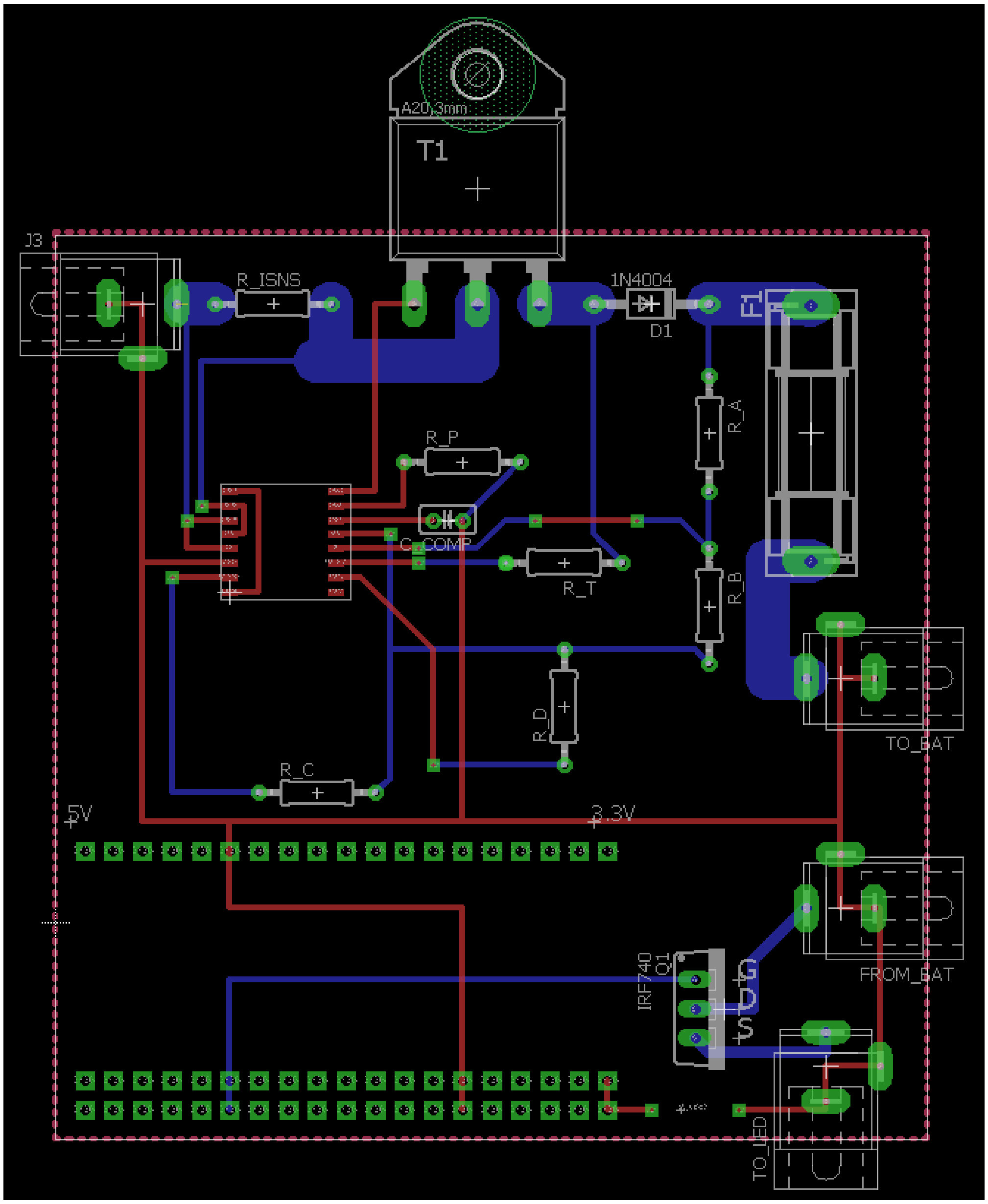

Figure 8. Main PCB: contains battery charging circuit, microcontroller, and LED driver circuit.

Appendix C: Final Implementation of Physical Design

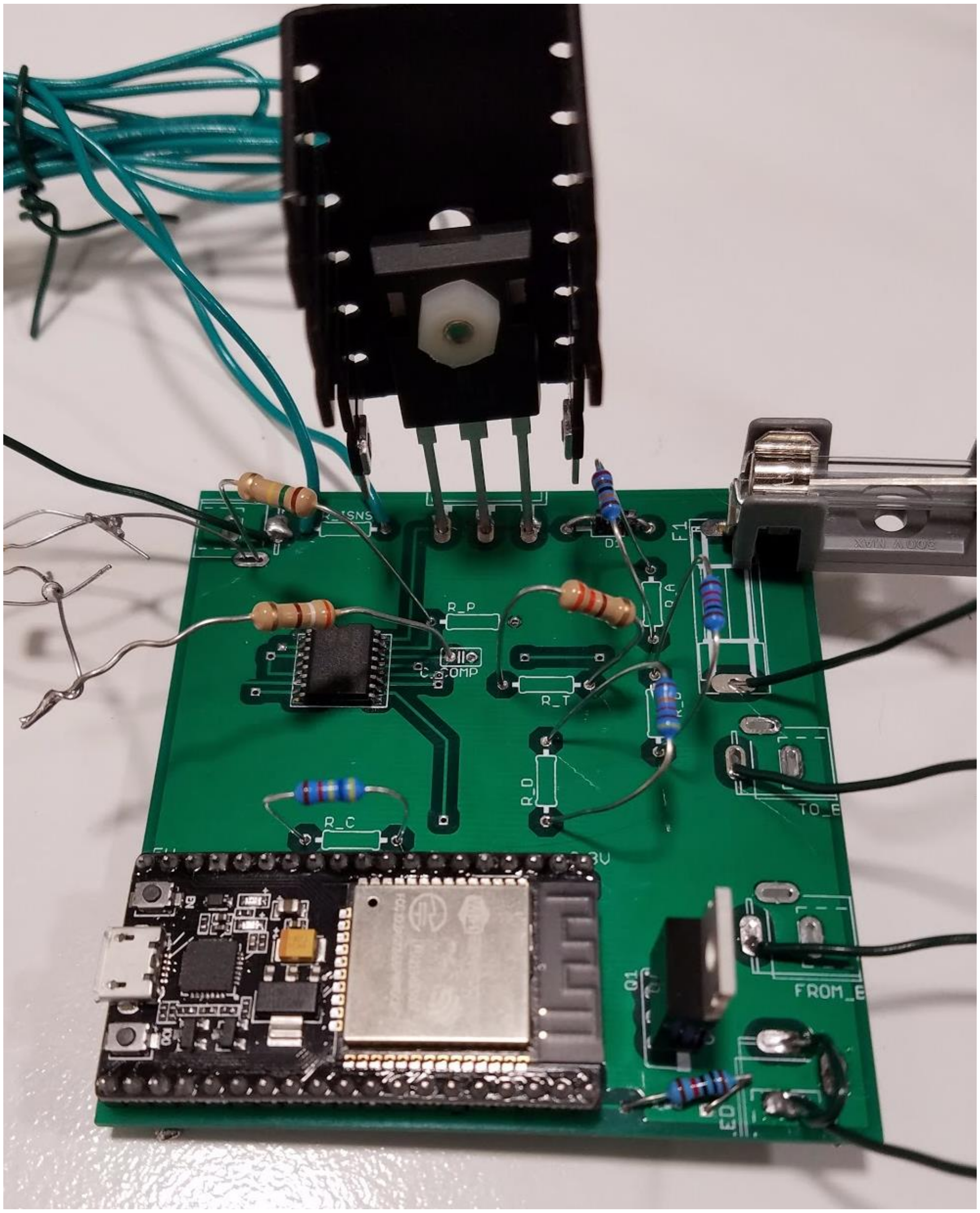

Figure 8. The final PCB used during the final demonstration.