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Smaller than Small, Faster than Fast, Cheaper than Cheap
The BARNACLE Satellite Project

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Abstract

The BARNACLE micro-satellite is an extremely simple low-cost space vehicle for the characterization of electronic instruments in space. The satellite was developed in less than one year by a group of seven undergraduate engineering students with no previous spacecraft design experience. The satellite was built for under $2,000 of the students own money with most of the hardware donated by industry and university sponsors.

The craft includes a Motorola 68HC11 microprocessor-based subsystem for system control, with a logic system to back up the processor in the case of failure. Power is regulated by high-efficiency switching mode regulators in the power subsystem. Communications between the craft and ground stations is handled by the communications subsystems providing full-duplex AFSK communications at 1200 baud. The instruments are interfaced to the control core logic and microprocessor through the sensor interface subsystem.

After testing, the satellite will be launched in a tube configuration aboard a non-orbital sounding rocket in August 1998. A cube configuration of the same satellite is being considered for an orbital launch in 1999.

1. Introduction

There is a strong demand for the space characterization of electronic instruments. Normally, costly earth simulations are used for this testing. Unfortunately, while testing on Earth provides preliminary evidence that the electronic instruments will function in space, it provides no absolute proof. University based projects offer a low cost and perhaps risky alternative to this method of instrument characterization.

With this in mind our team developed the BARNACLE Satellite, a very low cost micro-satellite for characterizing electronic instruments in space. To keep launch costs down, the satellite was designed to attach to a deployed portion of rocket shrouding as a secondary payload; thus the name BARNACLE, because our satellite will remain attached to a rocket similar to how a living barnacle attaches itself to a ship. Its first flight, in August of 1998, is a flight test of some COTS accelerometers for JPL and a subsystem test for Stanford University's SSDL. This flight is non-orbital sounding rocket launch of the completed satellite is currently scheduled for August 1998 as a part of the CATS[1] prize contest.

Expected out-of-pocket expenses have not yet exceeded $2,000 and the entire craft is valued at well under $50,000. Funding for the project has been provided by both the design team and through industry partner donations.

Stanford is also interested in the project management aspects of the project. Specifically, they are interested in how a group of seven undergraduate students built, tested, and launched a micro-satellite in about one year – which to our knowledge is a first at the university level. The rapid one year design timeline is shown in Figure 1.1, below. The project began in July 1997 with the orbital design completed in March 1998 and the rapid (and somewhat unexpected) non-orbital sounding rocket launch configuration design completed in May 1998.

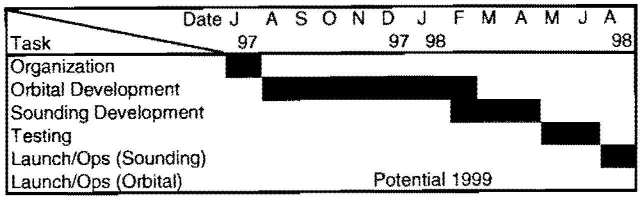

Figure 1.1 – Project Gantt Chart

In fact, because of the successes of this project, our mentors from Santa Clara University's SCREEM Laboratory and Stanford University's

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[1] CATS – (Cheap Access to Space) contest to be the first amateur group to launch a rocket beyond the 200km barrier. There is a cash prize and lots of publicity involved for the winner.

Space Systems Development Laboratory have together initiated the ParaSat space flight program [1]. The BARNACLE is now the first ParaSat. Similar to the BARNACLE design guidelines, the general ParaSat-class satellite design guidelines are: orbital lifetimes on the order of days or weeks are acceptable, cash expenditures are limited to about $5,000, limited or no functionality for several subsystems is permitted, and permanent attachment to spacecraft and/or rocket stages is acceptable.

The following sections provide a detailed look at various aspects of the BARNACLE satellite and its subsystems.

2. System Description

2.1. Systems Overview

The BARNACLE satellite has six discrete subsystems: structure, power, sensor, CPU, logic, and communications. Power is supplied by two separate battery packs and is regulated and made available to the system power bus through the power subsystem. Test instruments are connected to the sensor interface board that, in turn, connects the sensor data to the logic board via the system I/O and interface bus. The CPU and logic boards interface through their own I/O and power buses. An umbilical port allows the external monitoring of both the system power and I/O buses as well as allows an external power source to be connected to the craft via the power subsystem. The measured satellite power consumption is shown in Figure 2.3. A functional block diagram indicating the interaction of each subsystem as described is shown in Figure 2.1.

The mass of the satellite is an important factor for our sounding rocket launch provider as they are participating in the CATS contest. In order to be considered for launch as a secondary payload, we were required to keep the mass of our satellite low. The measured satellite mass is shown in Figure 2.2.

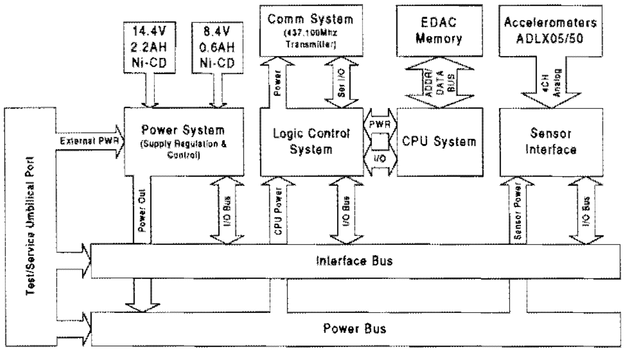

Figure 2.1 – System Block Diagram

Component	Mass (kg)
Electronics	1.475
Structure	5.75
Cabling	0.250
Batteries	12.70
Total	**20.175**

Figure 2.2 – Satellite Mass

	CPU Mode	Logic Mode
CPU:	125	0 mW
Logic Core:	25	25 mW
Communications:	432	450 mW
Sensor Subsystem:	64	21 mW
Power Subsystem:	65	65 mW
Regulation Losses:	205	160 mW
Total:	0.92	0.72 W

Figure 2.3 – Power Consumption

Each subsystem plays a vital role in the operation of the satellite; a detailed discussion of the systems follows:

2.1.1. Structure

Two mission-specific structures were designed to house the BARNACLE Satellite electronics and batteries. Designed for Low-Earth Orbit and a battery capacity sufficient to supply the satellite for three weeks, a 10” cubical form was favored. In order to accommodate the sounding rocket launch, a new structure was also realized in a 6” compact cylindrical form designed to carry battery power for a short duration flight of less than one hour.

The 10” LEO structure is an easy to manufacture, lightweight frame and enclosure that protects the internal satellite components from the launch and space environments. The internal LEO satellite structure measures 9”x 9”x 9”. Each side is composed of panels of a 3/8” thick aluminum panel milled to minimize mass and to form a strong supporting frame. The structure is composed of only four distinct parts, not including fasteners. This part standardization was used to preserve ease of manufacturing and assembly while also simplifying structural and thermal analysis.

To maintain temperature equilibrium and to keep the batteries and electronics within their operating temperature range, we utilized passive thermal control and decided to use large conductive pathways to transfer heat. We found that active thermal control, such as heaters and coolers, were unnecessarily complicated given both our short space life and rapid design cycle times.

We utilized three main methods to deal with resonance due to vibration during launch. First, we used short-length members with a high moment of inertia. Second, we attached masses at structural nodes. Lastly, we utilized a silicone gel for elastomeric dampening at locations where we expected or discovered vibration problems.

Figure 2.4 shows a simple layout of where each electronic subsystem is located in the LEO satellite structure. Figure 2.5 shows the assembled satellite in the LEO configuration.

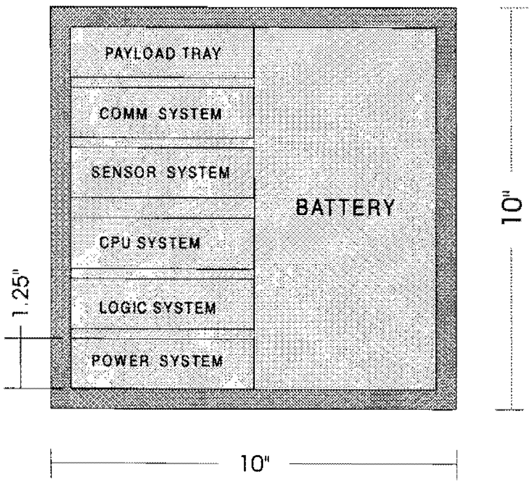

Figure 2.4 – Layout of LEO Structure

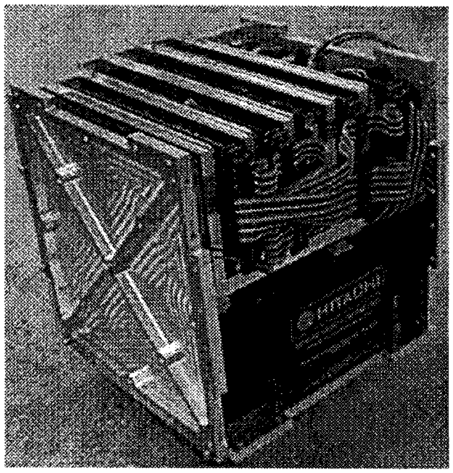

Figure 2.5 – The BARNACLE Satellite (Orbital Configuration)

The sounding rocket structure preserves all of the LEO structure features, lightweight, ease of manufacture, passive thermal management, etc, while significantly compacting the satellite. Unlike the 10" LEO cube, the rocket structure relies on the walls of the rocket itself to provides external environmental protection for electronics and batteries while it provides the mounting framework.

Figure 2.6 depicts the layout of electronic subsystems as they are located on the rocket satellite structure. Figure 2.7 shows the assembled satellite in the non-orbital sounding rocket configuration.

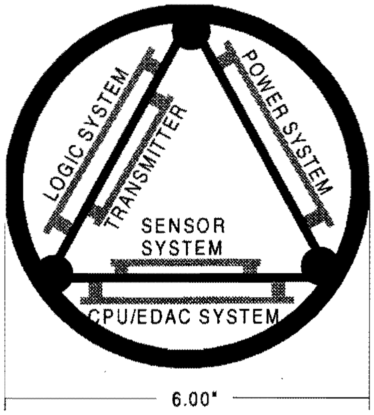

Figure 2.6 – Layout of Sounding-Rocket Structure (top view)

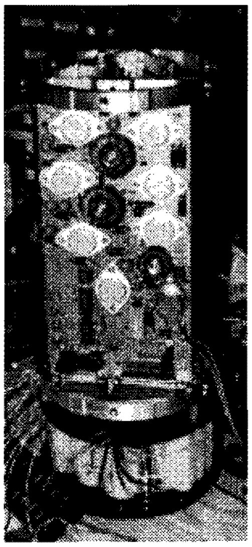

Figure 2.7 – The BARNACLE Satellite (Non-Orbital Configuration)

2.1.2. Power

The power subsystem was designed to provide stable, efficient, and reliable power. Power is central to all of the electronic subsystems; if it fails nothing else can function. The spacecraft can be powered from two battery packs for maximum efficiency or from a single pack for convenience. The main battery pack requires a minimum voltage of 14.4V and supplies power to the communications and sensor subsystems. Buck-mode switching regulators efficiently convert the battery pack voltage down to 12V for the communications and sensor subsystems and 5V is also provided for the sensor subsystem. The availability of both 5V and 12V lines for the sensor subsystem allowing for flexibility and accommodating many different types of sensors. Because of the fundamental importance of power to the entire satellite, a redundant regulator takes over in case of a primary supply failure. The rated and tested efficiency of these switching regulators is about 75% at the appropriate load currents. The logic and CPU subsystems can be powered from a separate battery source when total lifetime is a major concern. The separate battery was needed because the efficiency of switching regulators is very poor at the load current of the CPU, and therefore the CPU power draw would significantly reduce the maximum lifetime of the satellite if switching regulators were used. Because of this, the 5V CPU power is provided by a linear regulator used with a separate battery (7V minimum). This circuit also powers the logic components of the satellite. The resulting efficiency is a maximum of 67%, about twice as efficient as could be provided from the 14.4 battery. Figure 2.8 shows the interconnection of the power subsystem to the other subsystems.

An additional feature of the power subsystem is an overcurrent shutoff circuit. This circuit will shut off the power to the CPU if it draws too much current, as in the case of a hard latchup, which is often caused by radiation. The shut off is accomplished by sensing the current running to the CPU and if the current is significantly above the normal operating level, the power is switched off for about 10 seconds before it is switched on again. If the processor again draws excessive current, it will be switched off and the process repeated. There are many purposes for this overcurrent protection: it protects the processor from being damaged if an event such as a latchup occurs, and it also prevents the battery from being drained prematurely. In addition, the protection circuit allows the backup logic circuit to take control of the satellite and record that a processor failure has occurred.

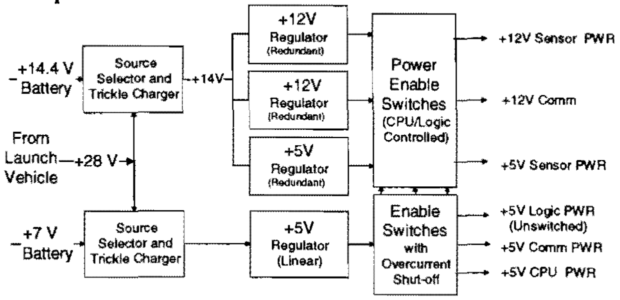

Figure 2.8 – Power Subsystem Block Diagram

2.1.3. Sensor

The sensor subsystem interfaces the CPU and logic subsystems to the primary sensor payload of the satellite being characterized. The goal of this subsystem, and the BARNACLE craft as a whole, is to allow a variety of sensors to be characterized without requiring a system redesign. This subsystem provides a flexible interface to external sensors with one to four digital or analog signal output channels and provides 12V and 5V power.

The primary sensor payload for the upcoming sounding rocket launch is four commercial off the shelf (COTS) accelerometers from Analog Devices. These sensors were chosen for three main reasons. First, the recent interest of the space industry in verifying and then utilizing COTS components in space pointed us towards sensors of this type. As students, with both time and money constraints that are far tighter than those of the space industry, we found the high availability and low cost of COTS components to be a big push toward getting these sensors. Second, these particular sensors are easily integrated into our bus. Third, because accelerometers will provide a good assessment of our spacecraft's design during the sounding rocket flight. In fact, launch simulation data suggests that we will be able predict the accelerometers output during the launch and subsequent decent of the rocket.

Specifically, the Analog Devices accelerometers that were chosen were the ADXL05 and the ADXL50. Each of these accelerometers can be configured to measure –5g to 5g and –50g to 50g's respectively. In their current configuration they output 2.5V at 0g, 0.5V at –5 or –50g (minimum value for the sensor), and 4.5V at 5 or 50g (maximum value for the sensor). This setup was perfect for the 0V to 5V A/D converter on our CPU subsystem.

The two ADXL05's are mounted to measure radial accelerations in the rocket and are configured to measure –5 to 5 g accelerations. One of the ADXL05's is configured to measure AC accelerations (from 0.1 Hz to 300 Hz) and the other is configured to measure DC accelerations (from 0 Hz to 300 Hz). The two ADXL50's are mounted to measure vertical accelerations in the rocket and are configured to measure accelerations from –50g to 50g. Like the ADXL05 configurations, one of the ADXL50's is configured to measure AC accelerations (from 0.1 Hz to 300 Hz) and the other is configured to measure DC accelerations (from 0 Hz to 300 Hz).

The 300 Hz cutoff frequency was chosen to prevent aliasing as the maximum sampling frequency of the A/D converter that will be used will be in the area of 600 Hz to 1kHz. For the sounding rocket launch the satellite operating system will be sampling the data at around 1kHz and sending the maximum, minimum, and average sensor values to earth. All of the sensor data cannot be sent due to bandwidth limitations (a 1200-baud modem). This portion of the software can be reconfigured for future flights depending upon the needs of the sensor payload provider. The interconnection of the accelerometer subsystem can be seen in Figure 2.9.

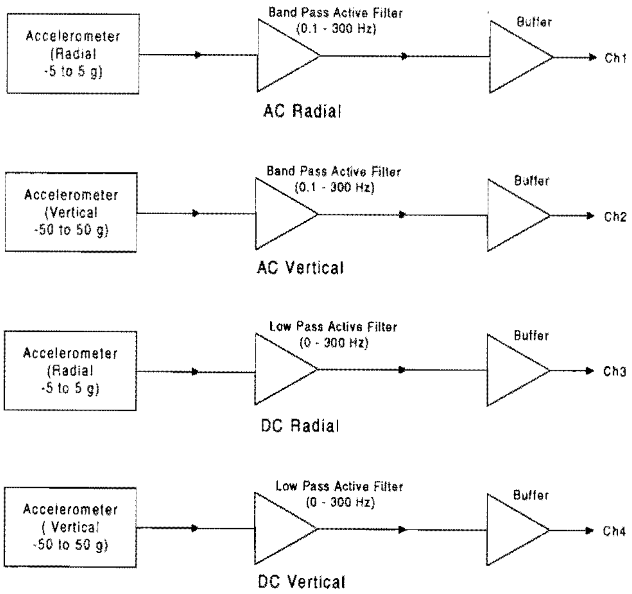

Figure 2.9 - Accelerometer Interface Block Diagram

2.1.4. CPU

We chose to utilize a CPU to control the satellite rather than logic alone (discussed in Section 2.1.5) for two main reasons. First, the CPU, long with memory, provides data logging capabilities allowing our customers to retrieve a complete orbit's worth of data rather than just real-time data during transmissions to ground stations. Second, the CPU can be more intelligent about when and what it samples and transmits, allowing more data to be collected versus power consumed. For example, during the sounding rocket launch the CPU will be collecting real-time data from the accelerometers at a high frequency and transmitting the max, min, and average values from the sensors to provide more information about sensor behavior.

We chose a Motorola 68HC11 microcontroller primarily because of our rapid development cycle time and our previous experience using the 68HC11. A processor tradeoff matrix based on the knowledge base, simplicity of use, availability, cost, space lifetime, embedded computing power, and power consumption is shown in Figure 2.10. Because of the widespread use of the microprocessor in the university environment, we found that if it were proven viable in space, the 68HC11 would provide a good alternative to more complicated, and expensive, space-rated microprocessors for university projects.

Category	**Rating**	**68HC11**	**x86**	**68332**	**COP8**⁺
Knowledge Base	0.4	90	50	40	10
Simplicity	0.3	85	40	45	50
Availability	0.1	100	90	85	100
Cost	0.05	100	60	80	100
Lifetime	0.05	80	100	100	100
Computing Power	0.05	100	100	100	100
Power Consumption	0.05	100	100	80	100
Adjusted Total	1	90.5	59	56	49

Note: ⁺ represents automatic disqualification.

Figure 2.10 – Processor Decision Matrix

The supporting hardware contains 16Kbytes of ROM. In addition the system includes a 32Kbyte RAM module used for system variables and sensor data storage. Given the risk of single even upsets due to cosmic radiation, error detection and correction (EDAC) is performed using two additional 32Kbyte RAM modules maintaining identical memory contents to the first and used in conjunction with supporting hardware to determine memory errors. The 68HC11 has an onboard 8 channel, 8-bit A/D converter used to sample the sensor data. In addition, both an internal and external watchdog timer are used to reset the CPU in the event of a problem. For both development and flight we chose a New Micros development board. The flight version of this board has been modified to make it more tolerant of the forces encountered in the launch and space environments.

The CPU operating system consists of a simple timer and event driven task scheduler. The primary purpose of the O/S is to sample, store, and transmit sensor data, so all operations and O/S design decisions were based on that fact. The O/S is flexible and can be changed up until very near launch time, allowing us maximum flexibility for changing payloads and customer needs. The CPU subsystem also handles all data packetizing including the KISS[2] framing allowing our data to pass through standard ground station hardware systems and be decoded in our ground station software package, or recorded for later decoding. The communications are discussed further in Section 2.5.1.

2.1.5. Logic

As previously stated, limited information suggests that the 68HC11 could fail in anywhere

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[2] KISS – Keep It Simple Stupid (a frame format including start and end flags along with frame size information).

from a few hours to a few months due to cosmic radiation. Radiation affects the processor in three ways, single event upsets, hard latchups, and total dose. A single event upset is the result of a high energy particle striking the processor causing a single bit to change state. A hard latchup occurs when a high energy particle strikes the processor and causes a short. Total dose is the result of the processor being exposed to radiation over a period of time such that the processor fails to function entirely [2].

Because of this potential for processor failure, a logic subsystem was designed to provide a backup. After 27 seconds of CPU inactivity the logic subsystem is activated. To ensure that the CPU was not prematurely deactivated the logic subsystem periodically resets the CPU. If the CPU is not dead then the CPU will resume control of the satellite. If the CPU continues to be unresponsive the logic subsystem takes over all satellite operations. This entails transmitting real-time digital status and instrument data serially to the ground station.

In addition to the hardware necessary to sample and transmit the data, we have hardware that stores the time of CPU failure, the number of times the CPU is reset, and switches to the logic backup system if and when CPU failure occurs.

There are currently two versions of the logic backup system. The initial version was designed and built to operate a satellite that would orbit in a LEO environment for several weeks. With such a long time in space, power consumption became a concern, so an uplink system was included in this version of the logic backup system. An uplink system enables the satellite to conserve power by allowing it to only transmit when a ground station is ready to receive and record data. The second version of the logic backup system is a simplified version of the system just described. This logic system was designed for a short flight on a sounding rocket. During this flight the satellite will be transmitting the entire time, so the uplink system was removed.

The connection interface between the logic subsystem and the rest of the subsystems is shown in Figure 2.11.

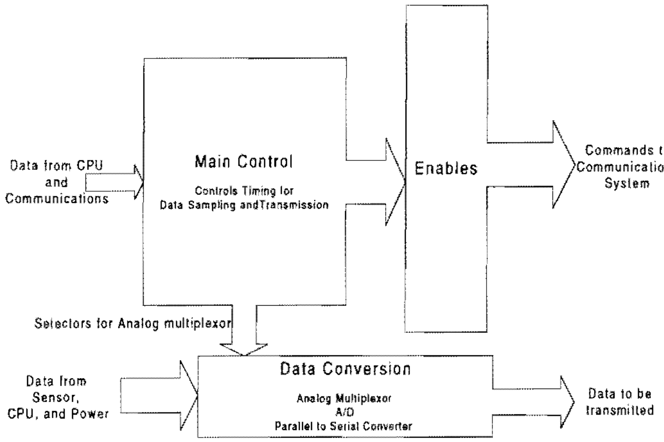

Figure 2.11 – Logic Control Core Block Diagram

2.1.6. Communication

The communication subsystem provides a reliable method of exchanging data with ground stations on Earth. While the comm system may be separated physically into three distinct parts, a modem, a radio receiver, and a radio transmitter, it functionally serves two purposes, uplink and downlink. The design for both the Low-Earth-Orbit and sounding-rocket versions of BARNACLE incorporate the same modem and transmitter for downlink while the LEO version adds a receiver to this configuration to support uplink.

Common to both the LEO and sounding-rocket versions of the BARNACLE Satellite is a downlink communication mode. During downlink, the modem receives serial digital data at 1200-baud from the CPU/Logic control system which it then encodes using AFSK[3] modulation. This baseband audio signal is passed to the RF section for transmission to earth. While this simple functionality is sufficient for sounding-rocket operation, for the longer LEO mission, an uplink was needed. Uplink operation reverses the data path; RF signals from a ground station are captured by the receiver and the resulting baseband signal is passed to the modem. Once filtered and demodulated, the modem sends the data, in digital form, to the CPU and Logic systems. The interconnection of the modem and radio components is shown in Figure 2.12.

The heart of the BARNACLE communication system is the modem. Based on the TCM3105 from Texas Instruments, the AFSK design conforms to the Bell 202[4] standard making the

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[3] AFSK – Audio Frequency Shift Keying (a form of data modulation).

[4] Bell 202 – Telecommunication tone standard (1200/2100Hz).

satellite compatible with terrestrial packet modems and allowing it to be easily contacted using existing amateur ground stations. The handshaking functions and packetizing normally associated with packet radio links is handled in the satellite by the CPU and Logic subsystems. To save board space on the sounding-rocket version of BARNACLE, the communications modem was incorporated into the logic control system.

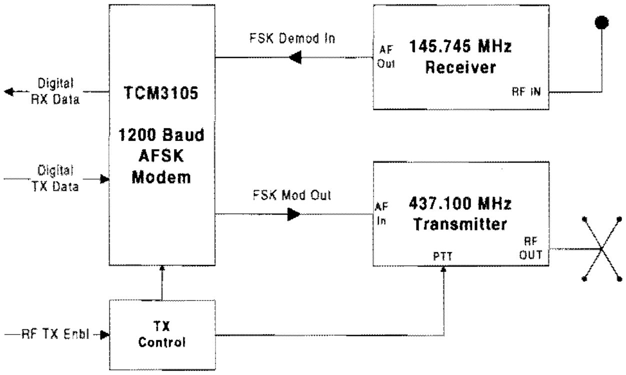

Figure 2.12 – Communications Subsystem Block Diagram

Since the satellite operates on Amateur radio bands, the communication system uses a J-Mode[5] link, a standard for amateur satellite communication. The RF hardware aboard the satellite includes a 145 MHz Hamtronics R144 receiver serving the satellite's uplink, and 437 MHz Hamtronics TA451 transmitter at 2-watts for downlink. These Hamtronics units were selected for their reliable performance, sharp bandwidth, and wide temperature stability. Since both the receiver and transmitter are designed for terrestrial use, they required modifications to withstand the vacuum and radiation environment of space. The LEO satellite utilizes a single 50cm quarter-wave whip antenna for receiving and a quadrapole antenna (17cm elements) for transmission. Alternatively, the sounding-rocket transmit-only antenna is a 34cm steel dipole mounted just behind the rocket's forward bulkhead which deflects the supersonic shock-wave. The link budget, Figure 2.13, describes the performance of the communications subsystem as a whole.

BARNACLE Communications Link Budget	Uplink	Downlink	Units
Frequency	145	437	Mhz
Distance to Satellite (max horizon range)	3200	3200	km
Transmitter Power (C)	16.99	3	dBW
Transmitter Antenna Gain (G)	14	-5	dBi
EIRP (Effective IsoTropic Radiated Power)	30.99	-2	dBW
Free Space Losses	150	150	dB
Receiver Antenna Gain	-15	14	dB
Receiver System Noise Temp (Te)	30	26.02	dBK
Bit Rate (1200bps)	30.79	30.79	dBHz
Boltzman constant	-288.6	-288.6	dB/K/Hz
G/Te (Receiver Ant Gain/Noise Temp)	-44	-12.02	dB/K
Desired Min. Eb/No (Bit Energy/Noise Ratio)	7	7	dB
Eb/No at receiver input	37	25	dB
Margin	30	18	dB

Figure 2.13 – Communications Link Budget

2.2. Feature Notes

In order to speed up production time and simplify implementation, some features found in larger more complex satellites are not part of the BARNACLE satellite. Two features that were not included are:

- Attitude control – All our communications and sensors were designed to operate in any orientation, so this feature was unnecessary and would only have required more development time. If future sensors need the satellite to be in a particular orientation, passive attitude control can be added without requiring design changes to any of the electronic subsystems.
- Solar cells – From testing we have demonstrated that we can fit enough battery power inside the system to last for the mission minimum requirement. Solar cells would provide a longer lifetime but are difficult to mount and must be done professionally to be space certified, because they may shatter and damage the launch provider. This feature could also drastically decrease our chances of obtaining a launch. This feature also would have extended our development time by nearly one year.

2.3. Mission Operations

The complete operations of the satellite are performed by hardware and software both on the satellite and on the ground. Figure 2.14 presents an overall picture of the satellite operations and the interaction between the satellite and Earth based ground stations. This system is designed for a satellite in orbit and the operations involved in an orbital environment. For the upcoming rocket launch of the satellite some of the orbital operations will not be in effect. During the rocket launch we will only transmit real-time min, max, and average accelerometer sensor values from the satellite and log

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[5] J-Mode – Satellite communication standard (437 Mhz downlink, 145 Mhz uplink).

that data in our ground station throughout the entire flight.

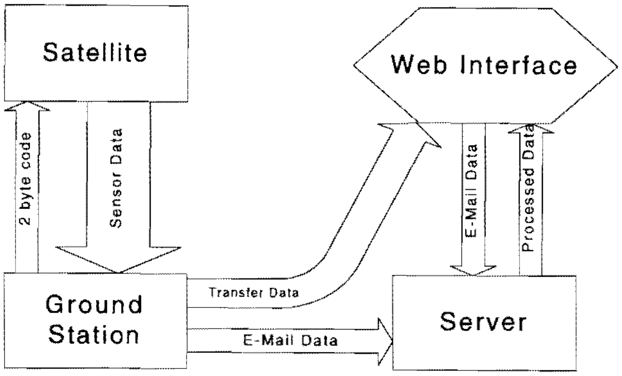

Figure 2.14 – Diagram of Operations

The operation of the satellite consists of collecting sensor data and transmitting that data to Earth. Once a ground station has received data from the satellite it collects that data and sends it to the server. Operations on the satellite and on the ground are discussed in the following sections.

2.4. Operations on the Satellite

The operational objective of the orbital satellite is to collect sensor data and send it to ground stations on Earth. The operations on the satellite are separated into two major divisions: data logging and transmitting data. Note that in the case of processor failure, data is not logged. Instead real-time data is sent down to Earth via the logic backup subsystem. The logic backup operational details can be found in Section 2.1.5 which describes the logic backup subsystem.

2.4.1. Logging the Data

The satellite collects an entire orbit's worth of data (approximately 90 minutes) to gain a complete picture of the satellite and sensor performance around the entire planet. For the non-orbital launch as much data as possible is logged along with the transmission of real-time data to allow potential data recovery upon rocket retrieval which would be useful in the case of a transmitter failure during the rocket flight.

2.4.2 Requesting/Transmitting Data

For the orbital O/S two modes for requesting and transmitting data were chosen: beacon mode and data mode. The data mode allows ground stations to collect all of the status and instrument data from the satellite. The beacon mode allows ground stations to monitor satellite health information as well as assist ground stations with their antenna positioning and tuning. For the sounding rocket launch no receiver is included on the satellite and the beacon mode is disabled. Instead, we begin transmitting real-time data as soon as the rocket begins its launch.

2.5. Operations on the Ground

All ground stations can be equipped with our Microsoft Windows 95/NT based application capable of communication with the satellite as well as collecting, decoding, analyzing, displaying, and transmitting the collected data to the server which can then archive and make the data publicly available through our web site. If a ground station does not have a machine running Microsoft Windows available it can collect the raw data in any terminal program and send it to our server via e-mail or transfer it through a form on our web site.

2.5.1. Communication with Satellite

Beacon mode transfers are performed by the satellite at fixed intervals and this data can be automatically picked up by the ground station application and added to the system health and status information logs. Once the satellite is within communication range the ground station must send a request code to the satellite which, upon receipt of the code, packetizes logged data and transmits it.

The data being sent from the satellite is packetized using our own format including redundant data for both error detection and correction. This data can be framed to pass through hardware TNC's[6] used in ground stations via KISS mode. Since no data validation is performed by the TNC we can log all data including possibly corrupt data. This has limited uses, but is important in cases where the logic backup subsystem has taken over, or we want partial data.

Once the packet data has been decoded it is stored in data files ready to be transferred to our server. Ground stations using our application are also able to examine the collected data graphically and numerically. This is useful for both scientific research and educational purposes.

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[6] TNC – Terminal Node Controller (a radio packet modem used for decoding the data received by the radio).

2.5.2 Communication with BARNACLE Server

Once a ground station has collected data it can send the data to our BARNACLE server for any additional post processing and archiving as depicted in Figure 2.11. Since we are including other ground stations in the data collection process we had to make it simple for anyone in the public to send us data and at the same time make sure the data sent was valid. Since receiving bad data could cause numerous problems and erroneous results, we have devised a scheme that both validates the data sent to us is "real" and also encourages people to collect and send us that data.

To perform this dual task every piece of data sent from the satellite includes a key which must be included with each data submission. This key is based on a combination of various information onboard the satellite such as running time and sensor values. This key and data can be quickly validated by our server at which point the person sending the data is allowed to enter their name, e-mail address, and a comment. We will keep a database of this information publicly displayed on our web site as a reward for those who take the time to collect data for us. This is designed to encourage people to collect data and to thank those that have.

Once the data has finally been transferred to the server and validated along with all additional decoding and post-processing it is archived and anyone can view the data via the web [3].

3. Testing

The satellite testing for the LEO orbit will involve three primary tests: shake, thermal vacuum, and radiation. These tests insure a launch provider that we will not damage or affect their equipment or primary payload in any way and verify that our craft will operate in space. After successfully passing each test, our satellite will be officially certified for launch.

3.1. Shake Test

The shake test serves to show our launch provider and the primary satellite owner that our satellite will not damage either the launch vehicle or the primary satellite during launch. The shake test simulates the forces and vibrations that the satellite must endure during launch. To prove that the structure of our satellite will not fail, the shake test will subject the satellite to conditions well beyond those expected. The forces and vibrations imposed on the satellite during test will sweep through a range of 0 to 20g's, with vibrations ranging from 2 – 2,000 Hz.

After being shaken, assuming the satellite does not physically break, it will be turned on to verify full electronic functionality. The results from this test will be evaluated using the success criterion that has been outlined in Section 3.4 below.

3.2. Thermal-Vacuum Test

The thermal-vacuum test assesses how the satellite will perform when subjected to the extreme temperature changes and vacuum found in space. Our two goals in performing this test are: 1) to ensure that the sub-system components can withstand a vacuum and 2) to ensure that the properties of the structure provide adequate thermal protection for the components inside. The thermal-vacuum chamber will subject the satellite to 0 – 500 W/m^2, while at the same time lowering the pressure to 10^{-6} Torr.

While in the thermal-vacuum chamber, the satellite will be run continuously and the results of the thermal/vacuum test will be evaluated using the success criteria outlined in Section 3.4 below.

3.3. Radiation Test

To simulate the effects of cosmic radiation on the 68HC11 microprocessor a series of radiation tests will be run. These tests are an important part of the testing strategy because of the importance that has been placed on determining the lifetime of the 68HC11 in space. The errors that can occur in a microprocessor due to radiation are put into three categories: single event upset, hard latchup, and total dose. Hans Thomas at Lawrence Livermore Labs has already performed previous testing on an unshielded 68HC11. His data indicates that a hard latchup occurs approximately once every hour. In order to prevent hard latchups from occurring so frequently the processor will be covered with a radiation hardened coating, and enclosed in a 100 mil. thick aluminum enclosure. Radiation testing will be performed on this new setup for the 68HC11 to see if the frequency of hard latchups has been reduced.

The radiation test is composed of two separate tests. The first test is mainly to determine the time before total dose occurs. The test is called a Cobalt 60 test. In this test the CPU will be bombarded with low energy radiation while it is running. The content of the CPU's memory will be monitored, as well as its frequency of resets. The second test is designed test for single event upsets. This test is performed by placing the CPU at one end of a proton accelerator and bombarding it with high-energy protons. The contents of the memory will be examined to see if individual bits have switched state. Upon completion of this test the results will be evaluated to determine if the processors performance has increased, decreased, or remained the same.

3.4. Success Criteria

3.4.1. Total Success

We define total success as all sub-systems performing to specifications and all sub-systems working together as designed. In order for the satellite to achieve total success, each sub-system and the entire craft must function flawlessly.

3.4.2. Partial Success

We separate partial success into three categories:

1. CPU failure, Logic success
2. Logic failure, CPU success
3. Sensor sub-system failure, CPU failure, Logic success

Partial success indicates that more testing must occur but will indicate that systems are functioning close to the design specifications.

3.4.3. Failure

If any components not listed in the partial success criteria fail, the satellite fails testing. If the satellite fails due to electronic failure, we will determine what caused the failure and repair the necessary subsystems. If the satellite fails structurally during either the shake testing or thermal-vacuum tests, some major change may need to be made to the satellite.

4. Conclusions

In summary, the BARNACLE micro-satellite is an extremely simple low-cost space vehicle for the characterization of electronic instruments in space. The satellite was developed in under one year by a group of seven undergraduate students with no previous spacecraft design experience for less than $2,000.

The satellite project has been very successful, giving us all a good glimpse into the real world of engineering. We took the project through the full engineering life-cycle: from conception and design to implementation and testing. Along the way we were faced with many real world engineering challenges: the harsh environment of launch and space, limited facilities (a lab set up in our garage), subsystem integration problems, changes in our launch provider and customer, changes in system requirements, major changes to the structure, and group problems. Adapting to these changes is where a large part of the learning experience in this project came from.

In addition, the project spanned three engineering disciplines, which added more to the learning experience than we ever expected. There is so much to be learned from a project like this it is something we feel should be a necessary component of every engineering student's curriculum.

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