

Integrating Lithium Polymer Charging and Peak Power Tracking on a CubeSat Class Satellite

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ABSTRACT

Every satellite must regulate incoming power from solar cells, charge batteries and regulate satellite power to maintain satellite health. The power system should be as light, small, and efficient as possible to allow a maximum of resources to satellite systems while minimizing complexity, and meeting CubeSat mechanical and thermal requirements. This paper describes a modular power system, which integrates peak power tracking, battery charging, and power regulation. In addition, it describes the entire power design of a CubeSat power system. This system includes the modular power system described above together with solar cells, and lithium polymer batteries. Due to a limited budget and limited efficiency of solar cells, there is very little power to supply the satellite. Therefore, the power system achieves good efficiency and low mass/volume by implementing a bang-bang peak power tracking system with integrated battery charging. This system will use a PWM buck-boost converter to control the current drawn from the solar cells as well as regulate the charging of the lithium polymer batteries. A micro-controller tracks the feedback from the peak power / charging system and adjusts the regulator accordingly. In addition to the peak power tracker, a power management scheme insures longer operating periods and a reliable downlink transmission. This design results in a highly integrated power system.

INTRODUCTION

A CubeSat^{1,2} class satellite, while small does have a complex mix of mechanical, thermal, and electrical requirements. It is also desirable for the satellite to perform well on orbit as several CubeSat Class satellites have demonstrated that they can perform significant missions, and perform them very well^{3,4}. At the same time, Swartwout has documented that it is difficult to develop successful satellites in which the training of students is a primary program objective. It is even more difficult to develop an educational satellite program which is sustained and returns to orbit after the first mission^{5,6}.

In an attempt to address the low success rate of student built satellites, recent projects^{7,8} at Taylor have focused on highly modular subsystems which are developed for a specific mission, but also have the system level requirement that they be modular and able to be “building blocks” for future satellite missions.

This past academic year, five Taylor University engineering seniors took on the task of developing a functional CubeSat system consisting of at least two

identical orbiting single cube satellites. This system is to demonstrate a functional wireless mesh network in space which enables collection of multipoint measurements of scientific data. The scientific purpose of these satellites is to collect data with both spatial and temporal resolution which is related to space weather. Such data is necessary to have a better understanding of space weather¹⁰. While developing this two satellite system, the students were to develop it in a way that the scientific subsystems were compatible with BUSAT⁹, a University Nanosatellite 5 project under development at Boston University for which Taylor has a subcontract to develop several subsystems.

This paper focuses attention on the power subsystem of the CubeSat satellites. This power system is again a highly modular design to allow for subsystem reuse. This system takes in energy from the solar cells, charges batteries, distributes power to other subsystems, and passes satellite power information to the ground communication module. This system is somewhat novel in that it charges the batteries in such a way to maximize the power coming into the satellite from the solar cells. This method of solar cell peak power

tracking reduces the components necessary for the power system as battery charging and solar peak power tracking are integrated. While this method of maximizing flow of electrical energy into the satellite is simple, the authors are not aware of its use in CubeSats other than earlier projects^{11,12} at Taylor University.

In this paper we will focus our attention on the power and battery charging system for CubeSat class satellites. To place this work in context we will first briefly describe the CubeSat satellites for which it is being developed. We will then describe in detail the power and battery charging system, including the power system requirements, description of the solar cells and batteries and a detailed description of the resulting CubeSat power system including integrated peak power tracking and battery charging.

POWER SYSTEM DEVELOPMENT CONTEXT

Before describing the power system directly, we first describe the context in which we carried out this work. While the power system is highly modular, many of the design decisions were influenced by the overall CubeSat system.

Mesh Network CubeSat

The main objective of this CubeSat mission is demonstration of a self-forming and self-healing wireless network in space. This type of network is called a mesh network and allows communication between nodes either through an established network topology or through point to point protocols. For example, in Figure 1 communication could follow the network topology or could follow point to point protocols. For instance, if node E broke, Node F could communicate directly to Node D if it was in RF range. If they were not in RF range, and Node E broke, Node F would rejoin the network as a child of some other node, thus re-establishing communication with Node D. In these networks, any node can be a repeater of information thus allowing large area network coverage even though the nodes themselves are inexpensive, low power and have a relatively short communication range. The applications of this type of networking technology in space are immense. A space mesh network would enable multipoint measurements of scientific data, provide a communications infrastructure for low cost satellites, provide continuous air-ground communication through a single terrestrial antenna and provide an inexpensive self-healing communications infrastructure for missions to the Earth, Moon and Mars.

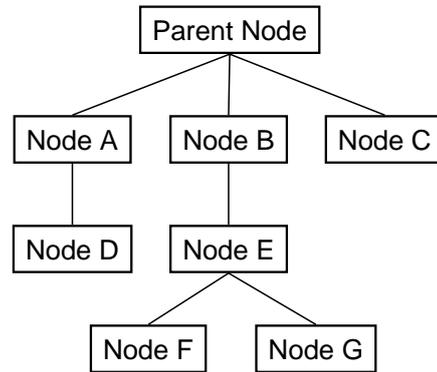


Figure 1 Example Mesh Network Topology

Satellite Systems

Figure 2 below shows the satellite block diagram. The satellite consists of four subsystems: power, communications, VLF receiver, a Langmuir plasma probe and the necessary mechanical systems to integrate and support the subsystems. Data communication is through an Inter-Integrated Chip (IIC or I²C) bus. The communications module provides long term storage of data before downlink and time synchronization signals. The data communication for both of these functions occurs through the IIC bus. Note that there are separate unregulated power lines from the power module to other subsystems. We made this design decision in order to increase modularity as discussed in the Circuit Design section below.

The VLF and Langmuir Plasma Probe systems were developed to demonstrate the ability to collect data in mesh network CubeSat system, but also to meet the requirements for Boston University’s University Nanosatellite 5 project, BUSAT. This is enabled by the highly modular design and designing these instruments primarily to the science mission of BUSAT, but the interface of the CubeSat class satellites. This way, a simple interface board for the larger BUSAT allows the instruments to work in both environments.

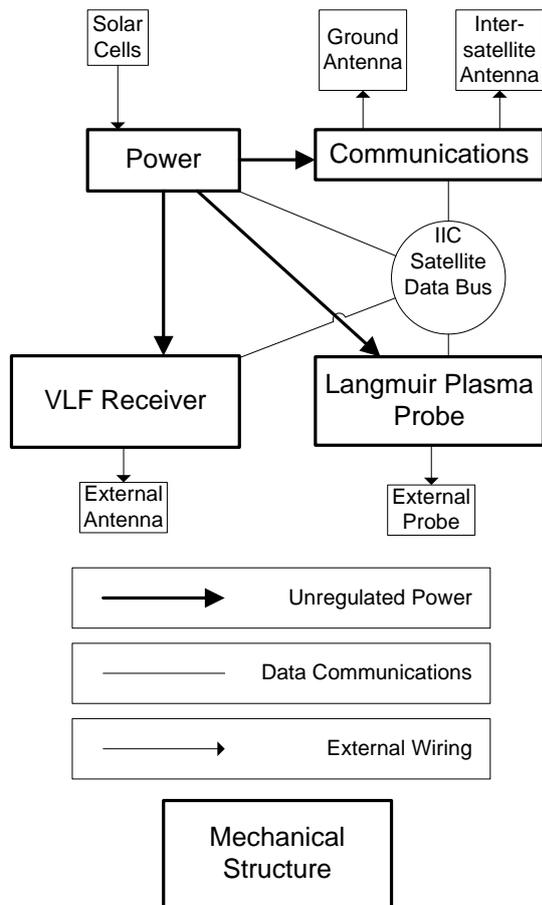


Figure 2 Satellite Block Diagram

Subsystem Connections and Mechanical Requirements

Of primary concern in the entire satellite design was the ability to integrate the satellite quickly and easily. Figure 3 shows the mechanical design of the satellite. Note that all electrical boards connect through a common connector. This common connector handles all electrical wiring with the exception of solar cells, batteries, and connection to external components such as antennas. These connections typically require a coaxial cable from the relevant circuit board to the external device. Because we desired modular subsystems which could be reused, the dimensions of the electrical boards is constrained to be 7.3 cm X 7.3 cm. This allows room for Coax wiring between any satellite wall and the circuit boards. While limiting the circuit boards to this size limits the available area for circuit components, it does allow more modularity and decreases the system level integration requirements.

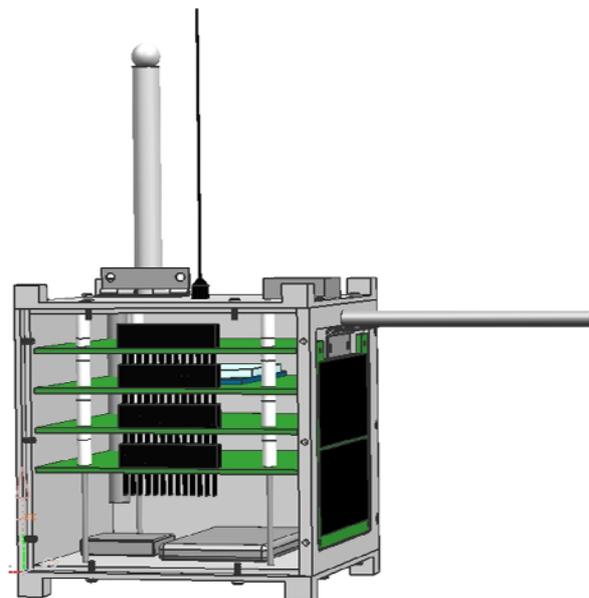


Figure 3 Mechanical Design of Satellite

Communications System

As an example of the subsystems which this power system is designed to feed, we show the block diagram for the communications system in Figure 4 below. Note in this figure that power regulation is a part of the subsystem. The subsystem receives unregulated power. Note also the IIC bus across which the power system and communication system can communicate. Finally, note that the communication system includes two antennas. One is for ground communication and the other is for satellite to satellite communication. We found that including two antennas and one radio gave the best balance of complexity, attitude control and satellite mass. This configuration enables the mesh network with both satellite – satellite communication as well as satellite – ground communication. Two radios, one for ground communication and one for satellite-satellite communications, was a good option, but the radios must be separated by several meters to keep from burning out the receiver front end when the other radio transmits at full power.

The communications subsystem is the main draw of power as it uses an estimated 80% of the satellite power.

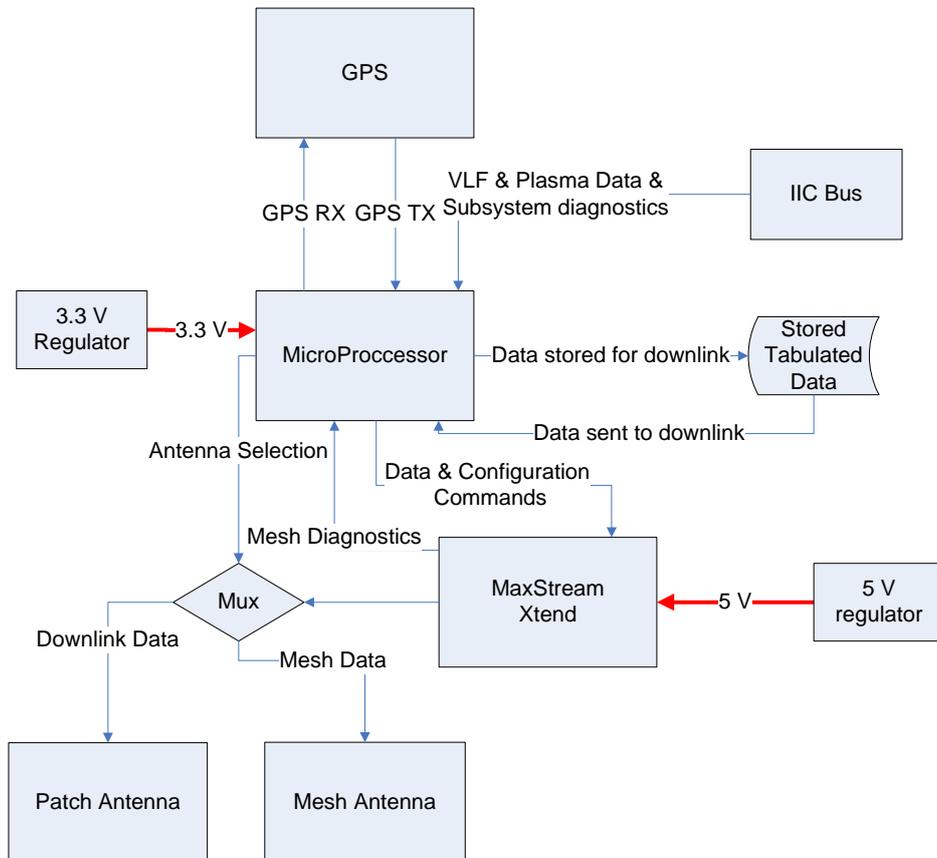


Figure 4 Communications System Block Diagram

POWER SYSTEM

In the balance of this paper, we describe in detail the power system for a CubeSat class satellite. This system is designed with a good deal of modularity to allow reuse in multiple satellites. We introduce the power system, discuss its requirements, batteries, solar cells, peak power tracking, battery charging and finally describe the actual circuit.

Power Introduction

The power system accounts for 25 to 50% of student designed/built satellite failures⁶, and it is one of two mission critical systems (the other being communication). Because of its importance and propensity for failure, we desire to develop a reliable and functional power system. The power system should maximize power from the solar cells, store excess energy in batteries and monitor/maintain power system health including battery charge level. CubeSat satellites

are especially power limited because of their small size and difficulty of deploying structures. This is further complicated by limited budgets for solar cells so that less efficient solar cells are typically used. These constraints as well as mass and volume constraints call for the development of an efficient power input and battery charging/monitoring system.

Figure 5 is the power system block diagram. Note that the inputs to this system are the solar cells and batteries, and that the outputs are five switched unregulated power connections. These connections include both power and ground so as to avoid unnecessary noise propagation through the satellite. The power system actually maintains these power lines at battery voltage which is between 3 and 4.2 volts. Finally, the power system communicates with the rest of the satellite through an I²C serial bus.

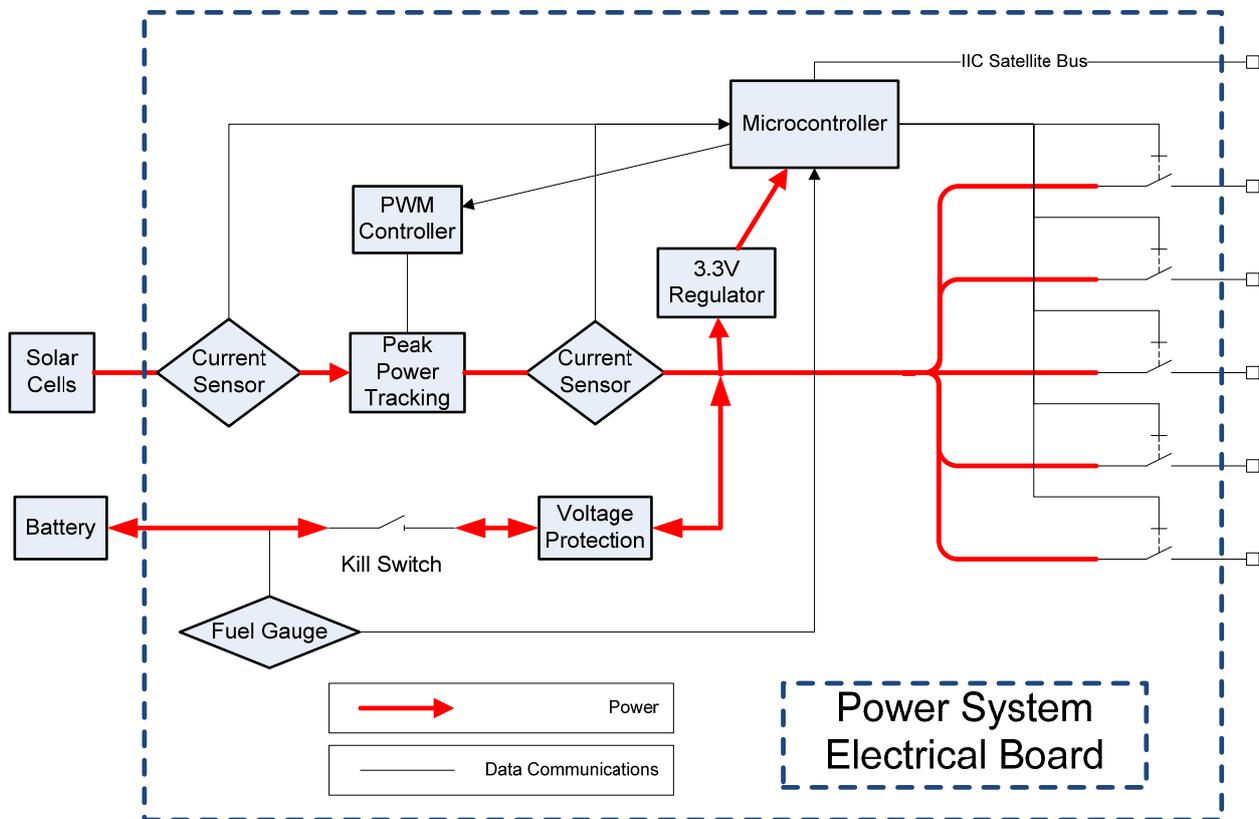


Figure 5 Power System Block Diagram

Power System Requirements

We begin our discussion of the power system by stating the power system requirements which we specified at the beginning of this project. The power system should maximize power efficiency, maintain a high degree of modularity, minimize complexity, and meet CubeSat mechanical/thermal requirements.

Dark Operations: We required that the satellite be able to operate in eclipse periods of at least 45 minutes with full functionality. While a significant reduction in operational ability during eclipses would be acceptable for a CubeSat class satellite, we did not want to lose the downlink bandwidth afforded by night operations. This requirement then placed requirements on the satellite battery capacity. Also during day operations, the power system should charge those batteries as efficiently as reasonably possible.

Power System Efficiency: The power system should lose not more than 20% of the available power. Ideally, it is preferred to be 100% efficient, but due to the nature of regulators, resistors and other electrical components, power loss is unavoidable. Due to the lack of monetary resources and time, a goal of 80% efficiency is still ambitious.

Maximize Flow of Solar Power into Satellite: In addition to limiting the dissipation of power through components, the solar cells also have a potential for power inefficiency. We limit this inefficiency through a peak power-tracker (PPT). Essentially a PPT is a control system that monitors the output of the solar cells to insure maximum power transfer. A more detailed explanation of the PPT will be discussed later in this paper.

Data Reporting: The system must report data on power system health/status once every minute. This data includes battery charge level and average voltage/currents into and out of the power system. This data is important for development/testing of the power management system as well as to evaluate the system's on orbit performance.

Battery Voltage: Since we chose a lithium polymer battery technology, we must maintain battery voltage between 3.0 and 4.2 volts. Lithium Polymer batteries can be damaged if discharged below 3 volts and possibly no longer maintain charge. Charging over 4.2 volts could result in an explosion and/or fire. We would prefer to avoid both of these situations. This requirement can be met with a hardware or software solution. Hardware voltage protection circuits exist, or

a microcontroller can monitor the battery voltage and turn off the charging circuit if the voltage gets too high or disconnect the load if the voltage gets too low. We chose a software solution with the integrated Peak power tracker / battery charger.

Maintain Downlink Capability: Since student designed/built satellites have a low success rate and the fact that the most important satellite function is to make ground contact, the available power level of the satellite needs to be maintained above two watt-hours to provide power for a possible downlink transmission. In addition, the length and number of available downlinks are limited and therefore limit the daily bandwidth. Therefore, every pass needs utilized. We meet this requirement through an intelligent but simple power management system that first reduces subsystem power usage and then actively disables subsystems when available power is close to the downlink requirement.

Solar Cells

As shown in Figure 5, the primary power source are solar cells. Gallium Arsenide (GaAs) solar cells are commonly used and are a suitable choice for spacecraft. The solar cells selected for this satellite are capable of providing up to $29.4\text{mW}/\text{cm}^2$ in full illumination. Each cell has a nominal voltage of 2.1 volts. The power system will be more efficient if the nominal input voltage is closer to the batteries nominal voltage of 3.7 volts. We accomplish this by connecting two cells in series for a nominal voltage of 4.2 volts. Each of the four sides of the satellite will house a pair of cells and each side will be connected in parallel with each other.

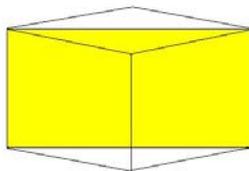


Figure 6 Highlighted area represents the projected solar cell surface area

Solar Cell Analysis

The sun produces on average $136\text{mW}/\text{cm}^2$ of power. The solar cells convert that energy to electricity at an efficiency of about 20%, which cuts the available power to $27\text{mW}/\text{cm}^2$. If solar cells are attached to the four sides of the satellite, only a percentage of the total solar cell area will be illuminated at one time. We find the effective solar cell area by averaging the minimum illuminated area and the maximum illuminated area. The minimum area is the solar cell area of one side and the maximum area is the projected area while looking

directly at an edge of the satellite as shown in Figure 6. Each cell measures $4\text{cm} \times 7\text{cm}$ and each side has two cells, resulting in 56cm^2 of solar cells per side. The length of the projected side is 11.3cm and its area is $11.3\text{cm} \times 7\text{cm}$ or 79.2cm^2 . The average of these two areas is 67.6cm^2 , which provides 1.976W to the satellite. For a typical CubeSat orbit it is reasonable to assume that the solar cells will be illuminated for 48% of the orbit and will be eclipsed for the remaining 52%. This means over a 90-minute orbit a total 1.423Wh s is provided to the satellite.

Batteries

We chose a single cell 1500mAh lithium polymer battery to store the necessary power. We chose lithium polymer for its high energy density (about 3 times better than NiCad or NiMH). This allows for a higher capacity battery in a small and lightweight size. This is a big advantage when dealing with CubeSat constraints. The desired lifetime for the satellite is 6 months, which is too long to power the satellite from one charge of the battery, so the ability to charge the battery is necessary. Lithium Polymer batteries require a specific charging scheme to avoid damaging the battery and to extend the battery lifetime. The charging scheme starts with charging at constant current until it reaches its nominal voltage of 4.2 volts. Once this voltage is achieved, the battery is charged at a constant voltage of 4.2 volts as the current flow is gradually reduced until the battery is completely charged.

Power Management

The limited power from solar cells demands a conservative management scheme. This is accomplished in several different ways. First, we limit the component power dissipation of the power board to 20%. This means the components in the high current loops need to be selected carefully to dissipate as little power as possible. Second, the power microcontroller will carefully monitor and manage the power used by each subsystem to insure there is enough power to run high priority processes such as transmitting data to the ground station.

We monitor battery status with an ISL6295 Fuel Gauge, which uses I²C to communicate with the power microcontroller. From that data, the microcontroller recognizes when the battery charge is low or turn off the battery charger to prevent overcharge. The microcontroller can turn on and off each subsystem using the solid state relays on the right hand side of Figure 5. In addition, we use the internal resistance of these relays as a crude current monitor for each system. This feature, while not temperature compensated, uses the microcontroller analog to digital conversion for a

very simple current measurement. While this may not be as accurate as other techniques, we only use this data for detecting large problems (shorts and opens); therefore, this method is good enough.

Peak Power Tracker / Battery Charger

As mentioned earlier, a Peak Power Tracker (PPT) allows the power system to maximize the power received from the solar cells. This requires some circuitry to control the current demanded from the solar cells. We use a variable buck-boost converter controlled by a microcontroller to control the current flowing from the solar cells as well as implement the lithium polymer charging scheme when needed.

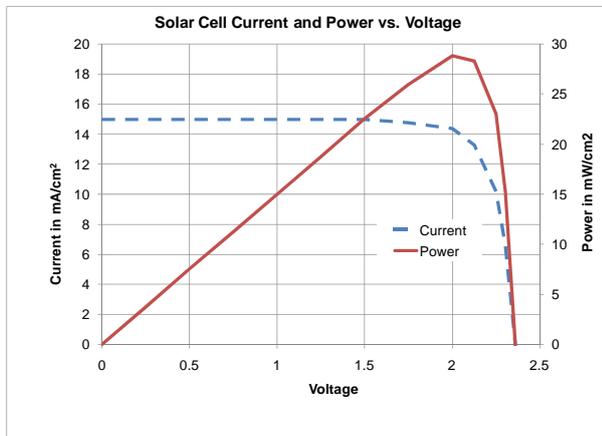


Figure 7 Typical Solar Cell Current and Power vs. Voltage¹³

A peak power tracker keeps the solar cells operating at the maximum possible power output. Figure 7 shows a typical solar cell current vs. voltage curve (IV curve) as well as the solar power as a function of cell voltage. The job of the peak power tracker is to keep the incoming power at a maximum regardless of irradiation or solar cell degradation. On the curve above, this means maintaining the voltage around 2 volts.

There are several peak power tracking algorithms, but perhaps the simplest is the “Bang Bang” algorithm which we chose to implement. This algorithm samples the power produced by the solar cells, then either demands more or less current (moves in either direction on the solar cell IV curve in Figure 7), a second sample is taken, if the power output decreased the PPT switches directions (if it increased the current last time it now decreases the current). If the power output increased the PPT continues in the same direction (if it just increased the current it continues to increase the current, or if it just decreased the current it continues to decrease the current).

As noted in Figure 5, the peak power tracker also serves to regulate the battery charging. Lithium Polymer batteries require a constant current / constant voltage charging algorithm in which the battery is first charged at a constant current until it reaches a specified voltage, 4.2 volts. It should then be charged at a constant voltage till the current drops to a specified value¹⁴. The current values are typically given in “C” rating in which the “C” is the battery capacity, typically given in milli Amp Hours (mAh). To find the “C” current, divide the capacity by hours to get mA. The charge current is then typically .5 C. So for our 1500 mAh battery, it should be charged at a rate of 750 mA. With one regulator performing peak power tracking and battery charging control with changing load and illumination, we will not be able to meet the specified charging profile exactly. However, with a six month satellite lifetime, we should be close enough.

The microcontroller which controls the peak power tracker must consider both peak power tracking and the battery charge state to properly regulate energy flow into the satellite and battery. When the battery voltage is below 4.2 volts the regulator will operate in peak power mode to maximize the flow of energy into the satellite and battery. At the same time it must limit the flow of energy into the battery to be below the maximum charge rate; however, with limited solar cells and proper battery sizing this limit will typically not be reached. When the battery is close to full, and the charging switches to constant voltage mode, the microcontroller adjusts the regulator to maintain the specified battery voltage. In this case, we are not concerned with maximizing the power transfer from the solar cells into the satellite since the satellite contains almost as much power as it can hold. Note that the satellite load will also affect the state of the regulator. If the transmitter turns on while the regulator is in battery charging mode, the current draw is such that power will typically be flowing from the battery and the regulator should quickly switch into peak power tracking mode.

As a final note on the integrated peak power tracker and battery charger, we note that the system would charge the battery better and transfer energy into the system better if two batteries were present with switches to change which battery is being charged or discharged. We decided that this performance increase was not worth the extra complexity and chose a single battery system.

CIRCUIT DESIGN

This section will explain in detail each part of the power board circuitry and the design decisions that were made in picking components and completing the

schematic. One of the design decisions was whether to keep all power regulation on the power board or to make all the individual subsystems regulate their own power. The advantage to keeping all the power regulators on the power board is that power regulation causes electrical noise which is bad for the small signal measurements being taken on the scientific boards and may distort the signal being sampled. Keeping the power regulators all on one board and not on the scientific boards is good noise control. An advantage to making all the subsystems regulate their own power is it increases the modularity of the system. The power board does not need to know what voltages are needed by the other boards, which allows for reusability. Modularity is one of the objectives of this design so in order to obtain a modular design the decision was made to have the power board supply an unregulated voltage and have each subsystem regulate its own power. If regulated voltages are desired for the satellite bus, a power regulation board could easily be added. This board would take as inputs the unregulated voltages on the right hand side of Figure 5, and would output regulated voltages at the desired levels.

The overall system roughly resembles the design of a car's power system, with the solar cells in place of the alternator, which supplies power to the battery, which then in turn powers the satellite. This design is simple, unlike some other designs that might need relays to switch a battery from being used to being charged and eliminates the need for two separate batteries. The resulting current flow is from left to right in Figure 5, starting with the solar cells, through the PPT, to the battery and then the subsystems draw current from the battery and/or solar cells. Finally the current flows through solid state relays that are controlled by a micro-controller.

Peak Power Tracker

The peak power tracker's input connects to the output of the solar cells and its output connects to the batteries. The PPT is built around a PWM controlled, buck-boost regulator. A PWM controlled buck-boost regulator works by switching a mosfet at a defined frequency and varying duty cycle to control the charging and discharging of an inductor. While the mosfet is off, energy is stored in the inductor. When the mosfet is turned on the inductor discharges the stored energy. Changing the duty cycle of the signal controlling the mosfet sets the output of the regulator as defined by equations 1 and 2 in which d is the duty cycle.

$$V_o/V_i = d/(1-d) \quad \text{eq. 1}$$

$$I_o/I_i = (1-d)/d \quad \text{eq. 2}$$

To compensate for the inverting nature of the buck-boost converter a negative voltage is supplied to the converter by connecting the positive solar cell terminal to system ground and the negative terminal to the input such that the rest of the system sees a positive voltage. This complicates taking measurements and sending control signals to PWM controller. The PWM controller has a ground that is approximately 4 volts lower than the micro-controller's ground and the rest of the satellite. The solution to this problem is to realize that system ground is still common between the two controllers, low for the micro-controller and high for the PWM controller. A discrete inverter is all that is needed to communicate between the two different levels. Some voltage measurements in the PPT also have to be inverted since they are negative in reference to system ground and the micro-controller cannot read negative voltages. An inverting amplifier in combination with a voltage divider (to scale the voltage down to be under 3.3 volts) is used measure the solar cell voltage and a differential amplifier measures the difference across a current sense resistor to calculate the incoming current. The power supplied by the solar cells (used by the PPT algorithm) is the product of the measured current and voltage (P=IV).

The PWM controller switches the mosfet at around 300 kHz, creating a noisy signal, which could damage the solar cells. LC filters are used on the front and back end of the PPT to protect the solar cells and the rest of the system from the noisy signal. If the battery is completely discharged, it will pull the system voltage down and may cause some components to enter a semi-on state therefore damaging them. A protection circuit consisting of two power resistors to raise the voltage, a diode to lock it down from jumping up to high, and a mosfet to bypass the circuit during normal operation is add to provide protection from this case.

The PWM controller in Figure 5 is a LT1619 PWM controller which receives feedback from several different sources. The microcontroller provides two of these inputs and the third is the differential voltage across a current sense resistor. One of the inputs from the microcontroller sets the frequency of the supplied PWM signal. The second input is how the microcontroller will tell the PWM controller how much current to sink from the solar cells (indirectly setting the duty cycle of the signal supplied to the gate of the switching mosfet).

Microcontroller

The microcontroller is a Texas Instruments MSP430. We chose this microcontroller because of our familiarity with it and the capability of low power

operation. All of the other subsystems in this satellite also use the MSP430, which simplifies communication through the I²C satellite bus. The MSP430 will also use I²C to communicate with the ISL6295 Lithium Polymer battery fuel gauge. A signal is periodically received on sync line from the communications module to keep all of the subsystems time synchronized. Finally, a connection is provided for programming the microcontroller after it is assembled in the satellite. The MSP430 requires a regulated 3.3-volts which is supplied by a Reg101-3.3 voltage regulator. It is a high efficiency fixed 3.3-volt regulator, which can supply up to 100mA.

The MSP430 will sample 10 different analog signals. Since there are not enough analog inputs on the controller the five most important signals will be sampled individually and the remaining six will be multiplexed using a 74AC151 multiplexer. The five most important signals are the voltage on the input of the PPT, the current entering the PPT, the voltage on the output of the PPT and the current leaving the PPT. These measurements are essential to accurate operation of the PPT. The five remaining signals are current measurements for each of the five outgoing voltage lines. These measurements are used to calculate the power consumed by each subsystem and better manage the distribution of the systems available power.

There are also 11 control signals for the MSP430 to supply to various parts of the system. Five of these signals are used to control PVN012 solid-state relays. These relays are used by the power management scheme to power on and off different subsystems. As mentioned earlier the PWM frequency is controlled by the MSP430. Also mentioned earlier, the MSP430 sets the output of the PPT by supplying an analog voltage with the controllers digital to analog converter. Finally, the protection circuit receives either a high or a low signal to turn it on or off, and the last three control lines are sent to the multiplexer to set which voltage to sample.

CONCLUSION

We have presented the design of an integrated peak power tracker / battery charging system for a CubeSat class satellite along with the mesh network satellites for which it was originally developed. At the time of writing this paper, this system is still undergoing development. The interested reader should also consult the presentation slides for project updates, or contact the authors directly at w Holmes@taylor.edu.

ACKNOWLEDGMENTS

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REFERENCES

1. Heidt, H.; Puig-Suari, J.; Moore, A.; Nakasuka, R.; Twiggs, R., "CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation," 13th Annual AIAA/USU Conference on Small Satellites , Logan, UT, August 2000.
2. Puig-Suari, Jordi; Turner, Clark and Twigs, Robert J., "CubeSat: The Development and Launch Support Infrastructure for Eighteen Different Satellite Customers on One Launch," 15th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2001.
3. Kitts, Christopher et al., "Flight Results from the GeneSat-1 Biological Microsatellite Mission," 21st Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2007.
4. Flagg, Scott et al., "Using Nanosats as a Proof of Concept for Space Science Missions: QuakeSat as an Operational Example," 18th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2004.
5. Swartwout, Michael, "Twenty Plus Years of University-Class Spacecraft: A Review of What Was, an Understanding of What is, and a Look at What Should Be Next," 20th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2006.
6. Swartwout, Michael "Beyond the Beep: Student-Built Satellites with Educational and 'Real' Missions," 21st Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2007.
7. Zapf, Joshua, "Robust Attitude Control with Fuzzy Momentum Unloading for Satellites Using Reaction Wheels," 20th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2006.
8. Strange, Andrew, "Communications On Board: A Satellite Data Handling and Ground Communication System," 20th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2006.
9. The BUSAT homepage is <http://www.bu.edu/busat/index.html>.
10. Swenson, Charles, "The Role of Small Satellites in Aeronomy," 20th Annual AIAA/USU

Conference on Small Satellites, Logan UT, August 2006.

11. Oehrig, Jacob et al., "TU-Sat 1 CubeSat," 15th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2002.
12. Holmes et al., "TU Sat 1: A Novel Communications and Scientific Satellite," 16th Annual AIAA/USU Conference on Small Satellites, Logan UT, August 2002.
13. Solar cell current vs. voltage curve (IV curve) taken from a [SpectroLab dual junction solar cell](http://www.spectrolab.com/DataSheets/DJCell/dj.pdf). <http://www.spectrolab.com/DataSheets/DJCell/dj.pdf>
14. Perhaps the best explanation of Li battery charging algorithm is found on [Panasonic's web site](http://www.panasonic.com/industrial/battery/oem/images/pdf/Panasonic_LiIon_Precautions.pdf), in the document at [http://www.panasonic.com/industrial/battery/oem/images/pdf/Panasonic LiIon Precautions.pdf](http://www.panasonic.com/industrial/battery/oem/images/pdf/Panasonic_LiIon_Precautions.pdf).