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CubeSat electronic power system

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Date: June 6th, 2014

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY:

Callie Wallace and Benjamin Lynch

ENTITLED:

CubeSat Electronic Power System

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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CubeSat Electronic Power System

by

Benjamin Lynch

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SENIOR DESIGN PROJECT REPORT

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for the degree of
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Abstract

Cube Satellites are small satellites used by NASA and other non-governmental space companies as a cost-effective means to get a payload into space to perform research and develop new technologies. The Robotic Systems Lab at Santa Clara University has designed and launched several Cube Satellites over the last ten years. We will be continuing the design of a 3U CubeSat began by a senior design team last year. The goal of this project is to design and build an electronic power system (EPS) for the CubeSat. The EPS must be able to power all system components, including the communication board, the radio and beacon, as well as any additional customer payload. The system is designed to provide power for the satellite throughout the entire orbit, even during periods of eclipse when the satellite will be unable to generate power. In addition, this project is experimenting with a new technology, supercapacitors, to test their potential uses in space. The EPS is a hybrid system utilizing both batteries as a reliable source of power storage and supercapacitors in order to test their capabilities.

Keywords

cube satellite, CubeSat, nano-satellite, supercapacitors, electronic power system

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1.1 Problem Statement

In collaboration with the SCU Robotic Systems Lab, this project designed a fully-functioning electronic power system (EPS) for a 3U CubeSat. The EPS will provide power for all system components and any additional customer payload throughout the entire orbit, including periods of eclipse without power generation. In addition to providing reliable power, the EPS will also experiment with a new technology, supercapacitors, in order to explore their potential uses in the space industry.

1.2 Background

As the space industry has grown, satellites have grown in complexity and size, which has improved their capabilities but also increased their costs. Space research and technology development is inhibited by the high-cost and high-risk of satellite development and launch. Large satellite projects tend to rely upon outdated technologies because of their proven flight history rather than experimenting with cutting-edge technologies. CubeSats were developed as a lower-risk and cost-effective means of satellite technology development as well as space research.

CubeSats, or nano-satellites, are small satellites typically between 1-10 kgs. CubeSats are typically student-built and low-cost under $50,000 to build. However, the reason they are so cost-effective is because CubeSats 'piggyback' onto the launches of larger satellite or rocket launches. Launching a CubeSat by itself could easily cost over $100,000. Using the Poly-Pico Satellite Orbital Deployer (P-POD), up to three CubeSats can be carried on a rocket as a secondary load and launched into a low-earth orbit. [1]

The low-cost nature of CubeSats makes them an ideal method for NASA, as well as other non-governmental space companies, to develop space technologies. Companies are willing to

[1] http://www.diyspaceexploration.com/what-are-cubesats/

experiment with and test technologies they are unwilling to risk on more expensive projects on CubeSats. In addition, CubeSats can also be used to perform space research and observation by carrying a camera or scientific measurement device, such as an accelerometer or magnetometer, to take measurements in space.

The SCU Robotic Systems Lab has designed and built several CubeSats over the last fourteen years. Our project continues the design of the Unspecified Payload Active Attitude Control Nano-satellite (UPAACN) began by a senior design team last year. The heritage of the RSL CubeSat program means projects are able to build upon past designs while furthering development of new ideas and technologies.

1.3 Project Objectives

The objective of this project is to design a fully-functioning electronic power system for the 3U CubeSat. The EPS must be able to power all system components, including the communications board, the Dallas Mastic controller, and the radio/beacon. The EPS must also be able to power an additional customer payload. Currently, the specific payload is unknown, so the system has been designed for the power needs of typical payloads based upon the experience of the RSL. Potential payloads include anything from a camera to scientific equipment like an accelerometer. The EPS must be able to sustain power during the satellite eclipse. A typical low-earth orbit (LEO) is 90 minutes with 60 minutes in sunlight and 30 minutes in eclipse.

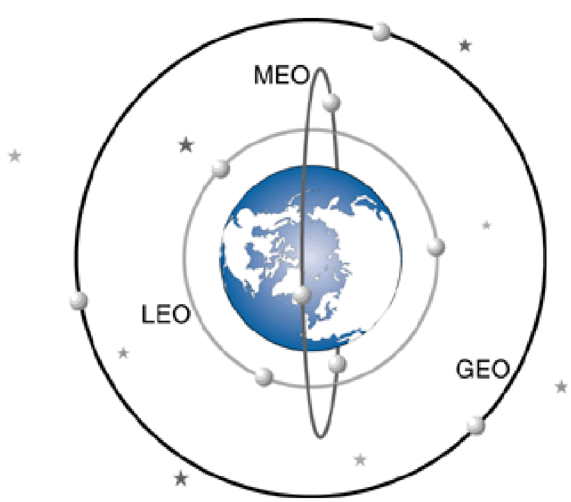

Figure 1: Low-Earth Orbit

The EPS must be able to store enough power to sustain satellite operation throughout the 30 minute eclipse without power generation. Finally, the project will experiment with a new technology: supercapacitors. The design of a hybrid-supercapacitor system will explore the potential for supercapacitors and open doors for future projects utilizing this exciting new technology

Chapter 2: System Overview

2.1 Electrical Components

The Power System being designed is part of a much larger electrical system. In Figure 2 below the System Block diagram can be seen.

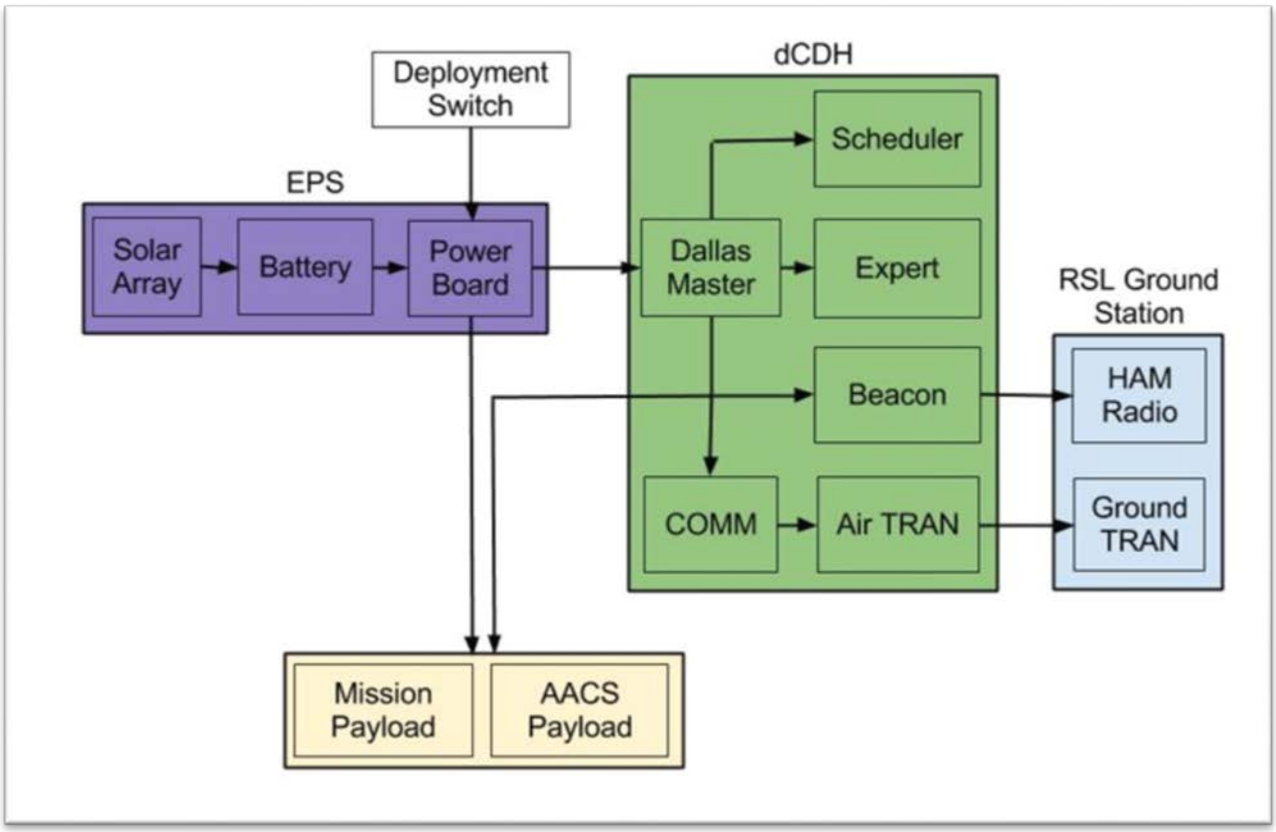

Figure 2: System Block Diagram[2]

Figure 2 shows all of the system components involved in operating the satellite. The green block in the center represents the communications board. The communications board is responsible for all the data collection and transmission, as well as any control systems management within the satellite. In order to power the components on the communications board, a 12V and 5V input

[2] https://scholarcommons.scu.edu/handle/11123/200

supply are required. At Santa Clara we have the equipment seen in the blue box on the right. The HAM Radio is for receiving data and there is a transmitter for sending commands to the satellite. On the bottom box is the customer payload, which will be determined as a last step of the process. Lastly, the purple box on the left contains the elements related to the power system. The Solar panels have been designed by a previous team, but the storage and distribution of that power is the focus of this project.

2.2 Power Generation

As mentioned above, the power input comes from a system of 4 solar panels. One panel is attached to each long side of the CubeSat frame so that while the satellite is rotating in space it will always be exposed to sunlight. At the max power point, each panel is able to output 10.95V at 280mA. Diodes are used to ensure that the panel outputting the most power is always the input of the circuit.

2.3 Power System Overview

Figure 3 shows the block diagram of the designed power system. The output of the solar panels is first run through the power path control. While in sunlight operation, the power path will select the voltage from the panels based on its higher voltage. The output of the Power Path control is sent to charge the supercapacitors and provide the power to the 5V and 12V Voltage regulators. During the eclipse, the power path will select the battery and use the stored energy to provide power to the circuit components.

In the schematic, the supercapacitors can be seen in the lower left. In this implementation, their sole purpose is to power the beacon. The Stenstat beacon pulses at 5V and up to 650mA. During the transmission window, the beacon may be pulsing regularly for up to 5 minutes. The supercapacitors have been used because of their potential in high power short duration applications. With the beacon drawing large spikes of power, it is believed that a supercapacitor could be an ideal component to fulfill this need.

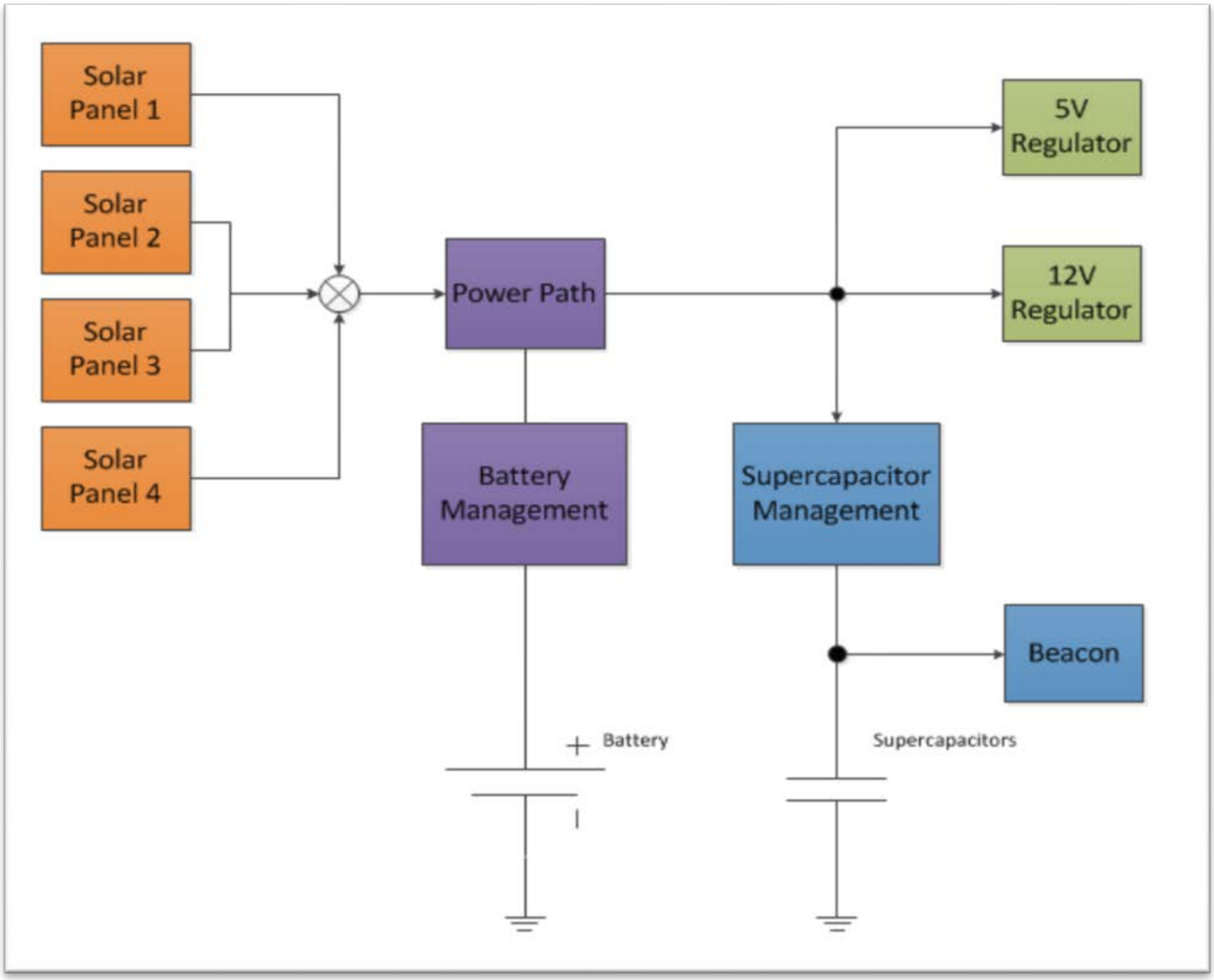

Figure 3: Power System Block Diagram

Chapter 3: Battery Management

3.1 Battery Selection

While the satellite is in eclipse, the system will be powered by a battery. This allows the satellite to continue normal operation throughout the entire orbit of the satellite, including when it is away from the sun. Traditionally, satellites are powered by Nickel Cadmium (Ni-Cd) batteries because they are more durable than other battery chemistries and have a wider operating temperature range, which is important in the extreme conditions of space. However, Ni-Cd batteries have many disadvantages, particularly in space-constrained CubeSats, because they are large and heavy. Over the last decade, the space industry has begun experimenting with and switching over to Lithium-Ion Li-Ion batteries. Although the RSL has always used Ni-Cd, we wanted to investigate whether or not it was time to also switch over to Li-Ion.

	Ni-Cd	Li-Ion
Maintenance	Durable	Fragile
Nominal Cell Voltage	1.2 V	3.6/3.7 V
Weight	Larger and Heavier – 33.84 oz	Smaller and Lighter – 3.5 oz
Discharge	Periodic Discharge	No Periodic Discharge
Disposal	Hazardous	Non-Hazardous
Specific Energy	40-60 Wh/kg	100-250 Wh/kg
Energy Density	50-150 Wh/L	250-520 Wh/L

Table 1: Battery Comparison Table

The table above shows a comparison of the two battery chemistries. As stated before, the primary advantage of Ni-Cd is its durability, which is important in the harsh conditions of space. Li-Ion batteries would need more protective circuitry to ensure proper operation. In particular, Li-Ion batteries are extremely sensitive to temperature and can even catch fire in unfavorable conditions. However, despite this disadvantage there are many more advantages to using Li-Ion batteries.

The nominal cell voltage of Ni-Cd is much lower at 1.2 V compared to the 3.6/3.7 V nominal cell voltage of Li-Ion batteries.[3] This means Ni-Cd battery packs are much larger and heavier because not only are the individual cells heavier, but also more cells are needed to get the same voltage in Ni-Cd battery packs than in Li-Ion battery packs. A Ni-Cd battery pack could weigh up to 33.84 oz compared to a comparable 3.5 oz Li-Ion battery pack. In addition, Ni-Cd batteries also suffer from periodic discharge. This means the entire battery needs to be discharged before recharging again or it may be damaged by memory effect. Memory effect means the battery may 'remember' what voltage it had been discharged to during previous cycles, and when it is at that point, it can suddenly lose voltage as if it had been discharged.[4] When the satellite is in orbit, we will not be able to control or guarantee the battery will be completely discharged before recharging, so it is preferable to not have to worry about memory effect. Ni-Cd is also considered a hazardous waste because cadmium is a toxic heavy metal. This means handling and disposal of Ni-Cd needs to be carefully regulated and may even require a fee for proper disposal after use. Finally, the specific energy and energy density of Li-Ion batteries is much higher than Ni-Cd batteries. The specific energy of a Li-Ion battery can range between 100-250 Wh/kg while Ni-Cd is typically less than 60 Wh/kg.[5] Similarly, the energy density of Li-Ion batteries is typically between 250-620 Wh/L while Ni-Cd is between 50-150 Wh/L.[6]

After comparing the batteries, Li-Ion batteries are clearly a better choice than Ni-Cd which raises the question of why the RSL and the rest of the space industry have continued to use Ni-Cd

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[3] http://www.diffen.com/difference/Li-ion_vs_NiCad
[4] http://www.diffen.com/difference/Li-ion_vs_NiCad
[5] http://www.diffen.com/difference/Li-ion_vs_NiCad
[6] http://www.diffen.com/difference/Li-ion_vs_NiCad

batteries for so long. The reason is primarily because Ni-Cd has been thoroughly tested and proven to work well in space. The expensive and high-risk nature of space launches means the space industry is slow to incorporate new technologies into projects. Organizations would rather use a technology that they know will work rather than test out a new technology in order to maximize chances of a successful mission. However, over the last ten years more and more companies and CubeSat teams have begun to successfully use Li-Ion batteries.

We decided it was also time for the RSL to make the switch, so we chose a 7.4 V, 2600 mAh Li-Ion Tenergy battery for our CubeSat as shown below.

Figure 4: Tenergy Li-Ion Battery

The typical charging cycle of the Li-Ion battery from the datasheet is shown below in Figure 5. The graph is actually for a 4.2 V battery, but although our battery is larger it should still have the same behavior. There are three distinct phases to the charging of this battery. First, the battery fast charges up until it reaches about 90% battery charge. At that point, it slowly charges until it reaches the maximum battery charge where it simply maintains the voltage until used. The charging current stays steady at about 1 A until maximum charge is reached at which point it drops off to 0 A.

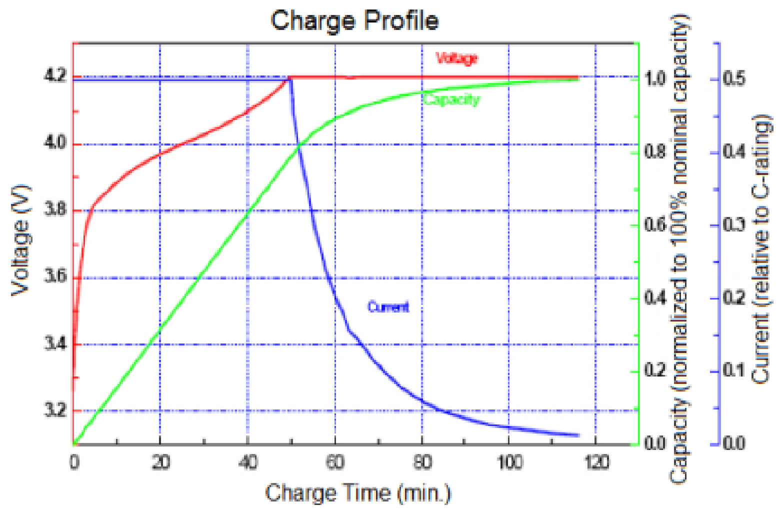

Figure 5: Charging Profile of Tenergy Li-Ion Battery

3.2 Battery Management System Comparison

The use of Li-Ion batteries means that the selection of a battery management system needed careful consideration to insure the battery is properly protected. Our choice came down to three devices: Texas Instruments BQ24210, Texas Instruments BQ25505, and Linear Technology LT3652. A comparison of the three devices is shown in Table 2. The reason these three devices were originally considered is that all three are specifically designed for a solar input. Most battery management devices are not designed for solar input, so this requirement narrowed our choices down considerably at the outset.

The next consideration in selecting a chip was temperature sensing. Li-Ion batteries are extremely sensitive to temperature, so temperature protection is essential in the cold conditions of space. Temperature sensing monitors the battery temperature and if the temperature goes outside of a programmable temperature range it will stop all charging and discharging of the battery to protect it until it is back at a safe temperature. Over-voltage protection is also necessary in order to prevent damaging the battery from over charging while under-voltage protection stops the battery from being discharged beyond what is safe for the battery. All three chips have temperature sensing and over-voltage protection, but only the TI25505 and LT3652 have under-voltage protection.

Power path is the next requirement needed for our system. Power path control is necessary in order to select between the solar panels and the battery as a source of power for the satellite system. Only the TI25505 and LT3652 had a system where power path could be easily integrated into the system. Therefore, the choice came down between these two chips. Finally, maximum peak power tracking (MPPT) is the last needed requirement. MPPT is a method to keep the output of the solar panels as high and as stable as possible despite varying environmental factors like temperature and solar irradiation. Only the LT3652 has MPPT capability, so the LT3652 has chosen as our battery management system.

	TI24210	**TI25505**	**LT3652**
Solar Input	✓	✓	✓
Temperature Sensing	✓	✓	✓
Over Voltage Protection	✓	✓	✓
Under Voltage Protection	✓	✓	✓
Power Path	✓	✓	✓
MPPT	✓	✓	✓

Table 2: Battery Management System Comparison

3.3 LT3652 Configuration

Several changes had to be made to the LT3652 circuit in order to configure the device for our needs. The first change was to set up the power path control. While the system is outputting power from the solar panels, the day diode will turn on and power will flow directly from the panels into the system loads as well as through the chip to charge the battery as shown in the left-side of Figure 6. When the satellite is in eclipse, the day diode turns off and the night diode turns on so power flows directly from the battery to the system loads as shown in the left-hand diagram in Figure 6.

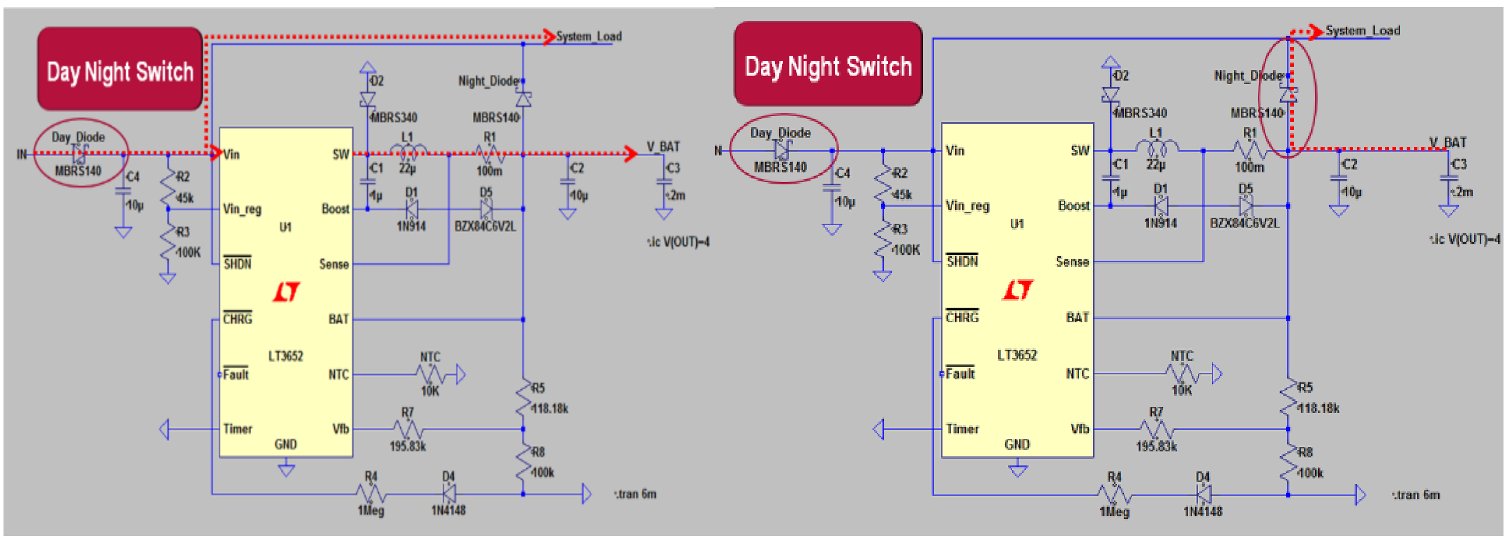

Figure 6: Power Path Control of LT3652 Chip

Next, the battery management system has to be programmed to charge a 7.4 V battery. As shown in Figure 7, the battery charge voltage is programmed using the Feedback Voltage Divider in the bottom left-hand corner of the schematic. The voltage divider is programmed using these equations:

$$R_8 = (V_{BAT(FLT)} * 2.5 * 10^5)/3.3$$

$$R_5 = (R_8 * (2.5*10^5))/(R_8 - (2.5*10^5))$$

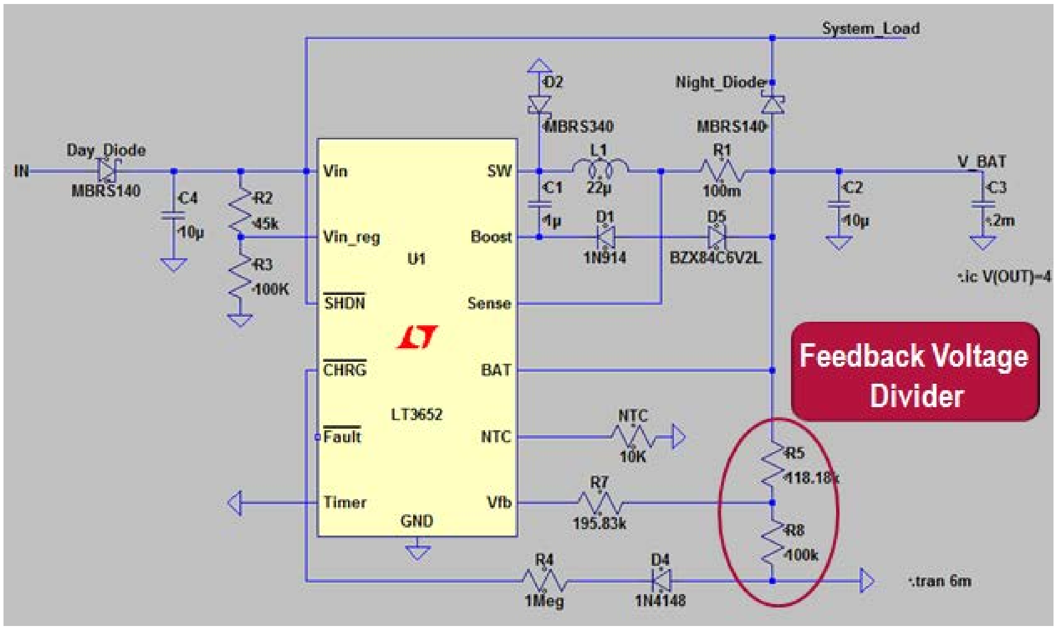

Figure 7: Configuration of Feedback Voltage Divider of LT3652

Finally, the MPPT system needed to be implemented in order to produce the highest possible output of the solar panels. The left-hand graph in Figure 8 shows the maximum peak power point found at the intersection of the maximum voltage and maximum current. A MPPT system strives to maintain the power as close to the peak power point as possible. MPPT works by monitoring the output of the solar panels and adjusting the total resistance of the solar panels in order to produce the maximum output. The implementation of the MPPT in the battery management system is shown in the schematic in Figure 8.

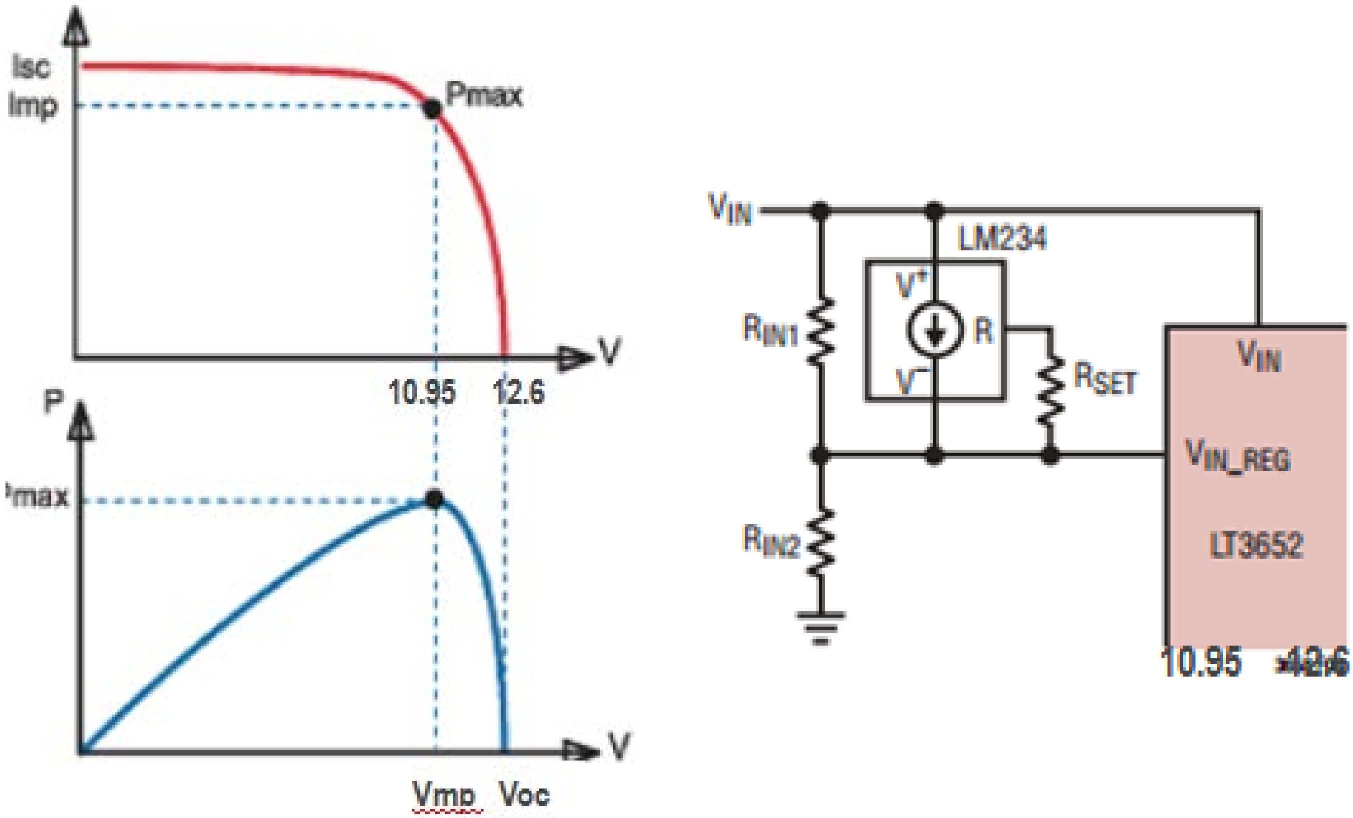

Figure 8: Right-Hand Graph: Power Curves of Solar Panels

Left-Hand Graph: Schematic of MPPT Implementation

The implementation of the MPPT requires a LM234 sensor and a resistor divider. The solar cells the satellite will be using are Triangular Advanced Solar Cells with an open-circuit voltage of 12.6 V, a maximum power voltage of 10.95 V and temperature coefficient of -31 mV/C.[7] With these specifications and choosing an RSET of 100 kOhms, we can calculate the necessary resistance values using these equations:

RIN1 = –RSET • (TC • 4405)

RIN1/({[VMP(25°C) + RIN1 • (0.0674/RSET)]/VIN_REG} – 1)

[7] datasheet

3.4 LT3652 Simulation

The next step was to simulate the charging cycle of a battery using the LT3652 on LTSpice as seen below in Figure 9.

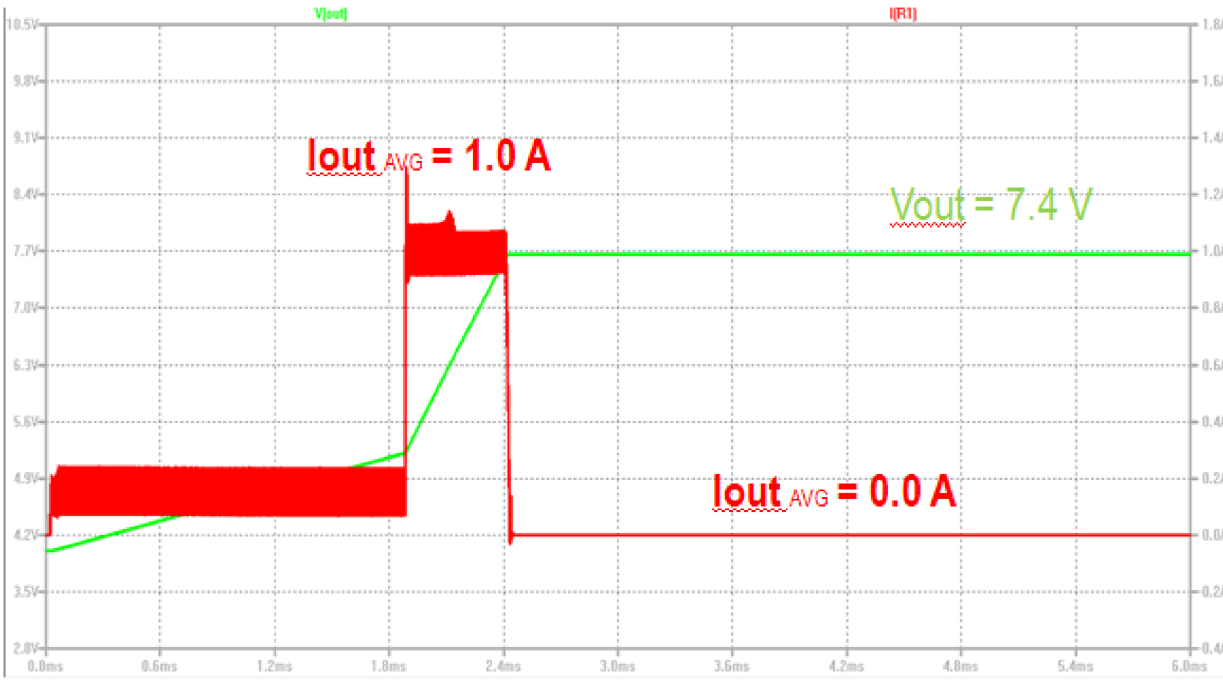

Figure 9: Charging Cycle Simulation of LT3652

The LT3652 charging cycle has three distinct sections to it. The simulated circuit has begins with a slow charge until the current spikes to 1.0 A and the battery fast charges up until its maximum charge. Then the current drops down to 0 A while the battery simply maintains its voltage.

3.5 LT3653 Demo Board Verification

The next step was to verify operations of the LT3652 using the demo board and the actual 7.4 V Tenergy battery. The experimental results are shown in Figure 10.

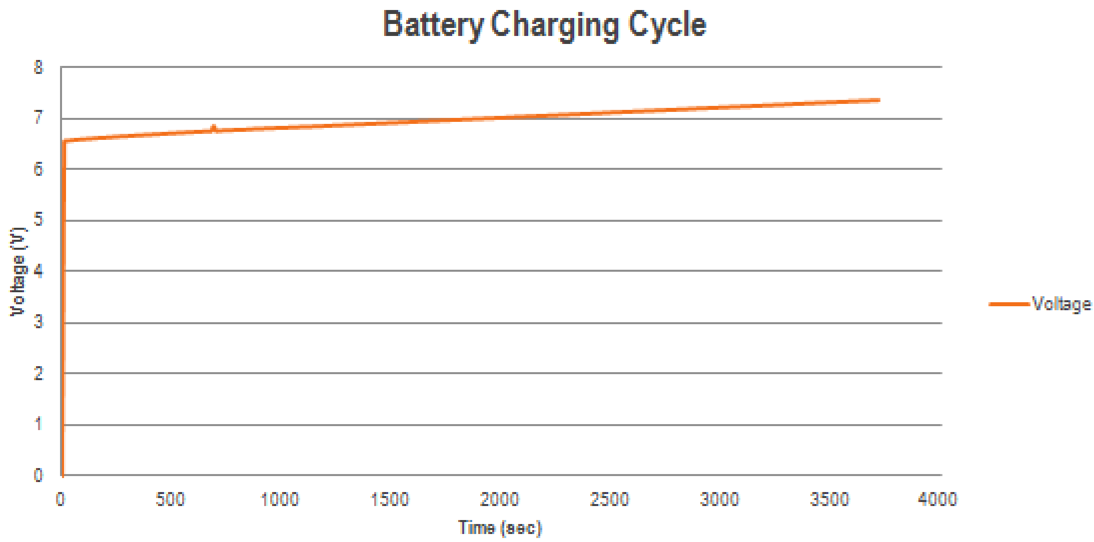

Figure 10: Charging Cycle Experiential Data

The battery charging cycle matches very closely with the expected curve from the battery datasheet. The battery fast-charged until approximately 6.8 V which is 90% charge and slow charged the rest of the way to 7.4 V. The demo board skipped the slow-charge seen in the simulation because we configured the demo board to fast-charge by changing the jumpers on the board.

Chapter 4: Supercapacitors

4.1 Objective

The Robotic Systems Laboratory (RSL) is always seeking to implement and experiment with new technology. In the interest of working on communication and cooperation between multiple satellites, the RSL is looking to use chip satellites as a cost effective means of launching multiple packages. Rather than an entire system contained within a U sized cube, a chip sat is a much smaller system consisting of a sensor, a transmitting beacon, and several supercapacitors for power storage. In such a system, the supercapacitors are ideal because they can provide a large amount of power instantaneously, which is required to power the beacon during transmission. Because the RSL has no experience with supercapacitor technology, the goal of this project was to implement a hybrid system of both batteries and supercapacitors with the supercapacitors being used to provide the pulse of energy to the beacon.

4.2 Supercapacitor Selection

The supercapacitor chosen for the system is a Maxwell PC-10 model. It is rated for 2.5V and 10F. These numbers provide for a base voltage that can be stacked to the 7.5 required volts and the 10F rating ample energy storage for the system. Additionally the rectangular package as seen in Figure Q means that the bank can save space vertically. In terms of reliability, the Maxwell model is ideal because it can operate between -40° C to +70° C and has a lifespan of 500,000 cycles. For space applications, it is made of stainless steel and hermetically sealed.

Figure 11: Maxwell PC-10 Supercapacitor

4.3 Charge Management

When it came to selecting a charge management chip for our supercapacitor bank our options were limited. Because supercapacitors are still a relatively new technology, the industry has yet to offer a wide variety charging technology. Ultimately, the only package to have built in temperature sensing was the Texas Instruments BQ24640 chip. The schematic of this circuit can be seen in the figure below. The temperature sensing is controlled by the 10k thermistor. Additionally, the feedback voltage divider and the charge current control were modified to yield 7.5 volts and 2 amps respectively.

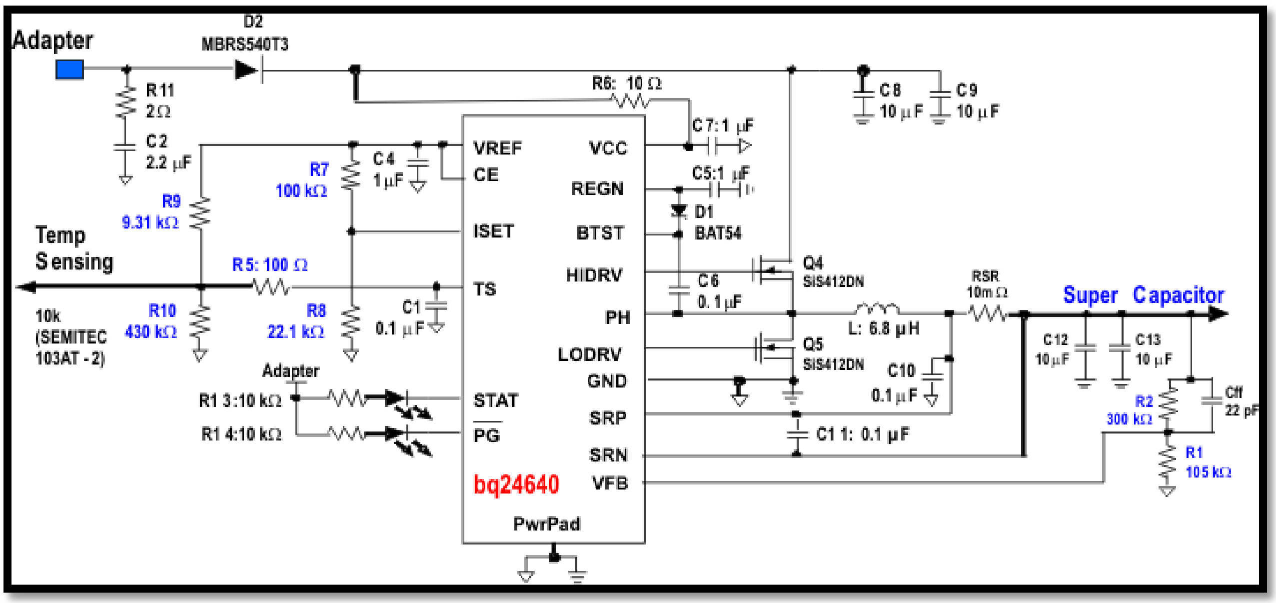

Figure 11: BQ24640 Schematic

4.4 Experimental Verification

The next step was to ensure that the supercapacitor charging profile could be accurately replicated. In order for the supercapacitors to be a useful component they must be able to deliver the pulse of power over a short duration. Additionally, a power storage system that charged quickly during sun exposure will ensure that the beacon will be able transmit whenever necessary. To test the supercapacitor functionality, the bank was charged fully through the circuit and discharged over a dummy load in order to pull the maximum power from the bank. The results below show that the supercapacitor bank was able to charge and discharge as shown by the manufacturer. Figure 12 shows the manufacturer charge profile and Figure 13 shows the experimental results of the testing.

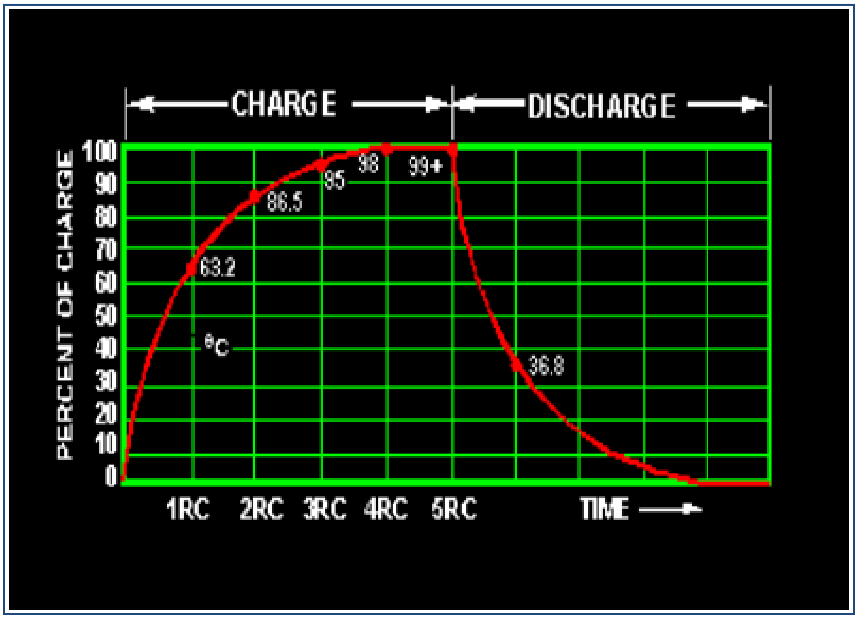

Figure 12: Supercapacitor Datasheet Charge and Discharge Profiles

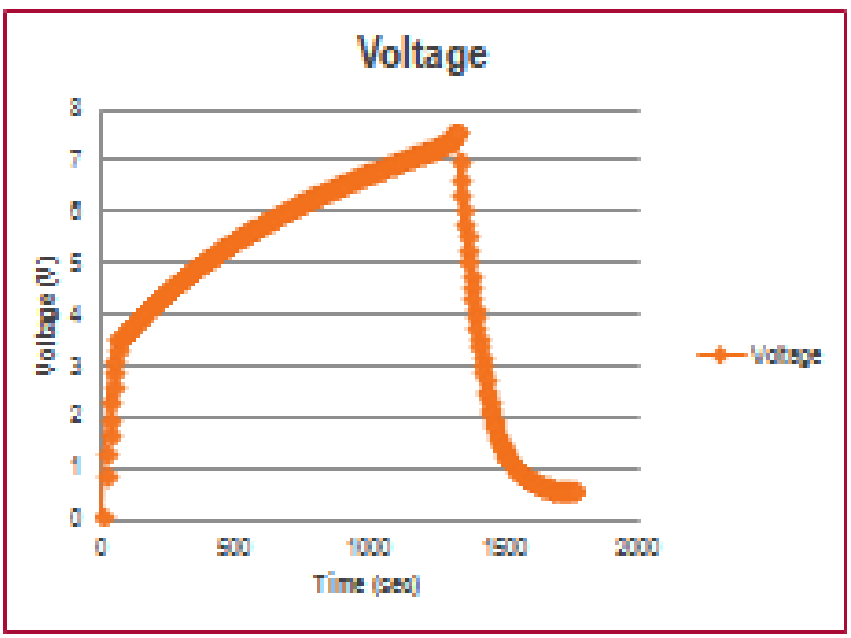

Figure 13: Experiential Supercapacitor Charge and Discharge Profile

4.5 Beacon Pulsing

Once the discharge profile had been verified, the final step was to confirm its ability to supply power to the beacon. While in orbit the satellite will have roughly 10 minutes in which to communicate with the ground station at Santa Clara. During this period it will be pulsing regularly in order transmit the data gathered from the customer payload. Without a payload yet selected, it was decided to test for a payload that would require a large amount of data transmission. A camera was chosen, meaning that the beacon would need to be pulsing regularly for approximately 5 minutes. To test the transmission, the fully charged supercapacitor bank was connected to the beacon as the sole power source and the beacon was pulsed at every five seconds. Under these conditions the beacon was able to pulse for over five minutes, confirming the viability of supercapacitors. Figure 14 below shows the experimental results of the testing.

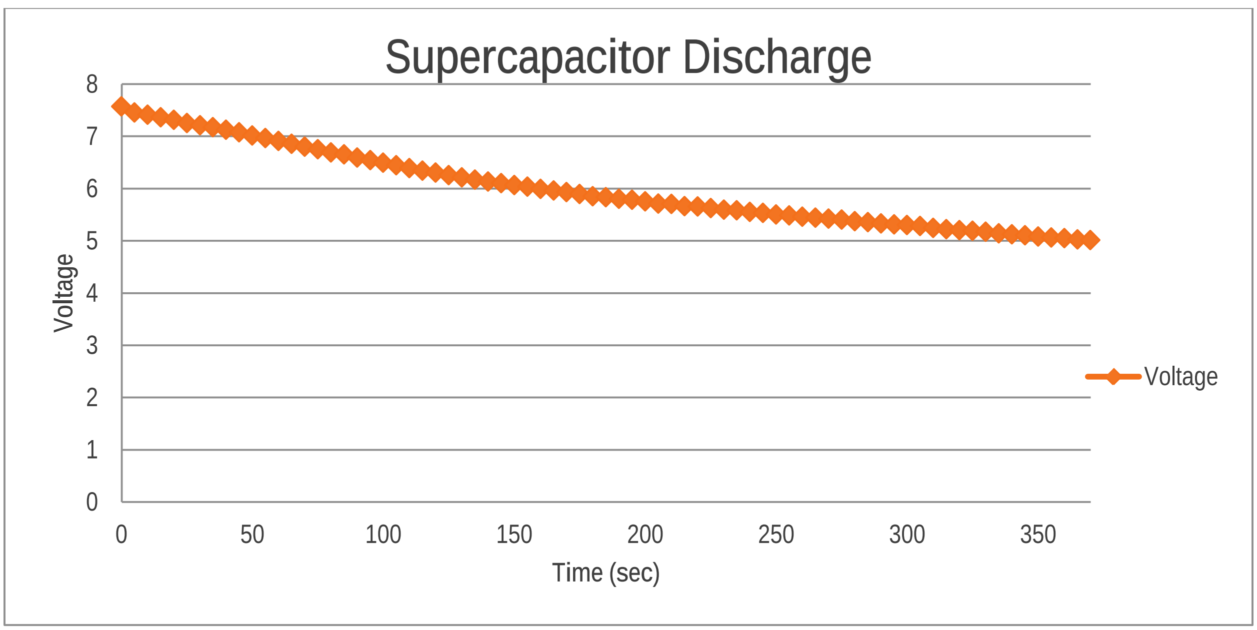

Figure 14: Beacon Pulsing Data

Chapter 5: Voltage Regulation

5.1 SEPIC Converter Selection

When choosing our two voltage regulators, we primarily considered Buck-Boost and SEPIC DC-DC converters because these two types of converters can both step-up and step-down voltage, which means the same convertor can be used for both the 12 V and the 5 V regulators. The LT3757 convertor was chosen because it had an extremely wide input voltage range from 3.5-36 V, meaning we will continue to be able to provide power to the satellite even when the battery is extremely low. Even when the battery is down to 3 V, the converters will still be able to boost the voltage up to 12 V and 5 V respectively.

5.2 LT3757 Configuration

The main adjustment made to the LT3757 converter was programming the feedback voltage divider to output the necessary voltage. The equations used to calculate R_3 and R_2 are:

$$R_2 = (V_{BAT(FLT)} * 2.5 * 10^5)/3.3$$

$$R_3 = (R_2 * (2.5*10^5))/(R_2 - (2.5*10^5))$$

Figure 15 shows the schematic of the LT3757 with R_2 and R_3 programmed for the 12 V output where R2 is 15.8 kOhms and R3 is 105 kOhms. The values had to be recalculated a second time for the 5 V output giving an R2 of 20 kOhms and an R3 of 42.2 kOhms.

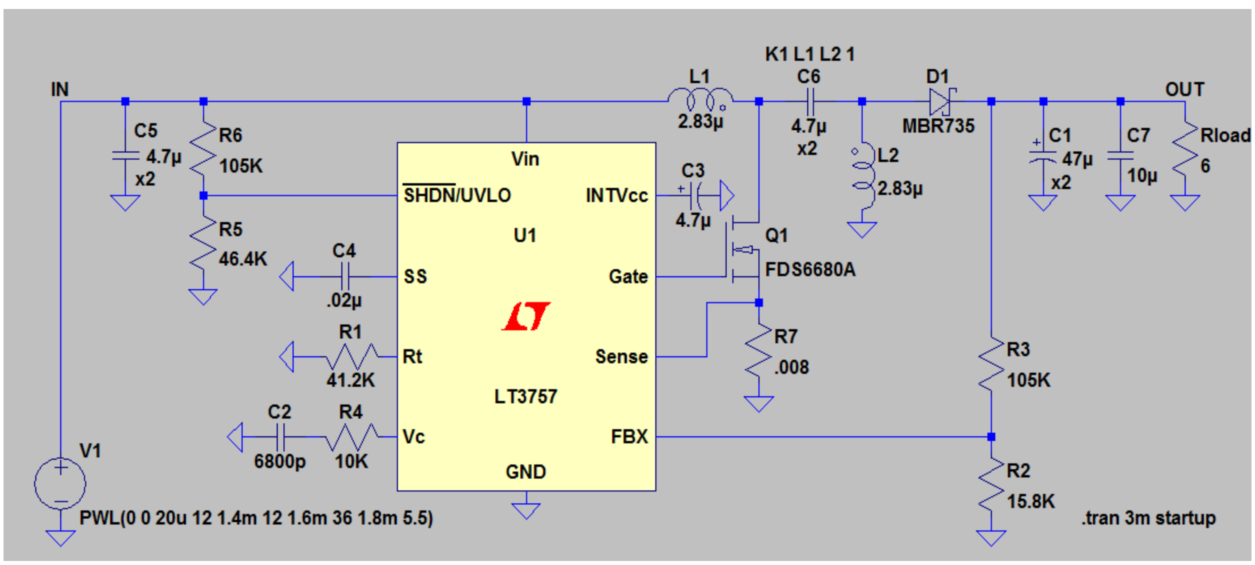

Figure 15: LT3757 SEPIC Converter

Chapter 6: Board Design

6.1 General Design Considerations

Once the functionality of the components had been verified through the demo boards, the next step was to create a board layout that could be placed directly into the satellite. When beginning this process, there were a number of factors that would guide our design. The first and foremost amongst these was space within the 3U frame. The width meant that anything we designed would have to be within the 100mm by 100mm border. Additionally, there will be a thermal casing installed before the satellite is completed that will take up additional horizontal spacing.

The second spatial requirement was vertical. Figure 16 below shows where existing satellite hardware. All of the boards are designed so that they can be stacked vertically to save space and provide room for the customer payload. When designing the power board, it was decided to make the package in two separate boards that could be stacked on top of each other. Having two boards allowed for all of the components to fit on the power board within the horizontal boundaries and also allowed the supercapacitors to be optional. Although this technology is now a focus of the RSL's research, the team recognizes that this may not be a technology that future teams would like to use. For this reason the boards are independent and can be removed to meet the needs of future teams.

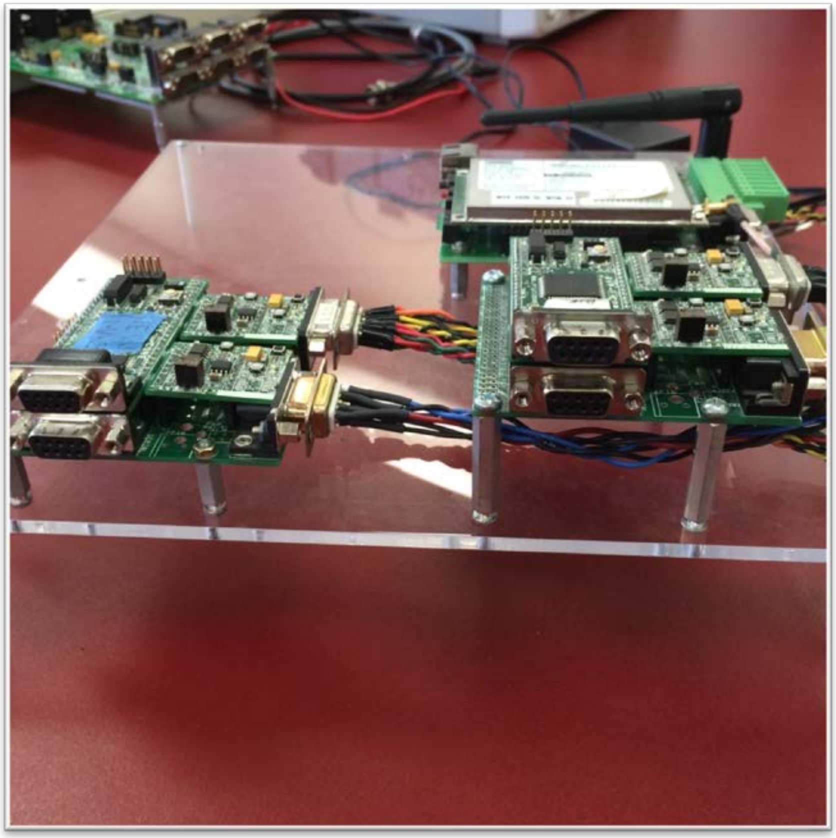

Figure 16: Hardware for Communications Board

The last piece to notice about the existing hardware is the use of serial ports. These are not conventionally used to transfer power; however, they are a convention within the CubeSat industry. They are widely accepted because space-rated and hermetically sealed versions are readily available and cost effective. Additionally, they can be used to transfer data and power simultaneously between different system components

The two figures below show the first versions of the board. Visible on the sides of the board are the serial ports for inputs and outputs. The power board contains the battery charge management as well as the two voltage regulators. The supercapacitor board is responsible for carrying the supercapacitor charge management and having an output directly to the beacon.

6.2 Power Board

Figure 17 shows the layout of the power board.

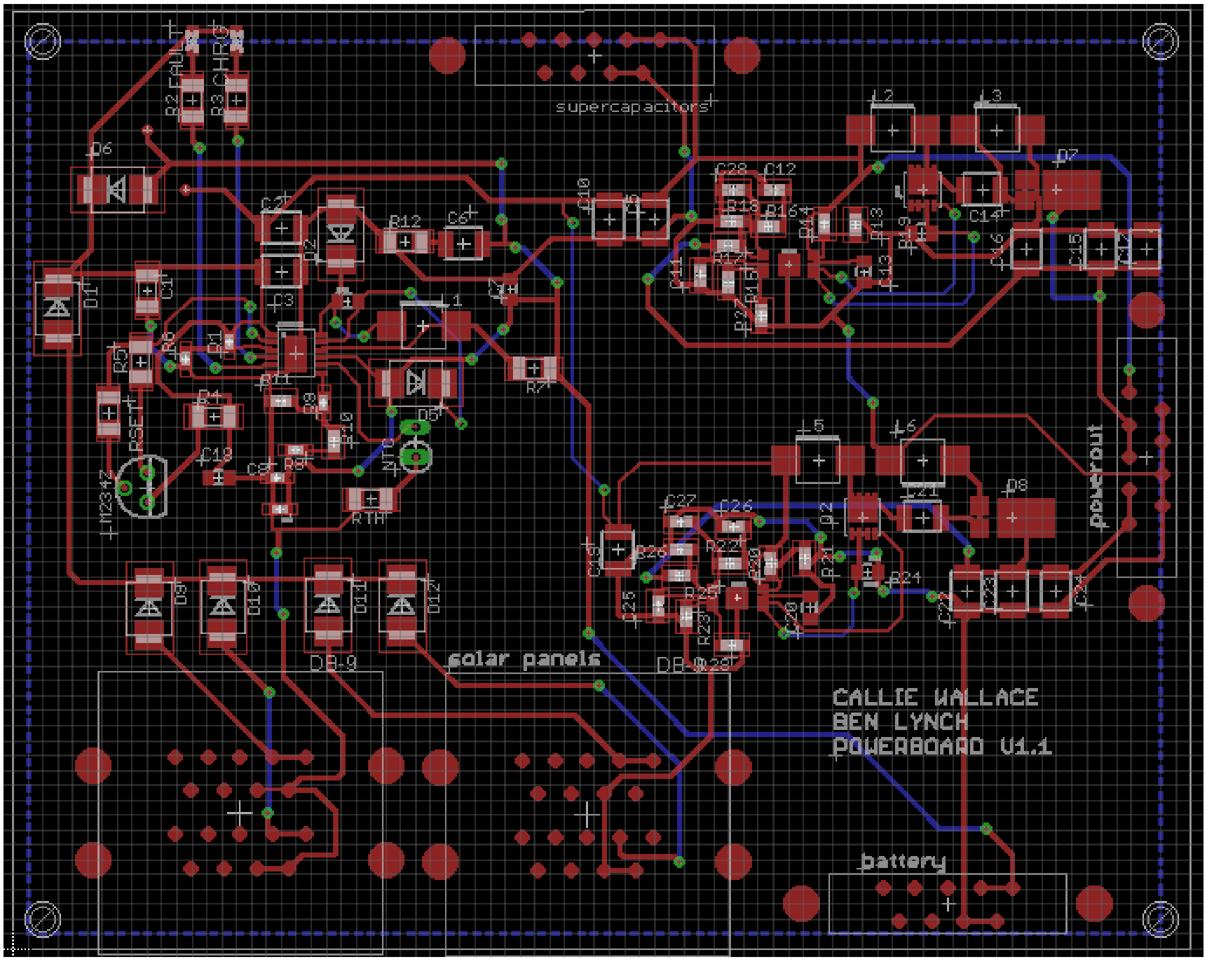

Figure 17: Power Board

6.3 Supercapacitor Board

Figure 18 shows the board layout for the supercapacitor board.

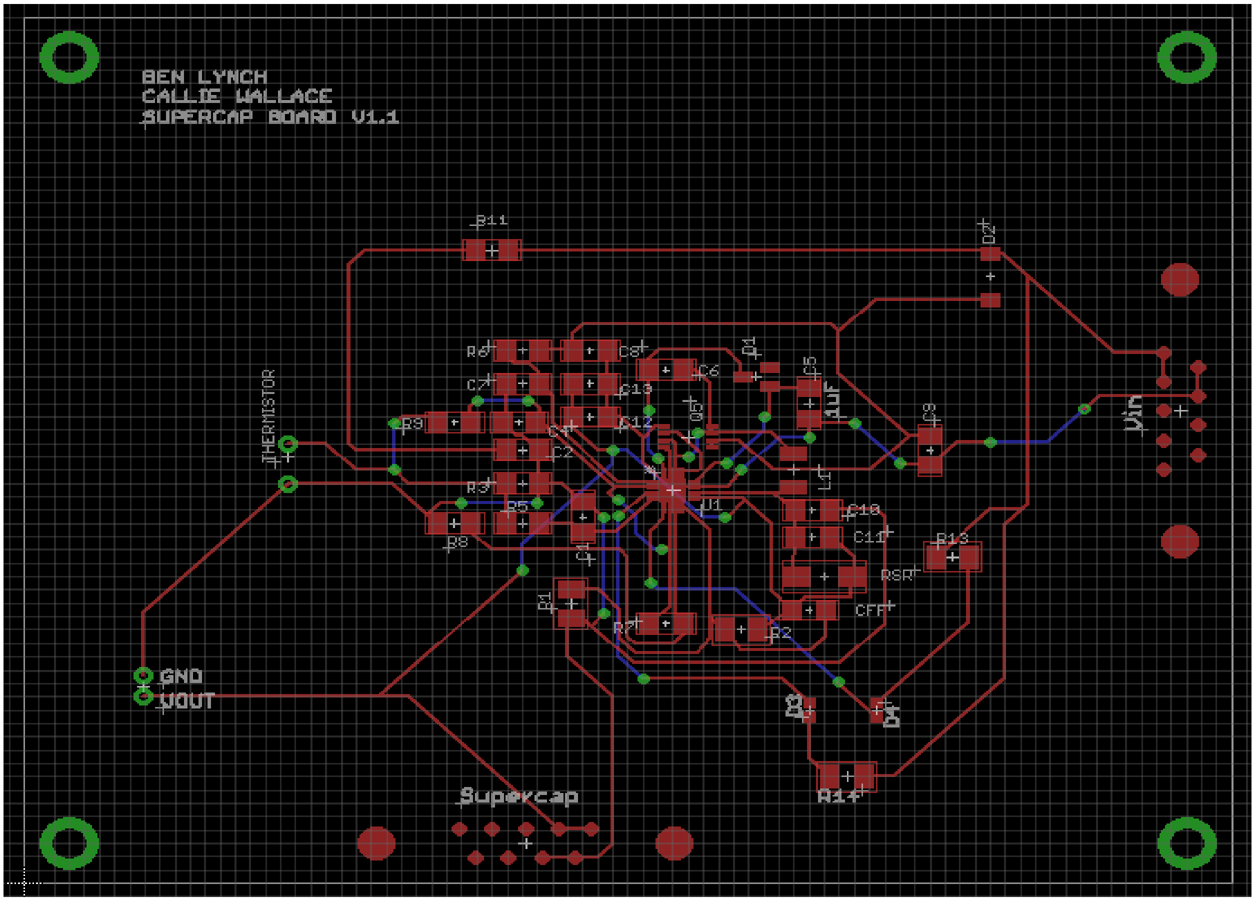

Figure 18: Supercapacitor Board

Chapter 7: Ethical and Aesthetic Considerations

7.1 Stakeholder Needs

Functional: Our project has resulted in the fabrication of a functional EPS board for use in a 3U satellite. The implementation of supercapacitors on a satellite is a new and concept in the Robotic Systems lab, a hybrid system including a Lithium-ion battery was designed. This way we can make sure the satellite will be properly powered by the battery in case of unforeseen failure in the supercapacitiors.

Financial: Supercapacitors have the potential to be a cheaper and more efficient option for energy storage on CubeSats. The cost of a supercapacitor bank where each individual 2.7V 350uF capacitor is approximately $11 is cheaper or comparable to most lithium ion battery packs, which start at approximately $44. They also can be charged and discharged with no deterioration much longer than batteries, meaning they can last longer and have to be replaced less.

Technical: We completed the first iteration of the EPS board design. We have left thorough explanation and documentation so future completing groups can make any necessary changes and implement the design. Our board will be fully functional for future implementation in a SCU CubeSat. We will also be able to provide data to potential investor looking to launch a payload to prove our satellite will be powered in space.

Societal: Supercapacitors are a new and relatively unexplored electronic component. People are still experimenting with them and figuring out how to maximize the potential of this technology. Our project will add this exploration by determining whether or not supercapacitors can be useful to power CubeSats elements. Additionally, by designing a power board for a small system satellite, we are participating in the ever changing and expanding field of extraterrestrial research.

7.2 Ethical Considerations

Considering the ethical issues surrounding small spacecraft like CubeSat satellites is important because of the potential negative effects spacecraft can have on the space environment. Exploration of outer space is a tremendous opportunity to advance and push the limits of human knowledge. It allows us to test devices in conditions impossible to replicate on earth. We can learn more about the current conditions of our own planet as well as the formation of our universe through mechanisms like advanced imaging, magnetic sensing, and radiation testing. The harsh conditions of space force engineers to innovate and test the boundaries of technology while designing technology. Finally, space and the potential for knowledge it holds is an endless supply of awe and inspiration for both engineers and laymen alike. Unfortunately, all important resources like space are also in danger of exploitation. Space conservation is incredibly important to ensure the continuing ability of researchers to explore and learn from outer space, and it is important that we consider and attempt to prevent all possible negative side-effects of launching a satellite.

The importance of communications satellites in modern technologies like cell phones, TV, radio, and GPS has led to severe overcrowding in the geo-synchronous orbit. The geo-synchronous orbit is especially important for these applications because satellites in this orbit do not move relative to the earth. This means geosynchronous satellites can be used for commercial and military communications.[8] Satellites in other orbits will move in and out of range as they orbit around the earth. The limited space in the geo-synchronous orbit has created competition between countries to determine who gets space in the orbit for their satellites. This is often exacerbated by the fact that many countries would prefer to have their own satellites rather than have to rely on data from other countries satellites. To partially solve this problem, the FCC has reduced the minimum required distance between satellites in order to fit more. However, this increases the danger for collision and interference between satellites, which could seriously affect communications around the world.[9]

Although the crowding issue is not as dire in the low-earth orbit (LEO) as it is in the geo-synchronous, it is still overcrowded and it will only get worse. The LEO is the orbit of choice for non-communication satellites and spacecraft built by governments, companies and universities including the CubeSat we are designing. Currently over 800 satellites are orbiting the earth performing research, testing technologies, and performing other research and commercial

[8] http://www.sciencedaily.com/articles/g/geosynchronous_orbit.htm
[9] http://onlinelibrary.wiley.com/doi/10.1029/EO065i038p00707-01/abstract

tasks.[10] The high numbers of satellites create the danger of collisions as well as interference with other spacecraft, experiments, and communications. Collisions and interferences could result in failed experiments or even inaccurate data. This is a problem because the high costs of building and launching spacecraft means every spacecraft represents a serious investment by governments and commercial companies. Space crowding can seriously inhibit the pursuit of knowledge if it is not controlled.

The crowding issue is further exacerbated by the increased amount of space junk surrounding the Earth. Satellites and spacecraft are permanently under fire from debris like abandoned satellites and broken components left behind by previous missions. Currently, NASA estimates there are over 500,000 pieces of debris orbiting around the Earth.[11] The fast speeds each piece is traveling at means even small pieces can do serious damage to spacecraft. Advanced spacecraft have the ability to maneuver to avoid debris but smaller satellites like our CubeSat are vulnerable to damage, which would likely result in leaving behind even more debris.[12]

Overcrowding and space debris have the potential to inhibit future space exploration and travel. Measures are being taken to destroy the larger and more dangerous pieces, but it is near impossible to clear space of all the debris we have left behind.[13] Every mission needs to be carefully considered to make sure the potential for quality research outweighs the possibility of further contributing to the pollution of space. Debris left behind by our spacecraft could go on to injure a larger and more important spacecraft or space stations carrying important equipment or personnel. It is our ethical duty as a design team to make sure the structure of the CubeSat is as strong as possible to reduce the risk of leaving something behind. Much of the debris is comprised of satellites that were simply abandoned in space. We instead plan on our satellite burning up in the atmosphere to prevent adding to the debris. It is also important that we make sure our CubeSat is being used in a constructive experiment that justifies launching the satellite and outweighs the risk of polluting outer space.

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[10] http://onlinelibrary.wiley.com/doi/10.1029/EO065i038p00707-01/abstract
[11] http://www.nasa.gov/mission_pages/station/news/orbital_debris.html#.UpwnzMSsiSo
[12] http://www.nasa.gov/mission_pages/station/news/orbital_debris.html#.UpwnzMSsiSo
[13] http://www.nasa.gov/mission_pages/station/news/orbital_debris.html#.UpwnzMSsiSo

CubeSats built by universities are typically contracted to carry a payload for NASA or commercial companies. We currently do not know what payload our satellite will carry when launched. This situation creates several potential ethical dilemmas for our team as we navigate the customer-client dynamic. We realize that some satellites are used for military purposes and technology exists to weaponize satellites in LEO. However, our goals for this project are solely to advance scientific research for civilian purposes. It is an important goal for our team to get our satellite launched, but it is even more important that we make sure our satellite is not used in a way that endangers life. If at any point the goal of the project is no longer simply to advance human knowledge then as a team we will have to seriously consider ending our research and grounding our satellite.

We also have several ethical responsibilities to the customer that will be depending upon our product in order to conduct research. It is our duty to supply a functional product to our customer, and it is important that we are transparent about any limitations of our system. It is unethical to omit information about potential failures of our satellite in order to ensure our satellite is launched. If we failed to inform the customer about any limitations and it fails in space, than we would be responsible for the failed mission. It could also damage the relationship between the contractor and our university and hurt the ability of future satellite teams to get their projects launched. We also have an obligation to make sure our satellite is safe to handle. The satellite should only be handled by qualified individuals, but it is still important to provide directions on handling to reduce possibilities of damage to the satellite or injury to the person.

Another important aspect of the project is ensuring secure communications from our satellite to ground control. The data transmitted from our satellite needs to be kept confidential and protected from interference or tampering. Confidentiality is important because it could be an important experiment for our contractor that needs to be kept from competitors prior to publication. If data is interfered with, it could result in wrong or misleading conclusions being drawn from our experiment which could hinder advancements of technology and knowledge. Failure to provide secure communications could easily result in a failed mission and damage the reputation of Santa Clara’s satellite program.

My team is specifically designing the electronic power system of the satellite. There is a lot of mechanical work left to do so we will need another design team next year in order to complete the project. We have many of the same ethical obligations to this future team that we have with our contractor. This future team will depend upon our design to power their satellite. It will likely be a team completely comprised of mechanical engineers so it will be difficult for them to detect and fix possibly failures of our system. It is again very important to not hide any limitations and failures of our power system. Even if these limitations do not affect the current design it could be reused for future projects with different specifications. It is therefore important for future teams to have plenty of information available to them so their projects do not fail because of ours.

7.3 Aesthetics of Senior Design

The end goal of our project is to create a finished CubeSat which will be launched by an outside company or contractor such as NASA to carry a payload into space. Aesthetics are important because we must convince a contractor that our satellite will not fail in space. Contractors looking at our satellite will primarily be technical people. The design must be simple and functional without needing any sort of user interface for non-technical users. The design should showcase elements of the satellite important to the company, like the design of the connections between the satellite and the payload. The external structure of the satellite is open so contractors can see into the satellite and see the circuit boards and components. The boards and components must therefore be organized in a logical, non-cluttered manner. The components must be properly attached with organized and secure wire connections. The thermal casing and other protective equipment must look trustworthy and perform properly.

The CubeSat will be very utilitarian due to the harsh conditions in space and the limited space on the satellite itself. Our design is streamlined as much as possible to use the minimum number of components because of the space constraints. Fortunately, in terms of aesthetics, the most elegant design is often the simplest one. By streamlining our design, the aesthetics of the satellite is also improved by reducing the clutter and organizing the components in a logical manner. The harsh conditions of space will also require protective casing around electrical components like the battery to prevent malfunctioning. Simple measures like making sure the casing of the components match the material used for the satellite structure will not affect functionality of the case but will improve the aesthetics. Extreme care should also be taken in the connections attaching the casing to the satellite and the wire connections between boards. Even if the connection is secure yet does not look like it is, people will not trust it and will doubt the functionality of the satellite.

Chapter 8: Conclusion

Using the demo board components, the functionality of the circuit has been proven. The solar panels will provide ample power and the battery and supercapacitor bank both have the required energy storage to make the circuit operational during eclipse. There is a board design in place to implement the circuit in the satellite package. This being said, there still remains a vast amount of work to be done on the power system.

Though the boards have been designed, there are still a wide range of tests that must be performed on the system to ensure that they not only function as intended, but are also able to withstand some of the harsh conditions and cycling requirements demanded by the mission. The first step will be to ensure that the circuit is in fact functional and that all of the connections have been made to ensure that power is delivered cleanly and efficiently. Once this testing and any necessary revisions have been made, the final testing process will be conditional testing which will have to done at the NASA Labs.

These tests will come as new teams continue to work on this CubeSat package and understanding that this work may change the system requirements this team is confident that it has delivered a system that is not only functional, but malleable as well. By incorporating new storage technologies in Li-ion batteries and supercapacitors, the team has modernized and enhanced the systems storage capabilities. By using SEPIC converters as the voltage regulators, the system can be easily modified to accommodate changing load needs in the satellite’s electronic components. Lastly, the team has proven that a supercapacitor bank can power a Stensat beacon, opening the door to future research into the field of small system chip satellites.

Appendix A: LT3652 Datasheet

Appendix B: LT3757 Datasheet

Appendix C: Tenergy Battery Datasheet

Appendix D: Maxwell PC10 Datasheet

Appendix E: TI BQ24620 Datasheet

Appendix F: Power Board BOM

Item	Qty	Reference - Des	Part Description	Manufacturer, Part #
REQUIRED CIRCUIT COMPONENTS				
1	2	C2,C3	CAP., X7R, 4.7uF, 50V, 10%, 1210	MURATA, GRM32ER71H475KA88L
2	1	C4	CAP CER 1UF 50V 10% X7R 0805	Samsung, CL21B105KBFNNNE
3	1	C6	CAP., X5R, 100µF, 10V, 20%, 1210	TAIYO YUDEN, LMK325BJ107MM-T
4	1	C7	CAP., X7R, 10uF, 10V, 10%, 0805	MURATA, GRM21BR71A106KE51L
6	2	D1,D2	DIODE SCHOTTKY 40V 1A SMB	Fairchild, MBRS140
7	1	D5	DIODE SCHOTTKY 40V 1A SMB	Fairchild, MBRS140
8	1	L1	INDUCTOR POWER 10UH SHIELD SMD	Bourns, SRP7030-100FM
9	1	R1	RES., CHIP, 1MEG, 1/16W, 1%, 0402	VISHAY, CRCW04021M00FKED
10	1	R4	RES 137K OHM 1/16W 1% 0402 SMD	VISHAY, CRCW0402137KFKED
		R5	RES 21.0K OHM 1/16W 1% 0402 SMD	Yageo, RC0402FR-0721KL
11	2	R6	RES., CHIP, 100K, 1/16W, 1%, 0402	VISHAY, CRCW0402100KFKED
12	1	R7	RES., CHIP, 0.05 OHM, 1/2W, 1%, 1206	IRC, LRC-LR1206-01-R050-F
13	1	R10	RES 619K OHM 1/10W 1% 0603 SMD	Vishay, CRCW0603619KFKEA
14	1	R11	RES 422K OHM 1/10W 1% 0603 SMD	Panasonic, ERJ-3EKF4223V
15	1	R12	RES 0.1 OHM 1/2W 1% 1206	Stackpole, CSR1206FKR100
16	1	U1	MULTI-CHEMISTRY 2A BATTERY CHARGER FOR SOLAR POWER	LINEAR TECH.,LT3652EDD
1	1	C1	CAP CER 10UF 50V 10% X5R 1206	Samsung, CL31A106KBHNNNE
3	2	C8,C9	CAP, CHIP, X7R, 0.022µF, ±10%, 16V, 0402	AVX, 0402YC223KAT2A
4	1	D3	LED, RED	Lite-On, LTST-C191KRKT
5	1	D4	LED, GREEN	LITE-ON, LTST-C190KGKT
6	0	D6	DIODE SCHOTTKY 40V 1A SMB	Fairchild, MBRS140
7	2	R2,R3	RES., CHIP, 5.1K,1/4W, 1%, 1206	VISHAY, CRCW12065K10FKEA
8	1	R8	RES 20 OHM 1/16W 5% 0402 SMD	Yageo, RC0402JR-0720RL
9	1	R9	RES 0.0 OHM 1/16W JUMP 0402 SMD	YAGEO, RC0402JR-070RL
			THERMISTOR NTC 10 5% RADIAL	Vishay, NTCLE100E3109JB0
		RSET	RES 910 OHM 1/8W 1% 0805 SMD	Yageo, RC0805FR-07910RL

Item	*Qty*	*Reference*	*Part Description*	*Manufacturer / Part #*
		REQUIRED CIRCUIT COMPONENTS:		
1	1	C5	CAP., X7R, 6.8µF, 50V, 20% 1812	TDK, C4532X7R1H685M
2	3	C16,C15,C17	CAP CER 100UF 6.3V 20% X5R 1206	Taiyo, JMK316BJ107ML-T
3	1	C14	CAP., X7S, 10µF, 50V, 20% 1210	Taiyo Yuden, UMK325BJ106MM-T
4	1	C13	CAP CER 4.7UF 10V 10% X5R 0805	Taiyo Yuden, LMK212BJ475KD-T
5	1	C12	CAP., X7R, 10nF, 50V, 10% 0603	TDK, C1608X7R1H103K
6	1	C28	CAP., C0G, 100pF, 50V, 5% 0603	TDK, C1608C0G1H101J
7	1	C11	CAP., X7R, 0.1uF, 25V, 10% 0603	TDK, C1608X7R1E104K
8	1	D7	DIODE, PDS1045, PowerDI-5	Diodes Inc., PDS1045-13
9	2	L2,L3	INDUCTOR POWER 6.8UH SHIELD SMD	Bourns SRP7030-6R8FM
10	1	Q1	N-Mosfet, Si7850DP Power-Pak So-8	VISHAY, Si7850DP-T1-E3
11	2	R15	RES., CHIP, 42.2K, 1/10W, 1% 0603	VISHAY, CRCW060342K2FKEA
		R17	RES 105K OHM 1/10W 1% 0603 SMD	Yageo, RC0603FR-07105KL
12	1	R18	RES 15.8K OHM 1/10W 1% 0603 SMD	Yageo, RC0603FR-0715K8L
13	1	R14	RES 187K OHM 1/10W 1% 0603 SMD	Yageo, RC0603FR-07187KL
14	1	R13	RES., CHIP, 100K, 1/10W, 1% 0603	VISHAY, CRCW0603100KFKEA
15	1	R19	RES., CHIP, 0.01Ω, 1W, 1%, 0815	THIN FILM, RL3720WT-R010-F
16	1	R16	RES., CHIP, 10.5K, 1/10W, 1% 0603	VISHAY, CRCW060310K5FKEA
17	1	R27	RES., CHIP, 10K, 1/10W, 5% 0603	VISHAY, CRCW060310K0JNEA
18	1	U1	I.C., LT3757EDD, DFN 10 (3X3)	LINEAR TECH., LT3757EDD#PBF
1	1	C10	CAP CER 4.7UF 16V 10% X5R 0805	Samsung, CL21A475KOFNNNE

Item	*Qty*	*Reference*	*Part Description*	*Manufacturer / Part #*
		REQUIRED CIRCUIT COMPONENTS:		
1	1	C19	CAP., X7R, 6.8µF, 50V, 20% 1812	TDK, C4532X7R1H685M
2	3	C22, C23, C24	CAP CER 100UF 6.3V 20% X5R 1206	Taiyo, JMK316BJ107ML-T
3	1	C21	CAP., X7S, 10µF, 50V, 20% 1210	Taiyo Yuden, UMK325BJ106MM-T
4	1	C20	CAP CER 4.7UF 10V 10% X5R 0805	Taiyo Yuden, LMK212BJ475KD-T
5	1	C26	CAP., X7R, 10nF, 50V, 10% 0603	TDK, C1608X7R1H103K
6	1	C27	CAP., C0G, 100pF, 50V, 5% 0603	TDK, C1608C0G1H101J
7	1	C25	CAP., X7R, 0.1uF, 25V, 10% 0603	TDK, C1608X7R1E104K
8	1	D8	DIODE, PDS1045, PowerDI-5	Diodes Inc., PDS1045-13
9	2	L5,L6	INDUCTOR POWER 6.8UH SHIELD SMD	Bourns, SRP7030-6R8FM
10	1	Q2	N-Mosfet, Si7850DP Power-Pak So-8	VISHAY, Si7850DP-T1-E3
11	2	R25,R23	RES., CHIP, 42.2K, 1/10W, 1% 0603	VISHAY, CRCW060342K2FKEA
12	1	R26	RES., CHIP, 20.0K, 1/10W, 1% 0603	VISHAY, CRCW060320K0FKEA
13	1	R20	RES 187K OHM 1/10W 1% 0603 SMD	Yageo, RC0603FR-07187KL
14	1	R21	RES., CHIP, 100K, 1/10W, 1% 0603	VISHAY, CRCW0603100KFKEA
15	1	R24	RES., CHIP, 0.01Ω, 1W, 1%, 0815	THIN FILM, RL3720WT-R010-F
16	1	R22	RES., CHIP, 10.5K, 1/10W, 1% 0603	VISHAY, CRCW060310K5FKEA
17	1	R28	RES., CHIP, 10K, 1/10W, 5% 0603	VISHAY, CRCW060310K0JNEA
18	1	U1	I.C., LT3757EDD, DFN 10 (3X3)	LINEAR TECH., LT3757EDD#PBF
1	1	C18	CAP CER 4.7UF 16V 10% X5R 0805	Samsung, CL21A475KOFNNNE

Appendix G: Supercapacitor BOM

Part Designator	Qty	Description
Required Circuit Components		
Q4, Q5	2	N-channel MOSFET, 30 V, 12 A, PowerPAK 1212-8, Vishay-Siliconix, Sis412DN
D1	1	Diode, Dual Schottky, 30 V, 200 mA, SOT23, Fairchild, BAT54C
D2	1	Schottky Diode, 40V, 5A, SMC, ON Semiconductor, MBRS540T3
D3, D4	2	LED Diode, Green, 2.1V, 10mΩ, Vishay-Dale, WSL2010R0100F
RSR	1	Sense Resistor, 10 mΩ, 1%, 1 W, 2010, Vishay-Dale, WSL2010R0100F
L	1	Inductor, 6.8 mH, 5.5A, Vishay-Dale IHLP2525CZ
C8, C9, C12, C13	4	Capacitor, Ceramic, 10 mF, 35 V, 20%, X7R
C4, C5	2	Capacitor, Ceramic, 1 mF, 16 V, 10%, X7R
C7	1	Capacitor, Ceramic, 1 mF, 50 V, 10%, X7R
C1, C6, C11	3	Capacitor, Ceramic, 0.1 mF, 16 V, 10%, X7R
C2	1	Capacitor, Ceramic, 2.2 mF, 50V, 10%, X7R
Cff	1	Capacitor, Ceramic, 22 pF, 35V, 10%, X7R
C10	1	Capacitor, Ceramic, 0.1 mF, 35V, 10%, X7R
R1	1	Resistor, Chip, 105 kΩ, 1/16W, 0.5%
R2	1	Resistor, Chip, 270 kΩ, 1/16W, 0.5%
R7	1	Resistor, Chip, 100 kΩ, 1/16W, 0.5%
R8	1	Resistor, Chip, 14 kΩ, 1/16W, 0.5%
R9	1	Resistor, Chip, 9.31 kΩ, 1/16W, 1%
R10	1	Resistor, Chip, 430 kΩ, 1/16W, 1%
R11	1	Resistor, Chip, 2 Ω, 1W, 5%
R13, R14	2	Resistor, Chip, 100 kΩ, 1/16W, 5%
R5	1	Resistor, Chip, 100 Ω, 1/16W, 0.5%
R6	1	Resistor, Chip, 10 Ω, 0.25W, 5%