Design of a High Power Cube Satellite Power System

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ABSTRACT

Special application nano-satellites increasingly require higher power usage.

Miltec internally funded the design and fabrication of an Electrical Power System (EPS) specifically for Cube satellites. This paper is an overview of Miltec's first generation EPS implementation currently on orbit and a discussion of lessons learned, orbit telemetry data and intended path forward to address higher power capabilities. The paper will cover the requirements placed on the hardware and the design considerations during the initial phase of the development. Because often times external factors are over looked that impact the design, the paper also discusses satisfying range safety and PPOD integration requirements that must be met and proven before a cube satellite begins launch integration activities. More than just insight into a design, the EPS hardware described has been built, tested, and is presently in orbit.

The paper will conclude with suggestions/guidance for designing an inexpensive solar panel simulator and a single Maximum Power Point Tracker (MPPT) Battery Charge Regulator (BCR) channel, ideal for university students interested in investigating, programming, and testing their own MPPT designs and algorithms.

INTRODUCTION

Within most system designs normal procedure is to design the power system last. It is not uncommon for systems engineers to first think about how to fill all the available system volume to provide numerous capabilities prior to considering the requirements for a battery and power management system. A good power system designer will attempt to collaborate with system engineering early to arrive at an optimal solution. The Power designer should do his/her best to ensure that the power system is as trouble free and transparent as possible to the overall system operation. Discussed here is Miltec's first cube satellite EPS design and implementation. This paper covers the design requirements, problems encountered, mistakes made, some of the work arounds and finally some thoughts and directions towards correcting design flaws and EPS improvements for the next generation. This paper is meant to provide a starting point for power designers new to the cube satellite arena.

DESIGN REQUIREMENTS

Normally only immediate mission requirements would be the driving factor within any design, however, that is somewhat of a naive concept. There can be other considerations from stakeholders regardless of whether that is actually needed to fulfill the mission. In some cases their wants are justifiable such as a requirement to over design the power throughput of the system in order to use the same design for a larger satellite later. That is a reasonable request and uses logical forethought.

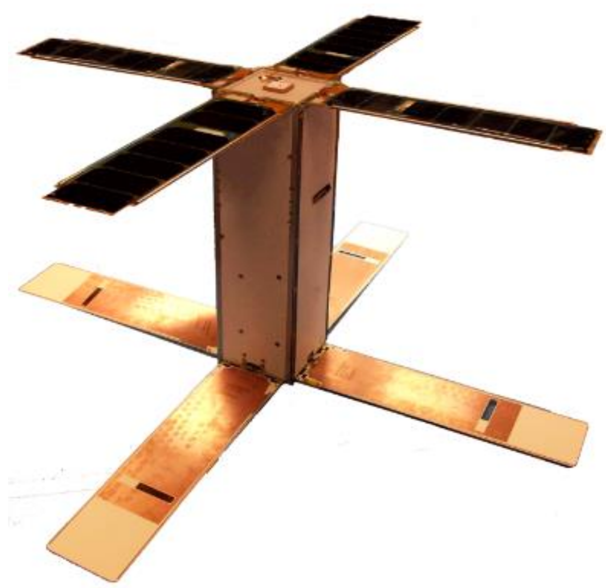

Figure 1: Satellite Solar Panel Concept

With these considerations in mind, there is even more pressure placed on the power engineer to get the design correct and in some cases meet requirements that may appear overly stressing. In any case the designer must respond to as many of these requirements as possible without adversely impacting the overall satellite design or negatively affecting the reliability of the system (e.g. building the EPS Printed Wiring Board (PWB) so thick that the reliability of the vias is adversely affected (this is discussed later).

Some of the specified design requirements were:

1. Four BCR channels each with independent MPPT
2. Capability to handle a minimum of 96 Watts throughput power from the solar panels
3. Support 6, 7 or 8 cell panels over a -50 to 100˚C temperature range
4. Support high power charging from ground support equipment
5. Charge the battery without powering any subsystems and also provide a charge in the event of an over discharged battery
6. Support Lithium-Ion and Lithium Polymer batteries up to 3 cells in series
7. Allow use of inexpensive Radio Control (RC) hobby type batteries (~$50.00) for testing and software development
8. Integrated remove before flight pin and separation switch circuitry
9. Battery over charge/over discharge protection
10. Minimize battery current drain for in situ long term battery storage (>1year)
11. Very quiet (high frequency noise and peak to peak ripple) 3.3 and 5 volt power converters with 4 amp minimum output current for each voltage
12. 12 volt, 2 amp and 28 volt, 1 amp boost converters
13. At a minimum: three output switches connected to the battery each capable of 7 amps; 2 line cutter circuits (for solar panel and line cutter release) each capable of 4 amps; One 45 minute delay switch for radio power (this was originally intended to meet a Launch Vehicle (LV) requirement to prevent any radio transmission while in close proximity to the Launch Vehicle)
14. Low current (1 Amp) 3.3, 5 and raw battery switches, at least one each
15. I2C buss for control and telemetry functions
16. Reverse input protections for ground charging, battery and solar panels
17. Standard PC/104 foot print
18. Provide a battery heater power switch and control function and a battery temperature measurement function
19. Temperature monitoring for all solar panels

There were other minor requirements but the list above represents the overall requirements.

DERIVED DESIGN REQUIREMENTS

Although this section may be of little use to an experienced designer, my desire is to provide some information to a novice that may not be readily apparent. The first item of information we needed was the expected input voltage range to the BCRs (or the expected voltage range from the solar panels). Since one of the requirements was support of 6, 7 or 8 cell panels over a -50 to 100˚C temperature range, we could calculate the extremes of the voltage range if we first choose a solar cell. Since at that time the Spectrolab, Inc. UTJ cell, standard size of 26.62cm^2, were available, these were base lined for the design.[1] This made determining the input voltage a matter of determining the open circuit voltage at minus 50˚C for the 8 cell panels for the high voltage and the MPPT voltage at 100˚C for the 6 cell panels for the low voltage.

From the author’s experience the typical electrical parameters for space grade solar cells are provided on the specification sheet for Air Mass Zero (AM0) at a temperature of 28˚C. Current mainly varies with angle to the sun and for the voltage range calculations, it can be ignored. Solar panel voltage varies inversely with temperature.

Also on the solar cell spec sheet you should find temperature coefficients for voltage at the maximum power point and the open circuit voltage, usually for different Fluence levels.

Referring to the Spectrolab Inc’s UTJ cell specification sheet, if we use the Beginning Of Life (BOL) coefficients, at negative 50˚C, the open circuit voltage for an 8 cell panel calculates to about 25 volts. For a 6 cell panel at maximum power point, the lowest working voltage at 100˚C is 11.3volts.[1]

So the BCR input voltage range is 11.3 to 25 volts.

RESEARCH AND MARKET SURVEY

With most of the design requirements now available, we began a market survey and research of components and methods to determine what components were available for use in the EPS design and the optimal design method. Miltec personnel expended a large number of hours in this market survey and design research. This time spent was instrumental in the successes that were gleaned from this effort.

Miltec personnel performed market surveys of the following commercial components:

1. Battery Charge Regulators
2. Ideal Diode Circuits
3. Power Converters, Buck and Boost
4. Electronic Switches capable of switching raw battery voltage (6.0 to 8.2 V), 3.3V, 5.0V, 12V and 28V rails, with TTL control and integrated over current protection
5. I2C components
6. Components for temperature measurement
7. Components for protection against reverse power connection
8. Transient voltage protection components
9. Timer circuits
10. Pulse Width Modulation circuits for battery heater control

Personnel also performed research into the following design methods:

1. Maximum Power Point Tracking (MPPT)
2. Limiting the battery drain during long time storage
3. Limiting battery over discharge and redundant overcharge protection
4. Meshing the power from the 4 different BCR channels into one power stream for the battery bus
5. I2C bus implementation and I2C telemetry gathering and switch control
6. Temperature measurement
7. Remove before flight and separation switch implementation

IMPLEMENTATION

These following sections will discuss how the design of the EPS was implemented. Lessons learned throughout the design phase will also be discussed.

There are a few design items that are considered company proprietary and will not be discussed in detail. The main intent of this paper is to provide enough information to aid other enginners who may not have much experience designing a cube satellite power system.

At the end of this paper in the appendix are a system overview drawing and an MPPT detail drawing for the reader's review.

POWER INPUT SECTION

Refer to figure 2 for a high level input power flow diagram.

Battery Charge Regulators

After a detailed market survey, the Linear Technology Corporation's LTM8062 was chosen as the base part for the BCRs.[2] The LTM8062 is a near complete battery charger module. It requires a few external components to program the input tracking voltage and battery float voltage. It is designed to charge Lithium Ion and Lithium Polymer batteries and can accommodate an input voltage up to 32 volts. For a 2 cell in series Lithium Polymer battery, it provides about 1.85 amps (lab measurements) max charge into a battery per individual LTM8062. Its efficiency is typically 81 to 83%. If you refer to the LTM8062 specification sheet, it was also thought that the V_{INREG} pin could be used to implement an MPPT function.[2]

The local Linear Technology Corporation's technical representative was able too provide a schematic indicating how the LTM8062s could be placed in parallel for addition power throughput.

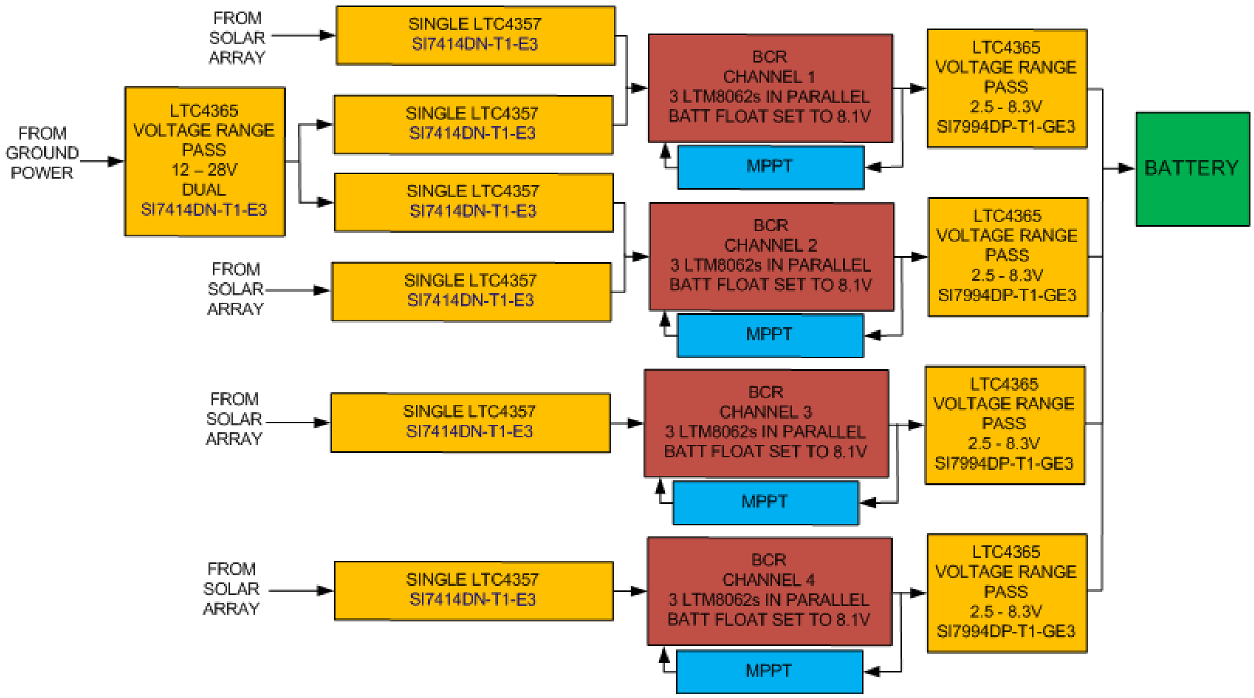

Figure 2: Solar Panel to Battery Power Flow

It was decided to use three LTM8062s in parallel per BCR channel. So each BCR channel would be capable of providing a maximum of 5.55 amps onto the battery bus.

The maximum current onto the battery bus from all four BCR channels is 22.2 amps.

For the available battery volume within a 3U cube satellite and considering the current state of the art for battery capacity that can be crammed into that volume this represents an enormous power system overdesign. However, if you considered that the design could be used in a 12U or even larger satellite, then this designed throughput seems not overly excessive.

The amount of waste heat generated by the BCRs at a full 22.2 amps output would be approximately 33 Watts. Special design precautions were incorporated into the PWB and satellite to remove this excess heat. This design is considered proprietary and will not be discussed within this paper.

The mission power requirements dictated that the current satellite is limited to only one 7 cell panel per BCR channel. However, during acceptance testing each BCR channel was tested to 27 Watts throughput or a total of 108 Watts for all 4 channels

Ideal Diode Circuit Controllers

Considerations for these parts included protection against reverse power input connection, protection against transients such as those encountered during hot plugging of batteries, or ground power sources or possible spikes from the solar panels as they exit the earth's shadow into direct sunlight.

At BCR channels 1 and 2, dual parallel ideal diode controllers were placed at the inputs to provide a method to feed ground power into those two channels. Channels 3 and 4 were only connected to their respective solar panels and therefore had no ground power feed capability. The four controllers connected to the solar panels also act to prevent a current back feed into the solar panels during periods when they are not illuminated.

Again after a comprehensive survey, two ideal diode controllers for design use were selected, the Linear Technology Corporation's LTC4357 and the LTC4365.

LTC4357

The LTC4357 is a positive high voltage ideal diode controller that drives a single external N-channel MOSFET.[3] It has a throughput voltage range of 9 to 80VDC. It is available in a 2x3mm DFN package. It does not protect against transients or reverse voltage connections. Additional components such as reverse connection protection diodes and transient voltage suppressor's were added to the circuits to provide additional protection.

This controller was used to feed the power from the solar panels to the BCRs. It also prevents a back feed of current from the battery to solar panels when they are not illuminated. Additional LTC4357s are connected to BCR channels 1 and 2 to allow feed from ground power. Refer to figure 2.

Ideal diode circuits were used rather than diodes in order to increase overall system efficiency. With each discreet diode, there is an associated power loss. For a schottky diode there is typically a 0.5 volt drop. At a current throughput of 0.43 amps (the approximate current from a single string solar panel using the Spectrolab UTJ cells), the power loss would be about 0.22 Watts. For a 95 minute orbit with 60 minutes of sun illumination and 4 BCR channels, that loss amounts to about 53 Watt-minutes (Watt-minutes is a convenient unit for cube satellite energy measurement). The MOSFETs chosen for use with the LTC4357 controllers was the Vishay SI7414DN which has a 3.3x3.3mm package capable of greater than 4 amps continuous throughput and a maximum drain source voltage of 60 VDC.[19] The SI7414DN has a drain to source resistance (R_{DS}) of 25 milli-Ohms at a gate source voltage (V_{GS}) of 10 volts. If we calculate the loss through the MOSFET, $P=I^2R=0.43^2*0.025=0.0046$ Watts. Again with a 60 minute sun illumination, the total loss for 4 channels is 1.1 Watt-minutes (W-m) or a net savings of 51.9 W-m per orbit. This savings would become much greater with the increased current provided from additional solar panels placed in parallel for each BCR channel.

Refer to the LTC4357 specification sheet for further design information.

LTC4365

The LTC4365 UV, OV and Reverse Supply Protection Controller is really more of a voltage range pass circuit controller.[4] It will pass a voltage range set by resistive divider circuits at the UV and OV the input pins. It also protects against reverse input connection. It can pass voltages between 2.5 and 34 volts and protect against voltages between -40 to 60 volts. It can prevent reverse back feed from circuits connected to its output but if the output circuit voltage is within the range of the voltage pass through set points, it will pass current from the output to the input unless it is actively cut off at the SHDN pin. Also if the output is reverse connected, it will destroy the controller.

Refer to the LTC4365 specification sheet for further design information.

The functions implemented using the LTC4365 include:

1. GSE power voltage pass through limitation
2. Power summing at the output of the BCRs
3. Redundant protection against battery over charge
4. Remove before flight jumper implementation
5. Separation switches/inhibits implementation
6. Protection of the battery against over discharge
7. Very low current drain during off state to accommodate long-term PPOD storage

Each of these functions will be discussed in turn.

LTC4365 GSE Power Voltage Pass through Limitation

Refer to Figure 3. The LTC 4365 was used for voltage feed through from the GSE to ensure the GSE charge voltage pass through was limited between 12 to 28 volts and to protect against GSE power reverse input protection. The MOSFET for this function was the same one used for the LTC4357, the Vishay SI7414DN.

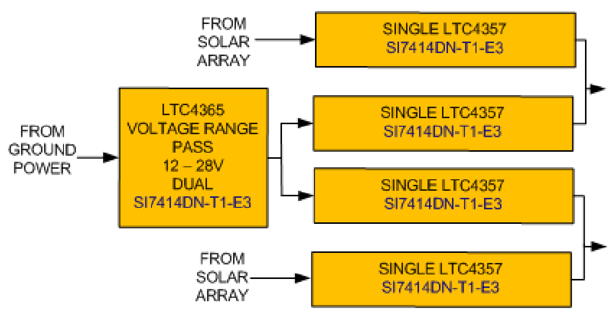

Figure 3: Ground Power Detail

LTC4365 Power Summing at the Output of the BCRs

Refer to Figure 2. The LTC4365 was also used at the output of all BCR channels to accommodate summing of the power flowing onto the battery bus and to interrupt the connection (there by preventing reverse current flow from the battery to the BCR and also providing redundant protection against back feed of current from the battery to the solar panels) whenever the BCR was not providing a charge current. This interruption is accomplished by connecting the LTM8062 NTC pin to the LTC4365 SHDN pin. The NTC pin pulls low whenever the LTM8062 is not charging thus turning off the LTC4365 and preventing current back feed from the battery to the BCR. The

MOSFET used for the summing point LTC4365s was the dual package Vishay SI7994DP-T1-GE3.[20]

Each BCR channel monitors the battery bus voltage to determine the level of battery charge and passes through current according to the battery bus voltage level. Each BCR channel has its' own independent battery float voltage feedback resistors. Each BCR contributes the maximum amount of current possible (depending upon the input power from its connected solar panel) during the constant current mode. Once the battery bus voltage enters constant voltage mode and nears the float voltage, typically one BCR channel with a slightly higher float voltage due to resistor tolerance variations will take over the final charging of the battery and the remaining BCR channels will turn off.

LTC4365 Redundant Protection Against Battery Over Charge

The LTC4365s were also used to provide a redundant method to protect the battery against over charge (the LTM8062 BCRs battery float setting providing the primary overvoltage protection). The 4 LTM4365s feeding BCR power to the battery bus were set to cut off any BCR voltage above 8.3 volts and thus act as a redundant method to protect the battery against over charge. Over charging Lithium-Ion and Lithium Polymer batteries often leads to catastrophic and spectacular failures.

LTC4365 Remove Before Flight Jumper Implementation and Separation Switches/Inhibits

Refer to figure 4 below. The remove before flight jumper acts to keep the LTC4365 SHDN pin pulled to ground even if the separation switches are released. This aids during satellite handling and storage outside a PPOD.

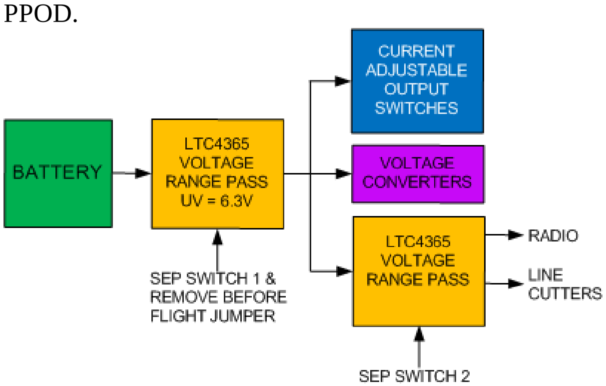

Figure 4: Separation Switches and Remove Before Flight Jumper

For our launch vehicle provider, a total of 3 inhibits (2 fault tolerance) were required to prevent any satellite transmissions or antenna/solar panel deployments. Also there was a requirement that transmissions or deployments could not occur until 45 minutes had elapsed after PPOD ejection.

Separation switch 1 acts as the first inhibit and allows current to pass from the battery providing the battery voltage is above the lower cutoff hysteresis voltage of 6.9 volts. The LTC4365 connected to the battery in figure 4 indicates an under voltage cut off of 6.3 volts. This is the point at which battery output is shut off as the voltage is decreasing. The LTC4365 has a built-in hysteresis function that then turns on the battery output at an increasing voltage level of 6.9 volts. Hence when separation switch 1 is initially released, the battery is only turned on if it is at a level of 6.9 volts or above. We will discuss why the 6.3 volt level was chosen later.

The LTC4365 on the right side of figure 4 is connected to separation switch number two and acts as the second inhibit. It was configured to pass through any voltage coming from the LTC4365 connected to the battery. It feeds power to the radio and the line cutters for antenna and solar panel release. The MOSFET used for the two LTC4365s in figure 4 was the International Rectifier IRF6619.[21] The MOSFETs used in conjunction with the battery output LTC4365s were only single MOSFET implementations sense there was no power source which could back feed through the LTC4365 circuits.

Both separation switches are connected to ground when they are depressed (stored in a PPOD). This keeps the LTC4365s in an off state. When the separation switches are released, they connect the SHDN pins to the battery bus through high impedance resistors. The high impedance resistors prevent high current from flowing through the separation switches and protects the battery against short-circuits. The SHDN pin at the LTC4365 connected to the battery also has a 10 µF capacitor connected to it to prevent inadvertent power on if separation switch 1 undergoes a momentary release during the severe shock and vibration encountered during launch.

A third timer inhibit was initially implemented by use of a hardware timer circuit that began a 49 minute countdown after the voltage converters were turned on. (the requirement was for 45 minutes minimum after release from the PPOD). This timer circuit was connected to the switches for radio and the line cutters via a two input 'AND' gate. Once the timer had expired it pulled one 'AND' gate input high. The other 'AND' gate input was controlled by the flight computer via the I2C Buss and had full control over the switch once the hardware timer expired. However, it was later determined by the launch provider that a hardware timer is not a valid inhibit but a software timer combined with inputs from solar panel telemetry and other parameters to verify the satellite is on orbit was considered a valid inhibit.

Note that your requirements for inhibits may vary from launch vehicle to launch vehicle and even change over time using the same launch vehicle. Close coordination with the launch vehicle safety representative to determine the correct implementation of all required inhibits must be included within the design requirements. That necessitates communications with a designated launch vehicle safety representative very early in the design process.

LTC4365 Protection of the Battery Against Over Discharge

As mentioned earlier, the LTC4365 connected directly to the battery is configured to turn off the battery output at a decreasing voltage of 6.3 volts. This turns off power to the entire satellite. It turns on again at an increasing voltage of 6.9 volts. This hysteresis allows the battery to charge back up to about 20% of its capacity prior to reenergizing the voltage converters. The flight computer is connected directly to the voltage converters and as the voltage converters power on so does the flight computer. If the flight computer is rebooted, onboard logic determines the status of the satellite and increases the battery charge state as necessary. If the separation switches are released and the battery voltage is between 6.3 and 6.9 volts, the LTC4365 connected directly to the battery will again keep the battery output turned off until it reaches a charge level of 6.9 volts.

The percent of total energy remaining within the battery at a cutoff of 6.3 volts is very small (1 to 3%) however since the total leakage current while the system is in off state is low, The 6.3 cut off was chosen to provide for enough energy reserve within the battery to provide for one to two week storage prior to dropping below the battery damage voltage of 6 volts.

Using this EPS, during 18 months of testing and development, no batteries (Flight or Lab throw away) have been over discharged, overcharged, accidentally shorted, or damaged in any manner.

LTC4365 Very Low Current Drain during off State to Accommodate Long-Term PPOD Storage

The measured battery leakage current while in off state is typically 300 to 400 micro amps on average. Due to leakage through the output MOSFET and current through the resistor network connected to OV and UV pins as well as other leakage paths. The fully charged six amp hour battery should theoretically last approximately 1.7 years in PPOD storage (neglecting any internal drain of the battery).

A satellite currently on orbit was fully charged and stored within a PPOD for approximately 5 months prior to launch and ejection. The expected energy loss was about 25%. The initial telemetry from the just ejected satellite indicated a battery voltage of about 7.8 volts or a loss of about 14% of the battery energy. Projecting that loss rate into the future would indicate a storage life of about 35 months.
This could indicate that the average leakage current is smaller than expected or perhaps the battery received a slight charge prior to gathering this early telemetry data.

BATTERIES

Flight Battery

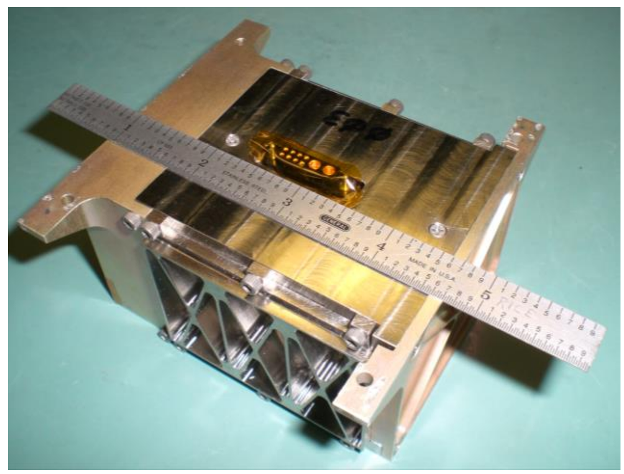

Figure 5: Flight Battery Assembly

The satellite flight battery was fabricated by connecting two Yardney Technical Products, Inc. part number LiAD7BM-1 6 Amp-Hour (AH) Lithium-Ion cells in series.

The LiAD7BM-1 was developed specifically for this program. The Yardney cells can trace their heritage back to many space programs including the "Spirit", "Opportunity" and "Curiosity" Mars rovers.
The Miltec designed battery assembly contains temperature sensors and heaters. Also the midpoint connection between the two battery cells is brought out to the battery connector to facilitate battery balance.

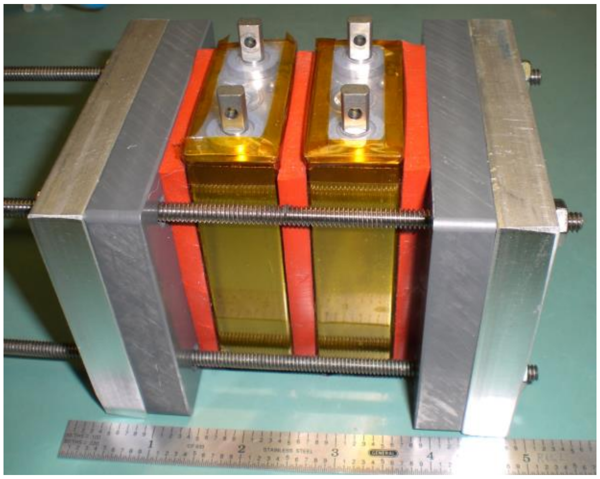

Figure 6: Battery Cells in Shipping Fixture

All large-format prismatic Lithium-ion cells (including the Yardney cells) require special handling techniques. During shipping, the cells are discharged to half capacity and the large sides are compressed within a special shipping fixture. Prior to integration within the Miltec designed battery assembly, the cells must be discharged to 6 volts, removed from the shipping fixture, integrated into the Miltec battery assembly and recompressed within eight hours. The battery assembly is then recharged to half capacity for storage. Failure to follow these procedures will adversely affect the cycle life of the battery.

Also be forewarned that the energy profile for a Lithium-Ion battery is very different from that of a Lithium Polymer battery. The Lithium-Ion batteries provide significant output current at a lower voltage range than the Lithium Polymer. The lower voltage cutoff for a similar Lithium Polymer battery would be set significantly higher than the 6.3 volts lower cutoff used for the Lithium-Ion.

Lab or Throwaway Battery

The EPS was also designed to use inexpensive RC hobby type Lithium Polymer (<$75) batteries during testing and software development thus negating the requirement to use expensive flight type batteries that will be rendered non-flight due to prolonged battery usage during lab operations.

The battery used for general laboratory testing and software development was the Hyperion G3 CX 5000 MAH 2S 7.4V 25C/45C LIPOLY Pack, part number HP25C50002S.[5] It was modified to emulate a flight battery. Temperature sensors, leads for heater connections and the same interface connector used for the flight battery were added to the Hyperion battery. Several of these lab batteries were fabricated and used throughout development and testing with no problems.

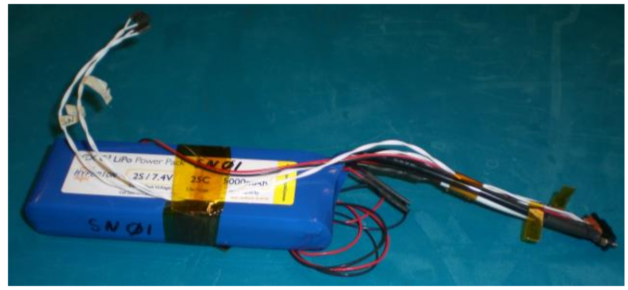

Figure 7: Hyperion Lab Battery Assembly

BATTERY SUPPORT CIRCUITS

Battery Heater Circuit

Refer to figure 8. Two transistors (Fairchild Semiconductor part number PZT3904) were installed in the battery assembly for use as temperature sensors in conjunction with Linear Technology Corporation part number LTC2997.[6,7] Refer to the LTC2997 specification sheet figure 8 for the design method. The LTC2997 V_{PTAT} pin outputs 4 mV per degree Kelvin. The V_{REF} pin outputs 1.8 volts and is used in conjunction with a voltage divider to set a 0˚C (1.09V) voltage threshold for the dual channel comparator.

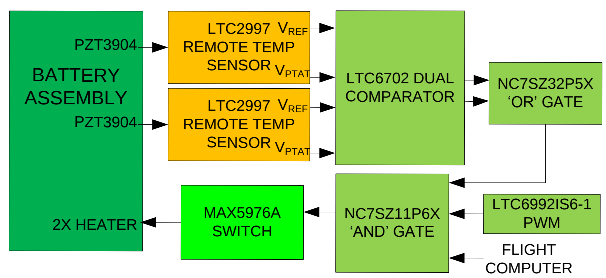

Figure 8: Battery Heater Circuit

Note the voltage divider resistors at V_{REF} are omitted in figure 8. As the voltage from V_{PTAT}, (either sensor) drops with temperature and passes through 0˚C, the comparator out puts a high into an 'OR' gate. The output of the 'OR' gate is fed to one input of a three input 'AND' gate. The second input is fed by a LTC6992IS6-1 voltage controlled Pulse Width Modulator (PWM).[8] The PWM is adjustable for frequency and duty cycle. For this design it was set to 10 Hz at a 20% duty cycle. The PWM circuit runs continuously as long as power is applied. The last input of the 'AND' gate is controlled by the flight computer via the I2C Buss. The Maxim Integrated Products

MAX5976A switch draws power from the LTC4365 circuit connected directly to the battery bus.[9]

There are two heaters on opposite sides of the battery cells wired in parallel installed within the battery assembly.

The heaters can only be energized if the temperature is below the temperature set point and the flight computer commands its' 'AND' gate input high.

Battery Balance Circuit

There are articles, papers and conjecture indicating that 2 cell in series Lithium-Ion batteries do not require battery balancing. There is even a renowned satellite battery fabricator that manufactures an eight cell in series Lithium-Ion battery without any provision for cell balancing. Their belief is that it is not necessary.

The author's opinion is cell balancing improves the stability of the battery assembly and as such have included this capability in our design. The other advantage is the desire and ability to gain more experience in designing cell balance circuits.

The Texas Instruments, Inc. part number bq29200 was the only identified cell balance IC designed specifically for balancing 2 cell in series Lithium-Ion batteries.[10] The bq29200 specification sheet indicates a current draw of not more than 6 µA while in standby mode. The part was design onto the EPS CCA with the ability to isolate it from the battery cells using solder jumpers. During initial testing of the EPS, the bq29200 was left isolated. The measured battery leakage current while the bq29200 was left isolated was typically 300 to 400 micro amps on average. Once the bq29200 was connected to the battery cells, the leakage current increased to between 600 to 900 micro amps. This amount of current would have caused the PPOD storage time to be cut in half. The bq29200 was then isolated from the battery cells and the decision was made that battery balance was not required. No attempt at troubleshooting the bq29200 circuit was made.

OUTPUT SWITCHES

All but one output switches are Maxim Integrated Products MAX5976A.[9] They operate from 2.7 to 18 volts. The output current limit can be adjusted via an external resistor. They are relatively small (5 x 5mm) and the 'A' version has an automatic retry after an over current condition. These switches are the main over current protection mechanisms for the entire EPS design.

The only other model switch within the EPS is located on the mezzanine CCA and is used on the 28 volt boost converter output. It is a Linear Technology Corporation part number LT1910 Protected High Side MOSFET Driver used in conjunction with a Vishay Siliconix SI7414DN MOSFET.[19, 22] It has an 8 to 48 volt range, provides adjustable over current protection and automatic restart in the event of an over current event.

SOLAR PANELS

The solar panels are custom-designed and fabricated by Pumpkin, Inc. They use seven Spectrolab, Inc. UTJ solar cells per panel.[1] The only other item of note on the solar panel design is that the temperature sensors are transistors. Each panel contains one Fairchild Semiconductor part number MMBT3904 designed to work in conjunction with Linear Technology Corporation part number LTC2997.[6,7] Refer to the LTC2997 specification sheet figure 8 for the design method. The outputs of the LTC2997s were fed into an analog-to-digital converter connected directly to the I2C Buss for telemetry purposes.

MAXIMUM POWER POINT TRACKING

Refer to the Maximum Power Point Tracking (MPPT) diagram contained within the appendix at the end of this paper.

The LTM8062s contain a V_{INREG} pin that sets the input voltage regulation point. Within the LTM8062 this pin is also connected to a 100KΩ resistor to ground.[2] So all that is needed is a resistor connected from V_{IN} pin to the V_{INREG} pin in order to program the input voltage regulation point. Once the input voltage regulation is set, the LTM8062 will servo the output current to maintain the programmed input voltage set point.

The use of the V_{INREG} pin for MPPT implementation seemed like a good idea. Recall that there are three LTM8062s per BCR channel. Since all of the V_{INREG} pins are connected within a single BCR channel, this would change the total resistance to ground at the V_{INREG} pins to 33.33KΩ.

In a low battery voltage situation, there would be no power (3.3V or 5.0V) to power the MPPT circuits. Therefore the BCRs were set up with a default tracking voltage of 14 volts (V_{IN} to V_{INREG} resistor value of 140KΩ) which would operate until power was provided to the MPPT circuits.

After MPPT power is available, the circuit is designed to work as follows:

The BCR channel feeds power into an Allegro Micro Systems, LLC part number ACS715ELCTR-20A-T current sensor.[11] The current sensor has a voltage offset of 0.1*V_{CC}. V_{CC} in this case is 5V, so the offset is 0.5 volts.

The output of the current sensor is then fed into a Linear Technology Corporation part number LTC2055 op amp configured as a differential amplifier.[12] The op amp subtracts the offset voltage and has a gain of three. The output of this op amp will be referred to as "new current value"

The differential amplifier output is then fed into two downstream components. Please refer to the diagram. The "new current value" first is directly sent to Linear Technologies, Inc. part number LTC6702 comparator "+IN" pin.[13] Note that this part is actually a dual channel comparator. For this discussion we will only consider one of the channels.

The other path for the "new current value" is connected to a Vishay Siliconix DG9422DV-T1-E3 switch.[14] The switch is turned on/off by the master clock. The master clock is a 10 Hz 50% duty cycle signal generated by a Linear Technology Corporation part number LTC6992IS6-1; a voltage controlled Pulse Width Modulator.[8] When the switch is on, it charges a 1 µF holding capacitor at it's output.

The holding capacitor is connected to another LTC2055 op amp in a "follower" configuration (gain equals 1).[12] The output of this op amp will be referred to as "old current value" and is connected to the"'–IN" pin at the same comparator as the "new current value".

The comparator outputs a one as long as the "new current value" is greater than the "old current value". As long as the "new current value" is greater than the "old current value", the MPPT will continue to move the input voltage regulation point in the same direction. Whenever the "new current value" is less than the "old current value" the MPPT will reverse the direction of the input voltage regulation.

The comparator output feeds a Texas Instruments, Inc. part number SN74HC74PWT Data flip-flop.[15] The flip-flop is clocked by the master clock plus a 30 ms delay. The delay is accomplished by a Linear Technology Corporation part number LTC6994HS6-2 programmable delay circuit.[16] The delay was provided so that the flip-flop could store the data from the comparator after the MPPT circuits had perturbed the input voltage regulation point from the previous setting. The output is the Q_N pin. So if the input to the flip-flop is high, the Q_N pin will be low. The only time the Q_N pin will be high is when the flip-flop input is low, indicating that the "new current value" is lower than the "old current value" and that the MPPT input voltage regulation is going in the wrong direction.

The Q_N output of the data flip-flop is fed to one input of a two input 'AND' gate. The "AND" gate is a Fairchild Semiconductor part number NC7SZ08P5X.[17] The other input is fed by the master clock plus a 30 ms delay. So the 'AND' gate output can only go high when the master clock plus 30 ms signal is high. If the "old current value" is greater than the "new current value", the data flip-flop should output a high which is then fed through the 'AND' gate into the clock pin of a data flip-flop rigged in a toggle configuration.

The toggle configuration flip-flop is a Texas Instruments, Inc. part number SN74HC74PWT Data flip-flop.[15] A high at the clock pin of the toggle flip-flop causes the output pin 'Q' to change states.

The output pin is connected to the U/D selection pin of an Analog Device, Inc. part number AD5220BRMZ100, 100KΩ, 128 position digital potentiometer.[18] The digital potentiometer is biased at the A1 and B1 pins such that the output wiper can only vary between 1 and 4.3 volts. The CLK pin is connected to the master clock. If the U/D is high, the wiper moves towards 4.3 volts. If the U/D is low, the wiper moves towards 1 volt.

The digital potentiometer wiper is connected to a Linear Technology Corporation LTC2054H op amp in a follower (gain equals 1) configuration.[12]

The op amp output was connected to a 25KΩ in series resistor to a Vishay Siliconix DG9422DV-T1-E3 switch.[14] The switch allows the MPPT circuits to be isolated from the LTM8062s V_{INREG} pin while the MPPT function was powered down and allowed the V_{INREG} pin to operate at a resistor programmed default voltage of 14 volts.

When the switch was closed, the op amp output was connected to the LTM8062s V_{INREG} pin. The V_{INREG} pin regulates its input to 2.7 volts. Again a resistor is typically connected from the V_{IN} pin to the V_{INREG} pin too program an input voltage regulation point.

The MPPT design was intended nudged this point up or down towards the maximum power point depending on the measurement of the output current of the BCR.

The MPPT Design Did Not Work!

The entire explanation placed within this paper only serves to illustrate less than optimum design. However, even an undesirable design can serve to provide insights towards a good design method.

One of the problems with the design was that the current sensors were more noisy than anticipated. Also they were designed to work over a 20 amp range and the resolution was not adjustable. Since we only used a single solar panel per BCR channel, this limited the BCR output current range to between about 0 and 0.9 amps or less than 5% of the current sensors range. This fact combined with the unanticipated extra noise in the current measurement output made it impossible for the maximum power point tracker to determine if the output current was increasing or decreasing. As designer, I should have chosen a sensor that had more resolution at the expected current levels and added an output noise filter to the circuit. This was a valuable lesson that can be carried forward to future designs.

Also the digital potentiometer could only take one step per measurement. Had there been some adjustability in the number of steps the digital potentiometer made between current measurements, the MPPT would have had a higher probability of success.

In any case any follow on design will be radically different from this first design attempt.

Since the MPPT function did not operate, all BCR channels were set to regulate the input voltage at 14 volts.

The 14 volt regulation point provided 6 Watts per BCR up to a panel voltage of 80˚C or 24 Watts total at the BCR inputs. Taking into account losses incurred by the BCRs, the power onto the battery bus is 19.7 Watts. If you assume an orbit with 60 minutes of sunlight, this provides 1182 Watt-minutes of power collection (the battery contains about 2600 Watt-minutes). This was power collection level was considered adequate to cover the satellite operating scenarios.

CIRCUIT CARD ASSEMBLY (CCA) IMPLEMENTATION

As the schematic design neared completion, we realized the EPS design would need to be broken up into multiple CCAs. Refer to figure 9 below.

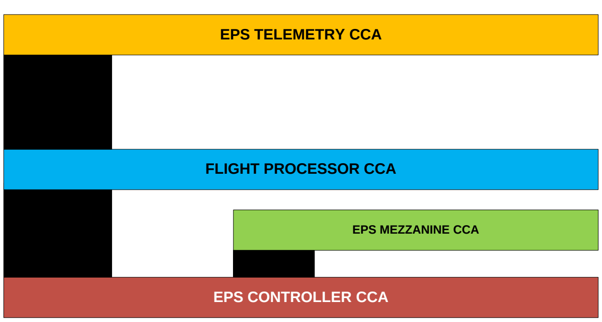

Figure 9: Satellite CCA Concept

All power converters would be placed on a mezzanine card attached directly to the EPS controller card (or mother card). Also since the mezzanine card was smaller, it was thought that it could be redesigned/re-fabricated quickly to accommodate unforeseen power requirements or other functions.

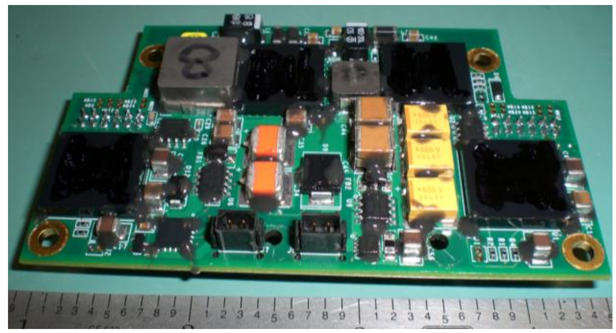

Figure 10: Mezzanine Top

Figure 11: Mezzanine Bottom

Figure 12: EPS Controller Top

Figure 13: EPS Controller Bottom

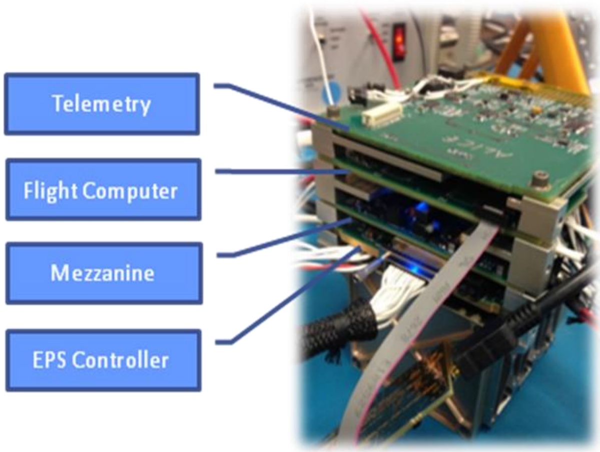

Figure 14: CCA Stack Up

Also a telemetry CCA was added to accommodate the required circuitry to make all the telemetry available to the I2C Buss. A list of the I2C telemetry functions includes: solar panel temperatures, solar panel voltages and currents, BCR output currents, battery voltage, and output current, all power converters output currents and voltages and PWB temperature from all CCAs.

Refer to figure 14. The flight processor CCA fits between the EPS controller and the telemetry CCAs.

RANGE SAFETY REQUIREMENTS

Inhibits

As stated earlier, our launch vehicle provider required a total of 3 inhibits to prevent any satellite transmissions or antenna/solar panel deployments. Also there was a requirement that transmissions or deployments could not occur until 45 minutes had elapsed after PPOD ejection.

The two separation switches were accepted as meeting the requirements for the first two inhibits. A hardware timer circuit was intended to provide the third inhibit but was found to be inadequate by launch vehicle safety personnel. To satisfy the deficiency a software timer combined with inputs from solar panel telemetry and other parameters to verify the satellite is on orbit was implemented as the third inhibit.

Again requirements for inhibits may vary from launch vehicle to launch vehicle and even change over time using the same launch vehicle. Close coordination with the launch vehicle safety representative to determine the correct implementation of all required inhibits must be included within the design requirements.

Battery Testing Requirements

Range safety personnel indicated that any battery testing requirements would be minimized for any battery that already had UL or MSA approval. I would recommend for any new power system the designer use batteries that already had UL or MSA approval or to attempt to identify and use a battery that had already been successfully tested and approved for another program.

For the Yardney battery cells used within this design no prior approvals existed from Range Safety. One item in our favor was that the Range Safety personnel were familiar with the quality of larger capacity Yardney battery cells used onboard other payloads. This heritage eased the qualification process

The batteries required testing against over charge, over discharge and reverse charge also a single cell would need to be short circuit tested.

In most commercial Lithium Polymer and Lithium-Ion batteries the circuitry to protect against over charge, over discharge, short circuit and reverse charge are built directly into the cell. In this design there is no protection circuitry built directly into the cells. The protection circuits are built into the EPS itself. The battery and the EPS are not designed to be used as separate entities.

Range safety personnel agreed testing could be performed with the combined battery and EPS assemblies to demonstrate circuitry to protect agains over charge and over discharge. The battery was reverse connection protected by placing an N-Channel MOSFET between the battery Anode and the CCA ground. The MOSFET Drain is connected to the battery Anode, the MOSFET Source is connected to the CCA ground and the Gate is connected to the CCA battery Cathode through a 20KΩ resistor. This along with the connector design between the EPS CCA and the battery makes it impossible to reverse connect the battery. So battery reverse charge testing was not considered necessary.

The testing for over charge and over discharge was performed in-house. Data was collected and a report was generated and submitted. There were no problems encountered. Since Yardney Technical Products, Inc. already had the equipment and a great deal of experience with cell short circuit testing, it was decided to have them perform the short circuit testing.

The key requirements for passing the short circuit test were that no rupture or out gassing of the cell could occur.

The test was performed, no problems were encountered, and a report was generated and submitted to range safety personnel.

All range safety battery testing requirements were met and the battery was approved for flight use.

ORBIT POWER DATA SAMPLE

Refer to figure 15 below.

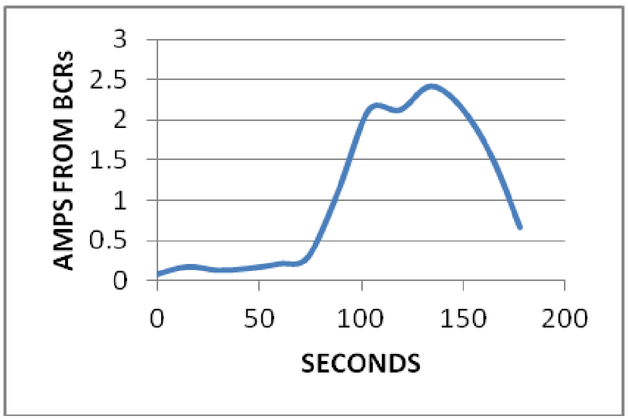

Figure 15: Orbit Power Sample

Figure 15 represents a 178 second block of time for a satellite on orbit with samples collected at approximately 15 second intervals.

The satellite has an attitude control system points the solar panels (refer to figure 1) towards the sun during the sun illumination section of the orbit. The satellite is rotating around its major axes (the long part) towards and away from the sun. The period of rotation is approximately 4 minutes.

Let us consider the current peak at the 140 second point. The measurement occurs at precisely 134 seconds and peeks out at 2.42 amps. The battery voltage is recorded as 8.0 volts. The maximum theoretical power available from the solar panels is 24.1 Watts. If we consider the losses that occur in the BCR channels, this number drops to 19.8 W flowing onto the battery bus. We can then determine the theoretical current by dividing the Watts by the battery voltage or 19.8/8.0 = amps 2.47 amps. This is a very close correspondence between actual measured current (2.42 amps) and theoretical calculated current (2.47 amps).

SUMMARY AND WHAT TO DO DIFFERENTLY

This was our first effort at designing a cube satellite electrical power system. There were successes and lessons learned to improve the design. The most important lesson was the design for the Maximum Power Point Tracker. Another iteration of the design would produce the hardware with a functioning MPPT necessary for actual flight use. Perhaps an MPPT design using a more conservative approach should have been initially considered to improve the probability of success.

There were other problems as well that were overcome by post-fabrication custom modifications to the CCAs. These fixes underscore the importance of having highly qualified technician support readily available. Most importantly the design was flown and is currently working on orbit.

EPS Controller Card

Other problems were manufacturing problems/defects associated with the EPS controller card.

In order to handle the large throughput power, the PWB had to be quite thick (~0.15 inches) in comparison to a normal PC/104 PWB. This presented problems in soldering through hole connectors to the PWB due to the large amount of heat required to melt the solder and adhere it to the large copper pours. Also half of the PWB/CCA builds were rejected do to defective vias between layers. Again this was attributed to the thickness of the PWB.

In any future build, I would either place the BCR's onto separate CCAs and sum the outputs at the battery connector or I would use a PWB that had completely separate signal and large current power sections.

Maximum Power Point Tracking

Firstly I would use less noisy current measurement sensors with zero offset voltage with the ability to adjust the measurement resolution. Next I would include a microcontroller to monitor the current sensors. I would then direct connect a digital potentiometer between the LTM8062s V_{IN} pin and

V_{INREG} pin and use the microcontroller to directly adjust the digital potentiometer in order to perturb the input voltage regulation point. Refer to figure 17.

Battery Balance

The original design unfortunately drew more current than it should have while connected to the cells. Since there do not seem to be any other off-the-shelf options for balancing a two cell in series battery, I would design from scratch the ability to feed the cell voltages through high impedance resistors into an op amp then to the microcontroller so that it could determine if the cells required balancing and then add solid-state relays controlled by the microcontroller across the individual cells with appropriate power dissipating resistors in series. The microcontroller would close the solid-state relay on the high cell until its voltage matched that of the low cell.

SUGGESTED STUDENT PROJECTS

Solar Panel Simulator

The testing of Maximum Power Point Trackers requires either a real solar panel and moving the required equipment out into the sunlight for testing or some sort of a solar panel simulator.

It is possible to construct a low-cost solar panel simulator using a lab power supply (in our case an Agilent E3236A), notebook processor and a software program to control the power supply.

Our Software Engineers were able to quickly write a program that monitored the lab supply output voltage as it was being changed by a Maximum Power Point Tracker and modified the supply output current limit according to a programmed solar panel current/voltage curve.

They created a GUI (refer to the figure below) that allows for quickly changing the simulated panel open circuit voltage and short circuit current and also displays the power supplies output. The operator can observe the "Percentage of Maximum" voltage and easily determine how well the Maximum Power Point Tracker is working. This proved to be a very useful tool during testing of new Maximum Power Point Tracker designs.

Figure 16: Solar Panel Simulator GUI

Maximum Power Point Tracker

After the failure of our first attempt at a Maximum Power Point Tracker design, we began investigating alternate methods of MPPT design and implementation.

Since design and fabrication of custom CCAs is expensive and time-consuming, we decided to utilize available low-cost demo cards for quick circuit implementation and testing.

This allowed design flexibility and the capability to quickly implement changes.

Refer to figure 17 below. We were able to purchase the required demo cards and other miscellaneous parts for less than $1000. The demo cards, Aardvark and battery were attached to a plywood board using various fasteners.

Developing your own circuit using low cost demo boards allows the designer to identify/choose components that may in fact improve the design (i.e. there are no limitations).

Cautions/Suggestions:

Ensure that the LTM8062 demo card is modified to the appropriate battery float resistors.

Consider reverse input protection at the point where the simulated solar panel voltage enters the circuit.

Consider reverse battery connection protection

Consider reverse input protection for all circuits that require external 3.3 or 5 volt power.

Ensure the digital potentiometer demo card is rated to the highest expected input voltage.

Consider installing a switch at the LTM8062 V_{IN} V_{INREG} pin to switch between the digital potentiometer and a resistor connected to V_{IN} in order to verify circuit operation prior to experimenting with the digital potentiometer.

You will also need a means to discharge the battery since the LTM8062 switches to constant voltage mode as the battery nears full charge. Something like a high wattage resistor with a fan blowing across it. You might also consider adding a LTC4365 demo card between the battery and the resistor to prevent over discharge of the battery.

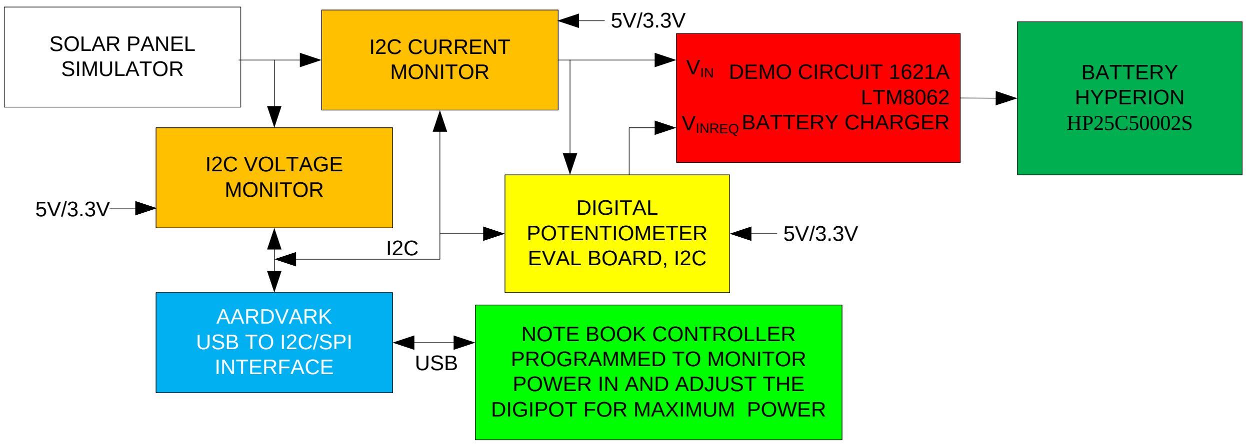

Figure 17: MPPT Experiment

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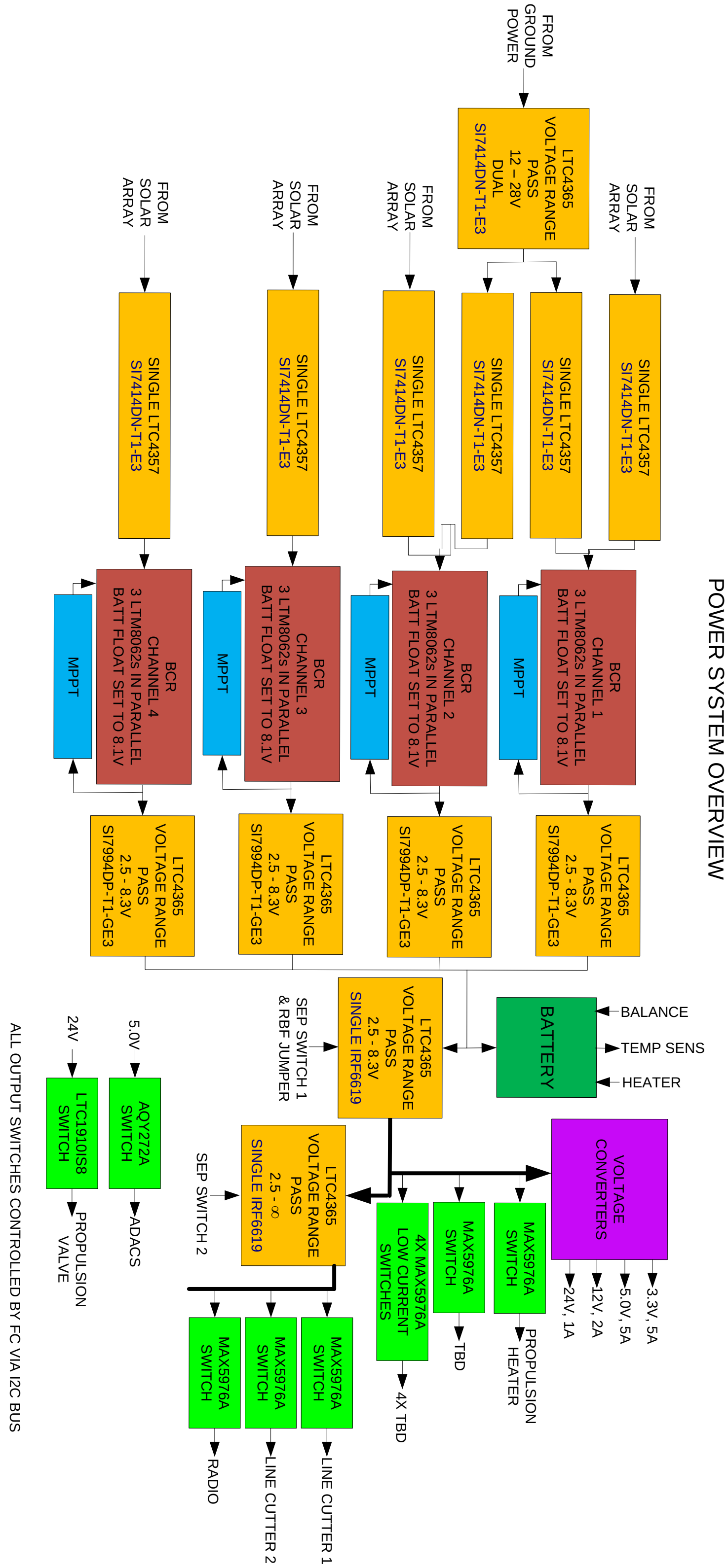
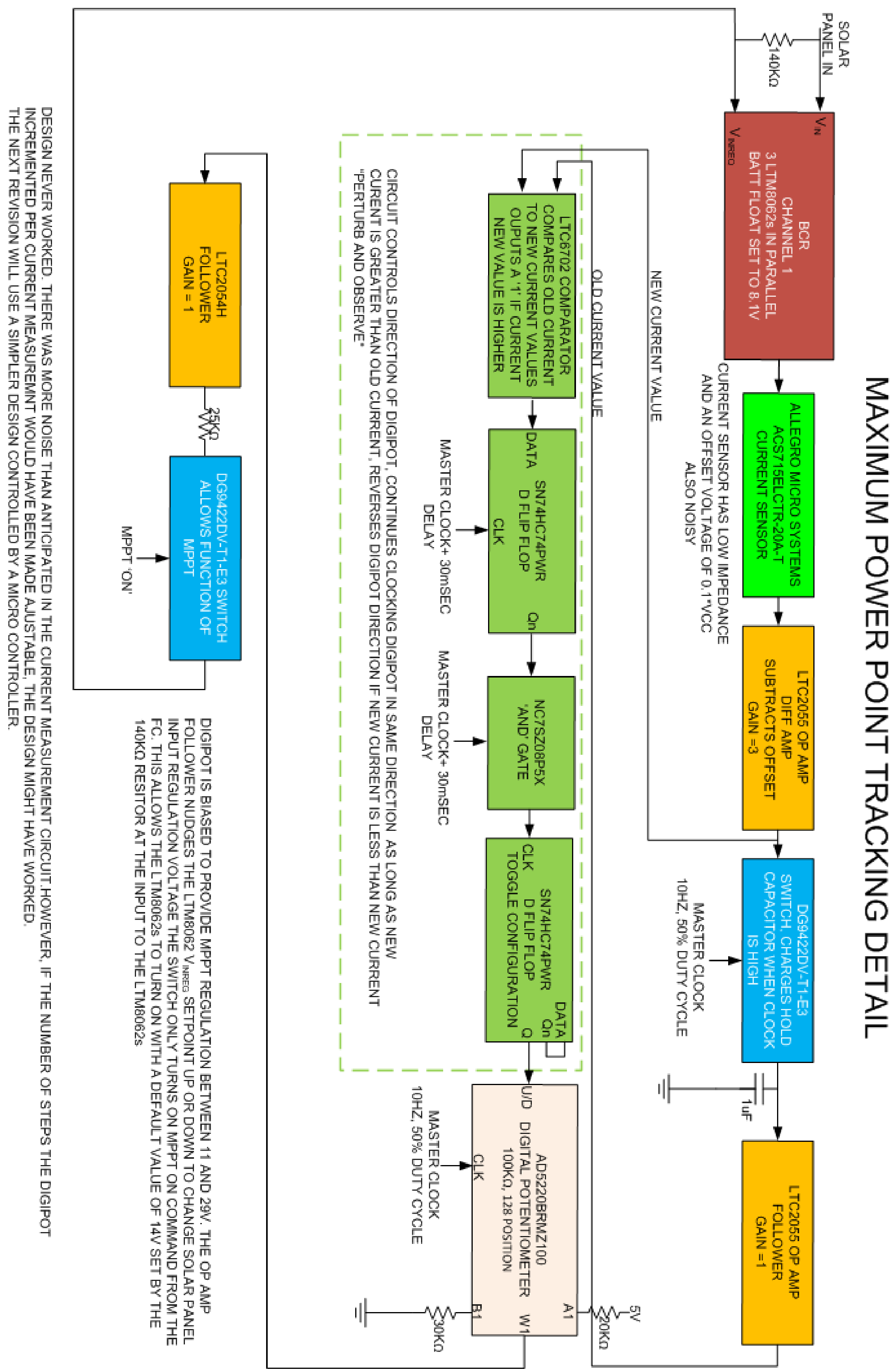
APPENDIX



POWER SYSTEM OVERVIEW
FROM GROUND POWER
LTC4365 VOLTAGE RANGE PASS 12 – 28V DUAL SI7414DN-T1-E3
FROM SOLAR ARRAY
FROM SOLAR ARRAY
FROM SOLAR ARRAY
FROM SOLAR ARRAY
SINGLE LTC4357 SI7414DN-T1-E3
SINGLE LTC4357 SI7414DN-T1-E3
SINGLE LTC4357 SI7414DN-T1-E3
SINGLE LTC4357 SI7414DN-T1-E3
SINGLE LTC4357 SI7414DN-T1-E3
SINGLE LTC4357 SI7414DN-T1-E3
BCR CHANNEL 1 3 LTM8062s IN PARALLEL BATT FLOAT SET TO 8.1V
BCR CHANNEL 2 3 LTM8062s IN PARALLEL BATT FLOAT SET TO 8.1V
BCR CHANNEL 3 3 LTM8062s IN PARALLEL BATT FLOAT SET TO 8.1V
BCR CHANNEL 4 3 LTM8062s IN PARALLEL BATT FLOAT SET TO 8.1V
MPPT
MPPT
MPPT
MPPT
LTC4365 VOLTAGE RANGE PASS 2.5 - 8.3V SI7994DP-T1-GE3
LTC4365 VOLTAGE RANGE PASS 2.5 - 8.3V SI7994DP-T1-GE3
LTC4365 VOLTAGE RANGE PASS 2.5 - 8.3V SI7994DP-T1-GE3
LTC4365 VOLTAGE RANGE PASS 2.5 - 8.3V SI7994DP-T1-GE3
BATTERY
BALANCE
TEMP SENS
HEATER
LTC4365 VOLTAGE RANGE PASS 2.5 - 8.3V SINGLE IRF6619
SEP SWITCH 1 & RBF JUMPER
VOLTAGE CONVERTERS
3.3V, 5A
5.0V, 5A
12V, 2A
24V, 1A
MAX5976A SWITCH
PROPULSION HEATER
MAX5976A SWITCH
TBD
4X MAX5976A LOW CURRENT SWITCHES
4X TBD
LTC4365 VOLTAGE RANGE PASS 2.5 - ∞ SINGLE IRF6619
SEP SWITCH 2
MAX5976A SWITCH
LINE CUTTER 1
MAX5976A SWITCH
LINE CUTTER 2
MAX5976A SWITCH
RADIO
5.0V
AQY272A SWITCH
ADACS
24V
LTC1910IS8 SWITCH
PROPULSION VALVE
ALL OUTPUT SWITCHES CONTROLLED BY FC VIA I2C BUS


MAXIMUM POWER POINT TRACKING DETAIL
SOLAR PANEL IN
140KΩ
V_{IN}
V_{INREG}
BCR CHANNEL 1
3 LTM8062s IN PARALLEL
BATT FLOAT SET TO 8.1V
ALLEGRO MICRO SYSTEMS ACS715ELCTR-20A-T CURRENT SENSOR
CURRENT SENSOR HAS LOW IMPEDANCE AND AN OFFSET VOLTAGE OF 0.1*VCC ALSO NOISY
LTC2055 OP AMP DIFF AMP SUBTRACTS OFFSET GAIN =3
DG9422DV-T1-E3 SWITCH, CHARGES HOLD CAPACITOR WHEN CLOCK IS HIGH
MASTER CLOCK 10HZ, 50% DUTY CYCLE
1uF
LTC2055 OP AMP FOLLOWER GAIN =1
NEW CURRENT VALUE
OLD CURRENT VALUE
LTC6702 COMPARATOR COMPARES OLD CURRENT TO NEW CURRENT VALUES OUPUTS A '1' IF CURRENT NEW VALUE IS HIGHER
DATA
SN74HC74PWR D FLIP FLOP
CLK
Qn
MASTER CLOCK+ 30mSEC DELAY
NC7SZ08P5X 'AND' GATE
MASTER CLOCK+ 30mSEC DELAY
SN74HC74PWR D FLIP FLOP TOGGLE CONFIGURATION
CLK
DATA
Qn
Q
CIRCUIT CONTROLS DIRECTION OF DIGIPOT, CONTINUES CLOCKING DIGIPOT IN SAME DIRECTION AS LONG AS NEW CURENT IS GREATER THAN OLD CURRENT, REVERSES DIGIPOT DIRECTION IF NEW CURRENT IS LESS THAN NEW CURRENT "PERTURB AND OBSERVE"
U/D
AD5220BRMZ100 DIGITAL POTENTIOMETER 100KΩ, 128 POSITION
CLK
A1
W1
B1
5V
20KΩ
30KΩ
MASTER CLOCK 10HZ, 50% DUTY CYCLE
DIGIPOT IS BIASED TO PROVIDE MPPT REGULATION BETWEEN 11 AND 29V. THE OP AMP FOLLOWER NUDGES THE LTM8062 V_{INREG} SETPOINT UP OR DOWN TO CHANGE SOLAR PANEL INPUT REGULATION VOLTAGE THE SWITCH ONLY TURNS ON MPPT ON COMMAND FROM THE FC. THIS ALLOWS THE LTM8062s TO TURN ON WITH A DEFAULT VALUE OF 14V SET BY THE 140KΩ RESITOR AT THE INPUT TO THE LTM8062s
LTC2054H FOLLOWER GAIN = 1
25KΩ
DG9422DV-T1-E3 SWITCH ALLOWS FUNCTION OF MPPT
MPPT 'ON'
DESIGN NEVER WORKED. THERE WAS MORE NOISE THAN ANTICIPATED IN THE CURRENT MEASUREMENT CIRCUIT.HOWEVER, IF THE NUMBER OF STEPS THE DIGIPOT INCREMENTED PER CURRENT MEASUREMINT WOULD HAVE BEEN MADE AJUSTABLE, THE DESIGN MIGHT HAVE WORKED.
THE NEXT REVISION WILL USE A SIMPLER DESIGN CONTROLLED BY A MICRO CONTROLLER.