2006-1989: BILLIKENSAT 1 – SAINT LOUIS UNIVERSITY'S FIRST CUBESAT DESIGN

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Abstract:

Billikensat 1 is the first multi-disciplinary **Senior Capstone** Spacecraft Design project at Parks College of Engineering, Aviation and Technology involving Aerospace, Electrical and Computer Engineering undergraduate students. This project was initiated as a part of Senior Capstone Design course in August 2005. The fundamental purpose for the BillikenSat project is twofold. First, it will provide the participating undergraduate students with practical experience in the design and construction / integration of a real space mission. Second, it will reinforce interest and support for space mission designs within the Aerospace Engineering program, Parks College, and the broader Saint Louis University community. It also has the potential for outreach program at the K-12 level. This paper gives an overall view of the current status of design and implementation process of various spacecraft subsystems. This paper also discusses the multidisciplinary nature of the project, its relevance to ABET criteria, and the integration of undergraduate research opportunities.

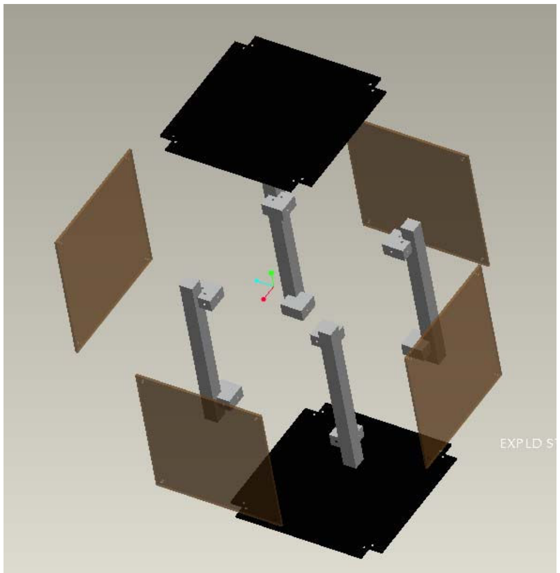
Introduction:

Small satellites can accomplish many missions and functions that their larger counterparts achieve, but at a fraction of the cost and design time, making them excellent for students involved satellite designs, remote sensing, quick-response science missions, novel communication networks, component evaluation, and technology demonstrations. Small Satellite Design offers excellent opportunities for undergraduate students to learn as a motivating example, the process of interdisciplinary system design and integration, which are closely related to the industry practices. In order to comply with the limited time frame of a study curriculum, California Polytechnic State University (CalPoly) has initiated and developed a program named "CubeSat" to meet the needs of a satellite design in the two-semester sequence for Senior Design course curriculum. While the CubeSat program levies certain design constraints on the satellite, it provides realistically priced launch services specifically intended for University customers, and is the only option that works with the senior capstone design timeline.

Therefore, to maximize support for space and student learning, this project intends to design, build, and launch a satellite under the guidelines of the California Polytechnic State University (CalPoly) CubeSat Program. The primary mission objective of this small satellite will be to:

- Conduct remote observations of the Earth, including – but not necessarily limited to – visual wavelength images.
- A possible secondary objective could consist of on-orbit demonstration of sponsored micro-satellite technology.

Senior students from Electrical Engineering department are designing, fabricating, and testing the necessary electronic subsystems of the satellite. Senior students in Aerospace Engineering department are simulating thermal conditions the BillikenSat1 will experience, as well as analyzing and testing structural components, and Senior Computer Engineering students are designing and developing the software required for smooth functioning of the BillikenSat1 in orbit.



(Exploded View)

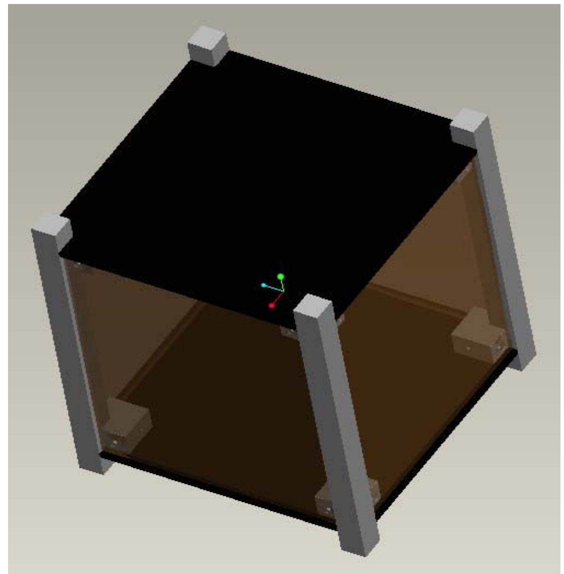


Figure 1: External Structure of the BillikenSat 1. It is made of Aluminum 6061 and weighs 254 grams

Through this **interdisciplinary** senior capstone design program, it is our intention to provide undergraduate students with the benefit of experiencing real-life issues– such as designing a system to meet realistic constraints such as **economic, manufacturability, sustainability** and **professional** and **ethical** responsibilities, as well as **teamwork** and **communication** skills.

SATELLITE BUS

The satellite bus is made up of all the necessary subsystems that are essential for normal operation of the satellite and completing its intended mission successfully. These subsystems include

- The Attitude Determination and Control System (ADCS)
- The Power Distribution System
- The Telemetry and Communications System
- The Structural Design and Analysis System
- The Command and Data Handling System, and
- The Camera Payload System

Many of the mentioned subsystems have made remarkable progress through the last six months. In the next sections, the paper discusses the current progress level of these subsystems. It should be noted that some of the subsystem design and analysis have progressed and matured much faster than other subsystems. It should also be noted that all the subsystems were designed based on the CubeSat design constraints and BillikenSat 1's mission constraints. All the subsystems went through rigorous design process (namely systems requirement, conceptual design, detailed design and final design). This paper gives the description of these subsystems at the Final Design Phase.

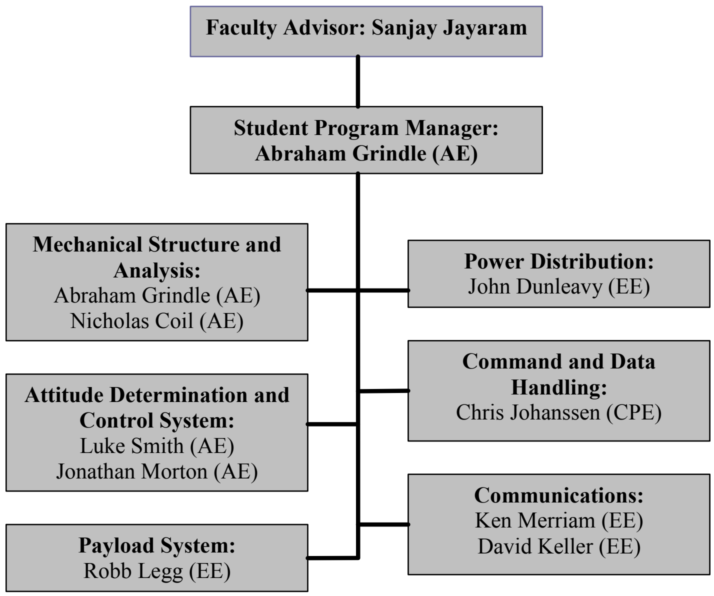


Figure (2): BillikenSat 1 Subsystem Teams and Team Participants

The Structural Design and Analysis System:

This subsystem team is responsible for the design and fabrication for all of the support structures for the on-board components, thermal analysis, thermal stress, and dynamic modeling of the satellite.

The most important responsibility of this team is to ensure that space-suitable materials are used for overall structure as well as the attachment of components in the BillikenSat 1. Part of this task requires a thermal stress analysis to determine whether temperature changes in space cause stress problems as a result of mismatched thermal expansion coefficients. Modal, harmonic, and transient finite element analyses are performed to determine the BillikenSat 1's natural frequencies, and whether the satellite and its components can safely survive the launch environment. Modal and transient experiments in three principal axes of the BillikenSat 1 are performed to simulate the launch environment, and the results compared with the finite element analysis computer simulations.

The thermal modeling effort includes the development of a computer code written specifically to simulate heat transfer in the BillikenSat 1. Some of the initial structural analysis results are shown in the figures below:

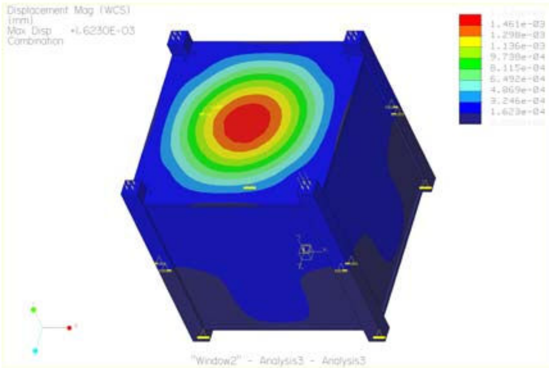


Figure (3): Top View – Actual displacement due to combined pressure and G loads

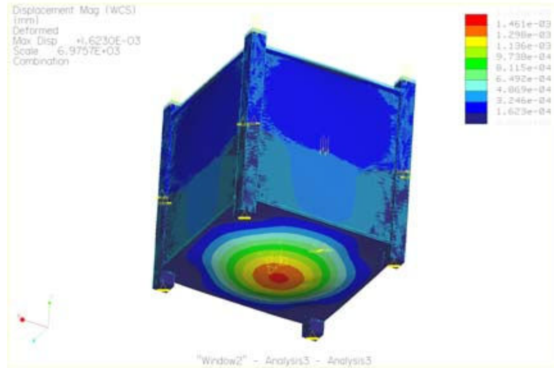


Figure (4): Bottom View – Actual displacement due to combined pressure and G loads

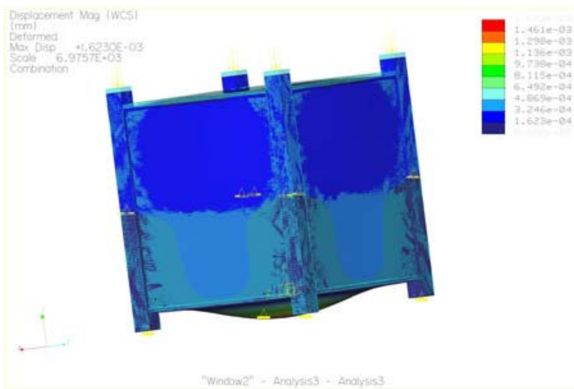


Figure (5): Side View – Actual displacement due to combined pressure and G loads

The Attitude Determination and Control System:

The primary objective of the Attitude Determination & Control System (ADCS) is to sense and determine where the satellite is and where it wants to be. For the purposes of BillikenSat 1, this will mean measuring the orbital parameters and applying corrective maneuvers as necessary. To coordinate all the actions of this system, a PIC Microcontroller will be used. This microcontroller will allow a more robust system, and it helps alleviate the large ADCS demand that would've otherwise been placed on the central processing unit. This system is divided into two subsystems: Attitude Determination and Attitude Control. The Attitude Determination system will return a wide range of gatherable data, including orbital parameters, magnetic field vectors, and angular rotation rates. The Attitude Control system will apply corrective maneuvers (through the use of Magnetic Torquer Coils) when determined to be necessary by the ADCS PIC. Passive control stabilization is also provided to the satellite through a gravity-gradient boom.

The attitude determination system will consist of a wide variety of components. Each component senses a different component of the spacecraft's attitude. The determination system is broken down into four main subsystems: magnetometers, gyroscopes, accelerometers, and sun sensors.

The magnetometers will be used to determine the earth's local magnetic field vector magnitude and direction. When compared with known values for the Earth's magnetic field, the spacecraft's attitude can be determined. The data provided by the magnetometers will also be used to calculate the direction and magnitude of the magnetic field that the spacecraft's torque coils must generate in order to actively stabilize the satellite. Honeywell HMC2003 3-axis magnetometer will be used due to its low mass, low power requirements, and the fact that it is a space-grade component. This sensor will generate an analog output that will be sent to the ADCS microcontroller.

Figure (6): HMC2003 Honeywell Three Axis Magnetometer

Gyroscopes will the measure the rotational rates of the spacecraft. Gyroscopes are inertial sensors that can provide attitude information without an absolute. The system we are planning on implementing will call for three single axis gyroscope sensors allowing us to measure angular accelerations on all three axes. This will determine the angular accelerations of the satellite in a body fixed reference frame. These rotational rates will be used by the ADCS microcontroller to determine the necessary torque that the torque coils need to apply in order to stabilize the system. With a mass of approximately half of a gram and a power requirement of no more than 50mW each, the Analog Devices ADXRS300 1-axis gyroscopes are ideal for the satellite. In order to deduce the rotational rates on all three axes, three of these gyroscopes will be employed. Each of these gyroscopes will have an analog output to the ADCS microcontroller. According to the manufacturer, the gyroscopes have an operational temperature range of -40 to 85 degrees Celsius.

As previously mentioned, gyroscopes will provide the rotational rates about each axis. Additional sensors will be needed in order to measure the translational rates of each axis. Accelerometers will allow for a complete understanding of the satellite's attitude in the body fixed reference frame. The accelerometers will monitor the deceleration as its orbit degrades during the mission. This can be used to determine a more precise mission life and reentry time after launch. Weighing less than a gram each, the ADXL213 2-axis accelerometers will be used.

The attitude control system will consist of both passive control system, by means of a gravity gradient boom and active control system, by means of magnet torquer coils (3 nos.). Gravity-gradient control utilizes the satellites inertial properties of the satellite to stabilize the satellite with respect to the Earth. Satellites that use this method of control are usually symmetric about the nadir vector, have near Earth orbits, minimal yaw orientation requirements, and often employ deployable booms to set up the necessary inertias. The primary disadvantage is that the system must be augmented to ensure attitude capture. This is due to the fact that the satellite is equally stable about the axis with the minimum moment of inertia. Torque coils operate by running a current through a coiled wire of specified dimension and a specified number of turns. That current creates a magnetic field, which interacts with the Earth's magnetic field and turns the satellite accordingly.

The Power Distribution System:

The Power Distribution subsystem team provides the power for the BillikneSat 1's electronic components. Power is generated with 25% efficiency gallium arsenide solar cells, manufactured by Spectrolab, Inc. Two solar cells, measuring 6.9 cm by 4.0 cm, are mounted on each side of the BillikenSat 1. With two cells to a side, it was calculated that one side exposed to sunlight would generate 2.6 W-hrs/orbit. The solar cells charge Ultralife lithium-ion batteries, rated at 1.8 Ampere hours (Ah). The batteries are used during the eclipse periods of the satellite orbit (when the satellite passes over the dark side of the Earth), or when the power demand exceeds the output of the solar cells.

(Spectrolab Triple Junction Solar Cell)

(Ultralife Lithium Ion Battery)

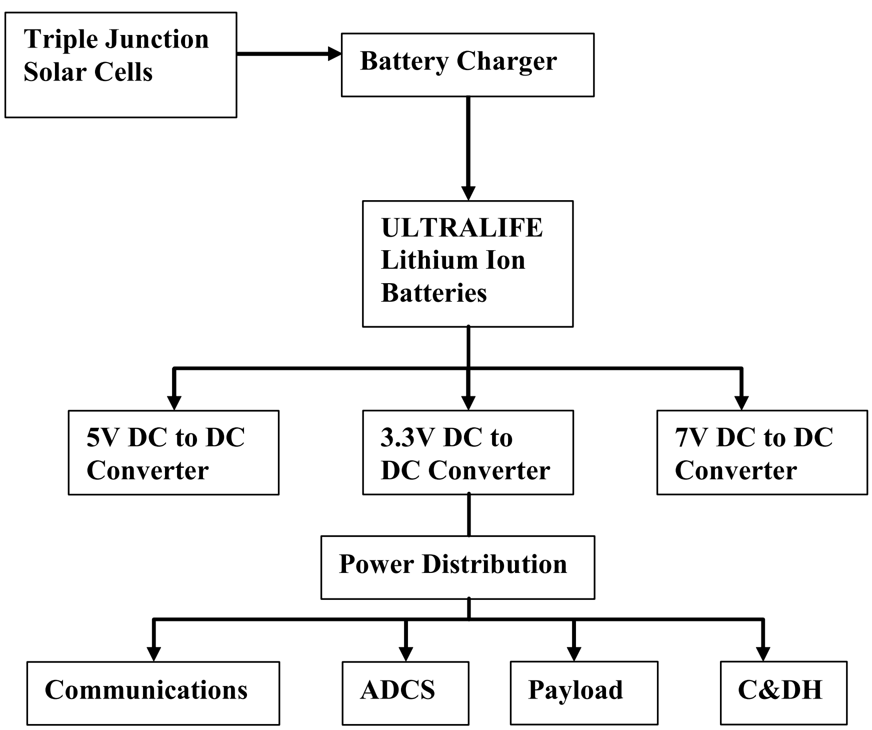


Figure (7): Power Distribution Subsystem Architecture

The Telemetry and Communication System:

The Communication subsystem team is responsible for the communication link between the satellite and satellite ground station. Our communication system design consists of two pieces of hardware which will be incorporated onto a printed circuit board (PCB) made out-of-house. The third piece of hardware in our system is the antenna mounted to the outside surface of a side of the satellite.

The transceiver that will be used is the Melexis TH7122. The transceiver also allows for a wide range of frequency: 27 to 930 MHz (the chosen frequencies for data transmission and reception is approximately 440 MHz). The transceiver is a very small integrated circuit. The power consumption of this part is minute and also contains a low power mode. The TNC (or Modem) that will be used is MXCOM MX614 or an equivalent model. The modem has 1200 bits per second baud rate and performs FSK modulation. The main advantage of FSK modulation is its reliability and precision. The satellite will have a chance to communicate with the ground station at Saint Louis University at least once per day. With each pass over Saint Louis, there will be an absolute minimum transmission window of five minutes. With a conservative transmission window estimate of five minutes and a baud rate of 1200, approximately 30KB will be able to be transferred at each pass.

The antenna device will be designed using the "tape measure" approach. The basic component of this device is a two meter long antenna that will likely be stowed until deployment in a rolled-up configuration (like a tape measure) and bound by a micro-ohm resistor that will disintegrate when a small current is passed through it. The antenna will be fabricated and designed in house during the second semester. The length of the antenna is still a work in progress, because there is also the possibility of using a half wavelength antenna instead of a full wavelength antenna. An advantage of the full wavelength antenna is the signal gain of the antenna, but a disadvantage is the mass; the mass of the full wavelength antenna is double that of the half wavelength antenna.

The Command and Data Handling System:

The Command and Data Handling subsystem team is responsible for the microprocessors and other on-board digital support circuitry. Automated tasks are run by a Rabbit Semiconductors (RCM 2020) microprocessor. The communication between the CPU and each secondary processor will be handled through the RS-232 signaling protocol. The RS-232 protocol was chosen because for two main reasons. First, the protocol is easy to use and implement in hardware. Second, all the microprocessors have a UART included.

Figure (8): The Rabbit Semiconductors RCM2020 Core Module

The Camera Payload System:

The payload subsystem will consist of a camera module and a microprocessor. The camera will be on the side of the satellite facing the earth. This positioning will be maintained by the attitude determination and control system (ADCS). The camera system will speak to the CPU, consume low power while in sleep mode, and have small dimensions with little mass. The camera microcontroller will be used to compress the images down to a data size to allow data transmission within the time frame that the satellite will communicate with the ground station.

The camera module that will be used is the C328-7640 from the online distributor electronics123.com. The image sensor and compression engine both come from Omnivision. The system was selected for its small size, low power consumption, and easy interfacing. This camera also includes a programmed microprocessor on board that compresses the picture. The camera will operate in two modes: a full power mode and a low power mode. The payload subsystem will interface to the CPU and the power bus.

Figure (9): Payload Camera Subsystem

For communication with the satellite to gather the telemetry data and to send necessary control command signals back to satellite, a Satellite Ground Station must be commissioned on the ground. Currently, a Satellite Ground Station is being designed and commissioned in the Saint Louis University campus. The next section describes the present state of the ground station.

Satellite Ground Station:

The goal of the Satellite Ground Station (SGS) is to communicate with the satellite, whenever the satellite passes over Saint Louis. This means that the ground station should be able to receive data from the satellite, and send any commands or other relevant data to the satellite.
For the SGS to perform properly, the minimum amount of hardware that is necessary is shown below:

- Tracking Antenna (UHF and VHF) for receiving and transmitting satellite data and satellite commands.
- Antenna rotators for autonomous antenna tracking.
- A radio transceiver to receive and transmit data.
- A Terminal Node Converter (TNC) Modem to convert analog data from transceiver to digital data for computer data handling and vice-versa.
- A Computer for data handling, satellite orbit prediction software and autonomous antenna tracking.

Figure (10) below shows the overview of the SGS hardware.

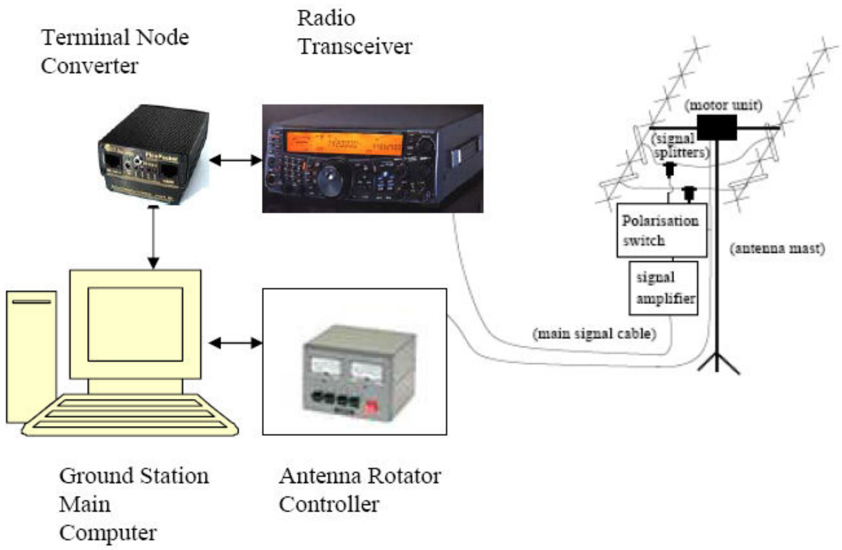


Figure (10): SLU Satellite Ground Station Hardware Architecture

Education and Learning Aspects of the Program:

With a growing number of universities and high school students participating in the CubeSat program, the educational benefits are tremendous. This program is assisting Parks College undergraduate engineering students, through hands on experience, to develop the necessary skills and knowledge needed to succeed in the Aerospace Industry.

Parks College of Engineering and Aviation at Saint Louis University strives to cultivate engineers by providing early and sustaining motivation as just one aspect of a good engineering curriculum. The engineering education experience is further enhanced through this Cubesat Program by allowing students to work on open-ended engineering projects that expose them to all of the realities of engineering: working to specifications, securing funding and keeping within budget, maintaining documentation, leading and working in multidisciplinary teams, conducting design reviews, and more.

By the Interdisciplinary nature of this program, undergraduate students are getting valuable experience in the following engineering education aspects:

- Acquire valuable education in a multi-engineering design environment, where the students have to collaborate and work with their counterparts from other departments to achieve a common goal.
- Provides students with real hands-on design experience.
- Students are obtaining System Engineering experience, where the students are supervisors and specialists.
- Students get exposed to the concept of "Teamwork", where it's about 'human resource', time and schedule management, workload distribution, PR in recruiting students and focusing on common goal.
- For the students to be more competitive by present them with both collaborative and competitive experiences with students from other institutions.

Since this project is a part of Senior Capstone Design course sequence, students are required to demonstrate all of the ABET criteria (a – k). Some of the additional ABET related learning outcomes articulated by the project to foster educational objectives are:

***Communications*:** Throughout the project, students held weekly subsystems team meetings. Leaders of each subsystem team met with each other weekly as well. Documentation has been archived in the form of written reports and web pages. A preliminary design review and critical design review involving all of the students and the Industrial Advisors took place. All of these activities reinforced the fact that communication was essential to project success.

Multidisciplinary Engineering: Electrical and Computer engineering students are exposed to other typically non-EE/CPE topics such as vibration, thermal dissipation, outgassing, and structure design and analysis. Similarly, Aerospace and Mechanical engineering students are learning how to tailor their antenna ground station structure to optimize signal reception and how the choice of battery system and on-board computer influences their decisions in designing and/or selecting actuators and sensors.

Mentoring: Senior undergraduate students currently involved in BillikenSat1 as their capstone design project are serving as team leaders for the various subsystems. Younger students, such as freshman, sophomore, and junior students who are involved in BillikenSat1 project are mentored by the seniors and serve as apprentices.

The proper balance between student management and faculty management is one of the positive outcomes of the project. Regardless of the level of student management, the BillikenSat1 project is subject to regular design reviews, which includes presentation and reports and performance tests. Local industry aerospace engineers are invited to participate in these events. These milestones are set to coincide with the semester schedule of SLU. Students also use proven systems engineering techniques such as needs assessment and trade studies during their design process.

Also, students have the opportunity to put into practice many subjects they had learnt in the university, gain valuable experience in satellite design, fabrication, integrated testing, launch, operation and analysis of results, gain multidisciplinary collaboration and design experience and finally a team-oriented training opportunity unlike any other undergraduate programs.

Conclusions:

In the first five months since the initiation of the BillikenSat 1 senior design effort, we have made excellent progress in refining the mission goals, defining the system architecture, and designing the BillikenSat 1 subsystems. The BillikenSat 1 project has achieved two primary objectives: (1) the group of students who have worked on the project will leave the university with a great deal of ”Hands-on experience” within satellite design and experience, working with a design project that requires multidisciplinary student involvement and cooperation, (2) This first satellite design will provide tremendous amount of feedback and experience to future Cubesat and Nanosatellite designs and will be a sound starting point for the next generation satellite projects at Saint Louis University. The newer crop of students will utilize all the experience gained from the BillikenSat 1 project. Many of the sophomores and junior undergraduate students are already working with the senior design students and various other steps are being taken to facilitate the transition to the next group of students.

Future Work:

In the next five months, the planned schedule will allow the students to start fabrication of the outer structure of the satellite and complete the thermal and stress analysis. All the required components and parts have already been purchased or donated from various companies. The Printed Circuit Board (PCB) designs of various subsystems will be completed and the boards will be fabricated. Subsystem Integration and Testing will be conducted using facilities like Vibration Test-bed and Thermal Vacuum Chamber. The completely integrated BillikenSat 1 will be subjected to various vibration and bake testing to satisfy the CubeSat Program specifications and also to satisfy the Launch Vehicle requirements. Our intention is to complete the Flight Model of the satellite, satisfying all the testing requirements by the end of May 2006 and probably request a launch window by end of 2006.

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