Satellite Solutions CubeSat Design Team
ASE 463Q
University of Texas at Austin

May 5, 2003

Dear Dr. Stearman,

This final report details the progress made by the Satellite Solutions CubeSat design team throughout the course of the spring semester. The main goal of our project was to successfully design a pico-satellite, to serve as a transition from the previous "Coke-can" sized CanSat from previous semesters to a 10 cm cube-shaped CubeSat. Our team divided tasks equally among members and made good progress towards meeting our goals. This report details the background and design choices for the structure, payload, power, and communication subsystems, and defines our management layout and budgetary analysis. Please feel free to contact any of the group members by the email addresses listed below, or stop by the Satellite Design Lab in WRW 407 to examine our work.

Sincerely,

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Abstract

The Satellite Solutions team has worked to design a functioning CubeSat to be launched on an ARLISS rocket in August of 2003, in accordance with the nanosat program begun by Dr. Twiggs at Stanford University. The goal of this semester's project was to transition from last summer's Coke-can sized satellite to a cubic structure, no larger than 10 cm on each side and weighing less than 1 kg. The Satellite Solutions team members have researched the various satellite subsystems and selected several of the design parameters, such as those that follow. The CubeSat payload will consist of several sensors, including GPS, temperature, pressure, and acceleration. The Atmega163 microcontroller has been chosen and work has begun to update the necessary C codes. The communication subsystem underwent several preliminary design changes and will consist of a MaxStream XStream 900 MHz OEM module, a 4-element Yagi-Uda antenna, and a laptop. The power system also has been extensively researched and Lithium-polymer batteries have been selected and will work in conjunction with a recharger, a voltage step-up regulator, and solar cells. Finally, the aluminum structure has been fabricated by the machine shop and a prototype has been built. An estimate of the budget has been calculated at approximately $1,900. The Satellite Solutions team has also outlined the work that needs to be completed by the summer group.

Acknowledgments

The Satellite Solutions CubeSat design team would like to thank the following individuals for their support of this project.

- Dr. Ronald Stearman
- Dr. Glenn Lightsey
- Dr. Takuji Ebinuma
- Dr. Jennifer Lehman
- Thomas Campbell
- Shaun Stewart
- Marcus Kruger

Qualifications

Mohit Garg

Mohit Garg is a senior aerospace engineer at the University of Texas at Austin. During his four years at University of Texas he has taken interest in both space and atmospheric systems. Before coming to UT Mohit received his Associates degree in Computer Graphics and Designing (AutoCAD). He also has a Commercial Pilot License with instrument and multi-engine ratings. He is currently designing a Mesoscale Friction Tester under Dr. K. M. Leichti and Dr. R. Chandar in the Engineering Mechanics Department. He is also involved in the designing of a Microdischarge Plasma Thruster for Dr. L. Raja and Dr. G. Lightsey for their FASTRAC nanosatellite project. All these projects and research project have given Mohit a better design perspective on experimentation setup and machine drawing skills. Mohit has also taken senior classes that required him to write extensive MATLAB codes; this has enhanced his programming skills. Therefore, Mohit is qualified for the project and will be an asset to the CubeSat Design Team.

Marcus Franki

Marcus Franki is a senior aerospace engineer at the University of Texas at Austin. During his four years at UT he has taken an interest in space system development and has excelled in areas requiring programming skills. Past research projects have focused on propulsion and power systems. While not attending school, Marcus works for The Boeing

Company supporting the International Space Station (ISS) in the area of Environmental Control and Life Support Systems (ECLSS). In ECLSS, Marcus has learned to about space systems and has experienced system integration first hand. Furthermore, Marcus's extensive programming at Boeing has given him an insight into problems associated with autonomous systems. For the aforementioned reasons, Marcus is more than qualified and will be an asset to the CubeSat Design Team.

Jennifer Sembera

Jennifer Sembera is also a senior in Aerospace Engineering at the University of Texas at Austin, specializing in spaceflight and control systems. Jennifer has interned at The Aerospace Corporation in El Segundo, California for the past two summers, and will return to the company after graduation in May as a Member of the Technical Staff. In her time there, Jennifer worked in the Electromechanical Controls Department in the Vehicle Systems Division, on projects including a Titan IV thrust vector control simulation, a Matlab SimMechanics software evaluation, and laser communication via fast-steering mirrors, among others. She has gained experience in the space communication field by serving as the lead for this subsystem on her Mission Design project last semester. Therefore, Jennifer is qualified to work on the CubeSat project.

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1.0 Introduction

In the summer of 2002, Sub-Orbital Technologies developed a low-altitude CanSat satellite at The University of Texas at Austin. At the end of the project, team members came to the conclusion that a Coke-can shaped satellite is difficult to implement and limited in capability. In January 2003, Satellite Solutions began to collaborate with members of Sub-Orbital Technologies on a new low-altitude satellite design, and the respective design teams decided that a new structural platform and improved electronics package were necessary. In addition, the teams agreed that Satellite Solutions would design the new satellite with some support from Sub-Orbital Technologies. Satellite Solutions is currently not technologically capable of designing a space-ready system, but has begun the groundwork for future development. Therefore, the members of Satellite Solutions, also known as the CubeSat Design Team (CSDT) decided to transition from a cylinder- to a cube-shaped satellite, but will continue low-altitude launches from sounding rockets.

Satellite Solutions has set several goals to be met throughout the course of the project. The overall objective is to design a 1000 cm^3, 1 kg CubeSat to serve as the platform for future nano-satellite development at the University of Texas. After a review of the previous CanSat mission, several problems were identified. Therefore, Satellite Solutions' first objective is to rectify these problems, which include improving the parachute design, developing a rechargeable power system, and designing a durable cubic structure. Next, the team must develop robust telemetry and communication systems for the duration of the CubeSat flight in the atmosphere. Finally, the CubeSat will be designed so that additional payloads and sensors may be added easily without any significant changes in the circuitry. This report is a preliminary design review of Satellite Solutions' CubeSat design, beginning with background for this report, consisting of a discussion of student satellite design platforms and UT student satellite design milestones.

1.1 Design Platforms

Currently, there are two universally recognized design platforms: the CanSat Program and the CubeSat Initiative. The two platforms are summarized in this section.

1.1.1 CanSat Program

The CanSat program was started in 1998 by Professor Bob Twiggs at a University Space Systems Symposium. The CanSat program provides universities with the opportunity to launch Coke-can size satellites on a sounding rocket for $80 dollars from a site in the Black Rock Desert of Nevada. The Aero Pac amateur rocket club launches the CanSats on a custom-built ARLISS (A Rocket Launch for International Student Satellites) rocket. Three CanSats, or one unlimited class satellite, can be launched at a time. Once an altitude of 12,000 feet is obtained, the CanSats are automatically ejected from the launcher by a black powder charge. Each CanSat falls to earth under its own parachute. Since 1998, seven universities have launched CanSats. Various designs implemented solar cells, video cameras, momentum torque devices, and attitude detection systems [Campbell and others, 2002].

1.1.2 CubeSat Initiative

California Polytechnic University and Stanford University's Space Systems Development Laboratory started the CubeSat Initiative in 1999. The purpose of the program is to provide uniform standards for nano-satellite design. Unlike the CanSat program, CubeSats are launched into space; therefore, meticulous design is critical for satellite survival. The primary design specifications require that the satellite be a cube with sides 10 centimeters in length and a mass of 1 kilogram or less. The requirements are necessary so that satellites “integrate properly with the deployer and neighboring satellites” [CubeSat, 2003]. The deployer, designed by CalPoly, launches up to three CubeSats from a commercial rocket. Although the CubeSat Initiative is more expensive than the CanSat program, it allows students to get hands-on experience with actual satellite hardware [CubeSat, 2003].

Currently, over thirty high schools, colleges, and universities worldwide are involved with the CubeSat Initiative. None of the educational institutions have placed a satellite in orbit, but some are waiting only for a launch date. A scientific payload on an individual CubeSat includes: attitude control, digital imagery, radiation detection, Global Positioning System, and others. While its primary mission is increasing student interest in orbital satellites, the CubeSat Initiative also hopes to reduce the cost and development time of satellites, increase accessibility to space, and increase the number of commercial launches per year [CubeSat, 2003].

1.2 UT Student Satellite Design Milestones

UT’s student satellite design area is one year old. In that year, a lab was created and a CanSat project was launched.

1.2.1 The University of Texas Satellite Design Lab (UTSDL)

Dr. Glenn Lightsey created the University of Texas Satellite Design Laboratory in the fall of 2001 in order to provide students with an opportunity to design and manufacture their own satellites. Currently, the UTSDL is the location of Satellite Solutions' CubeSat development, which will be the foundation of the future of UT's FASTRAC (Formation Autonomy Spacecraft with Thrust, Relnav, Attitude, and Crosslink) program. The CubeSat is the successor of the CanSat designed in the spring and summer of 2002 and will be the primary focus of future UT satellite groups. The UTSDL is a static free room, with all the necessary electronic equipment, two computers, books, and a satellite tracking station (its construction is in progress). The tracking station in UTSDL will provide University of Texas Students, and high school students with information about the satellites in orbit around the Earth and track the future nano-satellite (FASTRAC).

1.2.2 Previous CanSat Subsystems

The CanSat electronics consists of a Terminal Node Controller (TNC), microcontroller, sensors, radio, and power systems. The TNC is a device that prepares an up-linked input signal from the ground transmitter to be sent to the microcontroller (AT90S4433). Working in the reverse direction, the TNC prepares output data sent from the microcontroller (AT90S4433) to be down-linked using an Alinco radio. Typically, a TNC is bought as a preassembled component; however, to gain experience in electronics the CanSat team designed their own TNC using a DTMF decoder, microcontroller (AT90S2313), and modem. The microcontroller (AT90S4433), which is the "brain" of the CanSat, controls the data acquisition, storing, transmission, and performs ground commands. Sensors on board the CanSat include: temperature, pressure, and acceleration. Batteries provide power to various electronic components of the CanSat. Aluminum was selected as the structural material because of its ability to withstand high G-forces and its lightweight characteristics. The structure was used to house and protect the electronic payload. The dimensions of the CanSat are approximately those of a Coke-can. The final weight of the satellite is less than 388 grams, and measures 12.3 centimeters tall and 6.6 centimeters in diameter.

The design of the CubeSat for this semester includes the outer structure, as well as the interior electronic components. The subsequent sections discuss in detail in the remainder of this report include Command and Data Handling, Payload Sensors, Communication, Power, and Structural Subsystems. Finally, the Management section details the distribution of tasks, the schedule followed throughout the course of the semester, and the budget analysis.

2.0 Command and Data Handling Subsystem

The Command and Data Handling Subsystem is the ‘brain’ of the whole autonomous CubeSat. The C&DH system consists of an Onboard Computer, OBC, which controls the operation of the CanSat. The OBC has software installed that manages the programs written to handle various tasks; for example, a program whose function is to create a telemetry stream will read the status of the payload sensors and then encode the telemetry stream. The same program can further control the flow of the data from sensors to the temporary memories inside the microcontroller in the event of communication restrictions, such as the blocking of communication signals between the CubeSat and the ground station.

This section begins with a discussion of the C&DH Subsystem of the previous CanSat group. Further subsections discuss the requirements and constraints for the CubeSat followed by the choice and evaluation of microcontrollers. The last subsection discusses the modifications made to the hardware and software of the previous CanSat.

2.1 Background

The previous CanSat had an OBC for C&DH. The primary component of the OBC was the microcontroller, AT90S4433. The secondary components were EPROM and RAM. These components were used for storing the software and were built-in to the microcontroller. The software was written in C language that performed only one loop to run all subsystems. A separate function was written in C language to make the OBC accept commands from the ground station and to override any operating function during the falling phase of the CubeSat. All programming was done with the help of an STK 500 programming board, shown in Figure 1.

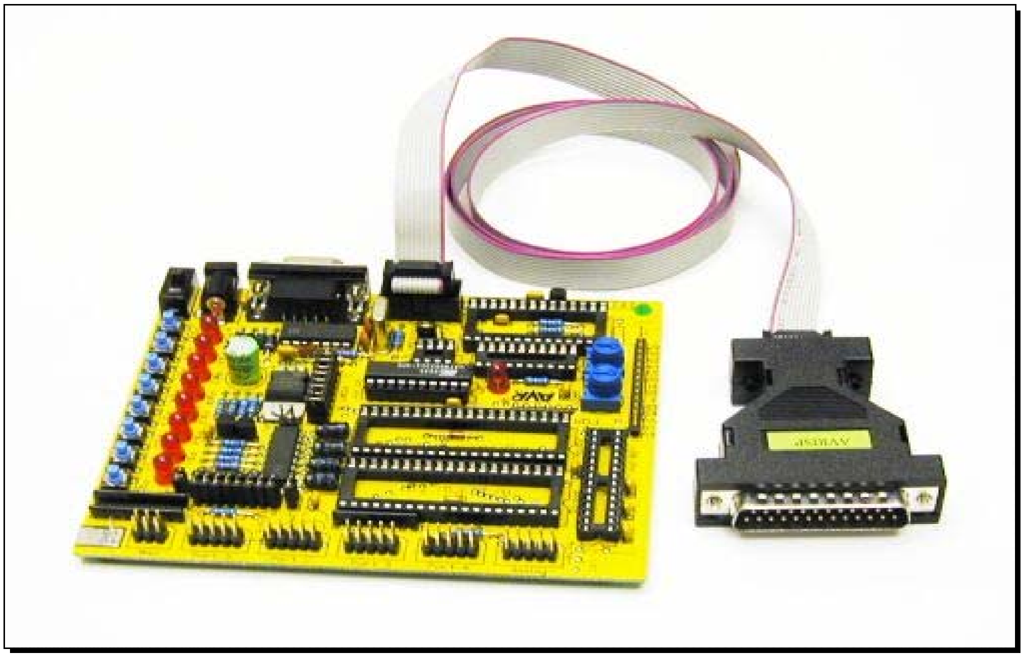


Figure 1: STK 500 AT89S/AT90S Series Flash Microcontroller Starter Kit [“Compass Lab,” 2003].

The following paragraphs discuss the advantageous as well as the flawed C&DH design considerations of the previous CanSat.

Advantageous Design Considerations:

- Control of Payload Sensors
- Control of Communication Subsystem
- Ability to transmit Telemetry Stream to the ground station during the falling phase of the CanSat

- Provision to store data from the accelerometer sensor during the ascending phase of the CanSat in RAM, so that data can be retrieved later (this provision failed and no data was stored).
- Control of quartz clocks that assisted in timing the data collection from temperature, pressure, and accelerometer sensors.

Flawed Design Considerations:

- Wiring between the OBC and other subsystems, see Figure 2.
- No repairing provisions.
- No additional Input and Output ports for additional payload sensors.

Overall, the design of the C&DH subsystem was very impressive, as it was simple in design and had about a 95 % success during the final field test.

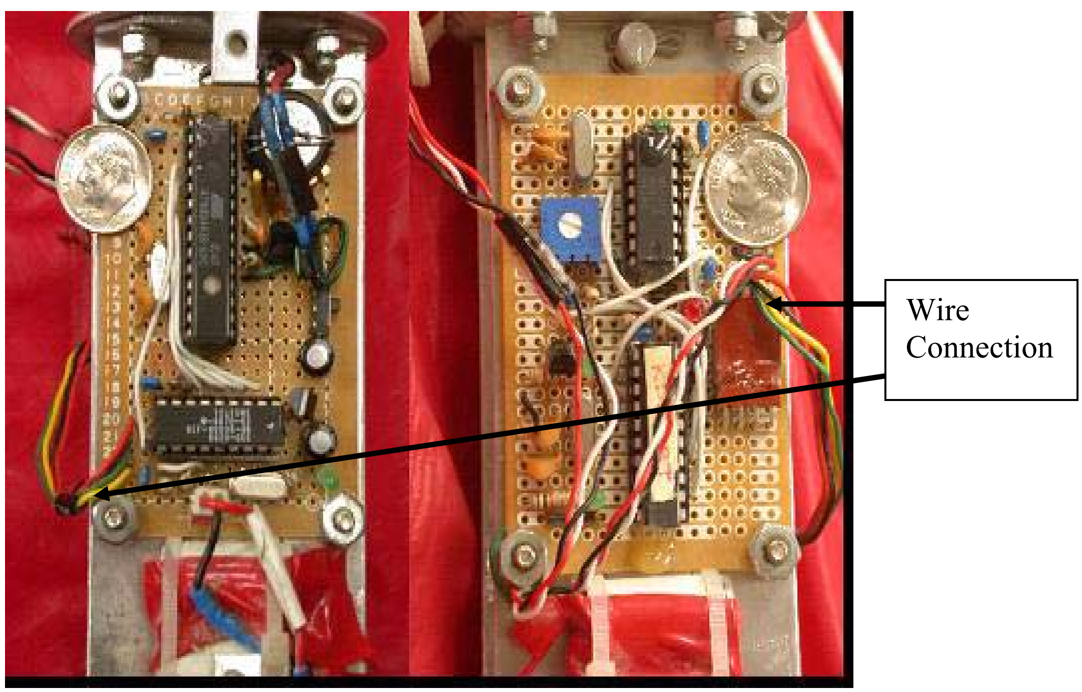


Figure 2: Wiring for connecting different Subsystems in Previous CanSat [Campbell and others, 2003].

2.2 Requirements and Constraints

The objective of the C&DH subsystem is to provide the CubeSat with operation sequences to various subsystems. Because of the size restrictions of the CubeSat, the C&DH subsystem needs to be efficient, small, lightweight, and easy to integrate with all of the other subsystems in CubeSat. This subsystem should be able to perform several tasks, as listed below:

- Subsystems control
- Communication with the ground station
- Data and software storage in allocated memories
- Fault detection and management
- Telemetry stream generation
- Data uplink and downlink feature.

In addition to the aforementioned objectives expected of the CubeSat, the Satellite Solutions group tried to meet additional design constraints, as listed below:

- Easy installation and repair provisions
- Provisions for additional subsystems for future work
- Efficient programming of the microcontroller (multiple loops instead of single loop code).

Each of the above requirements has different demands concerning the OBC and is also critical for efficient operation of the CubeSat. Hence, the proper evaluation of all options available for components that make up the OBC was necessary and are discussed in the next section.

2.3 Options and Evaluation

The OBC is made up of several components, such as microcontrollers, capacitors, resisters, voltage regulators, LEDs, memories (RAM, EEPROM, and ROM), and timers. Out of all of these components, memories, timers, and microcontrollers are the most important. Cost and ease of fabrication of these electronic components are the major factors that result in various configurations in which an OBC can be designed. The requirements restrained our team to choose components that result in a small and light-weight C&DH subsystem. We chose a microcontroller that has built-in memories and timers; this makes the microcontroller the most critical component in C&DH subsystem. To assist in selecting the right microcontroller (processor) and to meet the requirements of the OBC, a set of minimum specifications was developed and is listed below:

- Data and Nonvolatile Program Memory:
  - EEPROM (***E****lectrically* ***E****rasable* ***P****rogrammable* ***R****ead* ***O****nly* ***M****emory*) – min. 8 kB
  - Flash - minimum 512 bytes
  - SRAM (***S****tatic* ***R****ead* ***O****nly* ***M****emory*) - minimum 512 bytes
- Desirable features
  - High processing speed – more then 4 MHz
  - In-built Analog/Digital Converters
  - Programmable UART (***U****niversal* ***A****synchronous* ***R****eceiver-****T****ransmitter*)
  - Master/Slave SPI Serial Interface
  - Controllable I/O pins
  - Programmable timers, especially the watch-dog timer
  - Minimum 16 bit architecture
  - Avoid Ball-grid-array (BGA) microcontrollers (difficult to solder)
- Low Power consumption – less then 10 mA and voltage less then 5 volts
- Size – should fit on a 5 cm x 5 cm Printed Circuit Board

- C compiler - must be available for the processor (microcontroller)
- Operable in temperature range 0 – 40° C; however, wider range is preferable.

Next, several microcontrollers were investigated that best met the specifications set above. Table 1 below lists the microcontrollers (that meet the minimum specifications) that were examined along with the reason that they were rejected or selected.

Table 1: Microcontrollers list and the reason for their rejection.

Company	Reason for Rejection or Selection
Motorola	Hard to solder because of BMG configuration
Hitachi	Programming skills very limited
Intel	High power consumption
Microchip	Nothing wrong
PIC	Nothing wrong
ATMEL	Nothing wrong

Table 1 indicates that the Microchip, PIC, and ATMEL microcontrollers meet our requirements. All three have similar features, but ATMEL was picked because the previous CanSat group used an ATMEL microcontroller with satisfactory performance. In addition, all the programming accessories were available to Satellite Solutions. Finally, an ATMEL microcontroller, model number Atmega163 (Figure 3) was selected at an expense of only $6.42.

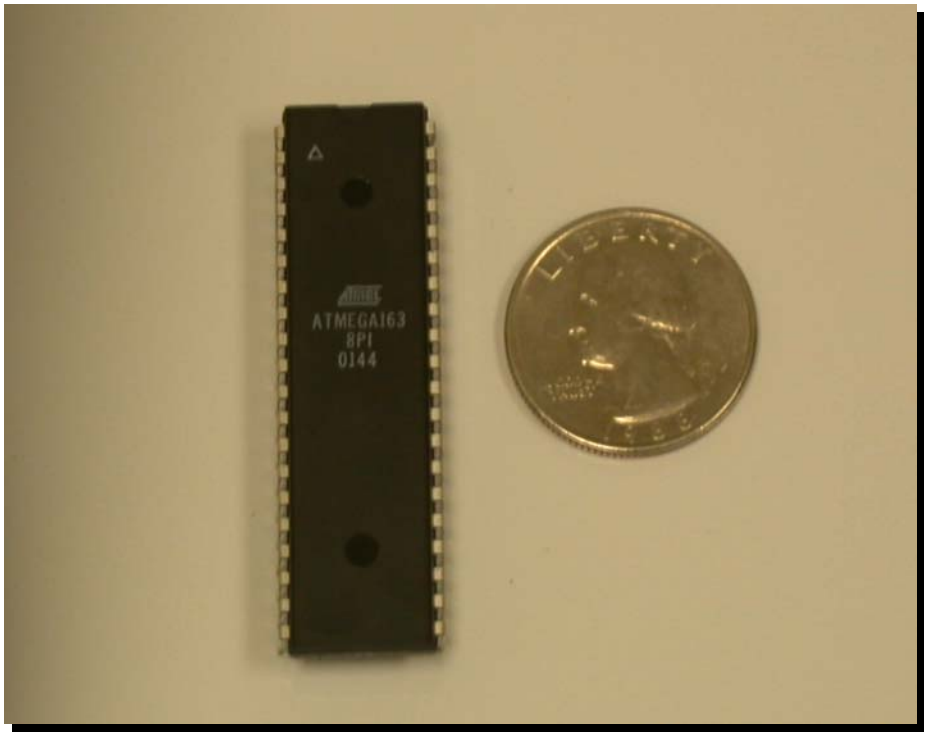


Figure 3: ATmega163 ATMEL microcontroller.

The main features of Atmega163 microcontroller are listed below:

Data and Nonvolatile Program memory

- 16 kB of in system Programmable Flash
- 1024 Bytes of SRAM
- 512 Bytes of Programmable EEPROM

Peripheral Features

- One 8 bit timer/counter
- One 16 bit timer/counter
- 8 channels and 10 bit Analog/Digital Converter
- Programmable watch-dog timer
- Programmable Serial UART
- Master/Slave SPI serial interface
- 32 programmable I/O lines

Power Consumption

- Maximum Current Consumption 5.0 mA
- Maximum Operating Voltage 5.5 V

Processor Speed: 8 MHz

Physical Size: 52.71 mm x 13.97 mm x 4.83 mm

2.4 On-Board Computer Design: Hardware and Software

Each of the requirements mentioned earlier has different demands concerning the OBC. The fact that the computer has to operate in an atmosphere with high gravitational forces acting on the system as a whole also implies that the system has to be designed in a special way. This section describes how these requirements affect the design of the OBC as well as the theoretical outline for the computer. The system described in this section is depicted in Figure 4.

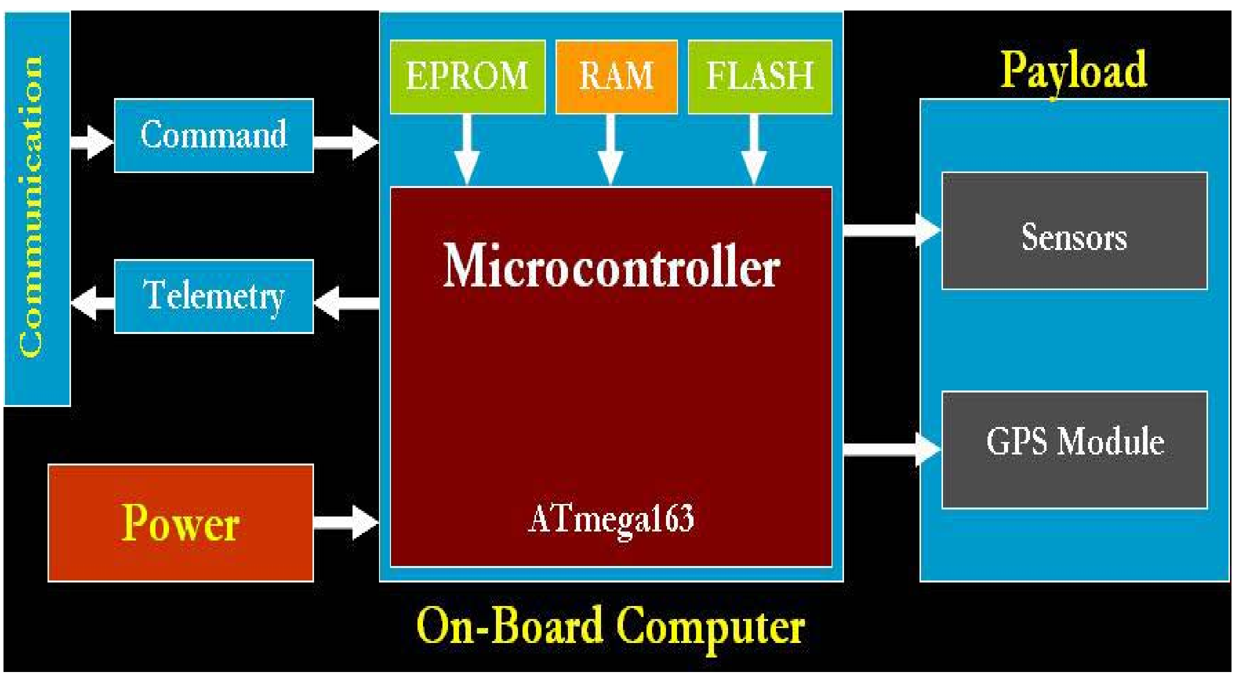


Figure 4: Block Diagram for C&DH Subsystem (middle) and other Subsystems.

2.4.1 Hardware

Figure 4 indicates a microcontroller with three built-in memories: EEPROM, Flash, and SRAM. These three types were chosen because this computer will operate in atmosphere where radiation sometimes leads to bit-flips in temporary memory (Flash), which results in unpredictable software errors. A programmable safety timer, called a watchdog timer, resets the processor if bit-flip occurs, and the processor reloads the boot-software from EEPROM to Flash. It is essential that the boot-software always works correctly, and therefore must be stored in a memory, where bit-flips do not occur [“The DTUsat,” 2003].

The Flash memory is used to store the main operating software and other subroutines, and a copy of this software will also be stored in EEPROM (permanent memory). The STK 500 starter kit helps in programming the memories in the microcontroller. Storage of software in this fashion is necessary in order to modify certain programming subroutines via the communication subsystem when the OBC is in the atmosphere [“The DTUsat,” 2003].

The SRAM temporary memory will be used to run the software and subroutines and also as a place to store the measured values from the payload sensors. Both Flash and SRAM suffer from bit-flips; therefore, an Error Detection and Correction Circuit (EDAC) consisting mainly of a watchdog timer and a delay interface between these temporary memories and the permanent memory is finalized for implementation in the hardware design [“The DTUsat,” 2003]. The CubeSat will be used as a testing platform for EDAC that is required by the FASTRAC nanosatellite project.

Next, in order to communicate with the ground station, the OBC must be connected to a radio or communication subsystem (see communication subsystem section for more details), as shown in Figure 4. The easiest way to implement communication is to use an UART, which converts signals between serial and parallel data and also handles the serial timing. The UART is a built-in peripheral inside the Atmega163 processor ["The DTUsat," 2002].

The OBC will have a number of two different interfaces to other parts of the CubeSat: analog and digital. The payload sensors produce the analog signals, and all the other subsystems discussed in later sections produce the digital signals, as shown in Figure 4. Since the communication subsystem accepts only digital signals, the microcontroller will convert the analog signals to digital signals with the help of an Analog to Digital converter (ADC) ["The DTUsat," 2002].

Next, two Real Time Clocks (RTCs), one 8-bit and the other 16-bit, as part of the microcontroller, will assist in scheduling tasks or operations to CubeSat's subsystems ["The DTUsat," 2003].

The delay interface is also of special interest. As mentioned earlier, this device is used along with watchdog timer in the EDAC. The purpose of this device is to find errors in the hardware and software design and to correct them by uploading new software to the Flash memory. The delay interface consists of measuring points (provided by the timer) for important signals and an interface to the processor and the flash memory.

As mentioned above, operating software is required to run the hardware. The following section discusses the features of such an operating software.

2.4.2 Software Design

The ATMEL Company requires C language for programming the microcontroller; therefore, Satellite Solutions assembled the required equipment for programming the microcontroller. The equipment basically consists of a desktop computer, the STK 500 starter kit, and an AVR studio software. The C language program is written, compiled, and then downloaded into the microcontroller with the help of AVR Studio software. The compiler converts C language into machine language (binary) that a microcontroller understands. In the end the STK-500 starter kit will be used to download the machine language from AVR Studio into the microcontroller. Mistakes are common while programming the microcontroller, but the problem can be fixed quickly because the ATMEL microcontroller's memory can be completely erased and rewritten 100,000 times.

The Satellite Solutions team failed to write complete C language code to meet the software requirements for CubeSat, as planned in the midterm report. Upon attempting to program the microcontroller, the team realized that this endeavor required much more knowledge of microcontrollers than was previously thought. However, Satellite Solutions performed the necessary research and laid out the software requirements, which will be robust, tested, and free of infinite loops.

The main operating software will be divided into several subroutines for the efficient operation of all of the CubeSat's subsystems. The reason for writing several subroutines is to avoid a major disadvantage which is inherent in an OBC. In an OBC different subsystems rely heavily on one another; as a result, a fatal error in a program without subroutines can result in a failure in execution of the parts of the program written for other subsystems. This failure in software can render the entire CubeSat inoperable. In addition the written code should be of minimum length to ensure that the program fits within 512 Bytes of EEPROM memory. The requirements made the programming very difficult for the Satellite Solutions team, but with the help of Shaun Stewart (advisor) and Mr. Pascal (graduate student at Santa Clara University), we were able to obtain some previously written subroutines, which need to be modified for the ATmega163 microcontroller. The codes are attached in Appendix B of this report.

3.0 Payload Sensors Subsystem

If the C&DH subsystem is the ‘brain’ of the CubeSat, then the Payload Sensors Subsystem is the ‘eyes and nose’ of the CubeSat. The payload sensors subsystem consists of several sensors, such as temperature, pressure, accelerometer, and GPS module.

3.1 Background

The previous CanSat had only temperature, pressure, and accelerator sensors installed in it. All of these sensors were analog, meaning that they produced a continuous stream of signal. These analog signals were then converted to digital signals via the A/D converter discussed in C&DH subsystem. All the data was stored in SRAM, where the microcontroller converts the data into a telemetry stream and sends it to the communication subsystem. The previous CanSat group had problems with the accelerometer and the temperature sensors. The accelerometer stopped working midway of the flight test, and the temperature sensor gave faulty data, as it was placed near the microcontroller that produced heat during data processing.

3.2 Requirements and Constraints

The objective of the payload sensors subsystem is to acquire scientific data as well as monitoring the health and progress of various subsystems of the CubeSat. Again, the payload sensors subsystem should be light in weight, consume a small amount of power, be high in sensitivity, and should be able to produce undistorted analog and digital signals. Moreover, the payload sensors subsystem should have room for extra payload sensors for future projects, and sensors should be easy to remove for repairing.

3.3 Options and Evaluations

The payload sensors have been chosen and range from $1.00 for a temperature sensor to about $ 200.00 for a GPS module. Many companies offer these sensors, so careful research was performed before we selected the appropriate ones for the CubeSat. The previous CanSat group purchased approximately five temperature sensors, model number LM 135 (see Figure 5), and used only one; therefore, these temperature sensors are available to Satellite Solutions for free. These temperature sensors have an operating range of -55°C to +150°C with an accuracy of ±1°C over a wide range. Figure 1 shows the picture of the temperature sensor installed near the microcontroller in the CanSat circuitry.

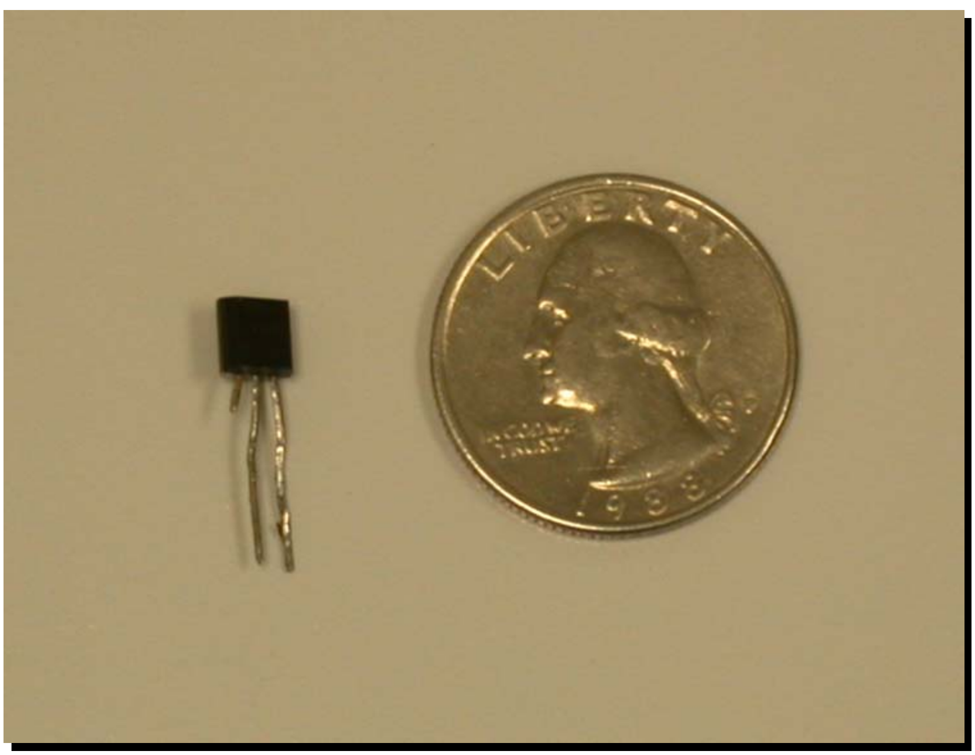


Figure 5: Temperature sensor, LM 135.

Figures 6, 7, 8, and 9 are pictures of the pressure sensor (MPX4115A), accelerometer (three axis from Motorola), and GPS module (Motorola M12+ Oncore), respectively.

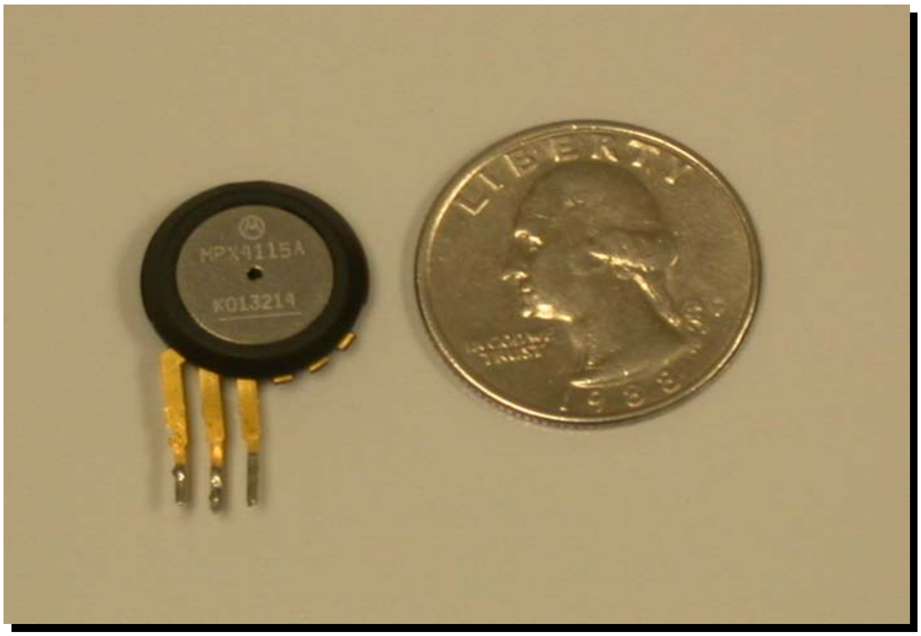


Figure 6: Pressure sensor, MPX4115A.

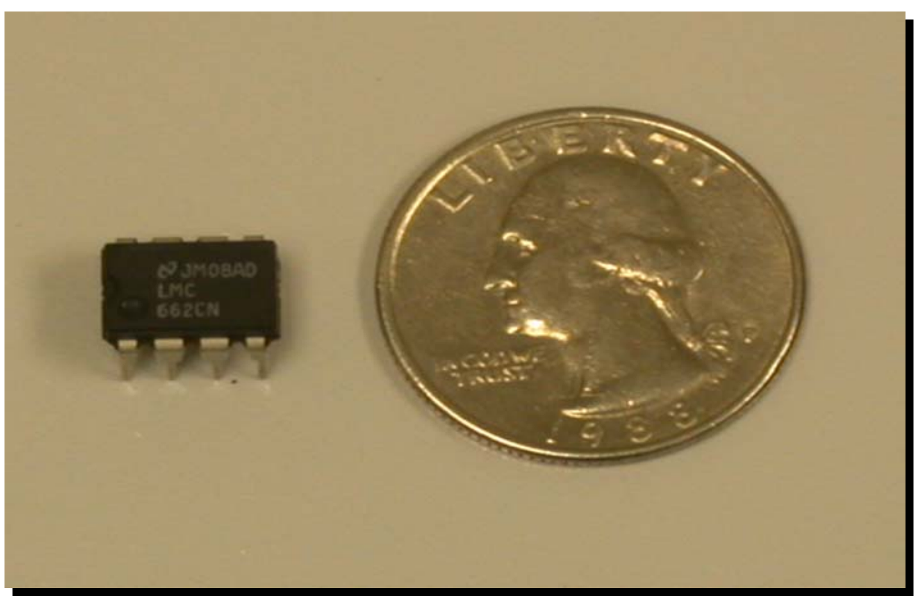


Figure 7: Three-axis accelerometer sensor from Motorola.

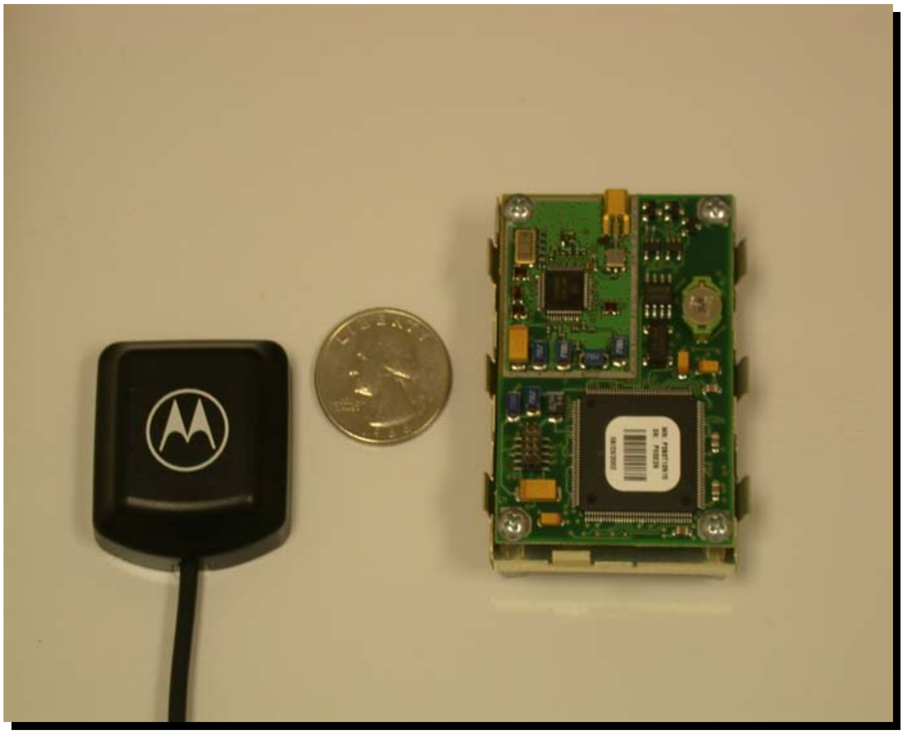


Figure 8: Motorola M12+ Oncore GPS Module.

3.4 Design

The payload sensors board will be easiest to fabricate because all the components are ready-made. Satellite Solutions will only have to solder everything onto a circuit board, measuring less than 6.5 x 9.5 centimeters. The temperature sensors will be placed at several places inside the CubeSat (TBD) to monitor the temperature variations for various subsystems. An additional temperature sensor will be placed on the outside surface to measure the ambient atmospheric temperature. The pressure sensor will be placed where the atmospheric pressure can be sensed, possibly on the bottom panel of the CubeSat. The accelerometer will be placed near the geometric center of the structure, closer to the batteries to read the acceleration in all three directions. The GPS module will be placed next to the MaxStream transmitter (see circuit board 1 in Figure 32) and its required GPS antenna on top of the C&DH subsystem circuit board (see circuit board 8 in Figure 32). The main required circuitry for all sensors will be placed on one circuit board (see circuit board 4 in Figure 32).

The Payload Sensor subsystem will have room for additional payloads and will be supplied with required controlling commands from CD&H subsystem. The analog output from the sensors will then be converted to SM band signals and will be transmitted to the ground station through the Communication Subsystem. The next section discusses the Communication subsystem in detail.

4.0 Communication Subsystem

The primary goal of the communication subsystem is to provide a link to relay data findings and send commands to and from the CubeSat. Telemetry and command subsystems will ensure continuous communication between the ground station and the CubeSat after ejection from the ARLISS rocket. To better understand the basics of the CubeSat communication architecture, the theory behind the system will be presented first, followed by a timeline of the progress that has been made throughout the semester.

4.1 Background

The CubeSat communication system is composed primarily of the telemetry and command systems, which send and receive data, respectively. Analog and digital data collected by the sensors and payload of the satellite must be relayed to the ground station via the telemetry system, which is composed of a transmitter that acts much like a "modem in a computer". The microcontroller will accumulates data from the sensors and convert these inputs into a stream of 8-bit binary numbers. This numerical string is encoded into AX.25 protocol by the terminal node controller (TNC), which serves to "packetize" the information and key the transmitter. The transmitter then sends the signal to the ground station through the satellite's antenna [Dominguez and others, 2002]. A radio operating in the ultrahigh frequency (UHF) band at the ground station will receive the data signal and encode the stream to a form that may be interpreted by software on a laptop.

Another vital aspect of the communication subsystem is the command/uplink portion. From the ground, moderators must be able to send commands to the system. All incoming signals from the ground station will be compared to all other inputs, and any errant signals are discarded [Dominguez and others, 2002].

The Satellite Solutions CubeSat design will implement commercially available transmitter and receiver packages that operate in UHF, and therefore, care must be taken to ensure that the correct radio-data protocol is followed for the transmission to be efficient, reliable, and robust. Also, the frequency of the signals must be transmitted within the correct FCC license regulations for the system. The most common protocol is AX.25, which was originally developed for amateur radio use as the basis for applications in mobile and radio-data transmission [Thorcom, 1998].

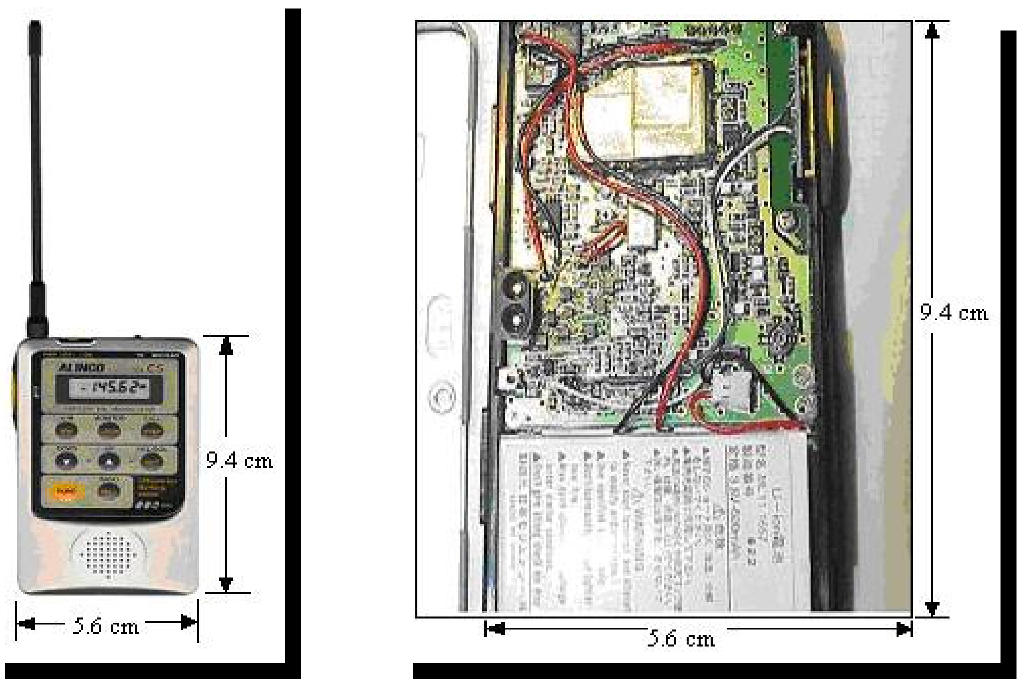
4.2 Requirements and Constraints

As mentioned previously, the CubeSat system must be no larger than 10 cm on each side and weigh less than 1 kg. Therefore, the internal components must be scaled to fit within these constraints. Since only a fraction of the 1000 cm^3 volume is allotted to communications, the team must select a transmitter and terminal node controller (TNC) that are miniaturized. The entire system must also be relatively inexpensive and operate within the designated frequency band allowed under the Federal Communications Commission (FCC) amateur radio guidelines. Finally, for adequate communication time, the data transmission rate is desired to be at least 9,600 baud, and the amount of working amperage drawn by the communication subsystem must not exceed the available power provided by the batteries or solar cells.

4.3 Options and Evaluation

One of the largest obstacles for the Satellite Solutions team was the overall lack of experience in radio communications. Therefore, the CubeSat communication subsystem will consist primarily of commercially available off-the-shelf (COTS) components for both the internal and ground station systems, in order to simplify the amount of modifications necessary to build a working system. Given the requirements listed above, several COTS options have been researched to aid in selection.

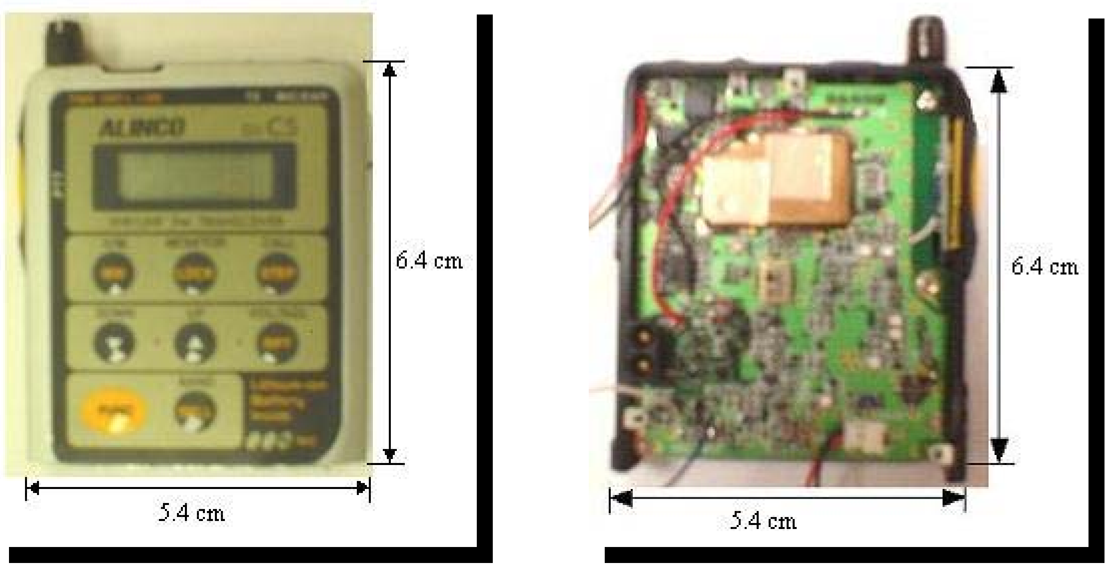
For the internal CubeSat communication system, an Alinco DJ-C5 transmitter was investigated. Figures 9 (a) and (b) show the external and internal view of the Alinco device.



(a) (b)

Figure 9: (a) Outside view of Alinco DJ-C5 transceiver prior to modifications [RigPix, 2001]. **(b)** Internal view of Alinco DJ-C5 transceiver prior to modifications. [PacComm, 2003].

The DJ-C5 is small, lightweight, and versatile, as it can transmit in the 144-146 and 430-440 MHz range [RigPix, 2001]. The CubeSat team disassembled and modified the transceiver to allow for further miniaturization and increased performance. First, the front and back plastic covers were removed. The flexible antenna was unscrewed from its connection point, and the Lithium-ion battery pack was disconnected. Next, a team member cut both sides of the transmitter's case with a Dremel tool to reduce the length of the device by approximately 3 cm. Figures 10 (a) and (b) show the Alinco DJ-C5 after the modifications were made.



(a) (b)

Figure 10: **(a)** Outside view of Alinco DJ-C5 transceiver after modifications.
(b) Internal view of Alinco DJ-C5 transceiver after modifications.

After all modifications were complete, the DJ-C5 was connected to the previous CanSat electronics and a power supply, to ensure that the transmitter still had the capability to send a signal despite the changes. The test was successful; the transmitter could indeed still send a data signal.

Next, different terminal node controllers were researched to find one that would work with the rest of the system, including the Alinco DJ-C5 transmitter and the Atmel microcontroller. The best option for this electronics package was the PacComm PicoPacket. This TNC would operate in transparent mode to control the flow of data to and from the microcontroller, as well as radio transmission and reception. The PicoPacket (Figure 11) was attractive because of its electronic capabilities, and since it was the only TNC found that could fit within the strict volume limits, with a total volume of approximately 180 cm^3 [PacComm].

Figure 11: PacComm PicoPacket miniature TNC [PacComm].

Another interesting possibility for the communication system employed a faster, more inclusive package manufactured by MaxStream. The MaxStream XStream™ 900 MHz Wireless OEM (Original Equipment Manufacturers), as shown in Figure 12, is a frequency-hopping module that allows for wireless communication and can sustain a continuous data stream at a given data rate.

Figure 12: Size of MaxStream XStream™ 900 MHz wireless OEM module.

This device has several advantageous features, which include [MaxStream]:

- Frequency-Hopping Spread Spectrum (FHSS) technology
- Noise and interface resistance
- Enhanced sensitivity and range
- Multiple Low-power modes
- Standard serial digital interface connection
- Built-in networking and addressing
- Simple AT command interface
- 9600 and 19200 baud transfer rates available
- Packet retries and acknowledgements

The 900 MHz unit has a transmission range from 7 miles with a dipole antenna to over 20 miles with a high-gain antenna [MaxStream]. This module would also allow for a much faster transmission of data from the CubeSat to the ground station. The XStream™ 900 MHz module was ordered as a “Development Kit,” which contained an almost complete communication package for the CubeSat mission, and eliminated the need for a separate modem, TNC, and ground station receiver.

Next, components were investigated for use in the ground station. The first choice for the ground station transceiver was the Kenwood TH-D7 dual-band hand-held transceiver (Figure 13), which was used in the 2002 CanSat project.

Figure 13: Kenwood TH-D7 transceiver [Radiohound, 2003].

The Kenwood TH-D7 has a built-in TNC and would be used to receive data from and send commands to the satellite after launch. This transceiver would then be connected via serial cable to a laptop. The laptop functions as the “control center” for the mission by receiving data with the standard “HyperTerminal” software package. For the Kenwood radio to communicate with the satellite, an antenna is needed. Since the

CanSat 2002 team implemented this ground station system, their 6-element Yagi-Uda antenna could again be used, as shown in Figure 14 [Campbell and others, 2002].

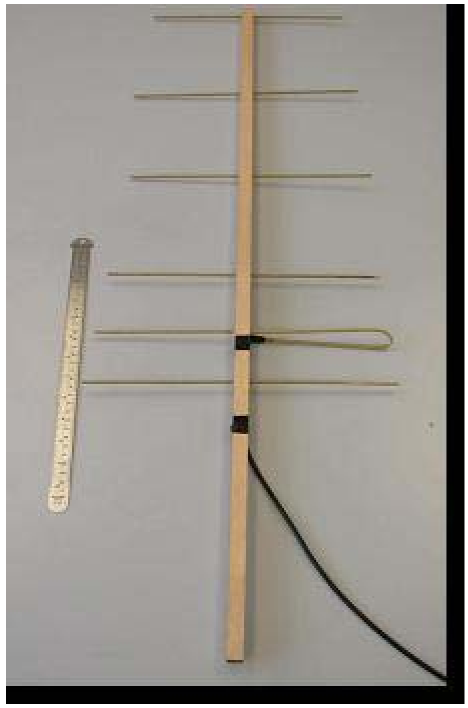


Figure 14: CanSat Ground Station Yagi-Uda Antenna [Campbell and others, 2002].

4.4 Product Evaluation and Selection

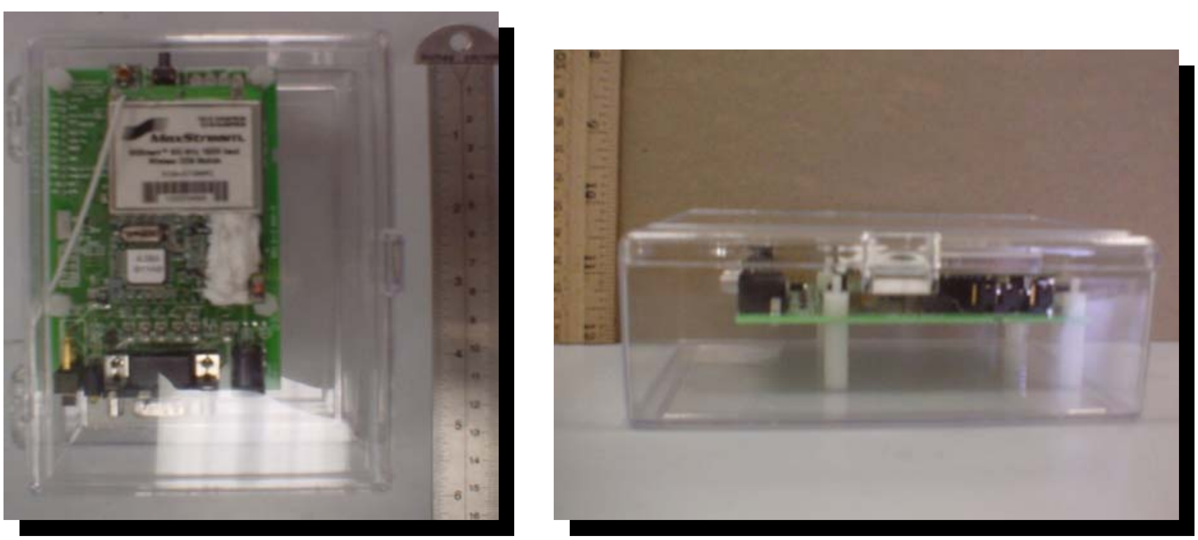
The COTS products listed in the previous section were each studied to determine whether or not they met the design criteria specified above. Table 2 compares some of the key characteristics of each device, and product information sheets may be found in the Appendix C.

Table 2: Devices evaluated for implementation in the communication subsystem [Radiohound], [Campbell and others, 2002], [RigPix, 2001], [PacComm], [MaxStream].

	Kenwood TH-D7	Alinco DJ-C5	PacComm PicoPacket	MaxStream XStream™ 900 MHz OEM
Dimensions (with case)	Length: 119.5 cm Width: 54 cm Depth: 35.5 cm	Length: 9.4 cm Width: 5.6 cm Depth: 1.36 cm	Length: 8.3 cm Width: 6.3 cm Thick: 2.5 cm	---
Dimensions (without case)	---	Length: 6.4 cm Width: 5.6 cm Depth: 1.36 cm	Length: 8.25 cm Width: 6.17 cm Depth: 2.50 cm	Length: 4.06 cm Width: 6.86 cm Depth: 0.89 cm
Weight	---	85 grams (with case, antenna, and battery)	57 grams (without case)	24 grams
Current Consumption	5.5 Watts at 13.6 V	Receiver: 30 mA (VHF), 40 mA (UHF) Transmitter: 240 mA (UHF), 300 mA (VHF)	50 mA to 70 mA	Transmit: 150 mA, Receive: 50mA, Power down: < 1μA
Operating Temperature	---	-10°C to +60°C	---	0°C to 70°C (-40°C to 85°C available)
Supply Voltage	---	Rechargeable 3.7 VDC Li-ion battery	7 VDC to 14 VDC Li-ion battery	5 VDC, ± 0.3V
Bit Rate	Built-in 1200/9600 baud TNC	9600 baud	1200 baud	9600 and 19,200 baud available
Frequency Range	144/430 MHz	144-146 / 430-440 MHz	---	900 MHz range
Cost	$500.00	$150.00	$159.99	$321.75
Order Status	Received	Received	**Discontinued**	Ordered

As Table 2 illustrates, all of the devices meet the size, weight, and performance constraints. The preliminary design of the internal communication system consisted of the Alinco DJ-C5 and the PacComm PicoPacket. However, the PicoPacket has been discontinued by the PacComm Company, and cannot be obtained. Therefore, the MaxStream XStream™ 900 MHz Wireless OEM module will be used as the transmitter. The MaxStream development kit has arrived, and preliminary testing was performed with the software included in the kit. However, additional communication testing between the two OEM devices as well as range tests still need to be completed to ensure a successful CubeSat mission.

With the MaxStream module in place, a new setup for the ground station had to be designed. The Kenwood transceiver cannot operate in the 900 MHz frequency range and therefore, cannot be used to receive data from the MaxStream transmitter. Satellite Solutions will implement the second MaxStream receiver connected to the development board contained in the development kit, as shown in Figure 15 (a) and (b).



(a) **(b)**

Figure 15: **(a)** Top view of the MaxStream 900 MHz OEM inside protective case.
(b) Side view of the MaxStream 900 MHz OEM inside protective case.

A small plastic box was purchased to protect the bare components from the desert environment, as shown in the above figure. Modifications must be made to this case to allow a high-gain antenna to be connected to the MaxStream OEM.

However, for adequate communication over a large distance, the OEM must be outfitted with a high-gain Yagi-Uda antenna to receive and transmit data from the ground station. The MaxStream Company was contacted regarding the type of antenna which would be successful with the OEM devices, and the technician recommended a 4-element high-gain Yagi. A design for the Yagi antenna was calculated using the "Yagi Antenna Design Program" based on the work of Gunter Hock, an amateur radio enthusiast, as published in Chapter 9 of the ARRL (Amateur Radio Relay League) UHF/Microwave Experimenter's Manual (1990). The program required the boom and element diameters, the operating frequency, and the number of elements as inputs and returned all of the values needed to construct an antenna. Program inputs are given in Table 3.

Table 3: Yagi element preliminary design inputs.

Design Parameter	**Value**
Number of Elements	4
Operating Frequency	900 MHz
Boom diameter	1 inch
Element diameter	0.375 inches

The output file given by the design program may be found in Appendix A. An AutoCAD drawing was then prepared, and materials were purchased for the elements and boom to begin the construction phase (Figure 16).

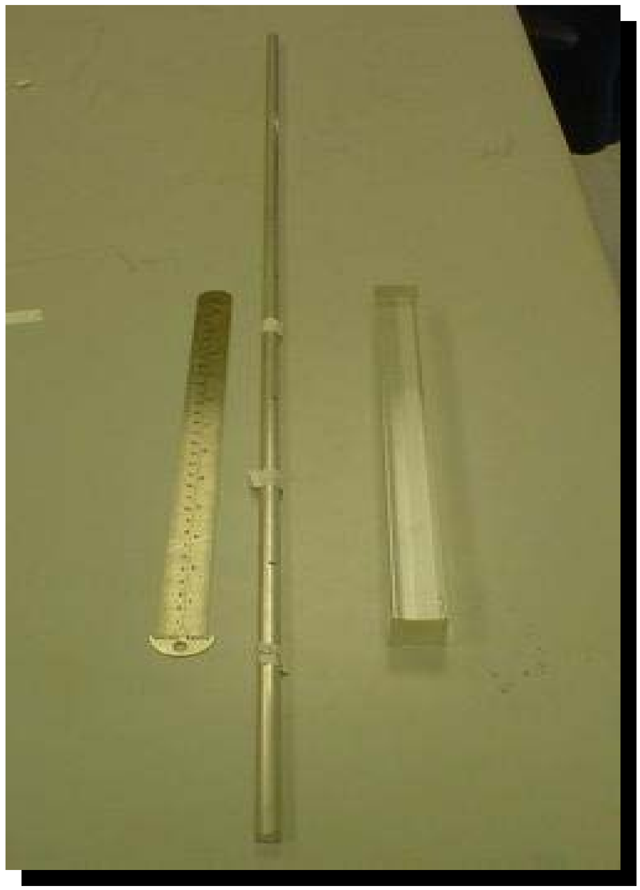


Figure 16: Materials for construction of the Yagi antenna. The Aluminum rod for the elements is pictured in the middle, and the acrylic rod for the boom is on the far right.

A general schematic of the final antenna design is shown in Figure 17 and a dimensioned drawing is in Appendix A.

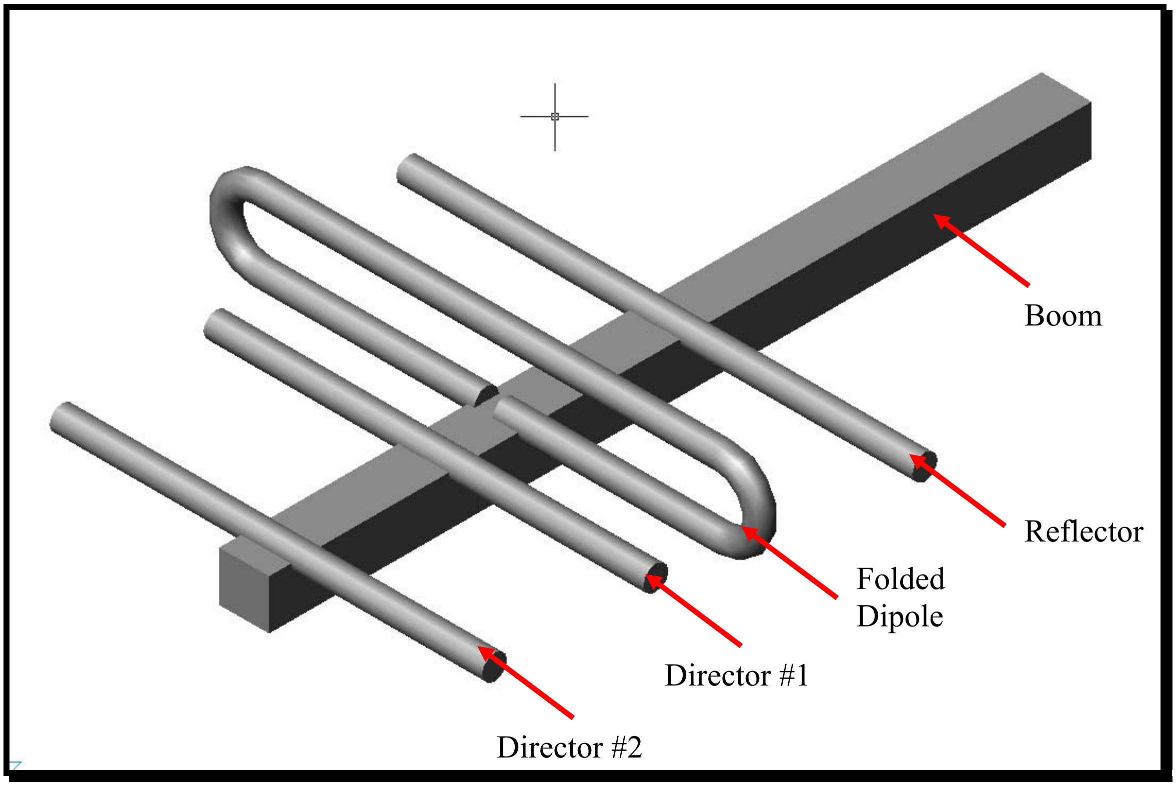


Figure 17: Yagi antenna design.

The coaxial cable and connectors, known as a "pigtail" cable, to link the antenna to the OEM module still needs to be purchased. Once the construction is complete, the Yagi antenna and ground station transceiver must undergo range tests to communicate with the MaxStream OEM that will be employed inside the CubeSat.

The Satellite Solutions team made good progress in laying the ground work for the communication subsystem. Future work that must be accomplished by the summer team is included in the management section.

5.0 Power Subsystem

The power system is necessary for the other CubeSat subsystems, such as the microcontroller and communication, to function. The design objectives of the power system include: providing sufficient power to the electrical subsystem, minimizing power drain from the batteries, ensuring efficient recharging of the batteries, and minimizing weight and volume. In addition, Satellite Solutions hopes to improve upon Sub-Orbital-Technologies' power system.

The preliminary design of Satellite Solutions' CubeSat power system implemented various power generation methods, a DC-to-DC boost converter, a battery charger, rechargeable batteries, and a DC-to-DC converter. Parts for that power system have been ordered; however, due to a back order of 8-14 weeks, a redesign of the system was necessary to provide parts faster. As a result, the power system has multiple design options due to different component specifications. Some of the design options change battery configuration (series or parallel) and the method of power delivery to the CubeSat subsystems. The redesign of the system also resulted in a new design strategy that examined the power system from the load to the source. The strategy is based on the idea that each component is dependent upon the component from which it receives power.

The following discussion presents a final design review of the power system by Satellite Solutions. First, the general operation and problems of the CanSat power system are given. Next, the CubeSat power system is divided into three main areas, which include: power generation, storage, and distribution. A general layout of the power system is presented in Figure 18, which provides a road map for discussing the areas of interest. Note that the power distribution and generation elements are explained first in order to define the requirements of the power storage element

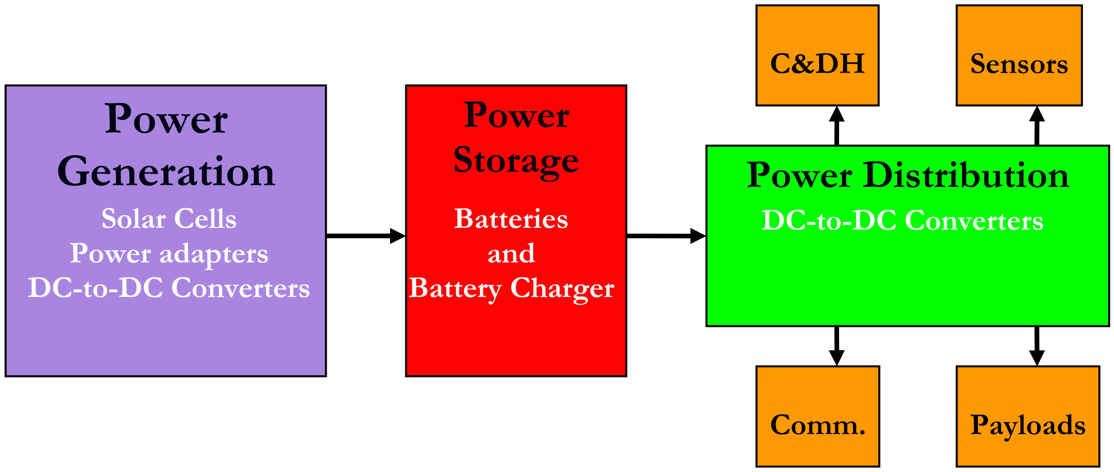


Figure 18: General Layout of the CubeSat Power System

Within each area, the component design, requirements, evaluation criteria, and best option(s) for a particular design are presented. The review of the power system provides general information about the components, but is mostly concerned with component evaluation. Last of all, final design options are presented based on the power system energy balance, cost, and future adaptability. A basic understanding of circuit theory is expected and assumed known for the following explanations.

5.1 Background

The CanSat power system is composed of two independent battery sources, a voltage regulator, and two capacitors, as seen in Figure 19. Despite its simplicity, the CanSat power system had some shortcomings: the dual battery sources added unnecessary weight, the batteries had to be replaced frequently, and the voltage regulator was incorrectly matched to the power supply (voltage drop out was too high).

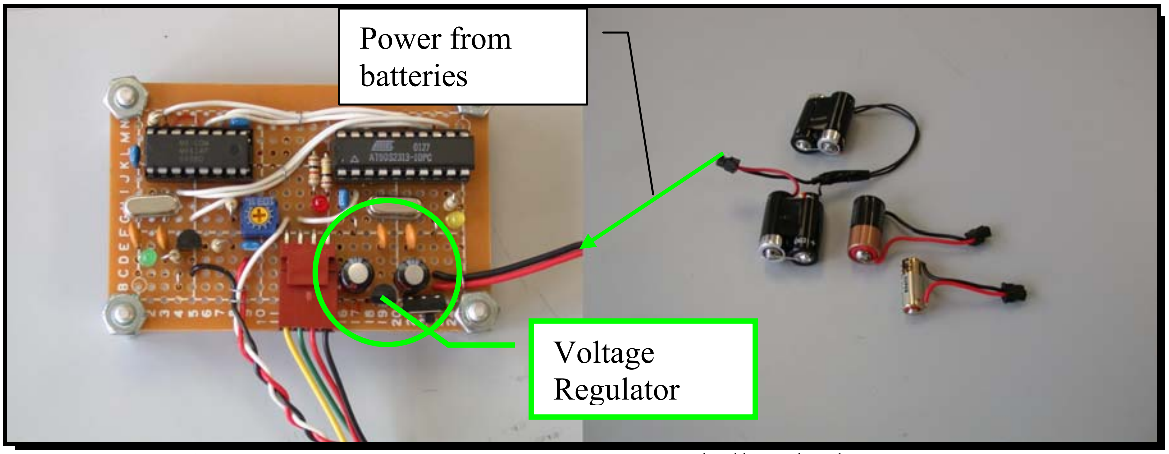


Figure 19: CanSat Power System [Campbell and others, 2002].

5.2 Component Theory

The principle idea of power system components is to adjust the respective output voltage and/or currents according to component and design needs. Components within a power system include linear regulators, DC-to-DC converters, charge pumps, and battery chargers just to name a few. Most power system components are made from diodes, transistors, and other electrical devices to obtain the desired outputs. A generalized block diagram of a power system component can be seen in Figure 20.

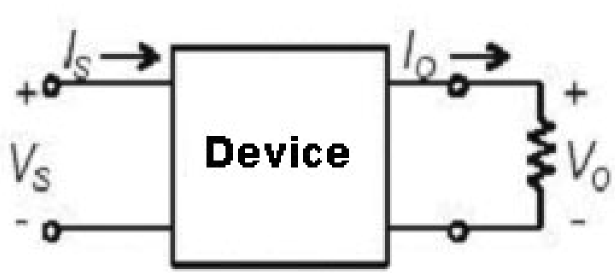


Figure 20: Representative Power System Component Block Diagram [Zulinski, 2003]

Although the current and voltage change from the input to the output in each device, ideally the power should remain the constant; however, this is not the case. The output power is always lower than the input power due to resistive losses [Zulinski, 2003]. As a result, the all power system components have an associated efficiency.

$$\eta = \frac{P_o}{P_s} = \frac{V_o I_o}{V_s I_s} \tag{1}$$

where

$P_o = Output\ \ Power$
$P_s = Source\ Power$
$V_o = Output\ \ Voltage$
$V_s = Source\ \ Voltage$
$I_o = Output\ \ Current$
$I_s = Source\ Current$

Linear regulators are somewhat different because the current remains nearly constant, which means that the output voltage divided by the input voltage equals the efficiency. In addition, a constant current implies that a linear regulator can only step down a voltage because efficiency cannot be greater than 100%. On the other hand, converters and battery chargers allow for varying input and output currents resulting in step-up and step-down voltage applications, as well as much higher efficiencies. Note that linear regulators will receive little attention due to their high inefficiency.

5.3 Power Distribution

The power distribution element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection.

5.3.1 Design

Design of the power distribution area centered around two options, seen in Figure 21. The first option assumes a low input voltage from the batteries, meaning a step-up device is required. The second option assumes a higher input voltage than the loads require, which means a pair of step-down devices are needed. The step-up/down device can be a charge pump, linear regulator, or DC-to-DC switch mode converter. The charge pump is not ideal for our application because it cannot produce the current output required. For our purposes, the inductor based DC-to-DC converters were examined. The only requirement for selection of various converters is that they meet the power needs of the CubeSat system load.

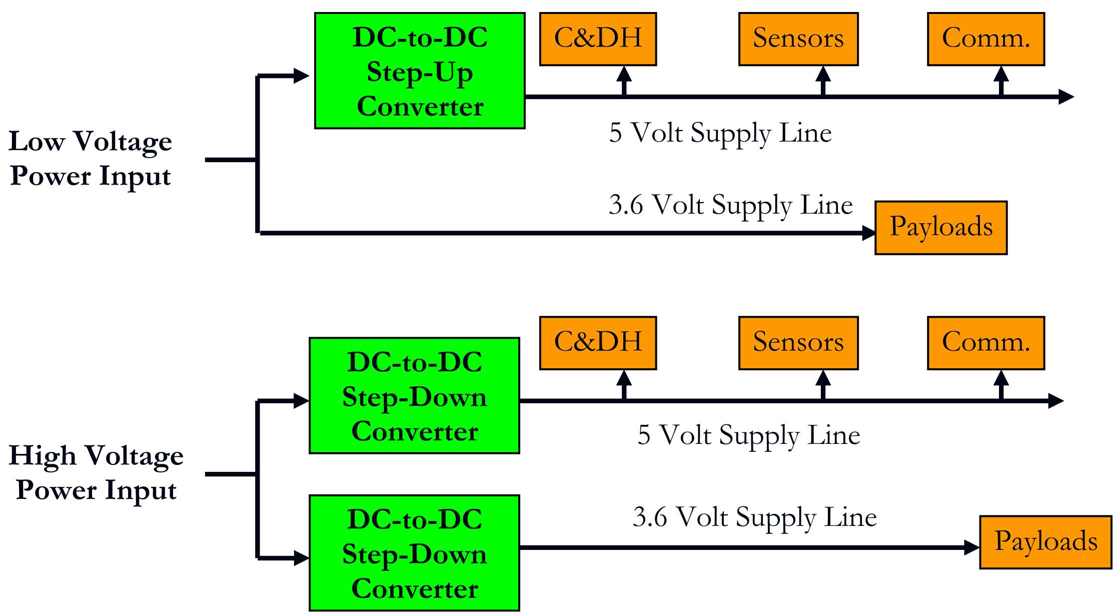


Figure 21: Power Distribution Design

5.3.2 Requirements

Manufacturers of the components within aforementioned subsystems provide voltage, current, and power requirements to operate each device. The chart in Figure 22 is a distribution of power based on the requirements of other subsystems, such as the C&DH, communications, sensors, and experiments.

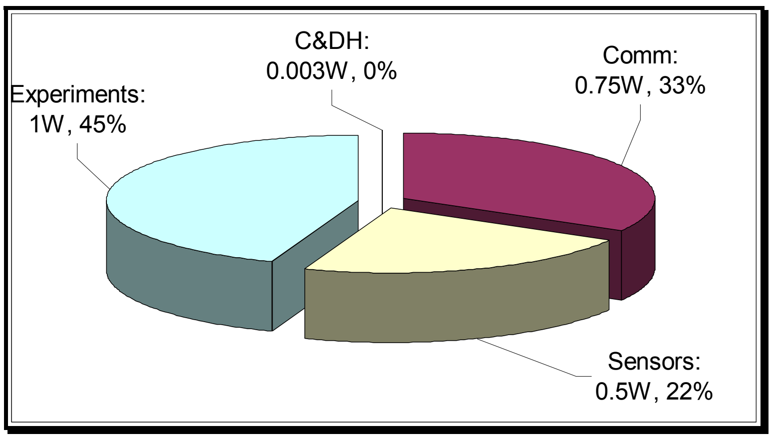


Figure 22: Power Requirement Breakdown by Subsystem.

The CSDT calculated the maximum power draw on the system to be 2.25 Watts. To account for future changes and additions to other subsystems, the power was assumed to increase to 2.5 Watts. In addition, manufactures of the communication system, microcontroller, and GPS provided voltage requirements, which were 3.6 or 5 Volts. Based on the maximum power requirements from each subsystem, approximately 56%, or 1.253 Watts, of the total CubeSat power is needed for the 5 Volt subsystems and 44%, or 1 Watts, for the 3.6 Volt subsystems. Therefore, the resulting minimum currents required for the 3.6 and 5 Volt supply lines are 0.278 and 0.251 Amps.

5.3.3 Component Evaluation Criteria and Selection

In addition to the power requirements, the efficiency of the converter is an important performance characteristic and should be as high as possible over a wide range of current. Figure 23 illustrates a good efficiency curve with respect to current draw.

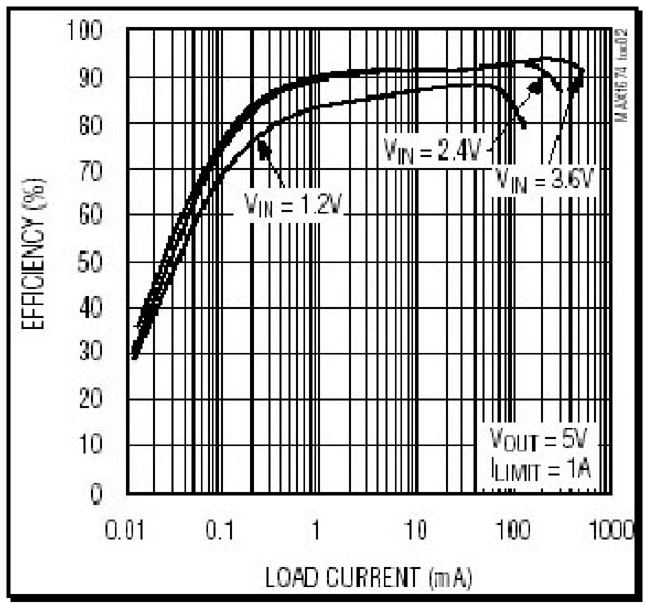


Figure 23: A Good Efficiency Curve for a DC-to-DC Converter [Maxim, 2003].

Other important characteristics include lowest possible input voltage, robustness, wide range of environmental temperatures, and cost. Research for converters uncovered numerous options by manufactures such as Maxim, Texas Instruments, National Semiconductor, and Linear Technology. Table 4 presents the chosen step-up and step-down converters for each design option and their specifications. All of the chosen components accommodate the necessary power requirements for the CubeSat system load.

Table 4: Converter Specifications for Power Distribution Design Options [Maxim, 2003], [National Semiconductor, 2003], [Texas Instruments, 2003]

Part Number	Type	Input Voltage (V)	Output Voltage (V)	Max Output Current (mA)	Max Efficiency (%)	Temperature Range (C)
MAX757	Step-Up	0.7 to 5.5	2.7 to 5	300 @5 Vout, 3.3 Vin	88 @5 Vout, 3.3 Vin	-40 to 85
MAX1795	Step-Up	0.7 to 5.5	2 to 5.5	300 @5 Vout, 3.6 Vin	95 @5 Vout, 3.6 Vin	-40 to 85
MAX1723	Step-Up	0.8 to 5.5	2 to 5.5	150 @5 Vout, 3.6 Vin	90 @5 Vout, 3.6 Vin	-40 to 85
TPS61130	Step-Up	1.8 to 5.5	2.5 to 5.5	200 @5 Vout, 3.6 Vin	87 @5 Vout, 3.6 Vin	-25 to 85
UCC2941	Step-Up	0.8 to 5	5	200 @5 Vout, 3 Vin	90 @5 Vout, 3 Vin	-55 to 150
LM2621	Step-Up	1.2 to 14	5	300 @5 Vout, 3.6 Vin	88 @5 Vout, 3.6 Vin	-40 to 85
LM2641	Step-Down	5.5 to 30	2.2 to 8	1000 @6.5 V	94 @6.5 V	0 to 125
LM1572	Step-Down	8.5 to 16	2.42 to 5	830 @5 Vout, 7.2 Vin	95 @5 Vout, 7.2 Vin	-40 to 125
TL497L	Step-Down	4.5 to 12	-25 to 30	N/A	>60	-60 to 150
MAX639	Step-Down	4 to 11.5	5	150 @5 Vout, 7.2 Vin	94 @5 Vout, 7.2 Vin	-55 to 125
MAX750A	Step-Down	4 to 11	1.25 to 11	600 @5 Vout, 7.2 Vin	93 @5 Vout, 7.2 Vin	-55 to 125
LM2655	Step-Down	4 to 14	1.238 to 5	500 @3.6 Vout, 7.2 Vin	96 @3.6 Vout, 0.5 Iout 7.2 Vin	-40 to 125
Max1761	Step-Down	4.5 to 20	1 to 5.5	600 @3.6 Vout, 7.2 Vin	94 @3.6 Vout, 7.2 Vin	-40 to 85

Often, setting the boost converter to its maximum output voltage results in degraded efficiency; therefore, the criteria for the efficiency and maximum output current were examined closely. The best step-up converter for the low voltage power input design is MAX1795. The selected step-down converter for the high voltage power input design is LM2655, which will be used on both the 3.6 and 5 Volt supply lines. Both of the chosen converters presented the best efficiency over a wide range of load currents.

The power input requirement for the power distribution element using MAX1795 and LM2655 are 2.4 and 2.51 Watts, which assumed 5% less efficiency than the maximum presented in Table 4.

5.4 Power Generation

The power generation element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection. The solar cells were thoroughly researched to ensure that an eventual space application for the CubeSat is possible. However, solar cells are not required for the sounding rocket launches in August.

5.4.1 Design

The design of the power generation area includes solar cells, a power adapter, and DC-to-DC converter, as seen in Figure 24. The solar cells can be wired in two different configurations. In the first configuration, all the cells are wired together in series, which means that the voltage adds while the current remains constant. The second configuration has the cells wired together in parallel on each face; then, the combined cells on each face are wired in series. Note that if the output voltage from the solar cells and power adapter are within the input voltage of the battery charger, then a DC-to-DC converter may not be necessary.

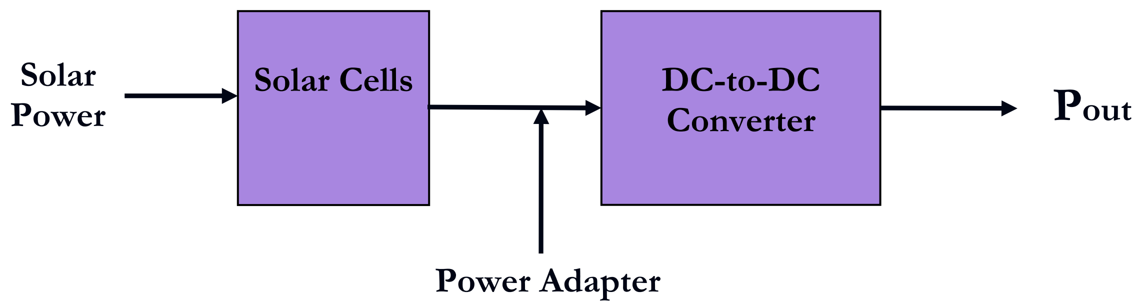


Figure 24: Power Generation Design

5.4.2 Requirements

Unfortunately, Satellite Solutions did not have the luxury of an unlimited budget; therefore, one of the major non-technical requirements for the CubeSat power system was the budget. The budget requirement mostly affects the solar cells because they are so expensive. The price of solar cells increases exponentially with increasing solar efficiency. Obviously, the highest efficiency and, therefore, most powerful solar cells are desirable; however, the solar cell expense was limited to $1100. In addition, surface area coverage was limited from a possible 600 cm^2 to 470 cm^2 because of antennas, data and power ports, and structural fasteners. Last of all, an external power source was a design requirement, set by our advisors. As a result, the power input from the power adapters had to be equivalent to the power input from solar.

5.4.3 Component Evaluation Criteria and Selection

The solar cells are a part of the flight hardware; therefore, the solar cells must be capable of withstanding deployment forces, vibration, and a wide range of operating temperatures. In addition, the solar cell best suited for our design should be light in weight and produce the greatest amount of power. The CSDT researched varying types of solar cells from three different corporations. All of the solar cells are space proven. Specifications for the varying solar cells are presented in Table 5.

Table 5: Specifications For Varying Solar Cells [Spectorlab, 2003], [Emcore Corporation, 2003], [Silicon Solar, 2000].

	Spectrolab	Emcore		Silcon Solar
	Dual Junction	Dual Junction	Tripple Junction	Single Junction
Supply Voltage (V)	2.05	2.08	2.57	0.51
Supply Current (mA)	230 to >286	427.50	427.50	3500 1300 250 75
Power (mW)	471 to >586	889.20	1096.54	1785 663 127.5 38.25
Energy Conversion Efficiency (%)	16.1 to >20	23.2	28.6	12.4
Size (cm)	3.12 x 6.91	3.72 x 7.61	3.72 x 7.61	10.3 x 10.3 6.25 x 6.25 1.7 x 6.25 2.6 x 1.7
Thickness (Microns)	140	155	155	N/A
Wieght (Grams)	N/A	2.4	2.4	N/A
Cost per Cell ($)	5.40 to 12.60 (Note: Must buy at least 50 cells)	260.00	260.00	6.00 3.00 1.50 1.00

In order to determine the maximum power and, therefore the best solar cell, the specifications must be examined with respect to efficiency and optimal surface area coverage. The efficiency is known, and the optimal surface area coverage for each manufacturer's solar cell was determined by assuming that a 0.5 cm minimum should be left uncovered from the surface of each edge of the CubeSat for structural fasteners. In addition, a minimum of a 6 cm^2 and 9 cm^2 sections were assumed uncovered for access ports and antennas. Furthermore, the solar cells were assumed to be in pure sunlight (solar constant = 0.1353 W/cm^2) where about ¼ of the CubeSat surface area received direct sunlight. The maximum power the solar cells will produce when in the sun is based on the optimal solar cell coverage, efficiency, solar constant, and average area receiving direct sunlight. Therefore, Table 6 presents the power capabilities of each solar cell.

Table 6: Power Capabilities of Each Solar Cell

	Manufacturer	Efficiency (%)	Area (cm^2)	All Cells in Series	Cells on each side in parallel, each side in series
Power (W) Voltage (V) Current (A)	Spectrolab	16	388	2.10 9.13 0.23	2.10 1.52 1.38
Power (W) Voltage (V) Current (A)	Spectrolab	17	388	2.23 8.92 0.25	2.23 1.49 1.50
Power (W) Voltage (V) Current (A)	Spectrolab	18	388	2.36 8.85 0.27	2.36 1.47 1.60
Power (W) Voltage (V) Current (A)	Spectrolab	19	388	2.49 9.10 0.27	2.49 1.52 1.64
Power (W) Voltage (V) Current (A)	Spectrolab	20	388	2.62 9.27 0.28	2.62 1.55 1.70
Power (W) Voltage (V) Current (A)	Emcore	23.8	340	2.74 11.90 0.23	2.74 1.98 1.38
Power (W) Voltage (V) Current (A)	Emcore	28.6	340	3.29 14.30 0.23	3.29 2.38 1.38
Power (W) Voltage (V) Current (A)	Silicon Solar	12.4	444	N/A	1.86 0.99 1.88

The AC and DC power adapters for supplying power to the battery charger are not a part of the actual CubeSat design and, therefore, the criteria applied to the solar cells do not apply in this situation. The AC and DC adapters require more research, but the desired requirements are easily attainable.

In the power distribution section, converters were discussed because two explicit predetermined voltages were set to run the other subsystems of the CubeSat. In this case, a converter might be required to obtain the necessary battery charger power input (particularly voltage) criteria if the solar cells cannot produce the desired characteristics. Besides the aforementioned requirement, the other criteria include those mentioned in the power distribution section. The important specifications of each model are presented in Table 7.

Table 7: Power Generation Converter Specifications

Part Number	Input Voltage (V)	Max Output Voltage (V)	Max Output Current (mA)	Max Efficiency (%)	Temperature Range (C)
LT1301	1.8	12	120 @ 12 Vout, 3.3 Vin	87 @ 12 Vout, 3.3 Vin	-65 to 150
LT1303	1.8	25	200 @ 5 Vout, 2 Vin	83 @ 5 Vout, 2 Vin	-65 to 150
LT1305	1.8	5	400 @ 5 Vout, 2 Vin	78 @ 5 Vout, 2 Vin	-65 to 150
LT1316	1.8	12	50 @ 5 Vout, 1.8 Vin	82 @ 5 Vout, 1.8 Vin	-65 to 150
LM2623	0.8 to 14	14	300 @ 5 Vout, 2.1 Vin	78 @ 5 Vout, 2.1 Vin	-65 to 150
MAX629	0.8 to Vout	28	100 @ 12 Vout, 3 Vin	80 @ 12 Vout, 3 Vin	-65 to 165
MAX772	2 to 16.5	15	1000 @ 15 Vout, 9 Vin	94 @ 15 Vout, 9 Vin	-65 to 160
MAX1674	0.7 to Vout	5.5	150 @ 5 Vout, 1.2 Vin	88 @ 5 Vout, 1.2 Vin	-65 to 165
MAX1703	0.7 to 5.5	5.5	400 @ 5 Vout, 1.2 Vin	88 @ 5 Vout, 1.2 Vin	-65 to 160
MAX1709	0.7 to 5.5	5.5	1300 @ 5 Vout, 2.5 Vin	88 @ 5 Vout, 2.5 Vin	-65 to 150

Often, setting the converter to its maximum output voltage results in degraded efficiency; therefore, the criteria for the efficiency and maximum output current were examined closely. If a converter is used in the power generation element, then MAX772 provides the best performance characteristics with a wide range of output voltages.

5.5 Power Storage

The power generation element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection.

5.5.1 Design

The battery charger receives power and energy from the power distribution element, and outputs power to the power distribution element. Generally, the battery charger is connected directly to the battery, which in turn, is connected to the system load, as seen in Figure 25. However, there are battery chargers that offer the capability to support the load and charge the batteries at the same time. Further research regarding load supporting battery chargers should be investigated by future semesters.

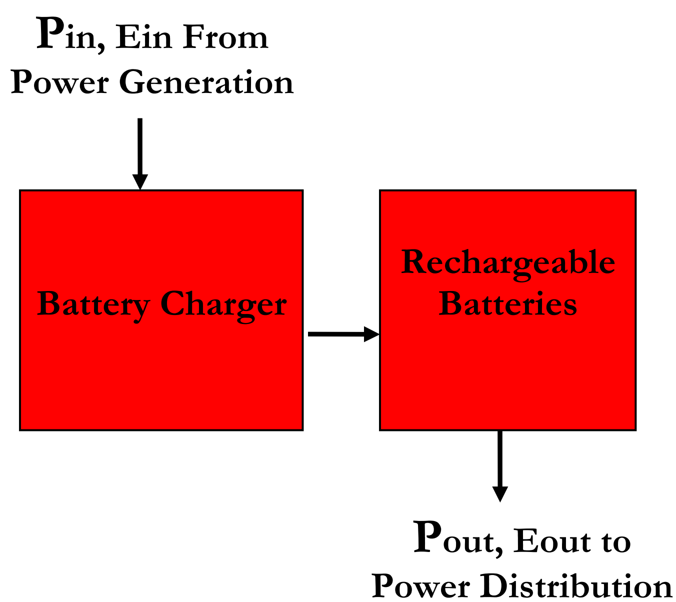


Figure 25: Basic Power Storage Design

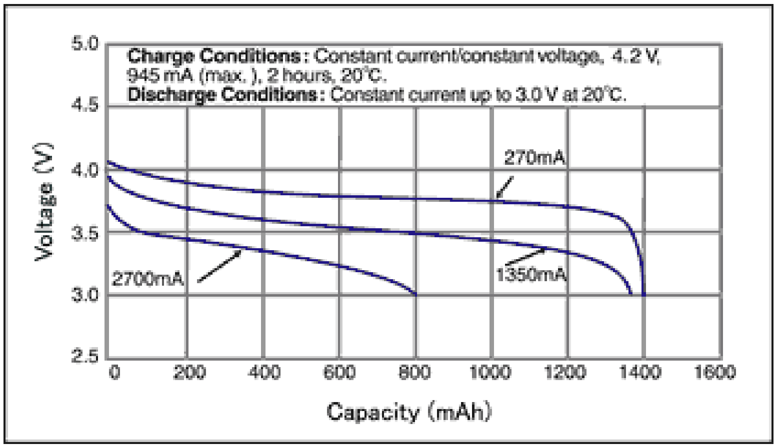
5.5.2 Requirements

The power storage element is required to support the system load (power distribution) and recharge the batteries. The output voltage from the batteries must be matched with the input voltage required for the power distribution element. Furthermore, the batteries should support the maximum power draw. Obviously, the battery charger must be capable of charging the selected battery chemistry. In addition, the input voltage of the battery charger must be matched with output voltage from the power generation element.

5.5.3 Component Evaluation Criteria and Selection

A battery is a device that converts chemical energy into electricity. All battery types derive power from electrochemical reactions. In order for a battery to be considered rechargeable, the electrochemical reactions must be reversible. But the fundamental difference between the two batteries, both rechargeable and non-rechargeable batteries discharge in a similar fashion.

The most important evaluation criterion for a battery is performance. The favorable performance characteristics of a battery include: high energy density, slow discharge (loss of voltage), and quick recharge capability. The energy density is defined as the capacity (Amps per hour) times voltage per weight (g) of the battery. A slow discharge means that battery voltage drops slowly with current draw. Graphically, a slow discharge curve is illustrated as shallow sloped curve over the discharge time of battery. Last, quick recharge means that the battery voltage increases rapidly with respect to time, as illustrated by a steep slope at the beginning of the charge curve. The general discharge and charge characteristics of a battery type are illustrated in Figure 26.



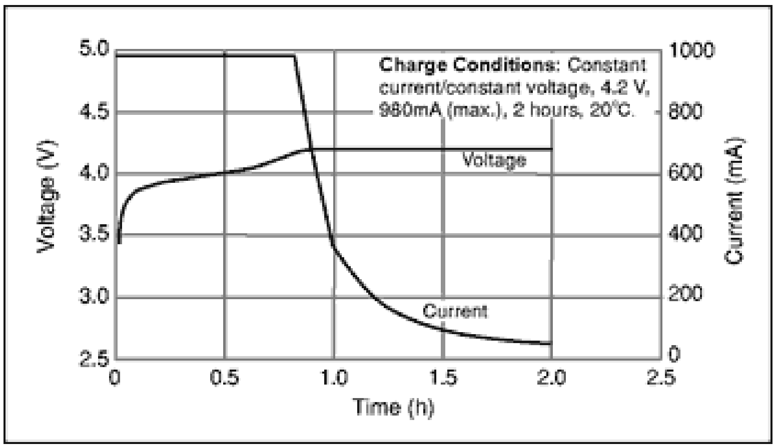


Figure 26: General Discharging (Top) and Charging (Bottom) Characteristics of Selected Battery Types [Matsushita Battery, 2003].

Also, rechargeable batteries are necessary for space application and help reduce maintenance time during ground testing. Other criteria used for comparison included: weight, volume, ease of use, charge cycles, environmental temperature range, and cost. Although theses characteristics are not essential criteria to the CubeSat design, they are extremely important and affect the CubeSat overall design. Typically, minimum battery weight and volume are desirable characteristics of a satellite. The ease of use refers to the complexity and difficulty in charging a particular battery chemistry. The charge cycles refers to how many times the battery can be recharged before a significant loss of memory. Typically, good batteries are costly, but extremely important to the performance of other subsystems. As a result, the CSDT is open to the idea of purchasing expensive batteries.

Research for batteries yielded three different battery types. The battery types are classified by their chemistry and include: Nickel-Metal Hydride (NiMH), Lithium Ion (Li Ion), and Lithium Polymer (Li Poly). The NiMH batteries have a positive electrode composed of nickel hydroxide, and a negative electrode made of a hydrogen-absorbing alloy. Both electrodes are exposed to an alkaline electrolyte. The metal casing is equipped with a safety valve to relieve excess pressure [Matsushita Battery, 2003]. Li Ion batteries have a negative electrode made of carbon and a positive electrode made of lithium cobalt oxide [Matsushita Battery, 2003]. Last of all, Li Poly batteries are the most technologically advanced and expensive. The difference between Lithium Ion and Lithium Polymer batteries lies in the electrolyte material. The polymer electrolyte of a Li Poly battery has a low intrinsic conductivity, which allows the cell to be very thin [Ultralife, 2002]. General specifications for NiMH, Li Ion, and Li Poly batteries are presented in Table 8.

Table 8: General Specifications for Various Rechargeable Battery Chemistries [Matsushita Battery, 2003], [Ultralife, 2002].

Criteria	Nickel Metal Hydride	Nickel Metal Hydride	Lithium Ion	Lithium Ion	Lithium Polymer
	Cylindrical	Prismatic	Cylindrical	Prismatic	Prismatic
Energy Density (mWh/g)	64	60	147	142	152
Charge Cycles	1000	1000	500	500	300
Difficulty of Charge	Easy	Easy	Difficult, due to safety concerns	Difficult, due to safety concerns	Difficult, due to safety concerns
Suseptible to Over Charge	No	No	Yes	Yes	Yes
Temperature Range (C)	0 to 45	0 to 45	-10 to 45	-10 to 45	-20 to 60
Cost per Cell ($)	$5	$8	$30	$30	$99

The battery configuration and the number of batteries are variable parameters, however, the best battery for the sole, series, and parallel design configurations where chosen by examining a multitude of characteristics, as seen in Table 9. The highlighted options indicate the preferred battery and configuration.

Table 9: The Best Options for Various Battery Configurations [Kokam, 2003], [Matsushita Battery, 2003], [Ultralife, 2002].

Part Number	Chemistry	Charge Current (mA)	Charge Time (min)	Configuration	Total Weight (g)	Total Volume (cm^3)	Total Capacity (mAh)	Total Voltage (V)
CGA633450A	Li Ion	980	120	Single Cell	24	10.8	1035	3.6
UBC433475	Li Poly	465	135	Single Cell	22.00	11.97	930	3.7
SLPB523462	Li Poly	980	70	Single Cell	20.50	11.58	1020	3.7
CGR17500	Li Ion	550	120	2 in Series	50.00	22.24	830	7.2
CGA523436	Li Ion	680	90	2 in Series	29.00	12.72	710	7.2
UBC383562	Li Poly	320	135	2 in Series	28.00	16.5	640	7.4
SLPB353452	Li Poly	540	70	2 in Series	24.00	13.2	560	7.4
HHR120AA	NiMH	1200	70	3 in Series	69	21.3	1150	3.6
HHF135T4	NiMH	1350	70	3 in Series	75.00	20.85	1350	3.6

Typically, a particular battery chemistry is required to be charged at a certain voltage, but the current can vary up to a certain limit. The higher the current the faster the battery(ies) will charge. If the voltage and current are known, then so is the power needed to supply the battery(ies). Like the converters, the power out is equal to the power in, but with some inefficiency. As a result, the charging current, efficiency, and input voltage are all important criteria. The power input comes from the previously discussed power generation element. In addition to the requirements and important criteria, battery charges were examined with respect to the number of batteries, monitoring options, and the environmental temperature range. Furthermore, the development of "home made" charges is often difficult due to chip size, equipment restrictions, and complexity. Accordingly, a prefabricated circuit board, seen in Figure 27, is advantageous for the battery charger because of the ease of installation. The only requirement of a prefabricated board, aside from those mentioned for the battery charger, is that it fit within the CubeSat structure.

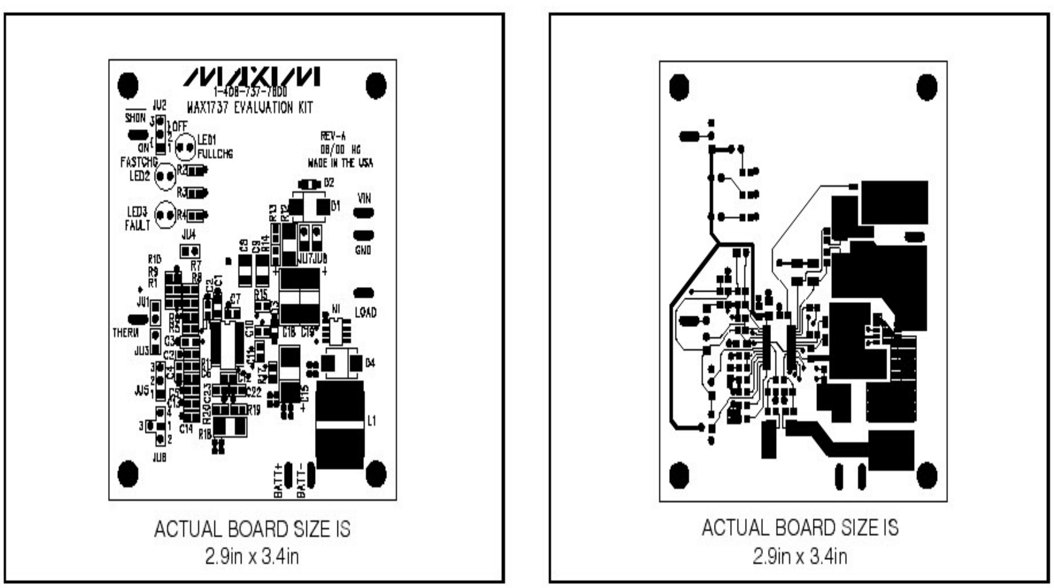


Figure 27: Prefabricated Battery Charger Circuit Board [Maxim, 2003].

The investigation of battery chargers has revealed a wealth of information at Maxim/Dallas Semiconductor Corporation. Other battery charger manufactures, such as Wes Tech, Kokam Engineering, Linear Technology, and Texas Instruments, also presented some competitive options. Ten different models of battery chargers were pre-selected as possible candidates for the final design. All ten models meet the aforementioned requirements for being able to charge one of the selected battery configurations. Furthermore, the chargers are stand-alone, which means the complicated charging logic does not need to be programmed into a microcontroller. Instead, the process is controlled by the chargers own microcontroller. The general specifications for each of the chargers are presented in Table 10.

Table 10: Specifications for Battery Charger Options [FMA Direct, 2003], [Maxim, 2003], [National Semiconductor, 2003], [Texas Instruments, 2003].

Part Number	Battery Type	Number of Batteries	Input Voltage (V) (note: min to max is given, but the min value increases with the number of cells)	Charging Current (Amps)	Temperature Range (Celsius)	Monitors Outputs	Cost ($)
LIPOCH102	Lithium Ion Li Poly	1	9 to 12	0.25	N/A	None	$30.00
LIPOCH202	Lithium Ion Li Poly	1 to 2	11 to 13.5	0.25	N/A	None	$30.00
Wes Tech	Lithium Ion Li Poly	1 to 3	11 to 26	Up to 1	N/A	None	$50.00
LM3621	Lithium Ion	1	3 to 5.5	Up to 1	0 to 70	N/A	N/A
BQ2057	Lithium Ion	1 or 2	4.5 to 15	Up to 1	-20 to 70	Temp and Current	N/A
MAX1737	Lithium Ion	1 to 4	6 to 28	Up to 4	-40 to 85	Voltage, Current, Temp,Time	$125.00
MAX1758	Lithium Ion	1 to 4	6 to 28	Up to 1.5	-40 to 85	Voltage, Current, Temp,Time	$125.00
MAX846A	Lithium Ion	1 to 2	6 or 10		0 to 70	Voltage and Current	
MAX712	NiMH	1 to 16	1.5V +(1.9V * # of cells)	Up to 4	-40 to 85	Temp, Time, and Voltage	$240.00
MAX1873	Lithium Ion Li Poly NMH	2 to 4 2 to 4 6 to10	9 to 28	Up to 4	-40 to 85	Voltage and Current	$60.00

Because of the variety of battery chemistries and configurations, four battery chargers have been selected: Wes Tech, LM3621, MAX1737, and BQ2005, MAX712. The exact charger is dependent on the battery chemistry and input voltage from the power generation element.

5.6 CubeSat Power Subsystem Design

Until now, the design process has concentrated on selecting components based on maximum power draw and generation. However, the most important requirement for the CubeSat power system, as a whole, is balancing the input energy with the output energy. The energy balance is crucial in the environment of space because the CubeSat has limited charging time per orbit, but will be continually using energy. The design theory is explained followed by a design option summary.

5.6.1 Design Theory

In order to support the load, the batteries must be able to produce the needed output energy for the period of one orbit. The output energy (to the power distribution element) is a function of power and operational percentage per orbit of each subsystem, the power distribution efficiency, and the orbital period.

$$E_{out} = \frac{T}{\eta_{pdc}} \sum_{i=1}^{n} P_i \beta_i \qquad (2)$$

where

T is the orbital period

η_{pdc} is the efficiency of the converter in the power distribution element

P_i is the power draw from a particular subsystem

β_i is the active operational percentage per orbit for a subsystem

The orbital period is calculated based on the altitude the CubeSat is above the Earth's surface. From Kepler's second law, the orbital period is

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{3}$$

where

a is the radius from the center Earth

μ is the gravitational constant for the Earth

The energy out of the battery depends on the capacity and voltage of the battery setup, and always needs to be greater than E_{out}.

$$E_{batt} = CV \tag{4}$$

where

C is the capacity of the battery

V is the voltage

By equating 2 and 3, the capacity of the battery setup is determined assuming the other variables are known. The number of batteries, wiring configuration, and capacity of each individual battery are adjusted to satisfy the power system design objectives while maintaining the necessary design specifications.

Furthermore, the output energy must be less than the input energy in order for the battery charger to resupply the batteries with the energy lost. In this circumstance, the energy is dependent on the orbital time in the sun and the power generated by the solar cells.

$$E_{in} = P_{pg}T\phi = [A_{sc}\eta_{sc}\alpha\psi]T\phi \quad (5)$$

where

P_{pg} is the power from the power generation element

ϕ is the percentage of the orbit period that CubeSat is in the sun

A_{sc} is the surface are that the solar cells cover

η_{sc} is the efficiency of the solar cells

α is the coefficient of average area for the CubeSat

ψ is the solar constant $= 0.1353 \, W/cm^2$

To summarize, the aforementioned relations and equations govern the design process of the power system. Failure to satisfy the conditions presented will result in a defective, inoperable power system.

5.6.2 Design Option Summary

The design options of the optimal power system are based on the overall design objectives, which are dependent on numerous design variables, component requirements, and criteria. There are two types of operational parameters, orbital trajectory and subsystem characteristics. The orbital trajectory has a direct effect on the amount of time the CubeSat is in the sun and, therefore, the amount of time the CubeSat can recharge its batteries. The orbital trajectory is dependent upon the organization that launches the CubeSat; therefore, the eccentricity and orbital altitude were assumed to be 0 (circular orbit) and 400 km, which resulted in a period of 92.56 minutes. The CSDT assumed that the CubeSat is in the sun 60% of its orbital time, or 55 min and 32 sec. The subsystem characteristics include items such as power requirements and active operational percentages for each subsystem. Table 11 presents all the operational parameters and their assumed values.

Table 11: Operational Parameters

Orbital Trajectory		
Altitude (km)	Period (min)	Time in Sun (min)
400.00	92.56	55.53

Subsystem	Voltage (V)	Current (A)		Power (W)		Operation (%)	Energy (Wh)	
	Continous	Active	Stand-by	Active	Stand-by	Active	Active	Stand-by
C&DH	5.000	0.001	0.000	0.003	0.001	100.000	0.005	0.000
Communications	5.000	0.150	0.050	0.750	0.250	50.000	0.578	0.193
Sensors	5.000	0.100	0.100	0.500	0.500	50.000	0.386	0.386
Experiments	3.600	0.278	0.000	1.000	0.000	10.000	0.154	0.000

Based upon the assumed operational parameters presented above, the CSDT has selected three promising power systems that balance energy, minimize weight and volume, and adhere to all component requirements. The final design options are presented from the cheapest to the most expensive.

Table 12: Option 1

Energy Capability of the Battery				
Component	Part Number	Voltage (V)	Capacity (Ah)	Energy (Wh)
Battery	HHR120AA	3.6	1.15	4.14

Energy Available to Charge the Batteries				
Component	Part Number	Efficiency (%)	Cell Coverage (cm^2)	Energy (Wh)
Solar Cells	Spectrolab	17.00	388.00	2.07
Converter	None	0.00	-------------------------------	2.07
Charger	BQ2005	90.00	-------------------------------	1.86

Energy Required By System Load			
Component	Part Number	Efficiency (%)	Energy (Wh)
Converter	LM2655	92.00	1.85

Table 13: Option 2

Energy Capability of the Battery				
Component	Part Number	Voltage (V)	Capacity (Ah)	Energy (Wh)
Battery	SLPB523462	3.7	1.02	3.774

Energy Available to Charge the Batteries				
Component	Part Number	Efficiency (%)	Cell Coverage (cm^2)	Energy (Wh)
Solar Cells	Spectrolab	18.00	388.00	2.19
Converter	None	0.00	-------------------------------	2.19
Charger	MAX1737	90.00	-------------------------------	1.97

Energy Required By System Load			
Component	Part Number	Efficiency (%)	Energy (Wh)
Converter	MAX1795	90.00	1.89

Table 14: Option 3

Energy Capability of the Battery				
Component	Part Number	Voltage (V)	Capacity (Ah)	Energy (Wh)
Battery	SLPB523462	3.7	1.02	3.774

Energy Available to Charge the Batteries				
Component	Part Number	Efficiency (%)	Cell Coverage (cm^2)	Energy (Wh)
Solar Cells	Spectrolab	20.00	388.00	2.43
Converter	MAX772	90.00	-------------------------------	2.19
Charger	Wes Tech	90.00	-------------------------------	1.97

Energy Required By System Load			
Component	Part Number	Efficiency (%)	Energy (Wh)
Converter	MAX1795	90.00	1.89

Please note that the best design option is not known; therefore, future CubeSat design teams should investigate and test each option to determine the optimal power/energy characteristics, minimum weight, and minimum volume. Details of future work on the power subsystem can be found in the management section of this report.

6.0 Structural Subsystem

The CubeSat Structural Subsystem is made of a lightweight material that provides adequate interfaces to each other subsystem to ensure safe passage through all phases of the mission. The ease of fabrication and assembly, light-weight, and free space for the payload sensors, circuitry, and batteries are the key features of the CubeSat structural subsystem design. The structural subsystem also has the ability to accommodate multiple payload sensors integrated in the subsystem in a simple manner.

This section begins with a discussion of the previous CanSat structural subsystem designs. Subsequent subsections will discuss the requirements and constraints for the new structural subsystem, followed by the options and evaluation of materials, and finally, the modifications to the current structural design. AutoCAD drawings of the structural components can be found in Appendix A.

6.1 Background

The previous CanSat (summer 2002) was a cylindrical-shaped structure, 12.3 centimeters tall and 6.6 centimeters in diameter, and weighed only 166 grams, as shown in Figure 28. The structure alone accounted for 50% of the total weight of the CanSat and was made from aluminum because of its light-weight and high tensile characteristics. The structure consisted of two sub-assemblies: a cover and a frame. When assembled with 3 mm stainless steel countersink bolts, the structure became a monocoque design that provided rigidity. The top plate had holes for parachute lines and an antenna. The parachute chords were attached directly to a bolt connected to the main frame. The circuit boards were mounted on the frame and the transceiver was placed between the walls of the frame. The frame of the structure provided extra protection for the expensive transceiver. The structural subsystem tests were conducted using various methods of vibration analyses, including static loading, and others. The final launch also proved that the CanSat design was able to withstand about 50 g's of load.

Figure 28: Previous Coke-Can size CanSat [Campbell and others, 2003].

The exterior of the CanSat design was strong; however, the interior setup lacked some planning. For example, incorrect temperature data was recorded because the temperature sensor was located next to an integrated microchip, see Figure 29. Furthermore, the location of the antenna (located on top of the CanSat, see Figure 30) created communication interruptions between the CanSat and the ground station. The communication interruptions occurred because the transceiver works on high frequencies that require line of sight communication. In addition, the off-center location of the center of gravity and improper setup of the parachute resulted in a continuous spin of the CanSat during the descent phase of the mission. The spinning of the CanSat also aggravated the communication interruptions. Next, since the structure was not properly sealed on all edges, an excessive amount of dust entered the CanSat when the parachute dragged the CanSat on the floor of the desert. The dust in return contaminated the circuit boards and the sensors. In addition, on the final project day, the parachute deployment rate was approximately 60%, according to the previous CanSat group; this resulted in a free fall of several CanSats, from different Universities, and caused their total destruction on the launch day. Furthermore, the CanSat did not have any external ports or peripherals; therefore, the previous group had to open the CanSat frequently to change the batteries and to upload and download data.

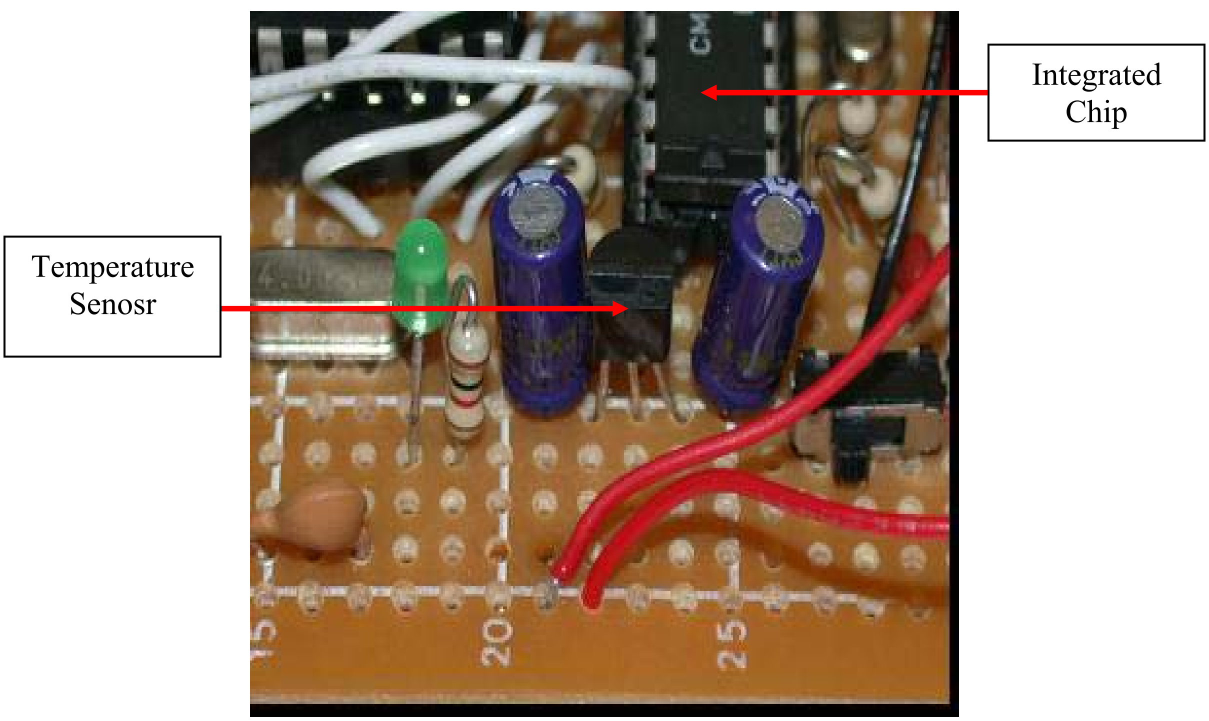


Figure 29: Location of Temperature Sensor Next to an Integrated Chip [Campbell and others, 2003].

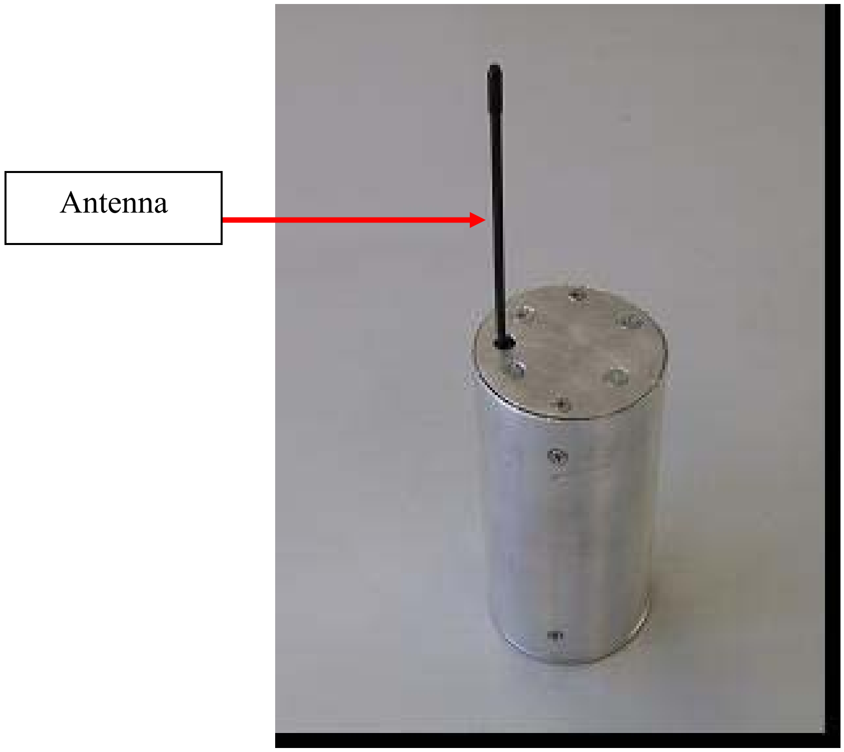


Figure 30: Location of Antenna on Previous CanSat [Campbell and others, 2003].

6.2 Requirements and Constraints

The objective of the structural subsystem for the CubeSat project is to provide a simple, sturdy structure that will survive launch loads, while providing an easily accessible data and power bus for debugging and assembly of components. Because of the size constraints of the CubeSat and small expense budget, this must be done with the philosophy of maximizing usable interior space, while minimizing the complexity and cost of the design. The design of the CubeSat conforms to the structural and launcher requirements set by the Stanford/Calpoly CubeSat program. The shape of CubeSat is essentially a cube, with outer dimensions of 10 x 10 x 10 cm, with 3.0 mm clearance above each face of the cube for mounting exterior components such as antenna, data link and power charger inlet port. The satellite must have four launch rails along four edges of the cube, allowing for easy ejection from the P-POD (Poly Picosatellite Orbital Deployer) launch tube, shown in Figure 31. To maintain spacing and prevent sticking with other CubeSats, standoff contacts or feet must exist at the ends of these rails; therefore the four rails are extruded by 5 mm on all ends. The center of mass of the CubeSat must be within ±2 cm of the geometric center. The maximum allowable mass of CubeSat is 1 kg, and it is desired that the structure be no more than approximately 30% of the total CubeSat mass, and should be able to withstand a minimum of 50 g's load [Wells, Stras, and Jeans, 2003]. The structural subsystem shall have an external power-off switch, such that when pressed should lie flush with the surface. The structure should be assembled with flat head metal screws and all sides should be sealed properly. The structure should also be able to pass harmonic and random vibration tests. There must be two holes, one on each diagonally opposite guide rail to connect the parachute chord. A hole will be carved on the lower surface to place the flexible antenna.

The suggested material for the main satellite structure is Aluminum 7075 or 6061, Stainless Steel, Titanium, Composites, and Honey Comb. If other materials are used they must have the equal or more value for thermal expansion and yield strength as the aluminum.

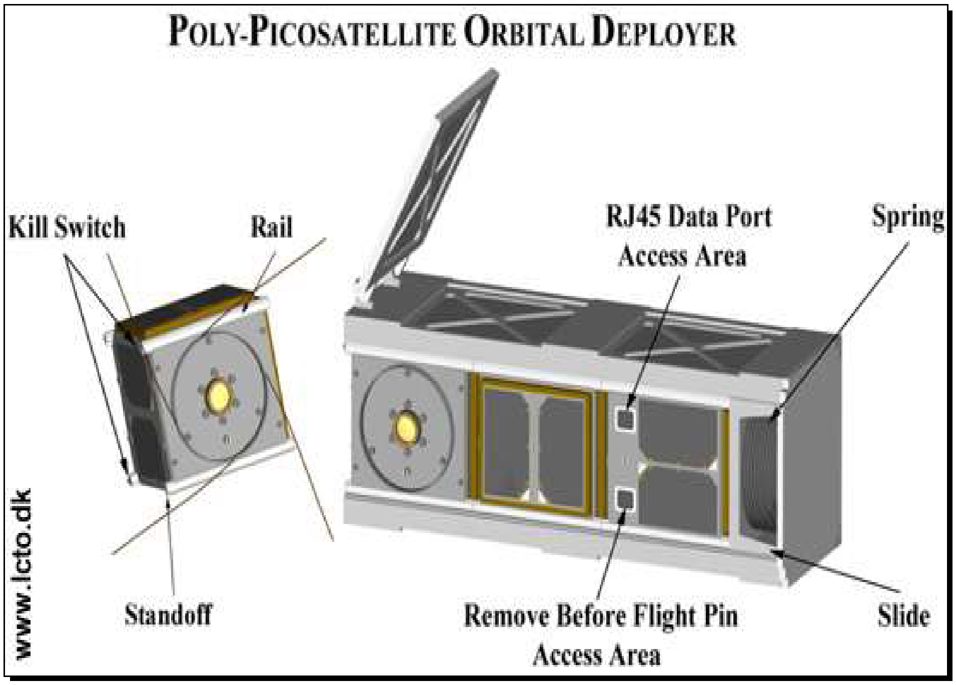


Figure 31: Poly-PicoSatellite Orbital Deployer [“About AAU CubeSat,” 2003].

6.3 Material Options and Evaluation

As suggested in the previous subsection, several materials were considered before selecting the final material. The criteria for selection were based on characteristics listed below:

- Strength
- Weight
- Machinability
- Cost

Table 15 lists several materials along with their strength, density, and cost for a 12 x 12 inch sheet. Some of the cost data is not available for 12 x 12 inch sheets, but the common knowledge available to an engineer relates that these materials would not meet the needs of our system.

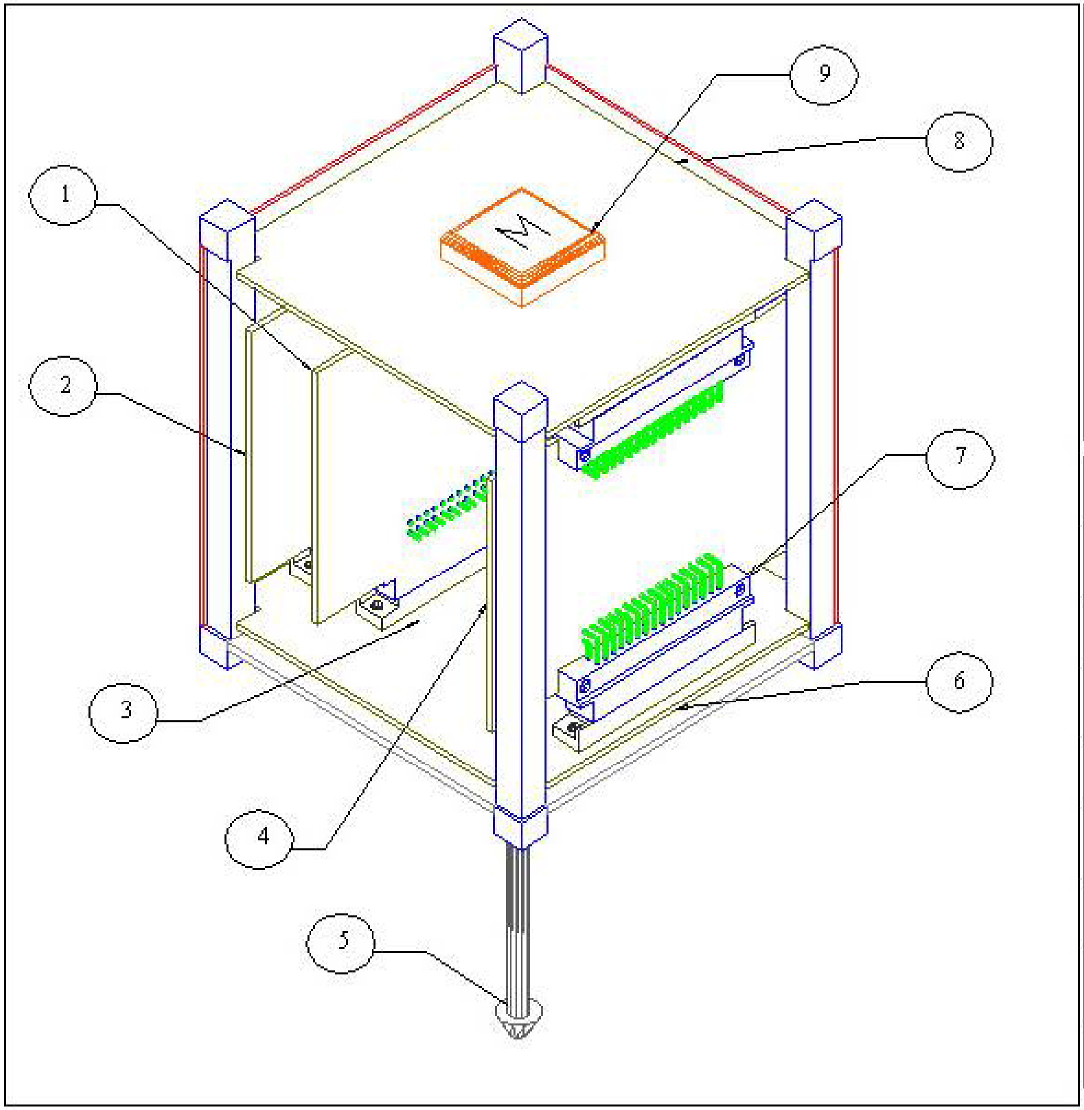
Table 15: Selected Material properties and cost data.

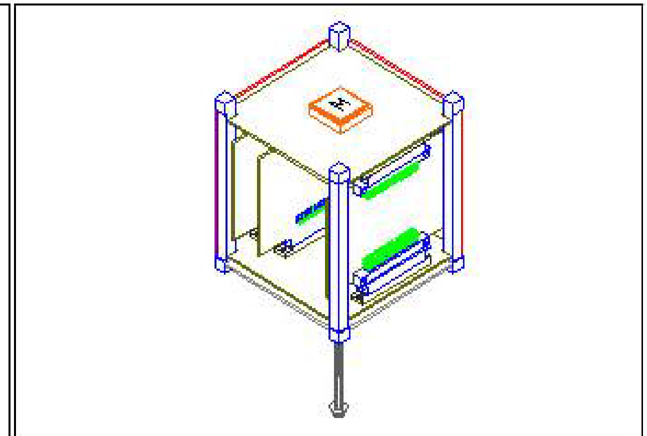
Material	Yield Strength	Density	Machinability	Cost/ft^2
Stainless Steel	790 MPa	7760 kg/m^3	Easy	$6.52
Titanium	900 MPa	4429 kg/m^3	Hard	NA
AL-6061-T6	320 MPa	2850 kg/m^3	Easy	$3.80
AL-7075-T6	340 MPa	2796 kg/m^3	Easy	NA
Composites	640 MPa	~1000 kg/m^3	Hard	NA
Inconel	848 MPa	8321 kg/m^3	Hard	$96.25

The above table clearly indicates that AL-6061-T6 meets the required criteria of high strength, light-weight, easy machinability, and cost; therefore, Aluminum 6061 was chosen as the structural material for the CubeSat.

6.4 Structure Bus Design: Exterior, Interior, and Assembly

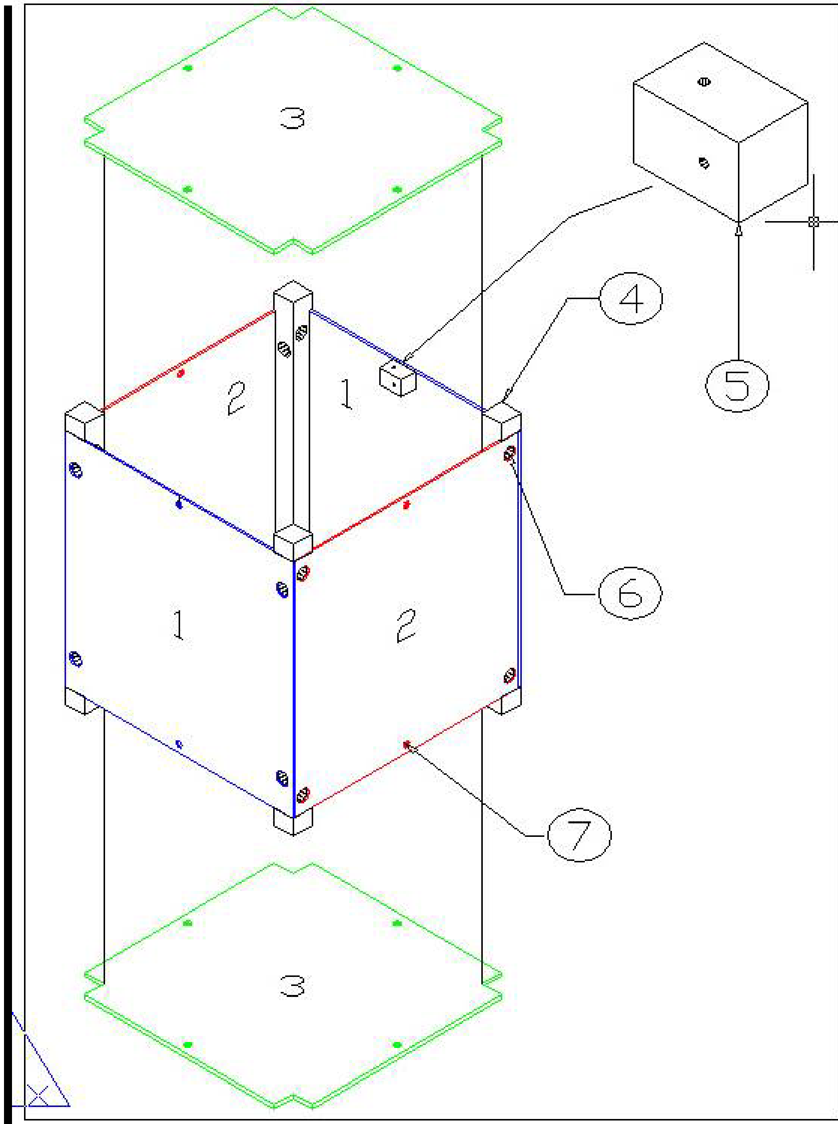
Access to the electrical components is an important design consideration. During the development and testing phase of the CubeSat, the circuit boards and the transceiver will be removed and replaced with great frequency. Easy access to these components will save a significant amount of time over the entire development and launch phase. In short, it is necessary to have a structure that is light, strong, versatile, and easy to disassemble [Campbell and others, 2002].

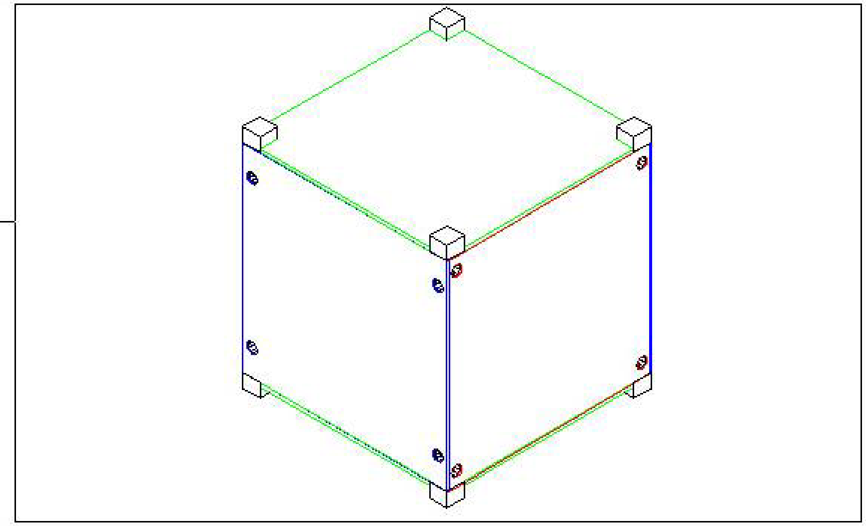




1	Additional Payload Board
2	Sensor Payload Circuit Board
3	Space for Batteries
4	GPS and Communication Subsystem Board
5	Communication Antenna
6	Power Subsystem Board
7	DIN Connector
8	Command & Data Handling Subsystem
9	GPS Antenna

Figure 32: Layout of CubeSat: Internal and External.





1	2 SIDE PANELS - 100 x 96 x 1 mm
2	2 SIDE PANELS - 98 x 96 x 1 mm
3	2 TOP & BOTTOM PANELS - 100 x 100 x 2 mm
4	4 GUIDE RAILS - 8.5 x 8.5 x 110 mm
5	8 DELRIN BOSS - 9.5 x 6.4 x 6.4 mm
6	16 X 2-56 THREADED THRU HOLES
7	16 X Ø 0.84" THRU HOLES

Figure 33: External Layout of CubeSat.

6.4.1 Exterior Structure

The CubeSat structure was designed using AutoCAD Power Pack software to ensure that all components fit together without interference, and to aid in the finite element analysis. The detail drawing of CubeSat's component made in AutoCAD can be seen in Appendix A.

The exterior structure of CubeSat consists of six aluminum (AL-6061-T6) walls connected together using stainless aluminum screws and 8 Delrin bosses. The orientation of the body axes is such that the Z axis is perpendicular to the top and bottom panel (panel 3 in Figure 33) of the CubeSat and the other two sides (panels 1 and 2 in Figure 33) are perpendicular to the X and Y axis, respectively. From this reference frame, the structural walls are named the ±1, ±2, ±3, accordingly. The ±3 aluminum walls have 2 mm thickness, while all other walls are 1 mm thick. The launch rails are incorporated in between the ±1 and ±2 walls, and are oriented parallel to the Z-axis. Attached to ±3 structural walls are circuit boards and solar panels. Panels number ±3 and + 2 will require rectangular cutouts to accommodate the GPS antenna (top panel), electronic data port (side panel) and a battery charger port (bottom). One circular cut out is required on the -3 wall for the communication antenna.

A finite element analysis of the bottom panel was done to ensure that the CubeSat will not experience unacceptable stresses or displacements during the launch which could create up to 50 g's load. The results given by the AutoCAD Power Pack FEM package are shown in (Figure 34). Figure 34 below clearly indicates that the maximum stress is at the point where the Delrin Boss and the base panel are connected and is 8.89 psi (less then yield strength of AL 6061-T6 (see Table 15). In addition Figure

35, which shows the results of the finite element analysis run on the bottom panel, indicates the maximum deflection that results because of the applied load (also shown in Figure 35) is 0.00016 in. at the periphery and 0.001245 in. at the center (also not a major deflection). Therefore, the preliminary run of the Finite Element Analysis method indicates that the designed CubeSat can withstand the 50 g's load. A more complete finite element analysis should be performed over the entire structure, but it requires a lot of computer memory.

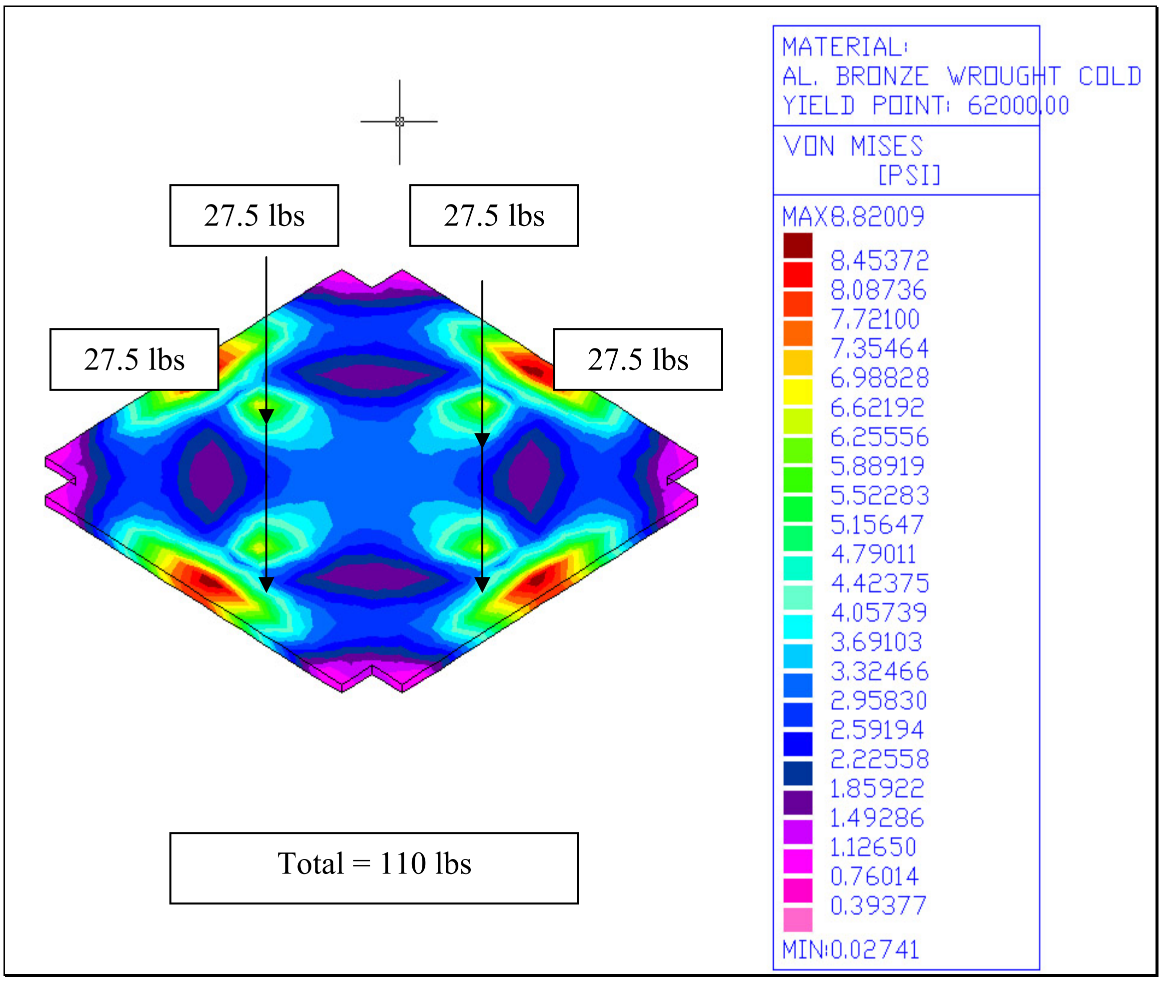


Figure34: Finite Element Analysis on the CubeSat's Bottom Panel for stress Analysis (AutoCAD Power Pack Software).

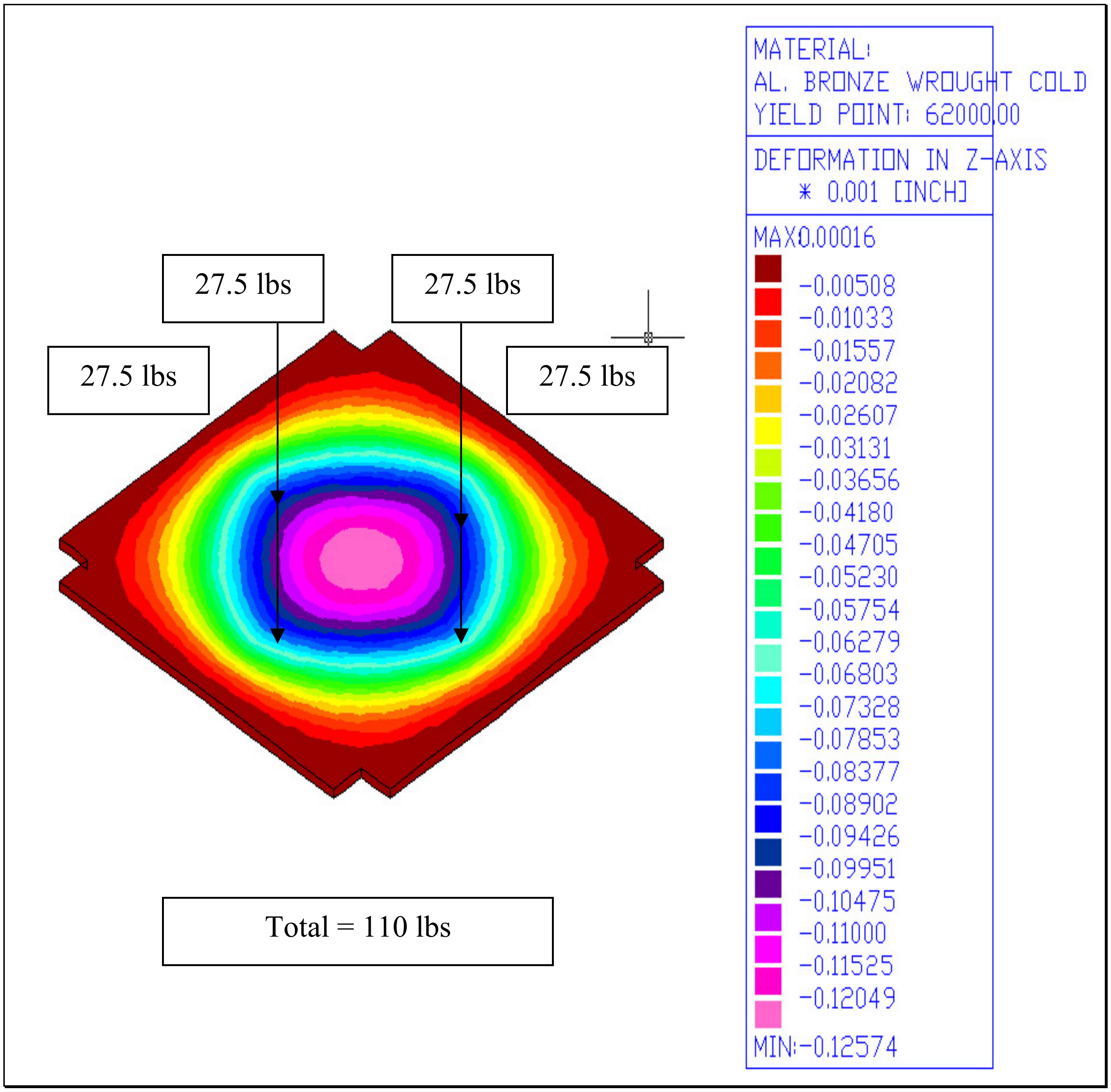


Figure 35: Finite Element Analysis on the CubeSat's Bottom Panel for Deformation Analysis (AutoCAD Power Pack Software).

6.4.2 Interior Structure

The interior structure of the CubeSat will consist of five circuit boards. Since the CD&H and the power subsystems are shared by all other subsystems, they are allocated Circuit Boards 8 and 6, respectively, as can be seen in Figure 32. The communication subsystem and GPS module are allotted Circuit Board 2, while Circuit Board 4 is reserved for payload sensors subsystem. The empty space represented as 3 in Figure 32 is allocated for batteries. The boards are spaced such that components do not interfere with each other, while the CubeSat mass center remains within its constrained range. The boards will be held in place using four columns of nylon spacers, see Figure 36. These columns will also act as structural supports along the Z-axis. The dimensions of the circuit boards can be found in Appendix A. The total mass of the interior and exterior structure is estimated to be 950 grams or 95 % plus 5 % for any unexpected weight during construction. Therefore, the total weight of the CubeSat is less then 1 kg, see Figure 37. In addition, Table 16 indicates the approximate space allotted to various subsystems [Wells, Stras, and Jeans, 2003].

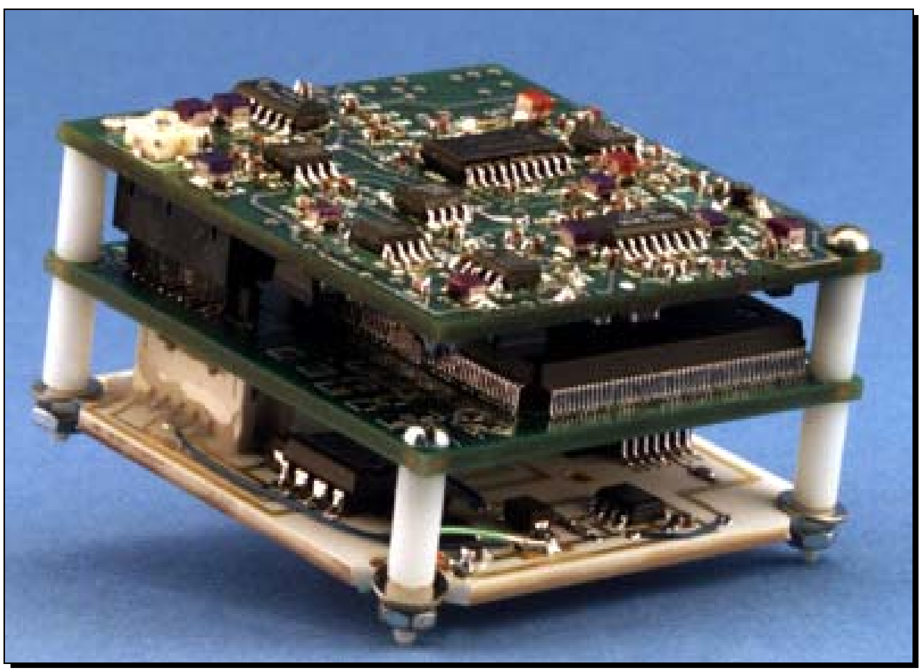


Figure 36: A sample of circuit boards connected with Plastic Spacers (the size is about 4 x 4 inches for each board; five boards will be connected in a similar manner) ["Tactical Systems," 2003].

6.4.3 Assembly

From the structural design, the satellite will be built from the inside out. This means that the interior electronics will be populated and assembled first using rubber washers and nylon spacers. The rubber washers will dampen the noise and vibrations during all phases of the CubeSat flight. All of the internal components will be fastened to the structure as a single package using rubber washers and fasteners. Next the +3 aluminum wall will be attached, followed by the ±1 walls, columns, and the -3 wall. Attaching the ±2 walls will complete the assembly. For debugging, the interior circuit boards can be removed easily by removing the screws on –3 and removing the +3 aluminum wall.

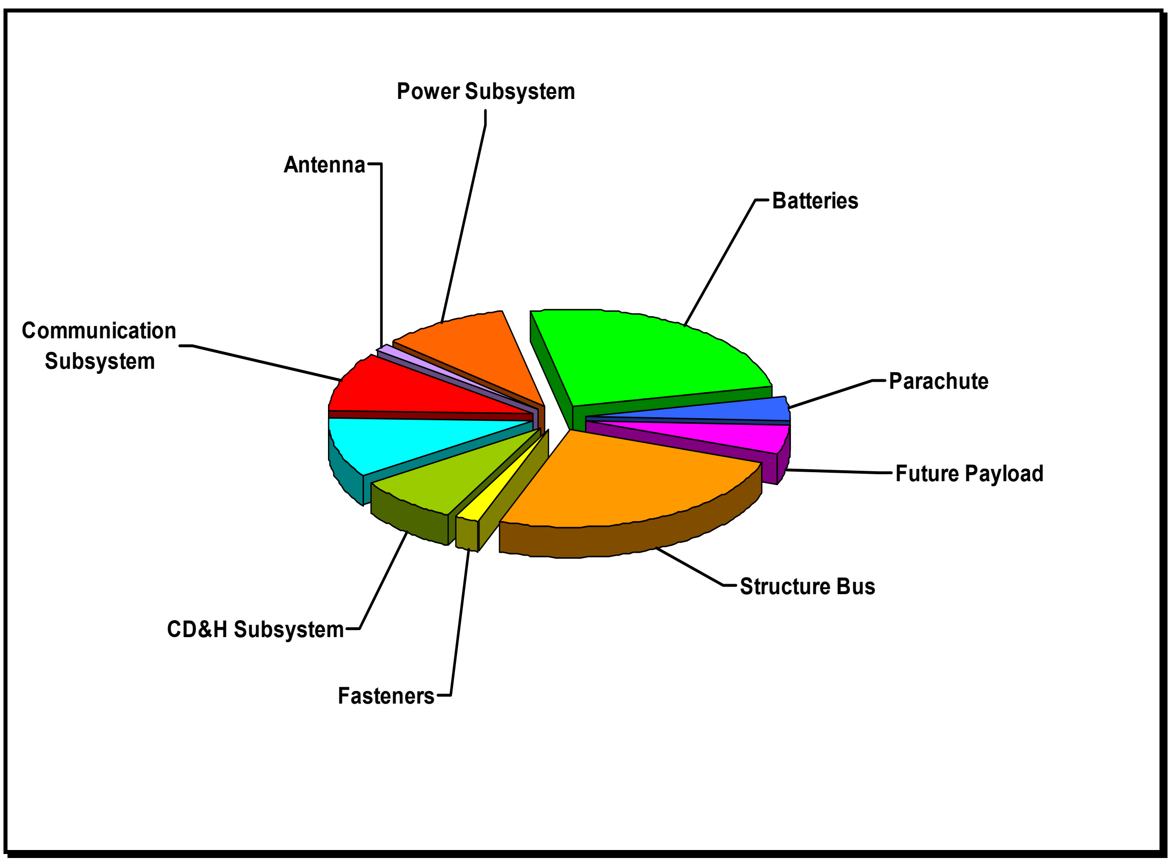


Figure 37: Estimated Weight Distribution for CubeSat (Total weight = 1 kg).

Table 16: Approximate Space Allotment for various components of the CubeSat.

Components and Subsystems	Space Allotted, Width (mm)
Command and Data Handling Subsystem	17.0
Payload Sensors	18.0
Communication Subsystem	5.0
Power Subsystem	17.0
Batteries	35.0
GPS Module	5.0
Margin	3.0
Total	100.0

7.0 Management

Before beginning the initial design phase, the Satellite Solutions team divided the project tasks among the members, and a preliminary schedule was developed as an outline for the course of the semester. A budgetary analysis was also performed to ensure a successful project as detailed in the following section.

7.1 Personnel

The Satellite Solutions team is comprised of three members, organized as shown in Figure 38.

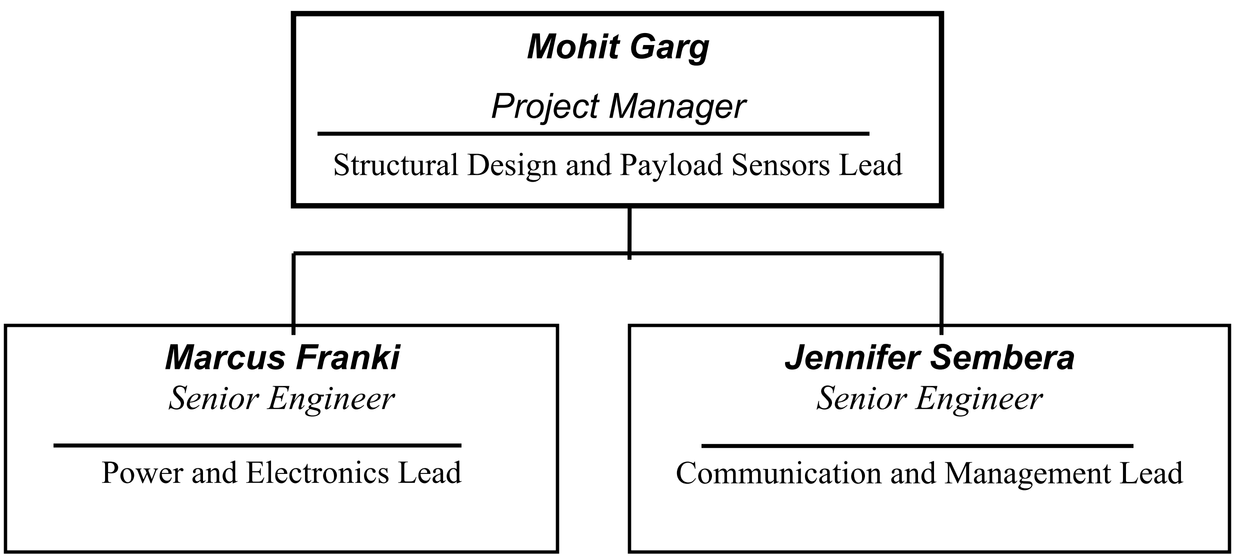


Figure 38: Team organization chart.

Specific areas of the project scope were designated for each team member but duties, information, and responsibilities were shared between everyone. Weekly team meetings were held on Thursdays from 2:30 to 3:30 pm in the Satellite Design Lab in W.R. Woolrich Laboratories, Room 407. At each meeting, group members discussed the progress of the CubeSat project and any problems or setbacks with team advisors: Dr. Takuji Ebinuma, Shaun Stewart, and Thomas Campbell.

7.2 Project Schedule

As shown in Figure 39 the Satellite Solutions team drafted a timeline of the project schedule in PERT form, broken down into nodes that indicate milestones along the path. The blue numbers indicate the number of weeks dedicated to that particular task.

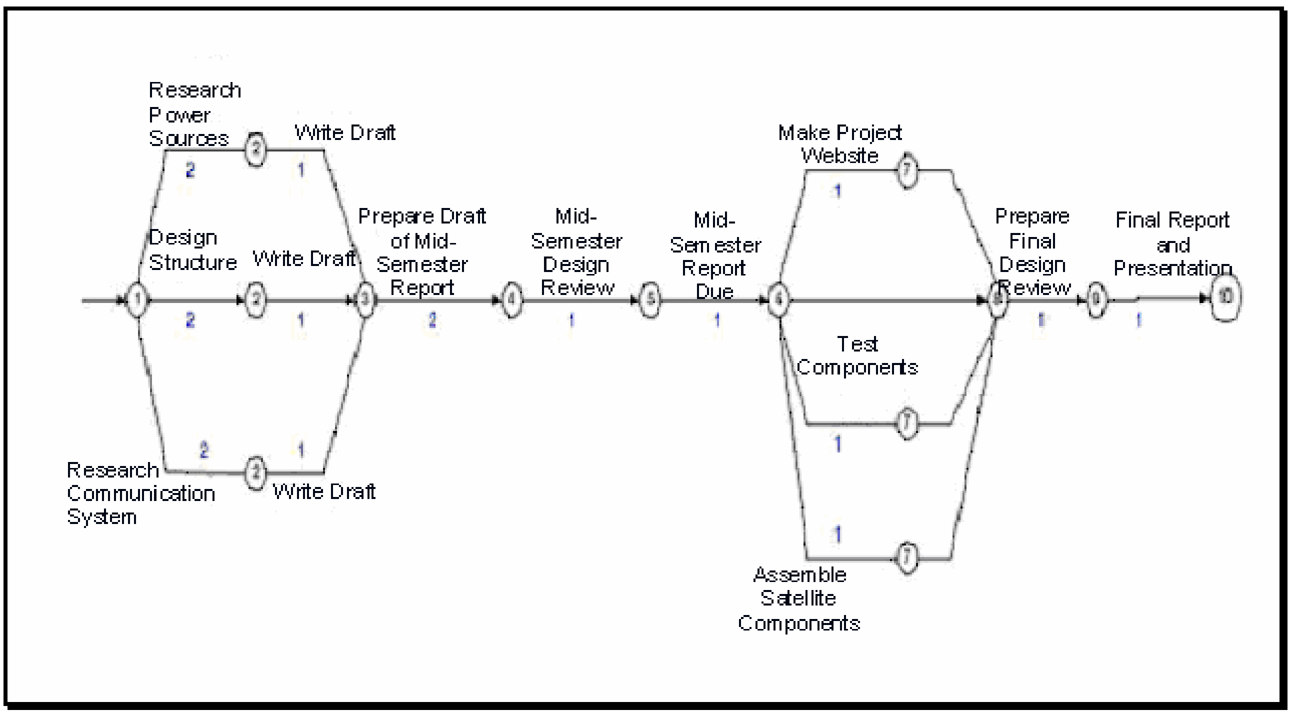


Figure 39: Network Diagram of Project Schedule (PERT).

A more detailed illustration of the required class tasks and team goals are shown in Gantt chart form in Figure 40.

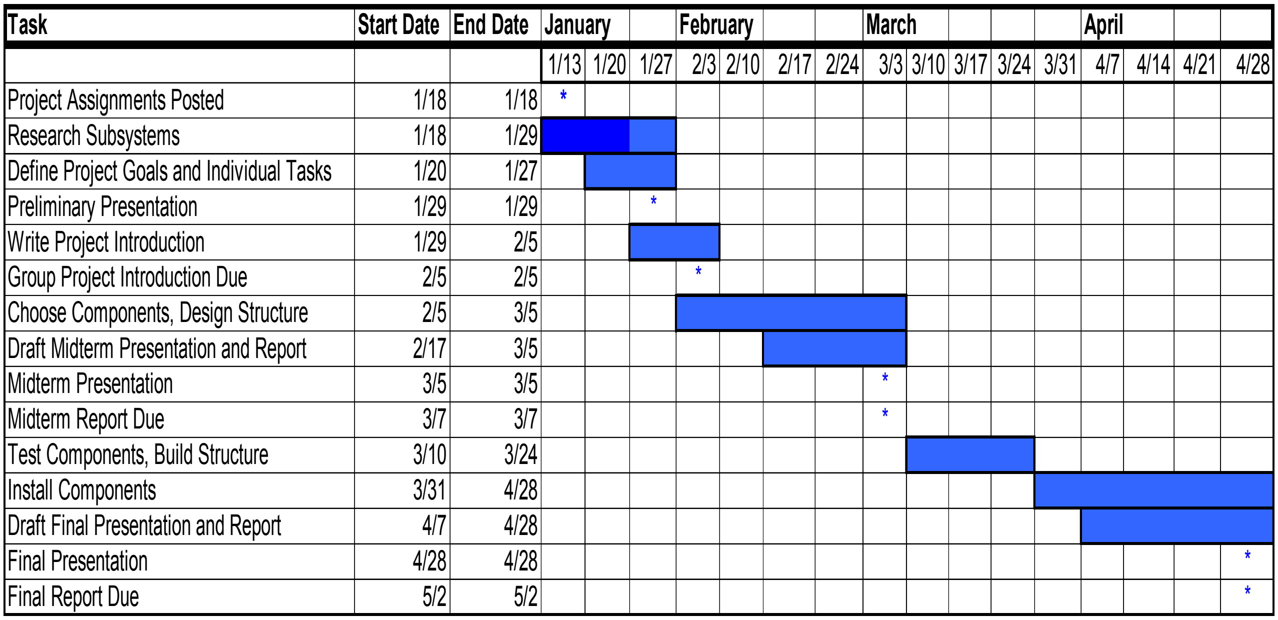


Figure 40: Gantt Chart of Project Schedule.

7.3 List of Deliverables

In accordance with the class requirements, the Satellite Solutions team will present the necessary deliverables to Dr. Ronald O. Stearman as outlined in Table 17.

Table 17: List of deliverables.

Deliverables	Date	Status
Group Introdution	January 29, 2003	Complete
Mid-Semester Design Review (Oral Presentation)	March 5, 2003	Complete
Mid-Semester Design Report	March 7, 2003	Complete
Final Design Review (Oral Presentation)	April 30, 2003	Complete
Final Design Report	May 5, 2003	Complete
Project Website	May 10, 2003	Complete
Project CD ROM	May 10, 2003	Complete

7.4 Material and Hardware Cost

The CubeSat project has a total material and hardware budget of $2000.00. Estimated material and hardware costs for the known components are collected in Table 18 and are depicted in Figure 41.

Table 18: Material and Hardware Cost.

Equipment	**Cost**
Structure	$30.00
Microcontroller	$6.82
Programming Board	$30.00
GPS Payload	$100.00
Communication (XStream 900 MHz transceiver)	$321.75
Antenna	$10.00
Batteries	$100.00
Battery Charger	$125.00
Voltage Converter	$60.00
Solar Cells	$1,100.00
TOTAL	**$1,948.57**

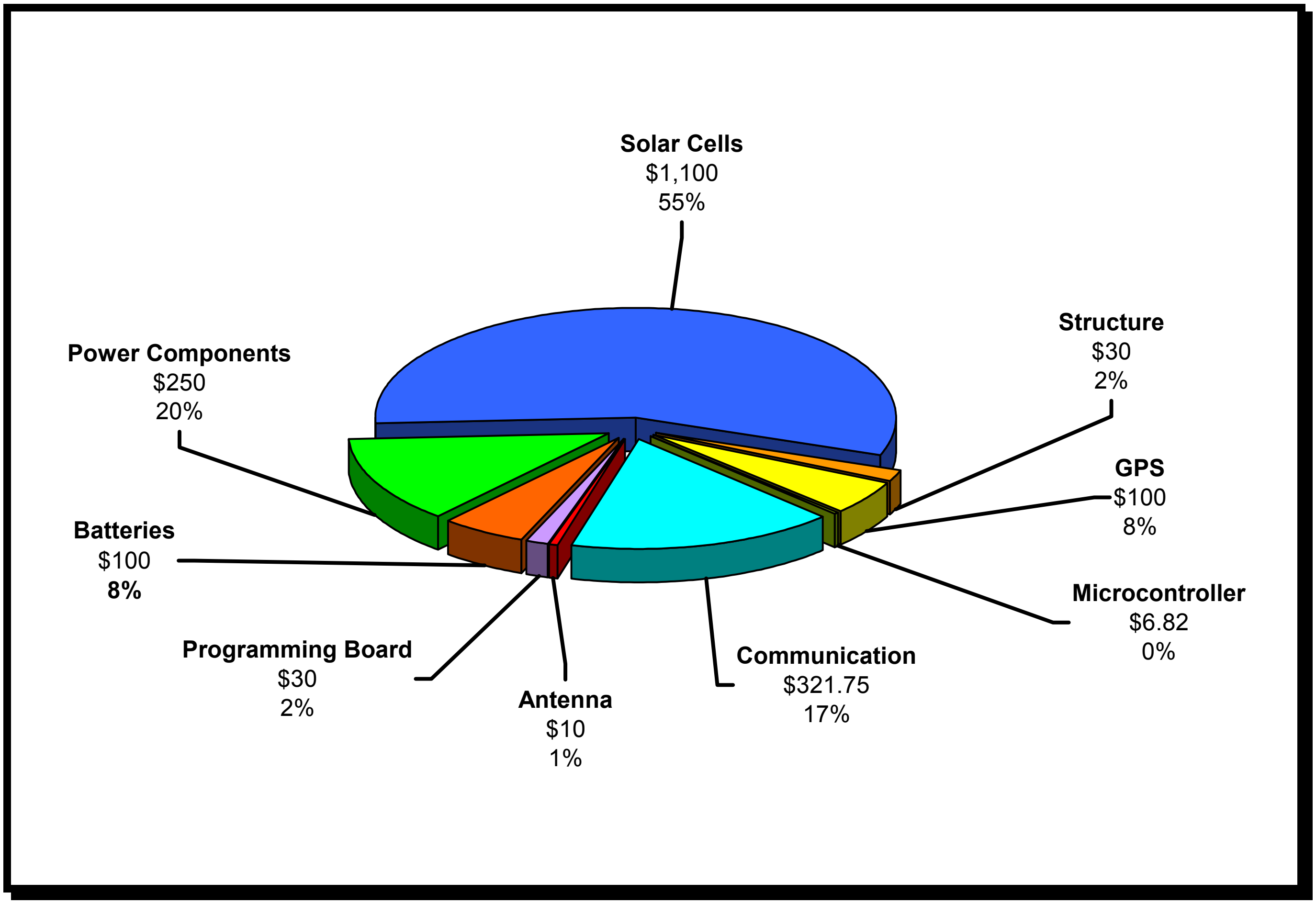


Figure 41: Breakdown of Equipment Costs.

The total estimated cost of equipment and materials, not including the solar cells is approximately $848.57. However, the Satellite Solutions team has allotted the remainder of the budget to purchase solar cells ($1,100). Dr. Lightsey has also allowed an extra $1,000 for travel costs to the launch in August.

7.5 Future Work

The Satellite Solutions team has made a decent progress in laying the ground work for several CubeSat subsystems. All the required components for the CD&H subsystems are currently available to us and need to be put together on a circuit board. The software for programming the microcontroller has glitches in it and needs debugging according to ATmega163 microcontroller. Next, all the sensors required for building the Payload Sensors subsystem are also available to us and again need to be assembled on the allotted circuit board. Currently, the Power subsystem has three options available to us and all the required components for these options have been ordered. The future work requires assembling all the power circuitry and evaluating the best performing one for the CubeSat. The two communication devices from MaxStream Incorporation have been obtained and preliminary tests of their communication ability were conducted. However, more extensive testing once the OEM is implemented into the CubeSat circuitry is needed. Range tests with the Yagi-Uda antenna must also be performed to ensure a communication link between the CubeSat and the ground station after the launch. Finally, the remaining materials to construct the pigtail connector for the Yagi antenna must be obtained, and fabrication of the antenna must be completed. Lastly, the Structural subsystem is ready and needs vibration tests under Dr. R.O. Stearman's and Teaching Assistant Marcus Kruger's supervision. A preliminary Finite Element Analysis on the bottom panel of the CubeSat has been performed and indicates that the CubeSat is able to withstand 50 g's loading during a rocket launch. Although, a Finite Element Analysis run for the whole CubeSat structure is suggested for determining the loads and stresses CubeSat will be able to take closer to the real situation.

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